HTS SUPERCONDUCTING COILS FOR APPLICATIONS IN ELECTRICAL ENGINEERING

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The HTS superconducting coils that are components of the rotating electrical machines made in ICPE-CA, work at the liquid nitrogen temperature (77K). They are made of ceramic material, YBCO type, which has a critical current of 130A (SuperPower) and 100A respectively (AMSC). There are analyzed two different types of coil for two prototypes of electrical machines: an electric motor (P = 4 kW) and an electric generator (P = 4.5 kW). They were made from HTS tape, in the form of simple and double racetrack pancake.

Within the paper the design parameters of these HTS coils are examined. Also, the generated magnetic field, the field numerical simulation and the optimal functioning conditions are analyzed.

Keywords: HTS superconductors, superconducting coils, electrical machines

1. Introduction

High temperature superconducting materials (HTS), discovered in 1986, are already commercially available.

The advantage of low cost HTS conductors coupled with reasonably priced refrigeration systems, has encouraged application of this technology to a variety of magnets and power equipment. Many prototypes have been constructed for electric power applications such as motors and generators, transformers, power transmission cables, fault current limiters, and magnets for applied physics research.

Large electrical magnets are employed for many industrial and military applications.

The manufacture of such magnets with HTS materials became more and more attractive. The HTS magnets have attractive features such as smaller weight

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and size, higher efficiency, higher magnetic fields, better stability and an easier and cheaper cooling.

The main HTS materials usable in applications are BSCCO-2212, BSCCO-2223, YBCO-123, and MgB_2. However, only BSCCO-2223 and YBCO-123 wires, which are operational in the temperature range of 30 to 77K, have achieved widespread application for manufacturing practical power equipment. The YBCO-123 in the form of coated conductors has also advanced significantly to provide current density capability suitable for application in practical devices.

The HTS conductors are also used for obtaining high field DC coils excitation poles of large AC hybrids synchronous motors and generators.

These coils are used in the rotor and are cooled with cryogens like liquid nitrogen or stationary refrigerator, employing thermo-siphon or gaseous helium loops. The cooling is accomplished with an interface gas like He or N, which transports thermal loads from coils to the stationary refrigerator like a cryocooler.

There are a few practical advantages of using HTS superconducting coils. The most obvious one is that due to the absence of the electrical resistivity there are no Joule losses in the winding and thus the efficiency of the superconducting machine is higher than that of a similar machine. Also due to much higher current density carried by the superconductors, very strong magnetic fields can be obtained with much less winding. This means that a superconducting machine has a lower weight and size than an equivalent conventional machine, if one doesn’t take into consideration the cooling system because it is not embedded in the electrical machine.

2. Design of the HTS superconducting coils

2.1. Superconducting coil design

Two superconducting electrical machines were designed and built at ICPE-CA. As part of the design phase their HTS coils were numerically modeled to analyze the magnetic field. The coils parameters are presented in the Table 1. We mention the fact that both coils are “racetrack” type. The first coil, simple pancake, is made to be used in the superconducting generator [12], and the second coil, double pancake type, was used in the construction of the superconducting synchronous electric motor [8].

Table 1

Characteristics of the HTS superconducting coils

No.	Characteristic	Coil 1 (pancake)	Coil 2 (double pancake)
1	HTS tape	YBCO*	YBCO**
2	Coil length	100 mm	80 mm
3	Coil width	40 mm	50 mm

4	Turns / pancake coil	18	35
5	HTS tape - width	6 mm	4.2 mm
6	HTS tape - thickness	0.11 mm	0.22 mm
7	Critical current @ 77K (c.c.)	130 A	100 A
8	Maximum critical density @ 77K	10300 A/cm^2	~ 10000 A/cm^2
9	Maximum bending diameter*	30 mm	30 mm

*from SuperPower; ** From AMSC

Fig. 1. HTS pancake coils for electric generator

Fig. 2. Double pancake coils for synchronous electric motor

Fig. 1 represents the simple pancake coil, part of the superconducting generator, and Fig. 2 represents the double pancake coil, part of the superconducting motor. Both are made from YBCO based superconducting tape. The main parameters of the coils are given in Table 1.

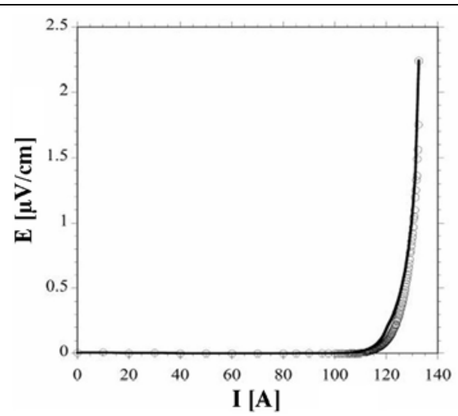

Fig. 3. Critical current determination of the YBCO - 123 tape at 77 K

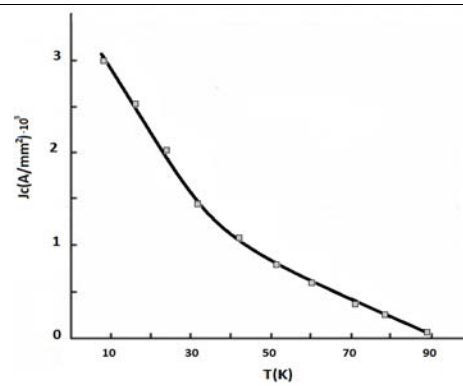

Fig. 4. Critical current density vs. temperature for YBCO - 123 tape [1]

In Fig. 3, the E = f (I) curve which was experimentally obtained in ICPE-CA is used for the determination of the critical current. The critical current is considered to be the value of the current for which the electric field is 1 μV/cm. In Fig. 4 the dependence of the critical current density vs. temperature for YBCO based superconducting tape is presented (based on data from SuperPower), which shows that at a higher temperature, the critical current density decreases, reaching zero for T = Tc. Also, if we want a higher current in the coil we must provide a lower temperature.

2.2. Conceptual model

The conceptual model of the superconducting coil starts from the following modeling hypotheses:

- One quarter of the racetrack coil is modelled.
- A current of 100 A is applied to the coil.
- The structure is described by a 3D model of one quarter of the racetrack coil, because of the symmetry properties of the coil.
- Considering the constant current, Maxwell's equations are defined according to the magnetostatic regime.
- The magnetic field is considered constant, so that it satisfies the magnetostatic regime.

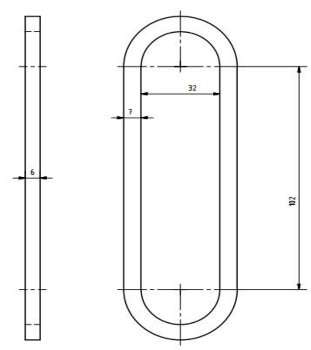

Fig. 5. Shape and dimensions of the HTS superconducting coil

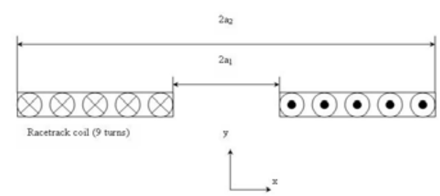

Fig. 6. Cross section of a racetrack coil [11]

The shape and dimensions of the HTS coils were determined by electromagnetic and mechanical design of the electrical machines. The shape and dimensions of the superconducting HTS racetrack coil used in the superconducting generator can be seen in Fig. 5. The coil used in the superconducting motor is identical as shape, only with different dimensions. The dimensions of both coils are presented in Table 1. The cross section of both racetrack coils is shown in Fig. 6 [11].

The numerical approach considered the coil geometry from Fig. 7. Notice that, because of the coil symmetry, the modeling and the simulation were made on a quarter of a coil.

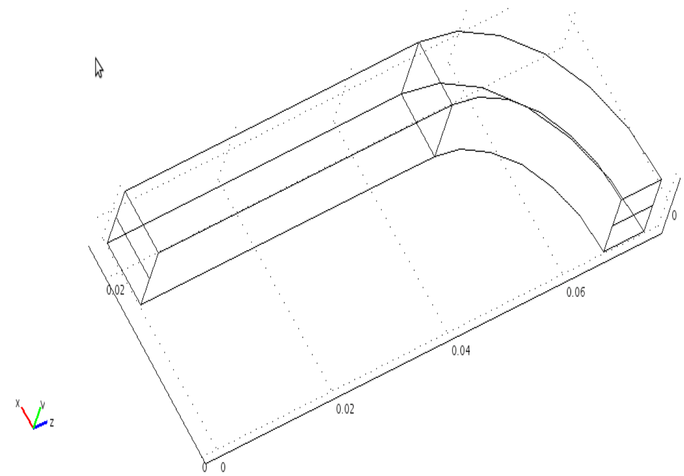

Fig. 7. Coil geometry

The presented model was analyzed in COMSOL Multiphysics 3.5a, which uses the finite elements method [9], [10].

3. Numerical simulations

The simulation of the magnetic field distribution for the two coils was performed with a computer that has the following configuration: processor i3 2100 3.1 GHz, 4GB RAM, 500GB HDD, integrated graphics unit. There were performed both 2D and 3D modeling and simulation of the magnetic field generated by the coils. The 2D modeling is useful a section view, while the 3D modeling is better for a spatial distribution view of the magnetic field lines.

3.1. Mathematical model for 2D and 3D simulations

The equations used are those of the magnetostatic regime (with current):
Ampere theorem:

$$rot\overrightarrow{H} = \overrightarrow{J} \tag{1}$$

Magnetic flux density theorem:

$$div\overrightarrow{B} = 0 \tag{2}$$

The relation between **H** and **B** is

$$\vec{B} = \mu_0 \left(\vec{H} + \vec{M} \right) \tag{3}$$

and, [15], the magnetic induction is given by

$$\vec{B} = rot \vec{A} \tag{4}$$

where $\vec{A}$ is the magnetic vector potential and $\vec{B}$ is the magnetic flux density that can be calculated using the formula [13], [14]:

$$div \vec{A} = 0 \tag{5}$$

Consequently, the magnetic potential in the homogeneous computational domain is a solution of the Poisson equation:

$$div \left[v grad \vec{A} \right] = \vec{J} \tag{6}$$

where $\nu = 1/\mu$.

It satisfies the Dirichlet boundary condition, A = 0, on the symmetry plane and the rest of the air computational domain.

3.2. 2D Modeling

In the case of simple pancake coil (Fig. 8), the computational domain has a triangular mesh that generates 13.689 degrees of freedom by discretizing Poisson equation with finite elements method. The problem was solved in 0.15 s.

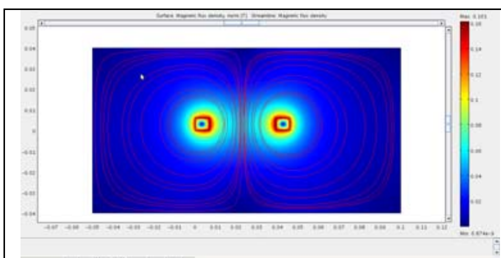

Fig. 8. Simple pancake – cross section, 2D modeling of the generated magnetic field

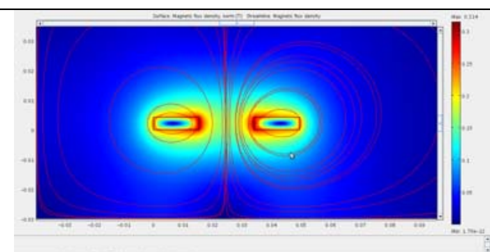

Fig. 9. Double pancake – cross section, 2D modeling of the generated magnetic field

In the case of double pancake coil (Fig. 9), the computational domain has a triangular mesh that generates 1.013.185 degrees of freedom by discretizing Poisson equation with finite elements method. The problem was solved in 17.5 s.

In Fig. 8 and Fig. 9 the results of the 2D modeling of the racetrack shaped HTS superconducting coils are presented, observing the magnetic field colour map and the closing of the field lines.

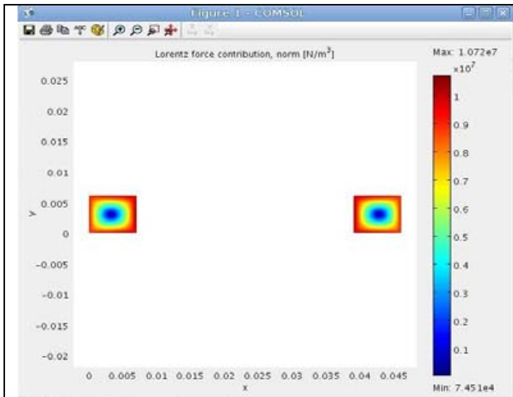

Fig. 10. Lorentz force density for the simple pancake coil

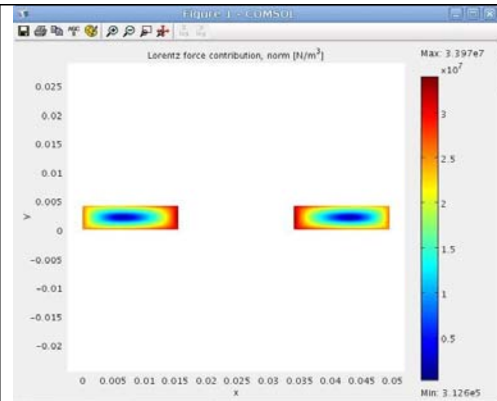

Fig. 11. Lorentz force density for the double pancake coil

In Fig. 10 and Fig. 11 the COMSOL modeling results of the two coils can be observed, more precisely the Lorentz force density, in N/m^3. It can be seen that the maximum value of the Lorentz force density for the simple pancake coil is 1.072×10^7 N/m^3, and for the double pancake coil is 3.397×10^7 N/m^3 or, a Lorentz (Laplace) force of about 90 N and 350 N respectively, considering the volume of the coils.

3.3. 3D Modeling

Tetrahedral mesh is used because it better fits the geometry of the coil and because in the 2D modeling the triangular mesh was used, which represents the counterpart of tetrahedral mesh for the 2D model.

In the case of simple pancake coil (Fig. 12), the computational domain has a tetrahedral mesh that generates 135.374 degrees of freedom by discretizing Poisson equation with finite elements method. The problem was solved in 7.2 s.

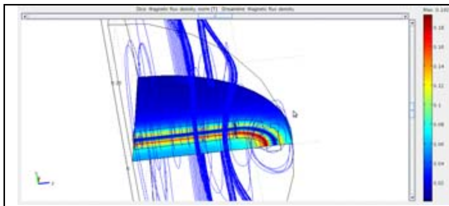

Fig. 12. Simple pancake – cross section, 3D modeling of the generated magnetic field

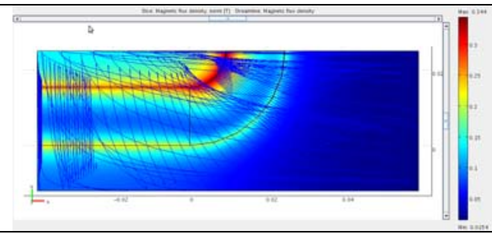

Fig. 13. Double pancake – cross section, 3D modeling of the generated magnetic field

In the case of double pancake coil (Fig. 13), the computational domain has a tetrahedral mesh that generates 1.614.062 degrees of freedom by discretizing the Poisson equation with finite elements method. The problem was solved in 208.2 s.

In Fig. 12 and Fig. 13 the results of the 3D modeling of the racetrack shaped HTS superconducting coils are presented, observing the magnetic field colour map and the closing of the field lines.

3.4. Results

In Tables 2 and 3 the magnetic induction at different currents through the superconducting coils is revealed. The results are obtained with COMSOL Multiphysics, considering the 3D model, and are plotted in Fig. 14 and Fig. 15.

Table 2

Double pancake coil, AMSC

I(A)	B(T)
0	0
25	0.038
50	0.077
80	0.124
100	0.155

In Table 2 the results obtained from the modeling in COMSOL Multiphysics of the double pancake coil from AMSC [2], are presented, which is used in the construction of the superconducting motor.

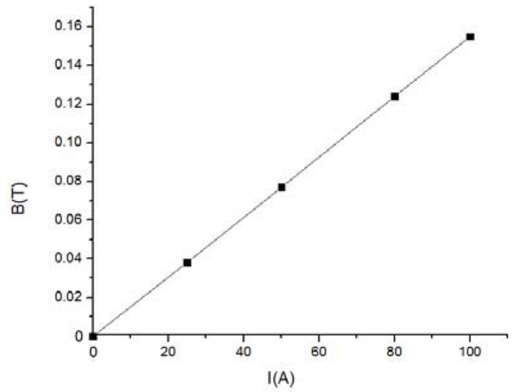

Fig. 14. The magnetic induction vs the current through the double pancake coil made from YBCO material from AMSC, for the superconducting motor

In Fig. 14 the dependence of the magnetic induction vs. the transport current through the coil of the superconducting motor is shown, using the numerical results from the modeling and the simulation of the coil.

Table 3

Simple pancake coil, SuperPower

I(A)	B(T)
0	0
30	0.023
60	0.046
100	0.076
130	0.099

In Table 3 the results obtained from the modeling in COMSOL of the simple pancake coil from SuperPower [1] are presented, with the main application in the construction of the superconducting generator.

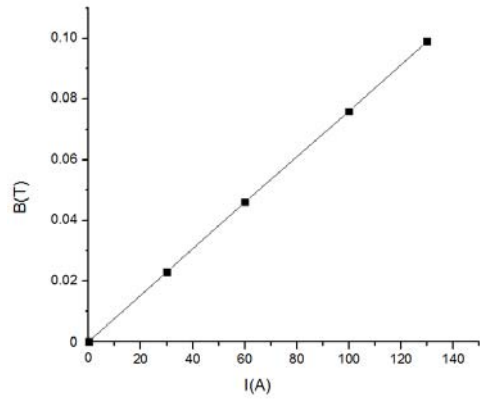

Fig. 15. The magnetic induction vs the current through the simple pancake coil made from YBCO material from SuperPower, for the superconducting generator

Fig. 15 shows the dependence of the magnetic induction vs. the transport current through the coil of the superconducting generator using the numerical results from the modeling and the simulation of the coil in COMSOL Multiphysics [9], [10].

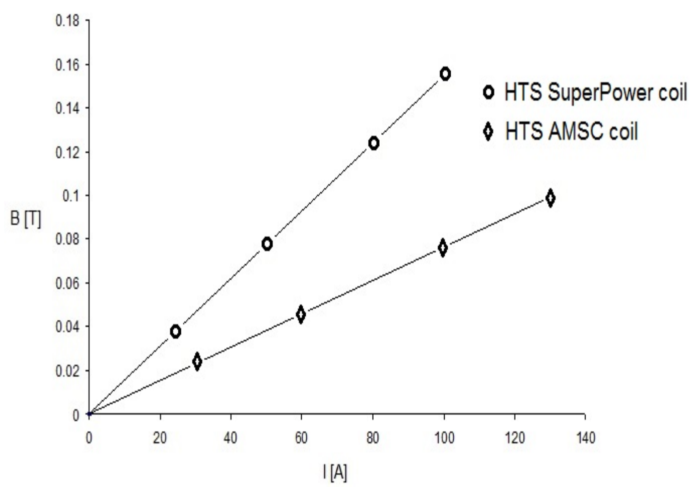

Fig. 16. Comparison between the magnetic induction depending on the current for the two types of coil

Fig. 16 shows the dependence of the magnetic induction vs. the transport current through both coils of the superconducting machines.

4. Conclusions

The HTS superconducting coils which are designated to be used by the superconducting rotating electrical machines made in ICPE-CA work at the liquid nitrogen temperature (77K) or lower. Two different coils for two types of electrical machines have been analyzed: an electric motor and an electric generator. They were made of YBCO tape, in the form of simple and double racetrack pancake respectively.

For the present work, YBCO type material was used because it is one of the best materials in terms of superconductivity, higher performances (critical parameters) and functional stability.

There are a few practical advantages of using HTS superconducting coils. The most important advantage is that due to the absence of the electrical resistivity there are no Joule losses in the winding and thus the efficiency of the superconducting machine is higher than that of a conventional machine. Also to achieve a very high magnetic field with HTS coils a lower number of coils is required, which means lower mass and volume. Because the magnetic field is higher it doesn't require the iron core to amplify it, which also means lower mass and volume. Thus the superconducting machine has a lower weight and size than a conventional, normal conductive electrical machine, if one doesn't take into consideration the cryogenic cooling system which it is not embedded in the electrical machine.

The HTS coils design and performances were imposed by the functional parameters required by the electrical machines for which they were intended.

The design parameters of these HTS coils and also the generated magnetic field by numerical simulation in COMSOL Multiphysics were analyzed.

The modeling and the simulation were made considering only a quarter of a coil in order to reduce the time of the actual simulation, this being possible due to the coils symmetry.

The results of the magnetic field numeric modeling of the field generated by the coils were presented within the paper, noticing the magnetic field in the colour map and the closing of the magnetic field lines.

The Lorentz forces acting over the superconducting windings were also evaluated in order to quantify the mechanical stress supported by the superconducting tape. One may conclude on the basis of the numerical simulations, these forces need to be taken into account for the mechanical anchoring of the coils in their position, inside the electrical machine. They also must be taken into account in the technological process of the HTS coil realization, by considering the rigidization of the winding through epoxi impregnation during execution.

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