Modelling of Two Topologies of Trapped-flux Machines with Second Generation Tapes Using T-A 3D Formulation

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***Abstract*—This work presents modelling and magnetization comparison of two topologies of partially superconducting trapped-flux machines with second generation tapes, one with spiral stacks and other with layers of sheets with holes. Modelling is done with finite element method and the T-A formulation in 3D. From results, it is found that the second topology has stronger magnetization.**

***Keywords*—3D modelling, finite elements, superconducting trapped-flux machine, T-A formulation**

I. Introduction

Superconducting electric machines are good candidates to supply the growing demand for high power density machinery in industries such as wind power generation and aviation [1]. Modelling such machines is crucial for the industries to achieve appropriate designs for their operations. Many formulations have been used to simulate superconducting machines, for example, H, A-V, A-V-H and T-A formulations. From those options, one that works very well to model stacks of coated conductors is the T-A formulation [2]. This is the modelling approach chosen in this work to simulate two topologies of partially superconducting trapped-flux machines with stacks of coated conductors. For the first one (T1), coated conductor stacks are made in spiral form, see Figure 1(a). This topology has been studied by our group, with its feasibility proven experimentally and through 2D simulations [3], [4]. However, a few points in its design can be changed to improve magnetization of the stacks, namely:

1) increasing the pathway for the current density to circulate through the superconducting material, decreasing critical current density (J_c) locally.
2) opening way for the magnetic field to increase magnetic flux density in the rotor core, improving flux linkage for the stacks and, therefore, improving magnetization in the stacks.

This may be achieved by considering stacks of superconducting sheets occupying the whole rotor length with holes allowing the magnetic flux to link rotor and stator cores. So, here we propose this topology (T2), see Figure 1(b). In this work, the aim is to analyze the differences in magnetization of these two topologies of superconducting trapped-flux machines with 3D simulations. The text is organized as follows. Topologies are described in section II. Modelling processes are described in section III. Results and discussions are presented in section IV. A brief conclusion is made in section V.

II. Superconducting trapped-flux machine with stacks of coated conductors

The superconducting trapped-flux machines with stacks of coated conductors studied in this work are composed by a common stator, with copper windings, and a rotor with the stacks of coated conductors arranged around the rotor core. This machine is expected to have two modes of operation: synchronous, with no losses coming from the stacks, and asynchronous, with losses. Magnetization of the stacks is induced on the tapes, therefore, this type of machine has to have full magnetic circuits, with ferromagnetic material both on stator and rotor, the same way it is done with synchronous/induction superconducting machines [5]. The gain here is to reduce the amount of this type of material with comparison to more common machines.

III. Methodology

As mentioned previously, modelling approach centers around finite element method and T-A formulation in 3D [2], with T as the current vector potential and A as the magnetic vector potential. As magnetization is induced, the total current in the stacks is always zero, meaning that

$$I_{\text{total}} = \oint_L T dl = 0 \tag{1}$$

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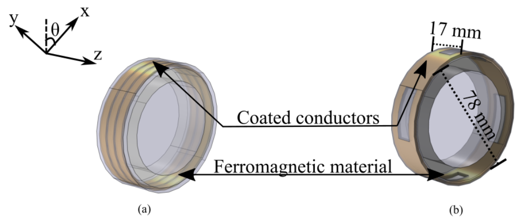

Fig. 1. Two topologies of superconducting trapped flux machines: (a) with three spiral stacks; (b) with superconducting sheets with holes.

for all paths that define the superconducting surfaces, here defined by L. So, Dirichlet boundary conditions of zero potential are imposed on all boundaries. For both T1 and T2, five layers of superconducting surfaces are modelled, with tapes being the SuperPower advanced pinning model, data taken from [6], with 4 mm width for T1. Four-millimiter tape is chosen for simplicity, as the simulation models are smaller than they would be with a 12 mm model, making computations faster. This is not a particular problem as part of the objective is to compare the effects of a number of stacks with tape width much smaller than the rotor width to those of a single stack occupying the whole rotor width. Stator currents are represented by a finite height current sheet. A current density pulse of 1.8×10^5 A.m^{-2} for 200 ms, generating four magnetic poles, is applied. The ferromagnetic material considered for stator and rotor magnetic circuits is silicon steel NGO 35PN250. The highest model radius is 39 mm.

IV. Results and discussions

Figures 2 and 3 show the current density 100 ms after the pulse ended. It is observed that magnetization is much stronger in model T2 compared to model T1, achieving around 0.4 of normalized persistent critical current density versus 0.2 of T1. This means that, for the same field, current in stator conductors have to be much higher to magnetize T1, increasing copper losses.

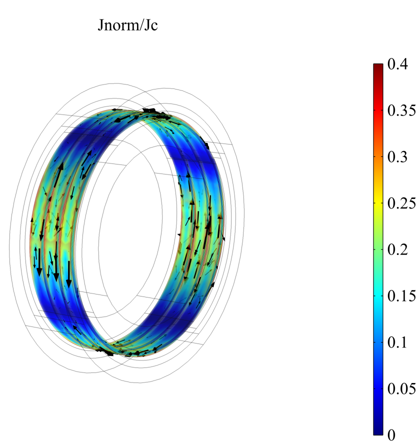

Fig. 2. Normalized current density norm (Jnorm/Jc) of T1 100 ms after the pulse ended. Arrows point current density direction.

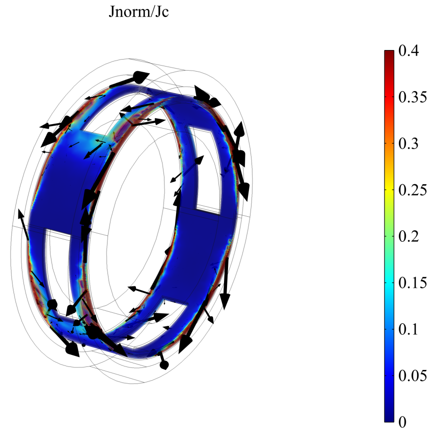

Fig. 3. Normalized current density norm (Jnorm/Jc) of T2 100 ms after the pulse ended. Arrows point current density direction.

Another important aspect is current density direction. The azimuthal component of current density, J_θ (see Fig. 1), dominates current paths in T1, and as they do not create torque for this topology, it indicates that much of the magnetization is not useful. For T2, although there is strong presence of J_θ, its contribution to current density norm is lower.

V. Conclusion

This work presents 3D modelling of two topologies of superconducting trapped-flux machines: one with spiral stacks, T1, and one with superconducting sheets with holes, T2. It is observed that magnetization is stronger in T2, and current density has a larger pathway to circulate, lowering critical current density locally.

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