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A New Inductor Topology for Superconducting Synchronous Machine: Analysis and Experimental Study

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Abstract— This paper presents a new kind of superconducting inductor for a two-poles synchronous machine. The inductor is composed of two circular superconducting coils placed on the same axis and fed by electrical currents having the same direction. The diamagnetic behavior of a superconducting bulk cooled under zero-field is used to obtain a variation of the magnetic flux density in the air-gap. In order to improve the flux density distribution, a ferromagnetic material surrounds the superconducting bulk. Compared to a classical synchronous machine, the studied superconducting inductor leads to a more important value for the flux density in the air-gap.

Key-words—Superconducting machine, magnetic field, high-temperature superconductor (HTS), three-dimensional field calculation.

I. INTRODUCTION

The improvement of electrical machines performances is a great challenge from several decades ago. One of the most important parameter to improve the machine performance is the generation of a high magnetic field in the air-gap. Superconducting materials are very interesting due to their characteristics and their abilities to suppress the Joule losses and by allowing very high current densities in the coils. So, they can be used to generate high magnetic field in the air-gap of electrical machines in order to achieve high performances. Another interesting property of superconducting materials (when they are used as bulks) is their flux shielding capability when they are cooled under zero magnetic field. It has been shown that this property can be used to achieve more efficient electrical machines [1-7].

Many applications have been proposed to study superconducting inductor using both low temperature superconducting wires and/or high temperature superconducting bulks. Many experimental studies have shown the ability of the superconductor materials (wires and/or bulks) to be used as an inductor for synchronous motors [5, 8].

As indicated previously, when a superconducting bulk is cooled before the magnetic field is applied, it behaves as a magnetic screen because surface currents are developed inside, and thus opposing an external magnetic field according to Lenz’s law. This behavior can be used to guide the flux or for shielding applications, because the magnetic flux into the superconducting stays equal to zero [8-12] as shown in Fig.1.

In this work, we propose an original structure of superconducting inductor for synchronous motor. The inductor uses an original topology with superconducting field coils and a superconducting bulk which play the role of magnetic screen, leading to an increase of the air-gap flux density. The advantage of the proposed structure is that the coils are very simple (solenoids) and we can obtain high magnetic field in the air gap above 5T. A three-dimensional magnetic field analysis is done (using a 3-D finite element software) to study the performance of the proposed inductor. The effect of the stator yoke on the magnetic field distribution is also studied. Finally, a rapid estimation of the back electromotive force induced in the stator coil is given.

II. MACHINE STRUCTURE

The studied electrical motor is composed of a classical stator yoke and an original superconducting inductor. The study developed in this paper concerns the superconducting inductor and the effect of the stator yoke on the air-gap flux density distribution.
A. Description of the inductor

Fig. 2 shows the structure of the proposed inductor. It is composed of two identical circular superconducting coils with a superconducting bulk placed between them.

The coils are fed by electrical currents having the same direction, which generate the magnetic field \( B_1, B_2 \) as shown in Fig. 2.

As indicated previously, a superconducting (SC) bulk is placed between the two coils. The SC bulk is inclined along the length of this inductor. This bulk is used as a flux barrier, which leads to a spatial variation of the magnetic field in the air-gap.

In order to improve the distribution of the radial component of the flux density in the air-gap, we use a ferromagnetic material between the two coils. The SC bulk is inserted between the iron yokes as shown in Fig. 2. As it will be shown in the next development, the iron parts will guide the magnetic field towards the air-gap region and thus will reduce the fringing field near the coils.

Fig. 3 shows the flux line distribution in a cutting plane \((r-z)\). From this result, we can observe that the SC bulk works as a flux barrier in order to obtain a two pole machine. The flux lines are roughly radially distributed at the armature bore in order to obtain good performance for the back electromotive force. It is worth noting that a large part of the flux lines are through the air with the proposed structure. This may cause electromagnetic compatibility (EMC) problems. In order to improve the performance of the machine and avoid EMC problems, it is preferable to add an external magnetic yoke (housing) to ensure a closed path for the flux. For practical reasons, the external yoke has not been added in our experimental bench.

The proposed superconducting inductor should be able to provide a two-pole machine and could be compared to a synchronous claw poles machines with flux guides [13]. This machine should develop a high electromagnetic torque due to the increase of the air-gap flux density. A technical representation of a motor made with this kind of inductor is shown in Fig. 4.
Moreover, the study proposed in this paper has been performed by adding the stator yoke to show its influence on the magnetic field generated by the inductor.

A non-linear magnetic characteristic $B$ (H) for the iron yokes has been used in the following analysis as shown in Fig. 5. The grade of the B-H curve used for the simulation corresponds to M-27 steel.

**Fig. 5. B (H) Curve of the ferromagnetic material (M-27 steel)**

### B. Analysis of the inductor

The simulation is done by considering two cases: the first case concerns the motor structure without iron yoke between the two coils. For the second case, the iron yokes have been added (around the superconducting bulk) in order to improve the waveform of the radial component of the flux density in the air-gap.

The geometrical parameters of the proposed structure are given in table I. These parameters are shown in Fig. 6.

The modeling of the superconducting coils has been defined with a current density of 100 A/mm$^2$, which is coherent with HTS superconductor tapes under 6 T at 25 K.

**Table I Geometrical parameters of the studied inductor**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius (Rex) (mm)</td>
<td>250</td>
</tr>
<tr>
<td>Inner radius (Ri) (mm)</td>
<td>150</td>
</tr>
<tr>
<td>Distance between the two solenoids (C) (mm)</td>
<td>150</td>
</tr>
<tr>
<td>Length of the solenoid (L) (mm)</td>
<td>150</td>
</tr>
<tr>
<td>Thickness of the superconductor plate (E) (mm)</td>
<td>10</td>
</tr>
<tr>
<td>Current density in the solenoids (J A/mm$^2$)</td>
<td>100</td>
</tr>
</tbody>
</table>
Looking at the geometry of the studied inductor (Fig.2), it is obviously seen that only a three dimensions study can be used to evaluate this topology adequately. Therefore, we have used the COMSOL-MULTI-PHYSICS 3D software.

Two types of models can be used for the numerical simulations. The first one is the Ampere model where we applied directly the current density in the coils. The results are obtained by determining the magnetic vector potential $\mathbf{A}$ (three components in 3D simulation). The second one is the Coulomb model, where the calculation will be carried out by the determination of a magnetic scalar potential $V$ (only one component in 3D simulation). In this study, we chose the Coulomb model because the variable is a scalar (one value to evaluate against three for the Ampere model), so the computational time will be faster.

Coulomb method is a “non-current” method, so equivalent magnetization corresponding to the current density $\mathbf{J}$ must be defined. In each part of a solenoid, we impose an equivalent magnetization ($\mathbf{M}_1$ and $\mathbf{M}_2$) as shown in Fig.7 according to the following equations [2]:

\[
\begin{align*}
\mathbf{M}_1 &= \mathbf{J} \cdot (R_i + e - r) \quad \text{if} \quad (R_i < r < R_i + e) \\
\mathbf{M}_2 &= \mathbf{J} e \quad \text{if} \quad (0 < r < R_i)
\end{align*}
\]

In which:
- $\mathbf{M}_1$ is the magnetization in the areas where the current density is non-zero.
- $\mathbf{M}_2$ is the magnetization inside the solenoid (area without current).
- $\mathbf{J}$ is the current density in the solenoid.
- $R_i$ is the inner radius.
- $e$ is the thickness of the solenoid.

In our system, the superconducting bulk is cooled down before a magnetic field is applied. Therefore, the flux cannot enter inside it, excepted on the edges [14]. The penetration depth depends on the physical characteristics of the bulk (impurities), on the temperature cooling, on the thickness of the bulk, and on the magnitude of the applied magnetic field.

For modeling a superconducting bulk, the classical power-law which link the electric field $\mathbf{E}$ to the current density $\mathbf{J}$ ($E/J = E_c (J/J_c)^p$) can be used (where $J_c$ is the critical current density, $E_c$ the critical electric field ($10^4$ V/m), $J$ the current density, $E$ the electrical field and $n$ is the power low index).

The power law model can be used, but it is much more complex for the study of 3-D superconducting motor problems which is the case of the studied inductor.

In order to simplify the analysis, we consider the superconductor bulk as a diamagnetic material with a very low relative permeability $\mu_r = 10^{-5}$. With this hypothesis, the flux is totally repelled from the HTS bulk.

III. RESULTS

A. Comparison of an inductor with and without iron

In this section, we will show the importance of adding a ferromagnetic material between the two superconducting coils by comparing the curves of the flux density in the air-gap with and without iron yokes.
The radial component of the flux density $B_r(z)$ is computed at $r = R_{ex} + 2\text{cm}$ (to take into account the cryogenic part) and at $\theta = \pi/2$, along the distance $C$ between the two coils (the line where $B_r(z)$ is computed is shown in Fig. 8).

Fig. 8. Lines for the calculation of the flux density

Fig. 9 shows the variation of $B_r$ along the $z$-direction for the inductor structure without iron yokes (continued line) and with iron yokes (line with circles). The maximum value of the flux density is about 1.7 T for the structure without iron, and the average value along the $z$-direction is about 1.15 T. However, after adding the iron yokes, the maximum value of the field rises to 1.9T and the average value is now equal to 1.5 T. The use of the ferromagnetic material allows a gain of around 30% on the average value along the $z$-direction.

The average value of $B_r$ along the $z$-direction represents an important quantity for the back electromotive force (EMF) of the motor.

Fig. 9. Radial component of the flux density along the Z-direction

(a)
The flux density variations $B_r(\theta)$ along the $\theta$ direction have been computed at $r = Rex + 2$ cm and for three values of $Z$ ($Z = -7$ cm, $Z = 0$ cm and $Z = 7$ cm). The results are given in Fig. 10 for the two studied cases: with or without iron yokes. As shown in Fig. 10-a, it is evident that for $Z = 0$, we obtain a spatial variation of the magnetic field corresponding to a two-pole configuration with $B_{max} = \pm 1.9$ T (with iron), and $B_{max} = \pm 1.4$ T without iron.

The waveforms of the flux density for two other values of $Z$ ($Z = \pm 7$ cm) are given respectively in Fig. 10-b and Fig. 10-c. We can observe that the variations of the flux density versus $\theta$ are not the same for the three cases. This must be taken into account for the design of the stator windings, because it will influence the back-EMF value of the synchronous motor.

According to these results, we conclude that for the same geometrical parameters and the same conditions, the average value of the flux density with iron yokes is greater than the one obtain without iron yokes. Therefore, we adopt the structure of the inductor with a ferromagnetic material in the following study.

B. **Effect of the stator yoke on the on the air-gap flux density**

We have added the stator yoke (Fig. 11) to show its influence on the air-gap flux density distribution. As it was shown in Fig. 9, the radial component of the flux density ($B_r$) decreases gradually along the $z$-direction and becomes negative for $z = 6.5$ cm (inductor with iron). In fact, the magnetic field is looped back around the superconducting plate which is used as a barrier. So, this has the effect of reversing the radial component of the flux density through the useful length C. For this, it is proposed to reduce the axial length at each end of the stator yoke to a size equivalent to the thickness of the superconducting plate as shown in Fig. 11-B.
In our study, many 3D numerical simulations have been carried out to find the optimal length of the stator yoke which gives the maximum value of the flux density. The two structures A and B shown in Fig. 11 have been compared. Structure A shows a motor with a stator yoke of length equal to C. Structure B shows the stator yoke after the reduction of its axial length.

Fig. 12 shows the air-gap flux density $B_r(Z)$ for the two configurations A and B. After comparing the average value of each configuration, we obtain an induction of $1.72$ T in the topology A and $2.06$ T for the topology B.

It is shown that the optimal result is obtained for a shorter length of the stator yoke, and therefore the topology (B) of Fig. 11 will be used for the motor.

Fig. 13 shows the distribution of the radial component of the flux density in the plane ($\theta$, $Z$) of the inductor (between the two coils) at $r = \text{Rex} + 2\text{cm}$. We can observe the two poles (north and south) which are obtained by the studied superconducting inductor.
IV. ELECTROMOTIVE FORCE INDUCED IN THE STATOR WINDING

We can calculate the electromotive force induced in a stator winding with a diametrical opening (full pitch coil). Fig. 14 shows a stator coil of length L, positioned between \( \theta = \pi/2 - \alpha \) and \( \theta = 3\pi/2 - \alpha \) (\( \alpha \) is the winding position at a given time). From the flux density distribution shown in Fig. 14, we can compute the magnetic flux through the coil. Results obtained from 3D FEM (Fig. 13 and Fig. 14) have shown that the radial component of the flux density is almost constant under a pole (plateau). We have simplified the calculation of the magnetic flux accordingly:

\[
\Phi(\alpha) = B S_1 - B S_2 \tag{3}
\]

The area \( S_1 \) corresponds to the positive field (+B), the area \( S_2 \) (hatched area) corresponds to the negative value of the field (-B).

For simplicity, we assume that the separation line between the north and south poles can be represented by a sinusoidal function.

\[
f(\theta) = CR/2 - CR/2 \cos \theta \tag{4}
\]

where \( R \) is the radius of the stator bore \((R=R_{cm}+2cm)\). The surfaces \( S_1 \) and \( S_2 \) are obtained from (4)

\[
S_2 = \pi CR/2 + RC \cos \alpha, \quad S_1 = \pi CR/2 - RC \cos \alpha \tag{5}
\]

So, by replacing (5) in (3), we obtain:

\[
\Phi(\alpha) = -2 BR C \cos \alpha \tag{6}
\]

If the stator coil moves at a constant angular speed \( \Omega (\alpha = \Omega t) \), the induced electromotive force is:

\[
e(t) = N \frac{d\Phi}{dt} = N \Omega \frac{d\Phi}{d\alpha} = 2BR \Omega N \sin(\Omega t) \tag{7}
\]

where \( N \) is the number of turns of the coil.

Thanks to the superconducting inductor, we obtain a large value for the radial component of the flux density \((B \approx 2.06 \, T)\) and therefore we can obtain a large value for the electromotive force. Experiments are ongoing for the back EMF measurements.

V. EXPERIMENT

We have manufactured a prototype based on this principle. For cost reasons, the superconducting coils have been realized by using niobium-titanium (NbTi) wires. NbTi superconducting material is a low critical temperature material cooled by liquid helium at 4.2 K. The superconducting shield is made with YBCO material.

At first, before carrying out the complete machine, we have tested the inductor alone. To do this, all of the inductor coils and shield are immersed in nitrogen liquid. The shield is superconducting at the temperature of liquid nitrogen. The coils, which are made with NbTi, are not superconducting at the liquid nitrogen temperature. They will therefore be supplied with very low electrical current amplitude to avoid destructive heating of the wire, but this current will be sufficient to have a quantifiable magnetic field. The aim of this experiment is to verify the magnetic induction obtained by this inductor and to verify our calculation tools. The inductor has been realized with the geometrical parameters given in Table II.
TABLE II. Geometrical parameters of the manufactured inductor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius Rex (mm)</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>Inner radius Ri (mm)</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Distance between the two solenoids C (mm)</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Length of the solenoid L (mm)</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Thickness of the superconductor plate E (mm)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Current density in the solenoids J (A/mm²)</td>
<td>10.6</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 15. Experimental bench

The experimental bench consists of our inductor placed in a nitrogen cryostat, and a Hall effect sensor that can be move along the height of the inductor and along its bore diameter. The test bench is also associated with the electrical supply of the superconducting coils, and the acquisition system. This is shown in Fig. 15.

Table for displacing the Hall sensor

<table>
<thead>
<tr>
<th>Supply</th>
<th>Cryostat</th>
<th>Superconducting inductor</th>
<th>Hall sensor Supply</th>
<th>Volt meter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 16. Comparison Between theoretical and experimental field distribution
The results are given in Fig. 16, Fig. 17 and Fig. 18. In Fig. 17, we present the variation of the induction along the bore diameter. Fig. 18 shows the variation of the induction along the useful length of the inductor. As previously stated, the induction values are low because we are far from the nominal current of the inductor (4 A instead of 200 A when the NbTi coils will be cooled in liquid helium). Measurements were conducted at a distance of 1.5 cm from the inductor radius. This value corresponds to the required thickness of the cryostat. We can observe good agreement for the waveforms and the amplitude between the theoretical and experimental results. The little difference between the experimental and theoretical results given in Fig. 17 and Fig. 18 can be explained by the difficulty to have a correct position for the Hall Effect sensor.

![Fig. 17. Comparison between theoretical and experimental results](image1)

![Fig. 18. Comparison between theoretical and experimental results](image2)

VI. CONCLUSION

A new kind of superconducting machines has been studied in this paper. We have shown that with this new inductor topology, we can obtain a flux density variation in the air-gap of around $\Delta B = 4.12$ T. This value was obtained with a 3D numerical simulation of the studied structure considering the superconducting coils fed by a current density of 100 A/mm$^2$. We have shown that the use of iron yokes placed between the superconducting bulk provides a gain of around 30% on the average value of the air-gap flux density. Moreover, we have studied the influence of the stator iron yoke length on the performance of the machine.

This interesting structure should lead to a very compact machine. From this principle, a machine is under construction with superconducting coils at low critical temperature (NbTi). The first experimental tests on the inductor have proved the validity of the proposed topology and the good prediction of the model.

REFERENCES


