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Finite Element Model of a Superconducting Generator for Aircraft Application Coupled to an External Electrical Circuit

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High temperature superconductor (HTS) material are strong candidates for the development of future electrical machines due to their high energy density at low AC losses resulting in greater electrical efficiency for lighter and compacter designs than traditional machines. The features are particularly appealing for transports. The present work focuses on the electromagnetic modelling of a superconducting synchronous generator for aeronautic applications with a particular interest in the coupling between Finite Element Model (FEM) and external electrical circuits. The FEM implements different formulations of the Maxwell equations, namely H-A, T-A and the classic A-V to find the best suited combination FEM - electrical circuit for computation load reduction (time and memory). The external circuit simulates a power converter interconnecting the machine to the load. The performance of both the machine as a whole and the superconductor is evaluated for different load conditions.

Index Terms—Finite element analysis, Generators, Rotating machines, Superconducting coils.

I. INTRODUCTION

THE present work deals with the use of compact and light superconducting (SC) generators for aircraft applications. The electromagnetic behavior of such machines is in part dictated by its design including the choice of materials [1] and in part by the nature of its interconnection with the electrical system. The latter is often ensured by a power converter. Both the machine and the power converter should be simulated with enough details to provide more reliable insight on the performance of the machine and, in this particular case, on the behavior of the superconductor as well. This simulation involves the coupling between FEM and external electrical circuit. Such approach has been recently considered to get the most realistic nonlinear behavior of SC machines inside electrical networks. Here, the model and the coupling with electrical circuit is carried out using the partial difference equation module of the Finite Element commercial software COMSOL Multiphysics [2] linked to MATLAB/Simulink to provide flexibility in one's own implementation. Different formulations of the Maxwell equations are compared to find the best combination (reduced computation time at lesser resources) for no-load and load conditions coupling FEM and external electrical circuit, the latter being composed of a power converter connected to an infinite bus.

II. DETAILS OF THE HTS SYNCHRONOUS GENERATOR

Fig. 1 shows the conceptual design of a 10 MW 5-pole generator with a maximum speed of 10,000 rpm. It is composed of a superconducting iron-less rotor and a conventional stator. The rotor has 5 coils; each coil is constituted of 300 turns of insulated REBCO tapes. The stator has 12 slots holding a

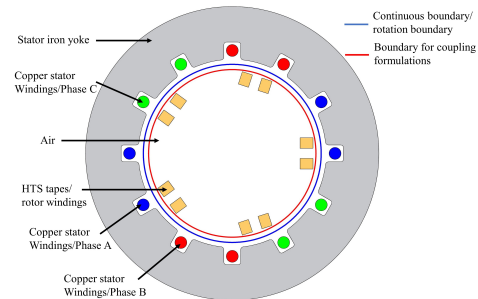


Fig. 1. Generator for aircraft application: SC rotor and conventional stator.

three-phase winding made of insulated Cu wires surrounded by ferromagnetic laminated material to lock the magnetic flux allowing a lighter design but avoiding large fringe field.

III. FORMULATION OF MAXWELL EQUATIONS

A. $\mathbf{H} - \mathbf{A}$ Formulation

Recently, the $\mathbf{H} - \mathbf{A}$ formulation has been successfully applied to simulate superconducting rotating machines [2]. The \mathbf{H} formulation solves the magnetic field and current density in the superconductors (rotor region with non linear resistivity ρ given by the power law and $\mu = \mu_0$) whereas the \mathbf{A} formulation solves the magnetic potential vector in the non-superconducting region including the iron core ($\mu = \mu(H)$). The governing equations for the \mathbf{H} and \mathbf{A} formulations are given below,

$$\nabla \times (\rho \nabla \times \mathbf{H}) = -\mu_0 \frac{\partial \mathbf{H}}{\partial t} \quad (1)$$

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} = \mathbf{J} \quad (2)$$

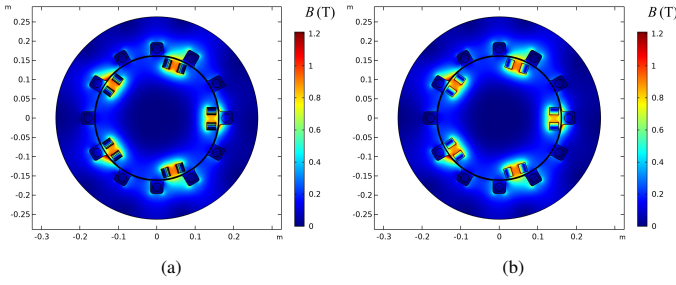


Fig. 2. Comparison of magnetic flux density distribution: (a) $\mathbf{H} - \mathbf{A}$ formulation and (b) $\mathbf{T} - \mathbf{A}$ formulation.

The two equations are coupled at the boundary of the domains ($\partial\Omega_{H-A}$) as shown by their weak form below,

$$\int_{\Omega_H} \rho \nabla \times \mathbf{H} \cdot \nabla \times \mathbf{H}^* d\Omega_H + \int_{\Omega_H} \mu_0 \partial_t \mathbf{H} \cdot \mathbf{H}^* d\Omega_H = \dots \int_{\partial\Omega_{H-A}} (-\partial_t \mathbf{A} \times \hat{\mathbf{n}}_H) \cdot \mathbf{H}^* d\partial\Omega_{H-A} \quad (3)$$

$$\int_{\Omega_A} \frac{1}{\mu} \nabla \times \mathbf{A} \cdot \nabla \times \mathbf{A}^* d\Omega_A - \int_{\Omega_A} \mathbf{J} \cdot \mathbf{A}^* d\Omega_A = \dots \int_{\partial\Omega_{H-A}} (\mathbf{H} \times \hat{\mathbf{n}}_A) \cdot \mathbf{A}^* d\partial\Omega_{H-A} \quad (4)$$

Homogenization technique is used where the current density \mathbf{J} as well as the critical current density J_c are scaled by a ratio of the surface of the superconductor layer to the surface of a tape.

B. $\mathbf{T} - \mathbf{A}$ Formulation

In the $\mathbf{T} - \mathbf{A}$ Formulation, the current vector potential \mathbf{T} is solved for the superconductor domain and the \mathbf{A} potential is solved for the complementary domain [3]. \mathbf{T} is related to the current density in the tape via $\mathbf{J} = \nabla \times \mathbf{T}$. From the Faraday's law, \mathbf{T} is solved knowing the magnetic flux density \mathbf{B} as follows,

$$\nabla \times \rho \nabla \times \mathbf{T} = -\frac{\partial \mathbf{B}}{\partial t} \quad (5)$$

The magnetic flux density \mathbf{B} is inferred from \mathbf{A} , computed via (2), as $\mathbf{B} = \nabla \times \mathbf{A}$. The boundary conditions at the edges of the coil allows imposing the actual current flowing through series-connected tapes I as $T_1 - T_2 = I/\delta$, 1 and 2 being opposite edges of the set of tapes and δ is the thickness of a single superconductor layer. On the remaining edges, a Newman condition is applied.

Fig. 2 shows the comparison of magnetic flux density distribution B obtained for both formulations $\mathbf{H} - \mathbf{A}$ and $\mathbf{T} - \mathbf{A}$. A good agreement in the distribution and magnitude is achieved.

C. Classic $\mathbf{A} - V$ Formulation

The $\mathbf{A} - V$ formulation is the most used formulation in the modelling of machines providing a reference to the present work. It combines the magnetic vector potential \mathbf{A} , and the electrical scalar potential V . The \mathbf{A} field is solved by modifying (2) and a new equation is added allowing to solve for the new unknown V as follows,

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} + \sigma (\partial_t \mathbf{A} + \nabla V) = \mathbf{J} \quad (6)$$

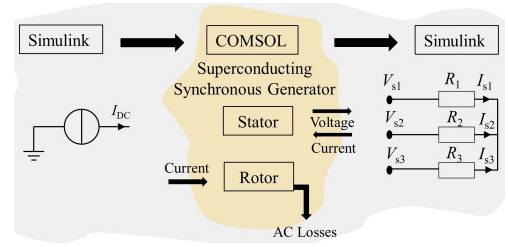


Fig. 3. Conceptual diagram of the coupling configuration COMSOL-Simulink.

$$\nabla \cdot \sigma (\partial_t \mathbf{A} + \nabla V) = 0 \quad (7)$$

where $\sigma = 1/\rho$ is a nonlinear function of the magnetic flux density and electric field in the superconductor [4].

IV. COSIMULATION: COUPLING FEM AND EXTERNAL CIRCUIT

The coupling between the Finite Element software COMSOL Multiphysics and Simulink is being implemented. It is carried out using the existing Function Unit interface (FMU) built in Java to relate dynamically COMSOL local variables to global variables in Simulink. The overall time stepping is controlled by Simulink while COMSOL manages its own solver during one time step from t to $t + \Delta t$ to ensure the proper convergence. Fig. 3 illustrates the coupling model that currently includes some basic components such as: 1) a controllable DC current source feeding the machine field winding using Simulink, 2) a 2D HTS generator simulated in COMSOL, and 3) a three-phase resistive load is considered here to establish the basis of the cosimulation but it will be replaced by a rectifier later on.

V. CONCLUSION

The most recent formulations of the Maxwell equations for HTS machine modeling are being compared to find the most appropriate state variables to solved the coupled FEM and electrical circuit problem to reduce the computation time and the resources. The model will be used to get some first insight on the performance of the HTS generator for aeronautic applications connected to the electrical network via a power converter. The FEM includes the nonlinear behavior of the superconductor via its resistance depending on magnetic flux density and current density. It also includes all the classic features of machine simulation to get the most realistic outcomes.

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