THE DEVELOPMENT OF A SMALL POWER, HIGH TEMPERATURE SUPERCONDUCTOR (HTS) SYNCHRONOUS MOTOR

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***Abstract* – This paper presents some preliminary results and the current state of the work conducted to build a small power high temperature superconductor (HTS) synchronous motor. The work was conducted at the National Research Institute for Electrical Engineering, ICPE-CA in Bucharest (overall design, prototype buildup, superconducting coils, rotor construction), in partnership with University POLITEHNICA of Bucharest (electromagnetic field and heat transfer numerical modeling), the Institute for Research in Electrical Motors, ICPE-ME (electromechanical design, stator construction) and the National Institute for Research in Cryogenics, ICSI in Rm. Vâlcea (cryogenics). The project was funded by the the National Center for Programs Management within the framework of the National Program II. The ultimate goal of the project is to develop a prototype of a high temperature superconductor (HTS) synchronous motor, in order to explore possibilities of employing superconductivity in this area. The prototype – 4 kW at 1,500 rpm – has a HTS DC field winding (in the rotor) and a conventional AC winding (in the stator). A 2D numerical simulation was used in the design phase to evaluate the electromagnetic field and the saturable regions, with the aim at optimizing the motor design. In our approach, the rotor HTS field winding is cooled cryogenically, with liquid Nitrogen, at 65 K. The preliminary results confirm that the cooling scheme adequately provides for safe temperature limits and working conditions.**

Keywords: *HTS field coils, cryogenic cooling system, HTS synchronous motor, small power, numerical analysis.*

1. INTRODUCTION

There are significant advantages in using superconductors in applications such as electric motors, electric generators, transformers, transmission power lines or current limiters, which are more efficient, compact, smaller, and power savers. The benefits of using the superconductors in electric motors lie in the reduction in losses and size, as compared with conventional engines in the same power range, due to the strong magnetic fields generated by the superconducting windings [1-2].

Due to the many advantages resulting from the usage of HTS windings in industrial motors, a series of projects were started since 1990 in the U.S.A. and Japan, in 2000 in Germany, and in 2001 in Korea [3]. In Romania, in 2008, a project funded by the CNMP [4] for a 4 kW at 1,500 rpm HTS motor prototype was started, in partnership with University POLITEHNICA of Bucharest (UPB) – the Faculty of Electrical Engineering – the Institute for Research in Electrical Engineering – Electric Machines (ICPE-ME), and the National Institute for Cryogenics (ICSI) of Rm. Vâlcea. The object of the project is a prototype of a high temperature superconducting (HTS) synchronous motor, aimed at exploring the advantages and difficulties related to the usage of the HTS technology in building high power and high efficiency electric motors for industrial use.

2. THE DESIGN AND PRELIMINARY TESTS

The first step in building the 4 KW HTS motor was the design phase that accounts for the specific working conditions of the HTS and the chosen constructive model. We considered the design where the HTS coils make the DC field (rotor) winding.

Rated power	4 kW
Rated speed	3,000 rpm
Pole number	2
Armature terminal voltage	380 V AC
Frequency	50 Hz
Field coil turns/pole	70
Field current	100 A DC
HTS conductor type	YBCO, tape

Table 1: The parameters of HTS electric motor.

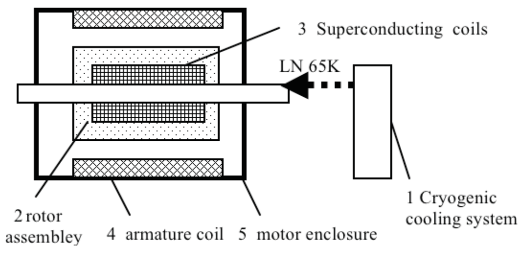

Figure 1: The sketch of the HTS motor.

Consequently, the rotor has to be cooled to cryogenic working temperature. The AC winding is of conventional type (with copper wire), hosted by the stator armature. The preliminary data design and parameters are shown in Table 1.

Figure 1 shows the schematic of the HTS synchronous machine, made of four main parts:

- the rotor with HTS field winding (2, 3)
- the armature, conventional winding (4)
- the motor case, vacuumed (5)
- the cryogenic cooling system (1)

2.1. The rotor

The rotor has a complex structure: it that contains the HTS field winding, and it has to provide for adequate operating conditions (temperature and current control). The rotor works closely with the cryogenic cooling system, which ensure the cryogenic fluid feed that is necessary to extract heat and ensure an as low as 65 K temperature at the HTS coils level.

The field coils are made of HTS type 344 AMSC tape [4], of racetrack shape, and double pancake coil.

The rotor has two poles, each pole provided with a double pancake field coil, with 70 turns per coil.

The rotor enclosure is vacuumed, and an AC flux shield is provided to protect the HTS winding against AC influences and against the heat generated by the armature winding – the shield is connected to the cold part of the rotor. Figures 2 and 3 show the HTS field coils and the rotor shaft-armature ensemble.

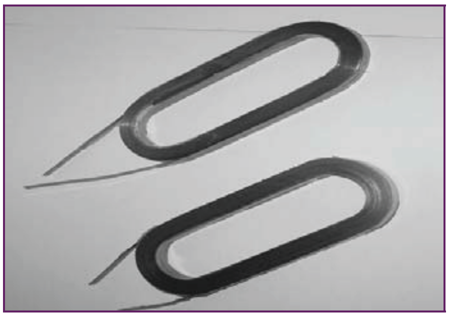

Figure 2: The HTS field coils.

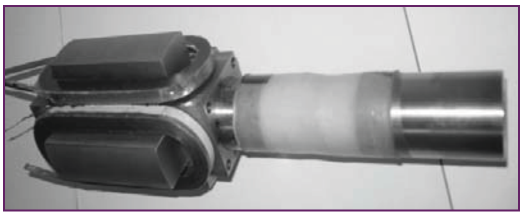

Figure 3: Shaft, armature, and HTS coils ensemble – all stainless steel.

Figure 4 exhibits the rotor ensemble. The HTS coils were impregnated with epoxy resin during the winding in pancake spools. After curing, the coils were tested to determine the appropriate working conditions, such as the critical current.

Figure 4: The rotor ensemble – all stainless steel.

The experimental results are shown in Fig. 5.

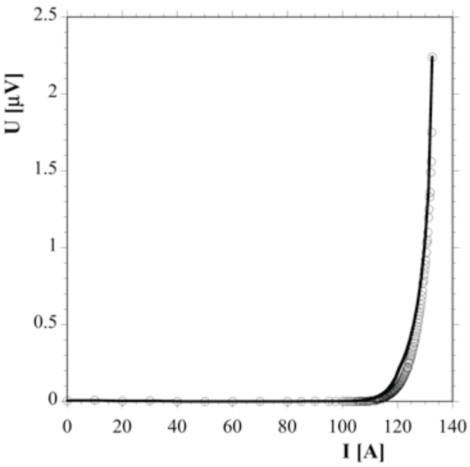

Figure 5: The critical current for the YBCO wire.

Apparently, the critical current is 130 A @ 77K, under self-field conditions. So, the coil may properly sustain 100 A @ 65 K.

2.2. The electromagnetic field – a 2D analysis

The machine is assumed to work as generator, *i.e.* the field winding is powered on, and the stator winding is open-circuit. We use a 2D Cartesian model for the design phase of the prototype. The electromagnetic field is modeled by the partial differential equation (PDE) for the magnetic vector potential [4,5]

$$\sigma \frac{\partial \mathbf{A}_z}{\partial t} + \nabla \times \left(\mu_0^{-1} \mu_r^{-1} \nabla \times \mathbf{A}_z \right) = \mathbf{J}_z^e, \qquad (1)$$

where $\mathbf{A}_z$ is the magnetic vector potential; $\mathbf{J}_z^e$ the external electrical current (Fig. 6,*a*); σ is the electrical conductivity; μ_0, $\mu_r(B)$ the magnetic permeability. The stator magnetization curve is shown in Fig. 7 (*H* is the magnetic field strength, *B* is the magnetic flux density).

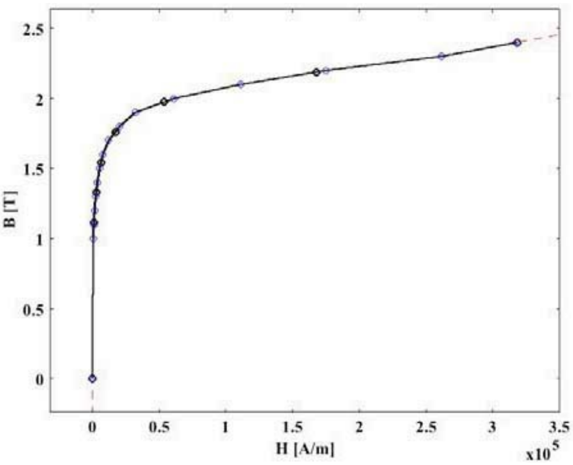

Figure 6: The magnetization curve for the iron core.

The rotor armature is made of stainless steel.

The boundary conditions that close the mathematical model are Dirichlet, homogeneous conditions for the magnetic vector potential on the stator armature outer surface. The mathematical model was implemented and solved for in the finite element (FEM) numerical technique, by using the COMSOL Multiphysics software package [4]. Figure 7 presents the FEM mesh made of approx. 32,000 triangular Lagrange quadratic elements.

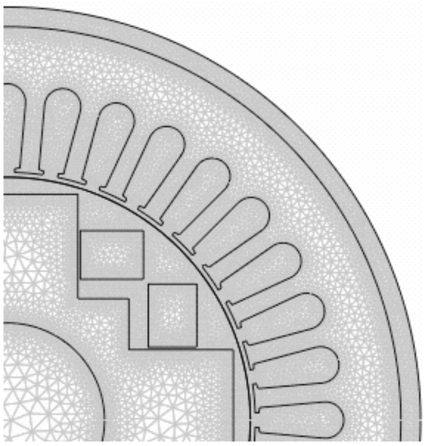

Figure 7: The FEM mesh made of approx. 32,000 vector elements – detail.

The relative rotor-stator motion, with prescribed angular velocity, was possible by using the ALE moving/deformable mesh technique [7].

Figure 8 shows the magnetic flux density through surface color maps magnetic vector potential contour lines, for two positions of the rotor. The high magnetic field, saturated regions are apparent, and these results were used to optimize the rotor design. The second problem, of major concern, is the thermal stability of the motor. Unlike classical machines, here the rotor is HTS. The thermal design technique – FEM assisted – is reported in [5].

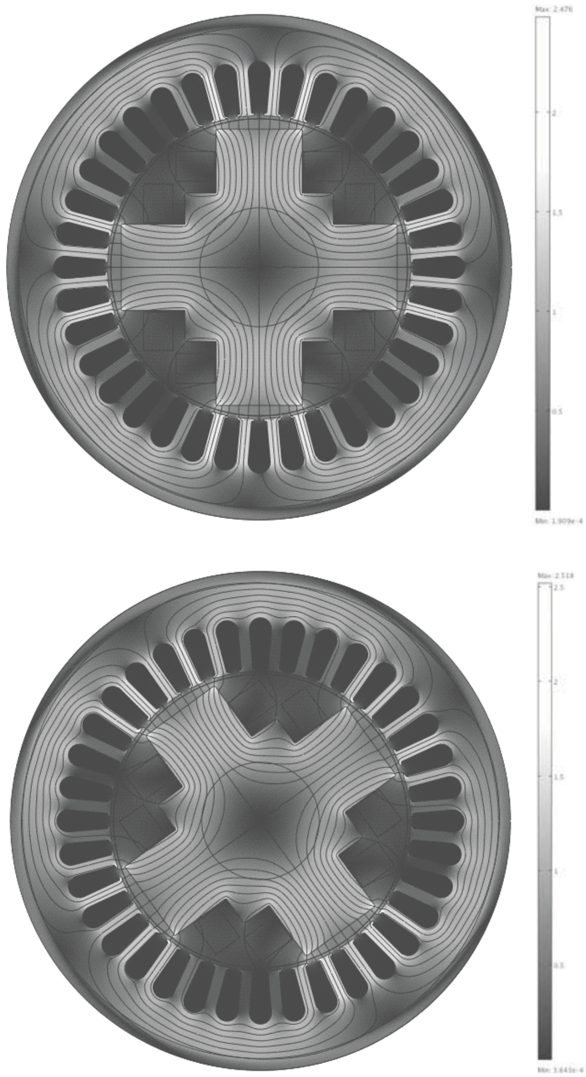

Figure 8: Magnetic flux density for two positions of the rotor.

2.1. The stator

The armature is of conventional design, with iron core. The stator winding are AC, three-phased, classical (copper). Figure 9 and 10 show the motor armature and the case.

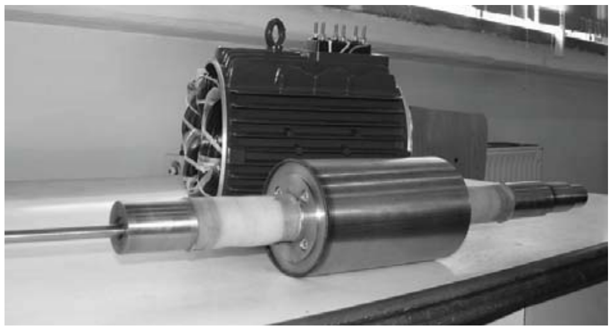

Figure 9: Stator and rotor before packing.

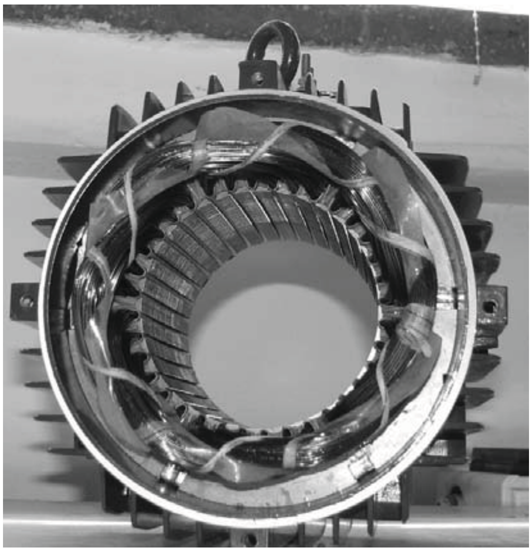

Figure 10: The stator – a conventional design.

The motor enclosure is made of stainless steel, and has several important functions: it ensures a vacuum-proof casing at a level of min. 10^{-3} torr, which helps reducing the heat leakage from the armature to rotor; it confines and supports the motor armature and the rotor housing; it sinks the heat produced within the armature winding; it provides for good structural stability of the motor.
The enclosure is made of a cylindrical shell, two flanges; is has a finned outer surface to improve the heat transfer to the ambient.

2.1. The cryogenic cooling system

The cryogenic cooling system provides for the cooling fluid needed for the rotor field coils to work properly, within safe temperature limits.

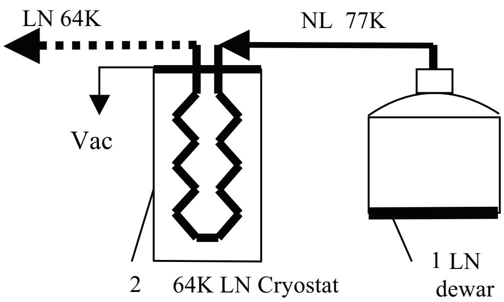

Figure 11: The schematic of the cooling system with liquid Nitrogen at 65 K.

Here, for demonstration purpose, a cooling system based on subcooled liquid Nitrogen (LN) was used (Fig. 11). Liquid Nitrogen enters a heat exchanger (at 77 K) placed in sub-cooled liquid Nitrogen (at 64 K), and exits at 64 K from the heat exchange cryostat.
At 64 K, the LN enters the rotor, and removes the heat, cooling the HTS coils down to 64 K. The LN was priority sub-cooled by controlled evaporation with a vacuum pump (Fig. 11).

3. CONCLUSIONS

The paper presents the work conducted to developing a small power HTS synchronous motor prototype. We designed and used an economic, efficient cooling system with supercooled Nitrogen for the YBCO tape conductor used in the field winding. The study is concerned also with the mathematical modeling and numerical simulation of electromagnetic field aimed at optimizing the design of the machine.

Acknowledgments

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