AC loss modeling of the stator of a 1 MW REBCO superconducting motor for aviation

Enric Pardo
Institute of Electrical Engineering,
Slovak Academy of Sciences
Bratislava, Slovakia
enric.pardo@savba.sk

Francesco Grilli
Institute of Technical Physics,
Karlsruhe Insittute of Technology
Karlsruhe, Germany
francesco.grilli@kit.edu

Thomas Reis
Oswald Elektromotoren GmbH
Miltenberg, Germany
thomas.reis@oswald.de

Abstract—**Electric and hybrid-electric aircrafts with distributed propulsion have the potential to reduce commercial-flight emissions. REBCO full superconducting motors are very promising to achieve the required power-over-weight ratio. However, there are concerns about their possibly high AC loss in the stator. Computer modeling can provide design solutions for low AC loss, but these need to be fast and efficient. Here, we present two modeling methods to compute the AC loss in the stator of a 1 MW superconducting motor for aviation. One method combines a commercial Finite Element Method (FEM) with an in-house method based on a variational principle, while the second uses a novel variational method to model the whole motor that does not need meshing the air, avoiding moving mesh issues. Our results show that transposition is not required for distributed stator windings with multi-tape conductors. We also found promisingly low AC loss values for the stator winding, which require neither transposed nor striated tapes.**

Keywords—Superconducting motors, high temperature superconductors, REBCO, variational methods, open-source code.

I. INTRODUCTION

Commercial aviation is a growing source of greenhouse-effect emissions. For this reason, the European ACARE Flightpath 2050 report targets a very strict reduction in emissions (75 % for CO_2 and 90 % for NO_x and particulates) [1]. Electric and hybrid-electric propulsion can help achieving these goals, but requires electric propulsion motors with high power-over-weight ratio (around 20 kW/kg). While this seems to be too much for conventional motors, REBCO high-temperature superconducting motors can fulfill these requirements for motors of 100+ passenger-aircraft, with an expected power of around 1-5 MW for each motor.

Due to the high inductance of the motor coils, usually several tapes in parallel are necessary to achieve the required current capacity, being stacks of parallel tapes the simplest solution. However, there may be coupling AC loss effects due to the alternating magnetic field along the tape wide surface, causing large AC loss. Therefore, modeling the influence of these coupling effects is of utter importance.

Here, we present two modeling methods to calculate the AC loss and other electro-magnetic properties and apply them to the final stator of the superconducting motor demonstrator for the EU Horizon 2020 project ASuMED [2]. We also analyze the impact on the AC loss of the coupling effects in the parallel-tape conductor and predict the expected AC loss in the stator of the ASuMED motor.

II. NUMERICAL METHODS

A. Combined method

The combined method first calculates the vector potential (and magnetic flux density) in the whole motor assuming uniform current density, J, in the superconducting coils and using FEM with A formulation in the static approach. Here, we also take each half-coil cross-section as a single uniform block. An example of the obtained magnetic flux density at the whole motor is in Fig. 1. Once the vector potential is obtained, we export A at all points of the half-coil sections to a different program that calculates the non-linear eddy current density by means of MEMEP (Fig. 1). The results of this combined method agree with those from FEM and TA formulation [3]. More details of the combined method can be found in [4].

B. Minimum Electro Magnetic Entropy Production (MEMEP) with non-linear ferromagnetic parts

The MEMEP method is a time-evolution electromagnetic modeling method that does not need to mesh the air, saving degrees of freedom [5], [6]. In short, the method solves the current density at every time step by minimizing a certain functional of the change of current density between time steps, $\Delta J(\mathbf{r})$, at each position $\mathbf{r}$. This method has also been developed for 3D modeling [6], [7]. The full code in C++ of this 3D software is **now available in open source** [8] (an overview will also be presented at the conference).

Here we present an extension that also takes the non-linear permeability of soft ferro-magnetic parts into account [9]. For this method, we take both components of the magnetization,

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$\mathbf{M}$, as state variable, thus avoiding again to solve quantities in the air. The functional to be minimized for $\mathbf{M}$ is

$$L_M = \int_V \mathrm{d}V \left[U(\mathbf{M}) - \frac{1}{2}\mathbf{B}_M \cdot \mathbf{M} - \mathbf{B}_a \cdot \mathbf{M} - \mathbf{B}_J \cdot \mathbf{M} \right],$$

where $U(\mathbf{M}) = \int_0^{\mathbf{M}} \mathrm{d}\mathbf{M}' \cdot \mathbf{B}(\mathbf{M}')$, $\mathbf{B}_M$, $\mathbf{B}_a$, and $\mathbf{B}_J$ are the magnetic flux densities generated by $\mathbf{M}$, the applied-field sources, and the current density, and $\mathbf{B}(\mathbf{M}')$ is the relation of the material between the flux density and $\mathbf{M}$. Following the same steps as in [6], we have demonstrated that there is always a minimum for this functional and it is unique. We solve the whole problem by minimizing iteratively both functionals, for ΔJ and $\mathbf{M}$, for each time step. An example solution for the no-load situation can be found in [10].

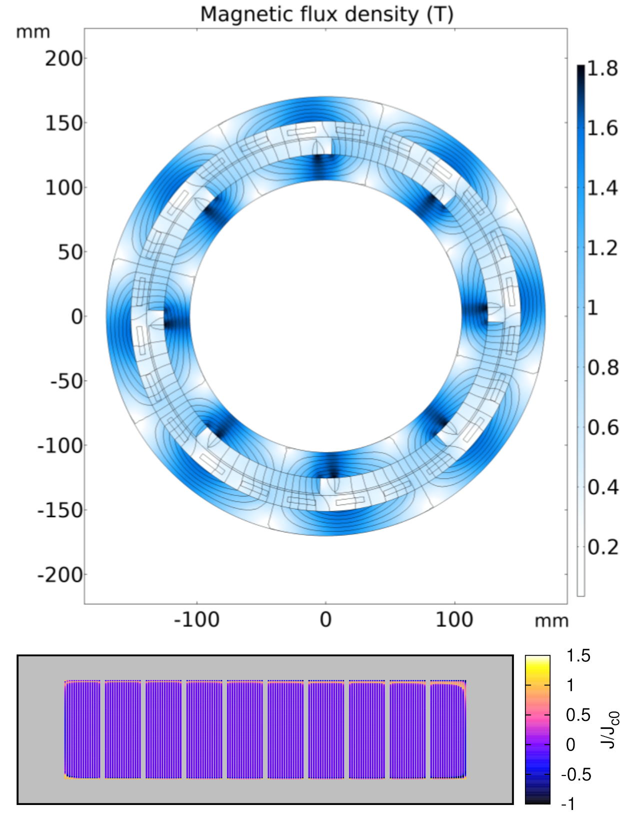

Fig. 1. (top) Magnetic flux density of the studied motor obtained by FEM, containing the final stator of the ASuMED motor [2]. In this article, we use a permanent-magnet rotor, for simplicity. (bottom) Current density obtained by MEMEP for one of the half-coils, where the top edge faces the rotor.

III. RESULTS AND CONCLUSIONS

We have found several interesting results with our models, mainly obtained by the combined method.

First, transposition in multi-tape conductors made of stack of tapes is not necessary in distributed windings, thanks to the self-transposition of the magnetic flux density [10], which cancels the magnetic flux crossing the stacked conductor in the radial direction [Fig. 1(top)]. Modeling results show that the AC loss for the fully coupled and uncoupled cases are the same [10].

For the final stator of the ASuMED motor [2], we predicted AC loss values of 245, 374, 569 W for 20, 30, and 40 K, respectively, taking the input $J_c(B,\theta)$ from the measurements in [11]. These are very low AC loss values, being well below 1 % of the motor power. However, the AC loss in the actual demonstrator might be higher because modeling does not take the J_c decrease at the tape edges, where most the the current penetration occurs (Fig. 1) but uniform J_c. Nevertheless, improvements in the overall J_c with the same relative edge J_c degradation will reduce the AC loss.

This contribution presented AC loss modeling for a motor with the final stator design of the ASuMED project, aming at a full superconducting motor for aviation. We also developed a novel modeling method for the full motor that does not require meshing the air, avoiding the moving mesh problem. Modeling shows that transposition of multi-tape conductors in distributed stators is not necessary, which may avoid the need of complex transposed cables. We also obtained promisingly low values of AC loss.

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