Use of Superconductors in the Excitation System of Electric Generators
Adapted to Renewable Energy Sources

YBCO superconducting magnets for low speed synchronous generators

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Abstract — This thesis studies the general use of high-temperature superconducting materials in the transverse flux excitation system for low speed electrical generators, in particular the use of YBCO superconductors. First, an electro-thermal coupled model for simulation of bulk superconductors and its hysteretic magnetization was developed, tested and experimentally verified. The characteristics of high temperature superconductors under the influence of time-varying magnetic fields have been studied, specifically for the material YBCO, and their implication on joule losses, namely taking advantage of the electro-thermal model implemented in a finite element software. It was found that joule losses increase with the applied magnetic field and, in an almost linear dependency, with its frequency. Similarly, for better internal characteristics of the material, which provide better performance, higher losses are obtained. Regarding the two cooling techniques, and due to the characteristic hysteresis cycle of the material, it has been shown that Field Cooling has lower losses than Zero Field Cooling. Some temperature analyzes are done to support the results obtained.

Keywords — High temperature superconductors; YBCO; HTS modelling; Superconducting magnets; Bulk superconductors

I. INTRODUCTION

This paper aims to describe the work developed in [1]. First an attempt to replicate the work of [2] was done, and from there an attempt to quantify the value of the losses was done by computing the hysteresis area, and the thermal losses were also introduced. The losses were then studied with respect to the characteristics of the applied magnetic field and intrinsic characteristics of the material.

The electromagnetic model was later coupled with a thermal model to better study the temperature influence in the losses of the superconductor.

II. BASIC CONCEPTS

A. The Superconducting State

In order to fully grasp the concepts shown in this thesis, it is vital to understand what exactly the superconducting state is and what high temperature superconductivity is. Superconductivity is not only characterized by a negligible resistivity, but also by magnetic field “expulsion” from the superconductor’s interior.

High temperature superconductivity is associated with Type-II superconductors. These have a property called flux pinning in which magnetic field can be trapped by the superconductor, thus acting like a permanent magnet. This phenomenon is possible in type-II superconductors since they have impurities in its volume, which are not in a superconducting state, and are surrounded by the induced currents circulating around them, producing the so-called flux pinning.

The transition to the state of superconductivity can be done in two different ways: with no applied magnetic field at the moment of transition, a technique called Zero Field Cooling (ZFC), or with an applied field, a technique called Field Cooling (FC).

B. Critical Region

There are three different quantities that restrict the superconducting state: the critical temperature $T_C$, the critical magnetic field $H_C$, or respective critical magnetic flux density $B_C$, and the critical current density $J_C$.

If any of these critical quantities is exceeded, the superconducting state is lost. However, it can happen that these quantities are exceeded only locally, turning some parts of the superconductor to a normal state. These parts will turn superconductive again once the quantities in question fall back below the respective critical value. In the case of type-II superconductors, two critical magnetic flux densities can be defined, shown in Figure II-2: the first, $B_{C1}$, where the superconductor loses the property of magnetic field “expulsion” and enter a state of flux pinning. The second, $B_{C2}$, when the field is high enough to disable the magnetic properties of the superconductor, causing the loss of superconductivity.

C. Constitutive Laws

In superconductors, as there is no proportionality between $E$ and $J$, resistivity cannot be defined as in equation (II.1). The relation between the electric field $E$ and the current density $J$ is given by the non-linear $E$-$J$ power-law [2]:

![Figure II-1 - Volume defining the superconducting region](image-url)
In this relation, $E_0$ and $n$ are constants depending on the superconductor type, and $J_c$ is the critical current density of the superconductor.

The critical current density is function of magnetic flux density applied in the superconductor, being formulated by equation (II.2). Here, $J_{c0}$ and $B_0$ are constants dependent of the material, and $B$ is the norm of the magnetic flux density vector ($B = |B|$) [2]:

$$J_c(B) = \frac{J_{c0}B_0}{B_0 + B} \quad \text{(II.2)}$$

The term $J_{c0}$ in (II.2) represents the maximum critical current density of the material (for $B = 0$), while $B_0$ represents the value of the applied magnetic flux density that reduces the value of the critical current density to half of its maximum value: $J_c(B_0) = J_{c0}/2$. The critical current density can also be considered dependent on the temperature, given by equation (II.3), as stated by [4]. In this equation, $\alpha$ represents the critical current density at 0 K with no applied field.

$$J_c(B,T) = \alpha \left(1 - \left(\frac{T}{T_{c0}}\right)^{\frac{3}{2}}\right) \frac{B_0}{B_0 + B} \quad \text{(II.3)}$$

The critical temperature is also affected by the magnetic flux density over the superconductor [5]. In this case, $T_{c0}$ is the critical temperature when $B = 0$.

$$T_c(B) = T_{c0}e^{-B/30} \quad \text{(II.4)}$$

D. Type-II Superconductors

In this thesis, only Type-II superconductors are studied in detail. However, it’s necessary to distinguish between the two types of superconductors, in order to better understand the work developed.

Type-I superconductors are known to expel all magnetic field from its interior, according to the Meissner effect. This type of superconductors can only sustain magnetic fields lower than $B_C$, for temperatures lower than $T_C$. Generally, Type-I superconductors are also low temperature superconductors (LTS), only able to hold their superconducting state at extremely low temperatures (usually below 10K) and most of them are elemental metals.

Figure II-2 indicates that Type-II superconductors not only repel magnetic fields, but can also trap it inside. These superconductors have two critical magnetic fields, $B_{C1}$ and $B_{C2}$. Figure II-3 shows that, below $B_{C1}$, all magnetic field is expelled (fully superconducting state). Between $B_{C1}$ and $B_{C2}$, the magnetic field partially penetrates the superconductor, in what it is defined as mixed state. Above $B_{C2}$, the superconductor loses its superconductivity (normal state).

1) Flux Pinning

In the mixed state, the magnetic field is able to penetrate inside the bulk of the superconductor. This penetration only exists in tiny tubes known as flux tubes (Figure II-4 (a)), which are surrounded by superconducting current vortices, as shown in Figure II-4 (b).

The flux tubes are enclosed in areas of non-superconducting region, surrounded by superconducting current vortices. Note that this continues to satisfy the condition of magnetic repulsion by the superconductor. Flux pinning is thus the phenomenon where the flux tubes are pinned in place by the superconducting vortices. As this happens in the mixed state, it is exclusive to Type-II superconductors. These vortices could move around the superconductor, as they tend to repel each other due to the Lorentz force interaction, but are held in place by impurities of the superconducting material, such as grain boundaries and lattice defects, with a pinning force [7]. However, if the Lorentz force is greater than the pinning force, the flux tubes move. This can happen because of two reasons. One is the reduction of the pinning force cause by superconductor heating (flux creep). The other is the increase of the Lorentz force due to current densities higher than the critical current density (flux flow).
E. Cooling Techniques

As discussed before, and considering the magnetic properties of high temperature superconductors, there are two ways that the transition to superconductivity can occur: with or without an applied fields.

1) Zero Field Cooling

The first technique is called Zero Field Cooling (ZFC), in which the temperature transition to superconductivity is made without any magnetic field applied on the material. After that, if an external field is applied, then the Meissner effect is observed, according to the phenomena described before.

a) Meissner Effect

The Meissner effect is the phenomenon of magnetic field expulsion occurring in the superconductor. This expulsion holds as long as the magnetic flux density applied is not higher than the critical magnetic flux density \( B_c \), above which the superconductivity is lost. However, the magnetic field is not completely expelled, penetrating in some depth at the surface of the superconductor, as illustrated in Figure II-5, where there are currents circulating in the superconductor that cancel the magnetic field inside the superconductor.

In Figure II-5 it is possible to visualize Faraday’s Law: the applied field is increasing with time in the y-direction. The electric field induced inside the superconductor produces a current density that produces an opposite magnetic field with time, according to the right hand rule, cancelling the magnetic field inside the superconductor.

2) Field Cooling

The second technique is called Field Cooling (FC), in which the transition is made with a magnetic field applied on the superconductor before the transition to the superconducting state. In this case, if the source of the field is removed, the superconductor will tend to maintain its previous internal field, becoming magnetized, and can be used like a permanent magnet.

III. ELECTROMAGNETIC AND THERMAL MODELLING

A. Electromagnetic modelling

The model to be presented was based in the 2D H-formulation model presented in [2]. The magnetic field is applied along the x-y plane, so the current density and electric field will only have a component in the z-direction (it is admitted that the rod has infinite length in the z-direction).

By applying Ampère’s Law, and assuming that Maxwell’s addition (the electric field derivative) is in this case negligible (quasi-static regime), the current density and the electric field in the superconductor, in the z-direction, can be obtained as given by (III.1) and (III.2), respectively. Notice that equation (III.2) is the result of using (III.1) in (II.1).

By applying Ampère’s Law, and assuming that Maxwell’s addition is in this case negligible, the current density and the electric field in the z-direction can be obtained as:

\[
J_{sc,z} = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \varepsilon_z
\]  

(III.1)

\[
E_{sc,z} = E_0 \left( \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \right) \varepsilon_z
\]  

(III.2)

Substituting the previous equations in Faraday’s Law results in two coupled equations, given by (III.4) that relates the magnetic field evolution in time with the electric field inside the superconductor. The relative magnetic permeability \( \mu_r \) was considered to be equal to 1.

\[
\begin{aligned}
\frac{\partial (E_{sc,x})}{\partial y} &= -\mu_0 \mu_r \frac{\partial H_x}{\partial t} \\
\frac{\partial (E_{sc,z})}{\partial x} &= -\mu_0 \mu_r \frac{\partial H_y}{\partial t}
\end{aligned}
\]  

(III.3)

The goal is to verify the effects of a time variable magnetic field when applied to an YBCO bulk material. In this example [2], the YBCO superconductor is a 12x4cm rod inserted in an air domain as shown in Figure II-7. Two simulations are done to take into account both phenomena of Zero Field Cooling (in which a sinusoidal magnetic field is applied) and Field Cooling (in which an initial magnetic field decreases linearly with time).
For the air domain, the relation between $E$ and $J$ is linear, $E = \rho J$, where $\rho$ is the resistivity of air ($\rho = 1 \times 10^{6} \Omega \cdot m$ [2]). Using this equation to define the electric field in (III.3) and also making use of equation (III.1), yields the coupled equations (III.4), for which was also used $\mu_r = 1$.

\[
\begin{aligned}
\partial (\rho J_{sc,x})/\partial y &= -\mu_0 \mu_r \partial H_x/\partial t \\
-\partial (\rho J_{sc,x})/\partial x &= -\mu_0 \mu_r \partial H_y/\partial t
\end{aligned}
\] (III.4)

On the outer boundary of the air domain a Dirichlet boundary condition is set in time as shown in (III.5).

\[
\begin{aligned}
H_x &= f_x(t) \\
H_y &= f_y(t)
\end{aligned}
\] (III.5)

The magnetization of a certain material can be defined as equation (III.6) where $N$ is the number of magnetic moments in the sample, $V$ is the total volume of the material, $n_m$ is the number density of magnetic moments and $m_0$ is the vector that defines the magnetic moment.

\[
M = N/V m_0 = n_m m_0 [A/m]
\] (III.6)

The magnetic moment vector is given by (III.7) where $r$ is the position vector pointing from the origin to the location of the volume element ($r = (x,y,z)$), $J$ is the current density vector.

\[
m_0 = r \times J
\] (III.7)

The magnetization is then given by equation (III.8).

\[
M = 1/V \int_V (r \times J) dV
\] (III.8)

Because the simulation is in 2D, and the magnetic field is applied only in the y-direction, it is useful to see the magnetization in that direction. $J$ becomes $J = (0,0,J_{sc,x})$. The magnetization is given by (III.9), where $S$ is the cross section of the superconductor domain.

\[
M = \frac{1}{S} \int_S (–x \cdot J_{sc,x}) dS
\] (III.9)

It is then possible to compute the YBCO hysteresis losses when subjected to a time-variant magnetic field, which are given by the area defined by its magnetization curve and computed using equation (III.10).

\[
W_H = \Phi B dM [J/m^3/cycle]
\] (III.10)

The magnetization starts at zero and as the magnetic field is increasing in the $y$-direction, it will acquire negative values in that same direction in order to counter the applied magnetic field (region 1). After a certain value of magnetic field applied, it enters in the mixed state, as described before (regions 2 and 3). Because multiple frequencies are used, it helps to see the results in power units:

\[
P_H = f \int B dM [W/m^3]
\] (III.11)

It is also possible to define joule power losses, by multiplying the internal current density by the electric field:

\[
Q = E_{sc,x} J_{sc,x} [W/m^3]
\] (III.12)

The average eddy current losses density can be computed averaging (III.12) in the superconductor cross section and averaging in the time period related with the frequency of the applied magnetic field:

\[
P_J = f \int_t^{t+t} \int_S Q dS [W/m^3]
\] (III.13)

In order to obtain a steady state result, the time average needs to be done for a full period of the mixed state (regions 2 and 3), after the initial fully superconducting state (region 1). In the case of Figure III-1, the frequency of the applied magnetic field was 5 Hz, so the period was 0.2 seconds. An average in time was done from 0.05 to 0.25 seconds to account for a full period, while ignoring the initial fully superconducting state.

B. Thermal modelling

The critical current density $I_c$ changes with temperature (equation (II.4)). Knowing the temperature distribution in the HTS bulk material allows estimating with more accuracy the local electromagnetic variables. The thermal phenomena, which appear as soon as an electric current or a magnetic field are applied to the superconductor, is characterized by the heat diffusion equation (III.14).

\[
\nabla \cdot \left( \lambda(T) \nabla T \right) - \rho_m(T) C_p(T) \frac{\partial T}{\partial t} + p_q = 0
\] (III.14)

In (III.14), $\lambda$ is the thermal conductivity (in $W/(m \cdot K)$), $\rho_m$ is the volumetric mass density (in $W/(m \cdot K)$), $C_p$ is the specific heat capacity (in $J/(Kg \cdot K)$). Variable $p_q$ is a volumetric power loss (in $W/m^3$) representing the heat source.
For equation (II.3), the parameter $\alpha$ was calculated to be $\alpha = 1.134 \times 10^8 \, A/m^2$ to fit with the assumption of a maximum critical current density $J_{\text{C}}$ defined to be $2 \times 10^7 \, A/m^2$ at 77 K (II.3). In (III.14), $\lambda$ is the thermal conductivity (in $W/(m \cdot K)$), $\rho_m$ is the mass density (in $W/(m \cdot K)$), $C_p$ is the specific heat capacity (in $J/(kg \cdot K)$). Variable $p_v$ is a volumetric power loss (in $W/m^3$) representing the heat source. Table III-1 shows the thermal parameters used for each material: YBCO, liquid nitrogen, styrofoam and air. The last two materials are used in exclusively thermal simulations.

IV. RESULTS ANALYSIS

In the YBCO model presented here, the parameters used were taken by [2]. For equation (II.1), the parameters are $E_0 = 1 \times 10^{-4} \, V/m$ and $n = 21$, and for equation (II.2), the parameters used are $J_{\text{C}} = 2 \times 10^7 \, A/m^2$ and $B_0 = 0.1 \, T$, which was determined to best fit with the results in [2].

A. Sinusoidal Magnetic Field Analysis

In (IV.1) and (IV.2) are shown the $x$- and $y$- magnetic field components for ZFC and FC, respectively. The amplitude of the sinusoidal field $H_m$ is defined by $B_m/\mu_0$, and the trapped field $H_T$ is defined by $B_M/\mu_0$. The default frequency was defined to be $f = 5 \, Hz$, with $\omega = 2\pi f$, and default magnetic flux densities were set to be $B_m = 1.26 \, T$ and $B_M = 1.26 \, T$.

\[
\begin{align*}
\text{ZFC}: \quad H_x &= 0 \quad \text{and} \quad H_y = H_m \sin(\omega t) \\
\text{FC}: \quad H_x &= 0 \quad \text{and} \quad H_y = H_m + H_m \sin(\omega t)
\end{align*}
\]

1) Magnetic field amplitude analysis

It is clear that the losses have a strong dependence with the magnetic field amplitude. In the ZFC case, particularly until 0.4 T, and in a less strong manner after that. The difference in the ZFC and FC cases will depend on the trapped field $B_M$. Higher trapped fields will yield lower losses for the same magnetic field amplitude. The values studied fall within practical values used in electric machines, thus it’s important to take this into account regarding the use of superconducting elements in practical applications.

![Figure IV-1](image1)

**Figure IV-1** – Power density losses dependency of magnetic flux density $B_m$

2) Frequency analysis

Frequency is a very important parameter to take into account using HTS bulks in electric machines. As can be seen, these materials have higher efficiencies for machines that work at low speeds.

3) $J_{\text{C}}$ analysis

![Figure IV-2](image2)

**Figure IV-2** – Power density losses dependency of applied frequency

It is shown that the $J_{\text{C}}$ parameter is critical regarding the power losses in the superconductor. The previous figures show an important dependency with the $J_{\text{C}}$ parameter. This parameter is very important since it specifies the expected maximum order of magnitude of the internal currents in the superconductor. It is easy to relate the higher current densities with higher losses. However, higher current densities also yield higher magnetizations. The non-linearity shown could be attributed to equation (II.2).
4) $B_0$ analysis

The results show that the $B_0$ parameter is also determining regarding the power losses of the superconductor. As higher values of this parameter are associated with higher critical current densities, they also come with higher power losses. The non-linearity shown could also be explained by equation (II.2). Still regarding this equation, it is seen that the $B_0$ parameter preferably takes the highest value possible in order to decrease the critical current density as least as possible, which will yield higher magnetizations, higher trapped magnetic fields and better magnetic shielding for higher magnetic fields. However, the higher losses for higher values of this parameter need to be taken into account.

5) Geometric dimensions analysis

From the results obtained, a linear dependency of the power density losses can be seen regarding the width of the superconductor. This leads to problems of optimization regarding the dimensions of the superconductors in electric machines. However, since a 2D FEM analysis was used, this result will have to be confirmed and studied further by 3D simulations.

B. Field Cooling Transient Analysis for Trapped Field

An external field is applied, decreasing linearly from an initial value $H_{M0}$, defined by $B_{M0}/\mu_0$, to zero for a specified time interval $P$. The Dirichlet boundary condition is set up as (IV.3):

$$\begin{align*}
H_x &= 0 \\
H_y &= H_{M0} - \frac{H_M}{P} t, \quad (0 \leq t \leq P)
\end{align*}$$

Default parameters used in this section are $B_{M0} = 0.05 \, T$, $P = 0.05 \, s$, $J_{C0} = 2 \times 10^7 A/m^2$ and $B_0 = 0.1 \, T$.

1) Initial magnetic flux density analysis

Given the results, it can be seen that the maximum initial field does not significantly affect the maximum trapped field for values equal or higher than 0.25 T, assuming the same values of $J_{C0}$ and $B_0$. For lower values, the initial field is approximately kept constant.

2) Applied field derivative analysis

According to the results obtained, the derivative of the applied field also does not affect the maximum trapped field in steady state. For lower derivatives, the trapped field is slightly lower at the moment when the external field is completely removed, although the differences are not significant in the long term.
3) \( J_{C0} \) analysis

Given the results achieved, it is evident that for higher maximum current densities, higher magnetic fields can be trapped.

4) \( B_0 \) analysis

The results predictably show that the higher the values of \( B_0 \), the higher is the magnetic field that can be trapped in the superconductor.

5) Geometric dimensions analysis

The results show an ability to trap higher magnetic fields for wider superconductors.

6) Long term study

The results show some decay in the maximum trapped value. However, in experiments done in the lab, this decay was not observed. In practical applications, the decay is very slow and negligible.
Results show that the demagnetization depends on the amplitude of the applied field and that the maximum magnetic field density tends to be reduced by the RMS value of the applied field (dashed lines).

C. Experimental Results

An experiment was done to verify how much time a superconductor magnetized using FC takes to lose its superconducting state when a periodic external magnetic field is applied. This was done by applying a sinusoidal magnetic field with different amplitudes. The YBCO bulk piece had dimensions of 4x4x1.5 cm, approximately.

A coil of 1mm diameter wire was used, with 1000 turns. A magnet was used in order to see the moment of loss of superconductivity (as the magnetic properties are lost, the magnet falls). The frequency applied was 50Hz. The magnetic flux density was produced using currents of 1, 2, 3 and 4 A. With the resources available, a current of 5 A was impossible to reach. The magnetic field was measured by placing a secondary coil, with 6 turns and 6 cm of diameter, in the position of the superconductor and calculated through the induced voltage. The values of magnetic flux density obtained were 46.9, 93.8, 140.1, 187.6 mT, respectively.

These results fit well with the expectations from the theoretical model and simulations. The average times were 2:14, 2:04, 1:51, 1:37, and 1:29, by order of magnetic field amplitude. The decrease in superconducting time is associated with higher losses for higher magnetic fields, which require higher currents to counter the applied field.

D. Thermal Analysis

The cooling process observed in the lab revealed a cooling time (from room temperature until superconductivity) around 1 minute for the YBCO bulk piece.

A FEM simulation of the cooling process was done. Observations in the lab revealed a cooling time (until superconductivity) around 1 minute. In the simulation, a bulk piece with a diameter of 4 cm and a height of 1.5 cm was used, and an initial temperature of 293.15 K (20 ºC) for the superconductor, styrofoam, and air and 77 K (-196.15 ºC) for the liquid nitrogen were used.

An adjustment of the parameters of the liquid nitrogen was done, as the first results did not fit with the experimental observations, adjusting its thermal conductivity and heat capacity, by multiplying these by factors K and CP, respectively.

By increasing both the thermal conductivity and the specific heat capacity simultaneously, in this case by the same factor (K=CP), results resembling the experimental ones were obtained.
It can be seen that for $K$ and $CP$ equal to 150, a cooling time of around 1 minute can be obtained.

### E. Electromagnetic and Thermal Analysis

The geometrical, electromagnetic and thermal parameters used are the same as used in the previous simulations. Note that these simulations do not take into account any phase change from liquid nitrogen to nitrogen gas, as they follow the model described.

1) **Heating analysis**

The default frequency for these studies was $f = 0.25 \text{ Hz}$.

Results show that the temperature evolution presents two distinct thermal constants: a shorter one of about 10 seconds, and a longer one in the order of minutes.

The internal currents originate from the edges, and have a higher value in these areas due to the trapped field in the middle. As such, the superconductor will tend to be hotter around these parts, but as they are also in contact in the liquid nitrogen, they are also the parts that are better cooled, making the hottest parts being between the middle and the edges of the piece.
An analysis of the frequency of the magnetic field was also done. With the results obtained, the influence of the frequency in the superconductor losses and its almost linear characteristic is evident, as for twice the frequency there is almost a double in temperature rise. However, in the case of higher frequency, the temperature evolution appears to be slightly lower than expected, suggesting the same decrease in power loss for higher temperatures. Higher frequencies were studied, for example 50 Hz for the same conditions, but it was found that the superconductor lost superconductivity too quickly for comparison with the previous examples. This loss of superconductivity was localized, not global, but it stopped the simulation and no solution was found to solve this problem. This does not mean that in real applications the same result will happen. As has been stated, the thermal part of the model cannot be seen as an accurate representation of real experiments.

Furthermore, a comparison between ZFC and FC conditions was done, with $B_M = 1.26 \, T$ for the FC process.

The results support the differences seen in the electromagnetic study, which for 1.26 T shows a difference of about twice the losses for ZFC, in comparison with the FC case.

2) Cooling analysis

It can be seen that in less than 30 seconds the maximum temperature drops below 77.5 K, which represents a drop larger than 1.5 K. From there, the temperature drop is slower. The first thermal constant can be attributed to the transient interval of the electromagnetic variables, and the second thermal constant is related with the stabilization of the same variables.

It can be seen a steep decrease in the ratio between the internal and critical current densities, falling quickly below 1, on average, and rendering the resistivity and the losses quickly negligible.
V. CONCLUSIONS

The electromagnetic analysis allowed for an extensive study regarding the behavior of high temperature superconductors subjected to magnetic fields. The magnetization and hysteresis cycle of an YBCO bulk superconductor was studied, and the dependency with the applied magnetic field and internal characteristics was characterized. In the intrinsic parameters study, the results show that these parameters can be a determining factor regarding the expected capabilities and losses of a bulk superconductor. The behavior of HTS regarding trapped fields was also studied, since the objective is to use them to replace permanent magnets. The dependency of the trapped field with the applied field and various parameters was studied. Experimentally, the conditions for which superconductivity is lost were studied. Results show that superconductivity is lost more rapidly for higher applied magnetic fields, as expected by the model. However, the loss of superconductivity was not observed experimentally while the superconductor was submerged in liquid nitrogen, and as such was not studied in the model.

The thermal and electromagnetic analysis allowed the understanding of the dynamics of HTS in a more practical environment when considering the liquid nitrogen. It was possible to observe the effect of the temperature rise on the superconductor and how it influences all the variables in the superconductor. However, the thermal model needs to be improved, since the liquid nitrogen has a phase change (from liquid to vapor), which has not been considered in the model. However, the model pointed out the thermal effects in the superconductor material and its characteristic time constants.

Regarding the advantages and disadvantages of using bulk HTS in the excitation systems of electric machines, they come down to the intrinsic characteristics of the superconductor and the cooling system used. As has been demonstrated, higher values of the intrinsic parameters $B_0$ and $J_{c0}$ give better results, in the sense that they allow for higher currents, which in turn improves performance in both magnetic shielding and magnetic field trapping. The dependence of the critical current density with temperature also provides better results for lower temperatures. These advantages come with disadvantages of their own. Higher values of the parameters mentioned also come with higher power losses due to the higher currents. Likewise, better cooling systems are more expensive. As has been mentioned, no loss of superconductivity was obtained with the superconductors submerged in liquid nitrogen. However, for more practical applications, mainly in the use in electric machines, a more specific analysis has to be made, specially an analysis with the superconductors inserted in the machine.

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