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3D Modeling of Coils for Pulsed Field Magnetization of HTS Bulk Pellets Acting as an Inductor of a Superconducting Electrical Machine

Kévin Berger, Jakub Kapek, Alexandre Colle, Mariusz Stepień, Bogusław Grzesik, Thierry Lubin, and Jean Lévêque

Abstract—Here, we propose to study and design a coil in order to magnetize, using PFM, an inductor of a radial flux superconducting machine with one pair of poles. Each pole contains 4 HTS bulks of 30 mm in diameter that can be placed in a square pattern. The cryostat already exists for this application and the temperature of the HTS bulks can vary from 4.2 K to their critical temperature, in transient state. For a given primary source of energy, here a capacitor bank of 10 kJ (5 mF, 2 kV), the PFM process strongly depends of the inductance value of the coil used to magnetize because it defines the waveform of the current: peak value and time constant. Thus, 3D modeling of the coil is required in order to be sure that its inductance and the magnetic field produced will allow us to fully magnetize the HTS bulks. From the practical point of view, we would like to achieve an average magnetization of each pole around 3T.

In this paper, numerical modeling of coils with different number of turns coupled with circuit's equations is achieved. Results are the maximum magnetic field that can be applied on the HTS bulks, and the estimated magnetization at the top center of each HTS bulk.

Index Terms—Bulk conductors, Inductance, Modeling, Pulse measurements, Superconducting rotating machines, Very high field and NMR magnets.

I. INTRODUCTION

THE DEVELOPMENT of cryo-magnets based on REBaCuO type superconductors, that can generate up to 17 T [1], [2], gives the opportunity to see a technological breakthrough in the application of electrical engineering. To ensure the development of such applications, the integration of the magnetization system, which includes the coils used to produce the magnetic field applied to the superconducting materials, is one of the key point. Currently, the most convenient way to magnetize a High Temperature Superconducting bulk is to use a pulsed magnetic field. This method is called PFM for Pulsed Field Magnetization [3], [4]. It can generate strong magnetic fields while using a relatively compact and simple coil. Thus, HTS bulks can be directly magnetized into the final application.

To the best of our knowledge, only a few teams have realized superconducting motors with HTS bulks acting as permanent magnets. As an example, one can mention an axial gap-type

motor that was designed and realized in Japan [5], [6]. It has been changed over the years to include now a double rotor and triple armature [7], [8]. As another example, a radial type motor has also been realized in UK [9]. The stator consists of six air-core HTS armature windings, and the rotor is made of 75 HTS bulks (15 columns, 5 pieces per column) which are surface mounted and to be magnetized as a four-pole permanent magnet. [10]–[13]. All the motors realized involving HTS bulks as permanent magnets have shown a trapped magnetic field by the HTS bulks lower than 1 T. Therefore, the magnetization of the HTS bulks remains one of main scientific and technical challenge in such applications. The goal is thus to obtain a trapped magnetic flux density by the HTS bulks greater than 3 T [7], [14].

Therefore, this paper deals with the design of the coils that are needed in order to magnetize HTS bulk pellets acting as the inductor of a superconducting electrical machine. After this introduction, the next section will be devoted to the presentation of the motor and to the foreseen specifications for the coils. In Section III, the description of the 3D numerical model used to design the PFM coils will be presented, as well as the obtained results.

II. MOTOR'S DESCRIPTION

The activities of the GREEN laboratory are mainly dedicated to the applications of superconductivity in electrical engineering. In 2014, a new configuration of superconducting motor called “magnetic flux barrier motor” has been successfully tested in the lab [15]–[17]. This motor, shown in Fig. 1, has the particularity to have an inductor mounted inside a stationary cryostat and a rotating armature outside the cryostat.

The next project of the GREEN, starting in October 2017, is the realization of a radial-type motor with magnetized HTS bulks acting as the inductor. It was decided to keep the armature and cryostat of the previous motor, Fig. 1, in order to avoid any extra cost.

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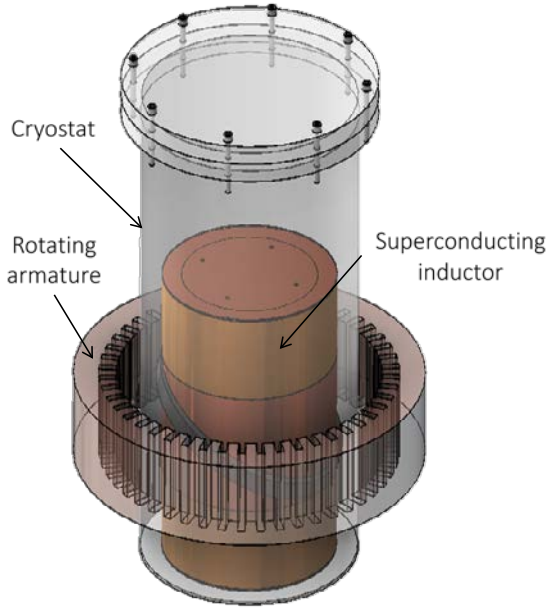


Fig. 1. Sketch of the “magnetic flux barrier motor” realized by the GREEN [16].

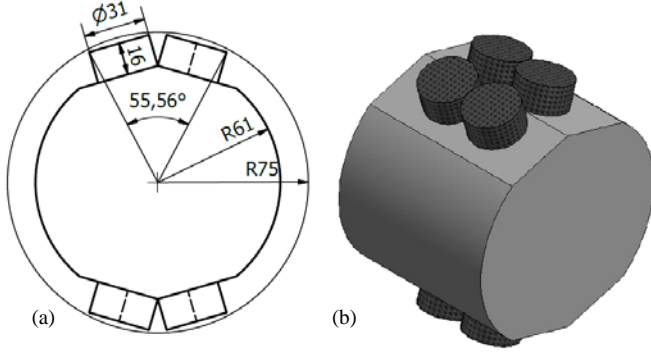


Fig. 2. Cross-sectional drawing of the inductor with dimensions in mm (a) and its 3D isometric view (b).

A. Description of the inductor

The inductor will consist of one-pole pairs as with the previous realization. Each pole contains four HTS bulks to be magnetized, mounted on a square pattern. We planned to use melt textured YBCO bulks from ATZ GmbH [18] or Can Superconductors [19]. These pellets are 16 mm high with a diameter of 31 mm. The trapped magnetic flux density is about 1 T at 77 K.

A cross-sectional drawing of the inductor with the bulks in place is shown in Fig. 2 (a), as well as a 3D isometric view Fig. 2 (b). Some geometrical parameters of the motor are also given in Table I.

B. Description of the impulse magnetizer

Previously, we used a homemade setup with a bank of 24 capacitors with a total capacitance value of 80 mF and voltage up to 300 V. This setup, which also includes a thyristor, can withstand peak currents up to 15 kA. The lab has recently bought an impulse magnetizer from Magnet-Physik [20]. The main technical characteristics are: 10 kJ of stored energy, a capacitance of 5 mF, charging up to 2 kV, a peak surge current of 20 kA, and a peak repetitive current of 35 kA.

TABLE I
SOME GEOMETRICAL PARAMETERS OF THE MOTOR

Symbol	Quantity	Value
R_{cyl}	radius of the ferromagnetic cylinder of the inductor	61 mm
R_{ind}	overall radius of the inductor including the HTS bulks	74 mm
e_1	mechanical air gap between the inductor and the cryostat	1 mm
R_{inn}	inner radius of the cryostat	75 mm
e_2	overall thickness of the cryostat	12 mm
R_{out}	outer radius of the cryostat	87 mm
e_3	mechanical air gap between the armature and the cryostat	2 mm
R_{arm}	inner radius of the armature	89 mm
e_t	total air gap between the inductor and the armature	15 mm
L_{arm}	active length of the armature	70 mm

By knowing these parameters, the next section will be devoted to the design of the coil required to magnetize simultaneously the four HTS bulks of one pole, or both poles at the same time.

III. DESIGN OF THE MAGNETIZING COIL

A. Description of the electrical system

A functional diagram of the electrical system is given in Fig. 3. Once the capacitors charged, the impulse current starts to flow in the magnetizing coil when the thyristor is switched on. The time evolution of this current is governed by the parameters of the RLC circuit, for instance, the capacitance C , the initial charge voltage of the capacitors U_{c0} , the resistance R_{mc} and the inductance L_{mc} of the magnetizing coil, the remaining resistance R_λ and inductance L_λ of the RLC circuit, e.g. of the cables.

All the above parameters are known except those of the magnetizing coil. The resistance R_{mc} depends on the operating temperature of the coil. We assume that this temperature will never be higher than 100 K. The inductance L_{mc} of the coil is shown as variable element in Fig. 3 because its value is non-linear due to the presence of the ferromagnetic and superconducting materials.

One of the difficulties in designing the magnetizing coil is that the current waveform and therefore, the maximum value of

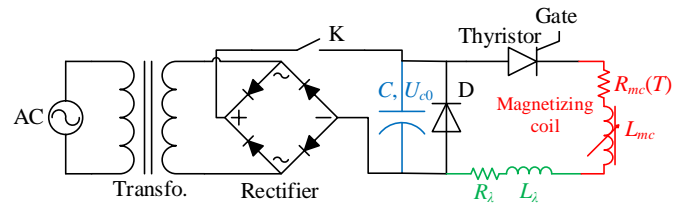


Fig. 3. Simplified electrical diagram of the installation used for magnetize the HTS bulks.

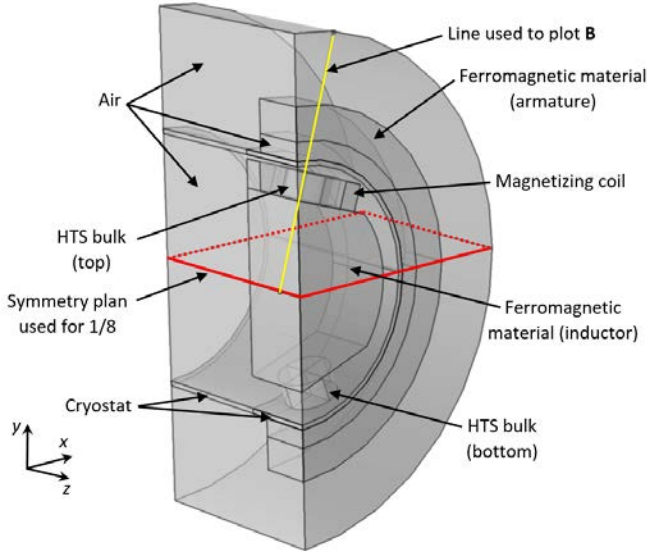


Fig. 4. Studied problem with 1/4 of the geometry.

the magnetic field applied to the HTS bulks, depend on the non-linear inductance L_{mc} .

B. 3D modeling of the magnetization of the inductor

Since the magnetizing coil's geometry is three-dimensional and non-linear, the only way to design this coil is to use a numerical software. On the basis of our experience, we have decided to use COMSOL® Multiphysics software [21]. It allows us to compute 3D electromagnetic problems using the *mf physics* package and to couple the equations with the RLC circuit shown in Fig. 3.

Previous coils have successfully been realized for magnetizing one single HTS pellet by using copper foil of 0.2 mm thickness, and the same width as the HTS bulk height. The coils proposed here will respect these criteria. Kapton tape of 25 μm thick is used between turns for insulation purpose. In order to optimize the magnetic flux produced by one pole, we have decided to design a single coil around the 4 HTS bulks of one pole instead of one coil around each bulk.

The inductor shown in Fig. 2 is composed of a cobalt iron cylinder VACODUR® 50 [22] and 8 HTS bulks. Due to the symmetries, if we decide to magnetize the 4 bulks of one pole, only 1/4 of the geometry needs to be simulated. If both poles are magnetized at the same time, symmetries lead to study 1/8 of the full geometry. Therefore, the studied problems with 1/4 of the geometry is shown in Fig. 4. On the basis of these choices, parametric simulations have been done for a number of turns between 18 and 28.

The current waveform for an initial voltage of the capacitor of 2 kV is shown during the magnetization of one single pole in Fig. 5(a) and for both poles in serial in Fig. 5(b). For 18 turns, the maximum current I_{max} is 16.69 kA and 11.97 kA during the magnetization of one pole and both poles respectively. In both cases, this value is acceptable for the components of the electrical circuit. The decrease of the peak current is mainly due to the increase of the inductance of the coil when both coils are in serial. Therefore, increasing the number of turns N leads to a decrease of I_{max} .

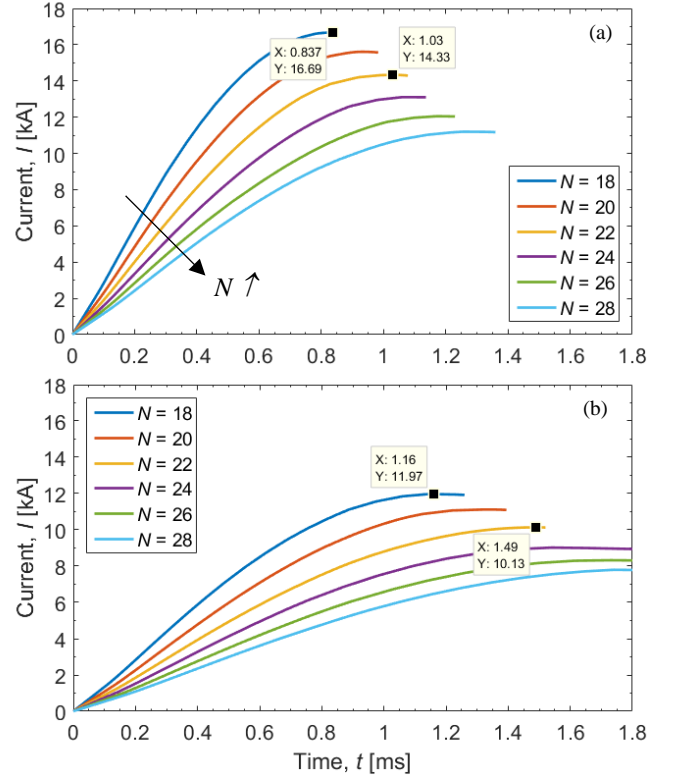


Fig. 5. Impulse current in the magnetizing coil for an initial voltage of the capacitor of 2 kV, during the magnetization of one single pole (a), and for both poles in serial (b).

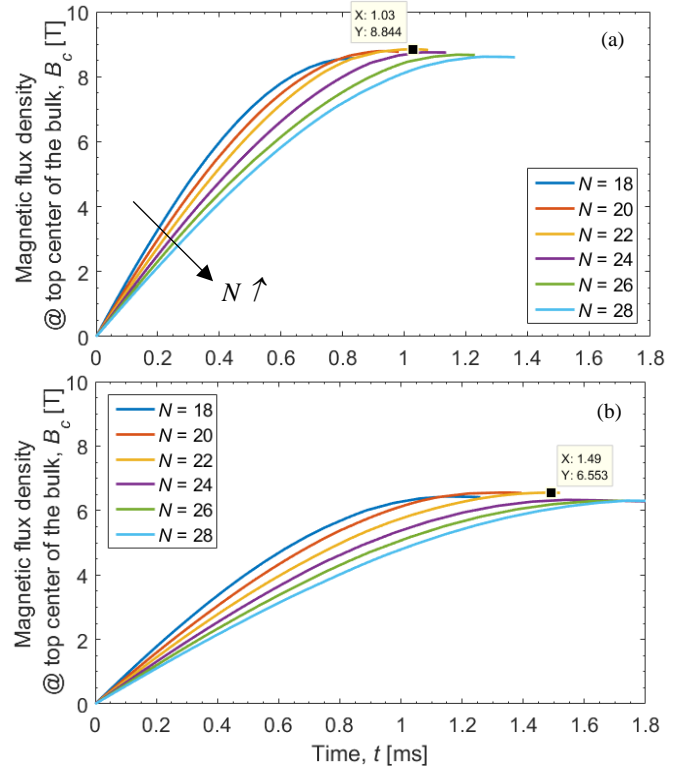


Fig. 6. Norm of the magnetic flux density B_c at the top center of one HTS bulk, for an initial voltage of the capacitor of 2 kV, during the magnetization of one single pole (a), and for both poles in serial (b).

Fig. 6 shows the norm of magnetic flux density B_c at the top center of one HTS bulk, during the magnetization of one single

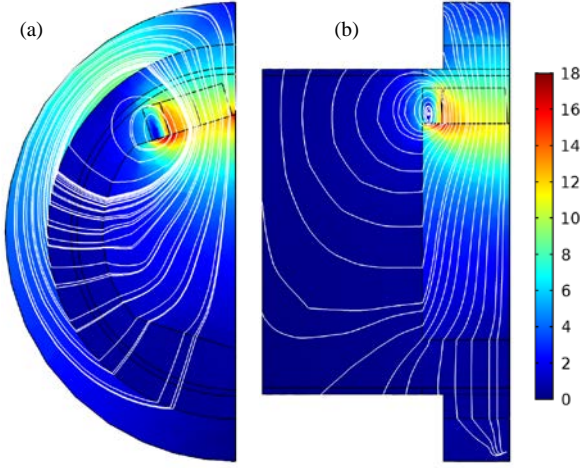


Fig. 7. Norm of the magnetic flux density in Tesla, and flux lines during the magnetization of one single pole at 1.03 ms, i.e. maximum current: in the xOy plane at the middle of the HTS bulk (a) and in the yOz plane $x = 0$ (b).

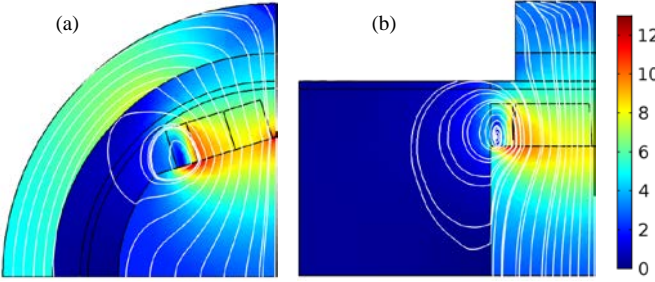


Fig. 8. Norm of the magnetic flux density in Tesla, and flux lines during the magnetization of both poles at 1.49 ms, i.e. maximum current: in the xOy plane at the middle of the HTS bulk (a) and in the yOz plane $x = 0$ (b).

pole Fig. 6(a), and for both poles in serial Fig. 6 (b). For both configurations, there is an optimal value of magnetic flux density that we can apply to the HTS bulks. This maximum value of B_c is obtained for 22 turns, while 20 turns give a very similar value. A maximum applied flux density of 8.844 T at the top center of the HTS bulk is obtained at 1.03 ms, and for a peak current of 14.33 kA, if one single pole is magnetized, Fig. 6(a). This maximum applied flux density is strongly decreased down to 6.553 T if both poles are magnetized simultaneously, Fig. 6(b). Indeed, if both magnetizing coils are in serial, the inductance increases which leads to a decrease of the peak current. For information purpose, the calculated inductance of one coil at 5 ms is 79.7 mH compared to 167.3 mH for both coils in serial, almost twice as much, which means that there are not well coupled. Based on those results, and assuming a Bean's critical state model for the HTS bulks, a maximum trapped magnetic flux density around 4.4 T, half of the maximum applied magnetic flux density, seems to be a manageable target.

Finally, the norm of the magnetic flux density and flux lines at the maximum current are shown for the magnetization of one pole in Fig. 7 and the magnetization of both poles in Fig. 8. The magnetic field distribution in the xOy plane at the middle of the HTS bulk are reported in Fig. 7(a) and Fig. 8(a), whereas Fig. 7(b) and Fig. 8(b) show the magnetic field distribution in the xOy plane at $x = 0$. Fig. 7 and Fig. 8 give us the information about flux leakage and magnetic flux density amplitude in the

whole inductor. The maximum magnetic flux density observed in Fig. 7 is around 18.3 T instead of 13.3 T in Fig. 8. We can also observe that many flux lines cross the air gap in Fig. 7 compared to Fig. 8.

IV. CONCLUSION

The optimal design of a coil for magnetizing an inductor of a superconducting electrical machine with one pair of poles and 4 HTS bulks on each pole has been achieved. The resulting coil consists of 22 turns of copper foil wound around the 4 pellets of each pole. The peak current of 14.33 kA is obtained at 1.04 ms and producing a magnetic flux density up to 8.844 T at the top center of the HTS bulk. From the point of view of the maximum magnetic flux density applied to the HTS bulk, the best process is to magnetize each pole one after one. Finally, we can expect a trapped magnetic flux density by the HTS bulks around 4.4 T, which is a promising value compared to state of the art in motors applications. The magnetizing coil and the inductor will be built during the next months and experimental results will give us confidence in the achievable trapped magnetic flux density for such application.

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