Preliminary Design and Simulation of a Superconducting Synchronous Machine for Aircraft Applications

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***Abstract*—This thesis investigates the preliminary design of an air-core superconducting synchronous machine for future aircraft applications. In the first part of the work, the state of the art of High Temperature Superconductors for electrical machines is presented. Then, two case studies are analyzed to find out a suitable modeling approach of superconductors in electrical machines. A specific formulation of the Maxwell's equations (T-A) is implemented as benchmark and it is demonstrated that an alternative approach, considering an equivalent constant current density in the superconductors, provides similar results at least from a macroscopic viewpoint. In the last part of the work, the features of air-core synchronous machines are carefully investigated. The preliminary design of a 2.61 MW, 2500 rpm air-core synchronous motor with superconducting field windings is carried out using analytical equations. The design is finally validated by FEM simulations. This motor is expected to be used to drive the propulsion fan of the STARC-ABL single-aisle turboelectric aircraft concept proposed by NASA.**

I. Introduction

Superconductivity is a phenomenon occurring in certain materials called superconductors. They exhibit a near-zero DC resistivity when they are operated inside their superconducting region as shown in Fig.1. This feature, together with the discovery of High Temperature Superconductors (HTS) in 1986, has increased the interest in developing superconducting wound field synchronous machines. By using HTS field windings in an air-core rotor, and copper windings in a slotless configuration in the stator, it is possible to considerably increase both the magnetic and the electrical loading of the machine. As a consequence, it is possible to develop light-weight and high-power-density electrical machines which are crucial for the electrification of the aviation sector.

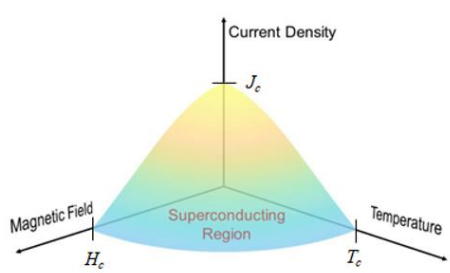

Fig. 1. Superconducting region defined by: critical temperature T_c, critical magnetic field H_c and critical current density J_c.

II. Numerical Modeling of Superconductors

In general, superconductors cannot be considered as ohmic conductors with negligible resistivity. The nonlinear constitutive relationship between the electric field E and the current density J in a superconductor can be described with a continuous Power-Law.

$$E = E_0(\frac{J}{J_c})^n \tag{1}$$

Where n is an index value and depends on the material. The critical electric field $E_0 = 1\frac{\mu V}{cm}$ is a reference value that is conventionally used to define the critical current density J_c in a superconductor. The parameter J_c represent the transportation capacity of the superconductor and it depends on the operating conditions: external applied magnetic field and temperature. To investigate in an accurate way the electromagnetic behavior of superconductors, it is possible to implement the Power Law through different formulations of the Maxwell's equations. In this thesis work, the T-A formulation was used. It consists in the definition of a current vector potential T in the superconducting region, such that $J = \nabla \times T$, and it is used as a state variable to calculate the current density distribution in the superconductors. The governing equations of the T-A formulation are:

$$\nabla \times [\rho \cdot \nabla \times T] = -\frac{\partial B}{\partial t} \tag{2}$$

$$\nabla \times \nabla \times A = \mu_0 J \tag{3}$$

Two case studies were investigated with the purpose of understanding if it was possible so simulate in a more simple way superconducting tapes in the machine. The first case study concern the simulation of a simple magnetic circuit and was used to familiarize with the simulation of superconductors, while the second one consists on the simulation of windings in air, and its results are shown in Fig.2. In each case study, superconductors were modeled and implemented in three different ways: the T-A formulation was used as benchmark, then superconductors were modeled as equivalent lines and an equivalent homogenized bulk and implemented with a constant current density J_{eq}. Comparing the results obtained with these three methods, thanks to the more accurate T-A formulation, it was possible to understand that even in DC conditions, the current density distribution in the superconductors is not uniform, Fig.2. However, the simulations proved that, if the tapes are tightly constrained to each other, the uneven distribution

of J in the superconductors does not affect the distribution of B over a control line and the control rectangle shown in Fig.2. For this reason, the stack of tapes in the machine was simulated as an homogeneous bulk with an equivalent constant current density, since the focus was on the macroscopic behavior of the superconductors. On the contrary, if the goal of the study is the evaluation of the losses in the tapes, it is necessary to use some strategies to reduce computational time and take into account the internal distribution of current density with the T-A formulation.

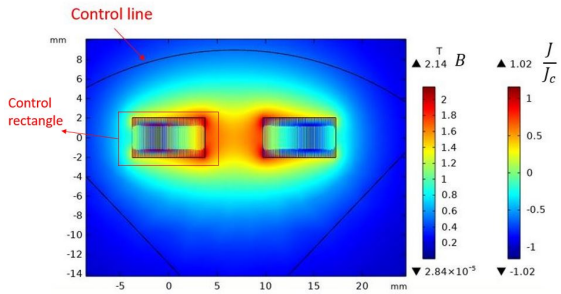

Fig. 2. Current density distribution along the tapes with T-A formulation. Highlighted in red the control line and rectangle over which the check on the magnetic flux density was carried out.

III. Preliminary Design and Simulation

Generally speaking, the theory of the conventional iron core machines is based on the separate consideration of: magnetic field in the air-gap and leakage fields. This approach is justified by the large amount of iron and the small air-gap. Unfortunately, this approach fails with air-core machines because there is no longer a clear-cut division between the two field components. For this reason, it is important to derive proper expressions for the magnetic field distribution in the machine. The parameters of capital importance for the preliminary design are the radii of the windings and of the iron yoke, as depicted in Fig.3.

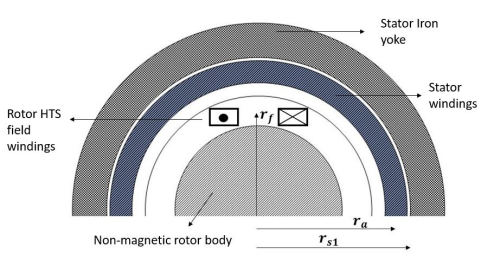

Fig. 3. Geometrical parameters for the design of an HTS air-core machine.

With reference to the parameters of Figure 3, equation 4 represents the total magnetomotive force needed for achieving the desired value of B_{s0}, which is the peak value of the fundamental of the magnetic flux density at the mean armature windings radius (r_a). This magnetic flux density value is the one considered in the sizing equation for the electromagnetic design of the machine.

$$N_f I_f = k_c \frac{\pi r_f B_{s0}}{\mu_0 (\frac{r_f}{r_a})^{p+1} [1 + (\frac{r_a}{r_s 1})^{2p}]} \tag{4}$$

The harmonic content of the distribution of B at the mean armature windings radius was improved thanks to the adjustment of the distance between the two field coils. Moreover, in this work, a correction factor k_c was introduced in eq.4, for improving the estimation of the mmf in the machine. The specifications of the designed HTS synchronous motor are summarized in Table I. Four stacks made of 150 YBCO tapes each were used for the field windings. Their transportation current is 500 A at an operating temperature of 20 K, according to the manufacturer indications. In order to maximize the magnetic flux density in the machine, and to minimize the thickness of the stator yoke, CoFe iron was used for the stator yoke which was operated at 2 T.

TABLE I
Main design specifications of the HTS motor.

Parameter	Value
Output Power P_M[MW]	2.61
Peak value Line Voltage[kV]	2
Rated shaft speed [rpm]	2500

It was decided a number of pole pairs $p = 3$, a magnetic flux density in the armature windings $B_{s0} = 2.3T$ and an electrical loading $A = 250\frac{kA}{m}$. The obtained machine dimensions are: external diameter $D = 464mm$, axial length $L = 160mm$. The torque computed analytically is $T = 10.045kNm$. Subsequently, the design was validated by FEM (Comsol) and the value obtained for B_{s0} is 2.31 T, while the torque is $T = 10.026kNm$, with a very low ripple due to the reduced harmonic content of the B distribution. In Fig.4 the results at load of the FEM simulation of the designed machine are shown.

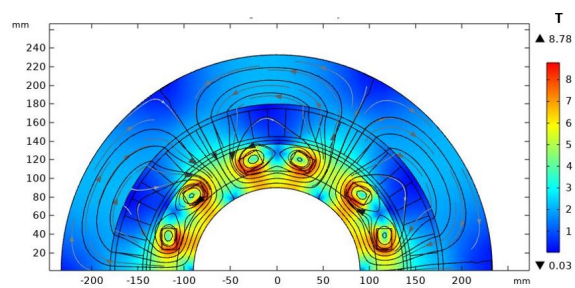

Fig. 4. Flux density map of the designed HTS motor at load.

IV. Conclusions

This thesis investigates an air-core superconducting synchronous motor for future aircraft applications. On the basis of the results of the case studies, if the goal is to evaluate the macroscopic behavior in terms of magnetic flux density, it is possible to model and simulate superconductors as an homogenized bulk with a constant current density. However, for an estimation of the losses in the tapes, it is necessary to use specific formulations that take into account the physics of the superconductors. Moreover, the preliminary design of an HTS machine for aircraft propulsion applications was carried out using a relatively simple procedure and obtaining a good match between analytical and FEM results.