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► **To cite this version:**

Carlos Vargas-Llanos, Felix Huber, Nicolo Riva, Min Zhang, Francesco Grilli. Modeling of HTS coils with complex geometries by using the T-A homogenization in 3D. 8th International Workshop on Numerical Modelling of High Temperature Superconductors (HTS 2022), Kévin Berger (Université de Lorraine - GREEN), Jun 2022, Nancy, France. hal-03791530

HAL Id: hal-03791530

<https://hal.science/hal-03791530v1>

Submitted on 29 Sep 2022

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Modeling of HTS coils with complex geometries by using the T-A homogenization in 3D

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Abstract—The modeling and analysis of superconducting coils is an essential task in the design stage of most HTS based devices. These calculations allow verifying basic estimations/assumptions, proposing improvements, and computing quantities (such as AC losses) that are not easy to calculate with analytical approaches. Typically, 2D finite element analysis is used for this purpose. However, these 2D models are usually a representation of infinitely long or axially symmetric geometries. Therefore, they cannot be used to analyze end effects and complex 3D configurations. In this work, we use the T-A homogenization in 3D for the analysis of superconducting coils with complex geometries where a 2D approach can not provide accurate analyses and verification of assumptions. For these complex geometries, the modeling methodology allows an easier implementation in commercial software (COMSOL Multiphysics) than the currently available 3D H homogenization.

Keywords—T-A formulation, 3D modeling, homogenization, high-temperature superconductors, AC losses, superconducting coil.

I. INTRODUCTION

The electrical properties of high-temperature superconductors (HTS) have inspired several applications in different fields such as electrical machines [1], [2], [3]; fault current limiters [4]; magnets for scientific research [5]; energy storage [6] and transmission [7]. The design of these devices usually requires an electromagnetic analysis that allows establishing rated characteristics as well as studying the behavior under different operating conditions. Moreover, losses in the superconducting tapes and wires must be estimated to design the cooling system. These AC losses can be decisive for the practical and economic realization of superconducting devices.

Several analytical solutions have been developed to estimate losses in HTS tapes [8], [9], and infinite stacks of tapes [10], [11], [12]. However, these solutions are only valid under specific operating conditions such as AC transport current or externally applied magnetic field. Therefore, they can not be directly used to estimate losses in most superconducting machines and equipment. For these reasons, a finite element model is typically used to analyze the electromagnetic behavior and estimate hysteretic losses in the HTS tapes.

There are two main formulations of Maxwell's equations that are commonly used to model superconductors by using the finite elements method (FEM). The first one is based on the magnetic field strength (\mathbf{H}) and has already been used to study numerous applications [13], [14]. The second one was introduced in [15] and is based on the current vector potential (\mathbf{T}) and magnetic vector potential (\mathbf{A}). This T-A formulation is mostly used to analyze superconducting layers by applying a thin strip approximation. The approximation allows a reduction of dimensions that decreases the number of degrees of freedom and computation time. Therefore, it has been used to study the cross-section of magnets [5] and electrical machines with hundreds and thousands of tapes [16], [17], [18].

Most of the FEM-based models used to study superconducting devices are 2D. They usually represent the cross-section of an infinite long or axisymmetric arrangement. Therefore, the end effects are not considered. Moreover, complex geometries and operating conditions can not be fully studied with a 2D model. For instance, the transport current (without externally applied magnetic field) operating condition in a saddle coil (figure 1) presents a complex 3D behavior of the current. In the middle of the straight section, the current flows parallel to the x -axis. However, the curve section works as a transition zone for the current vector from the x -direction to the y -direction,

by following the winding/position of the tapes. This end effect can not be analyzed by using a 2D model.

Due to the complex behavior of the current density (\mathbf{J}) in 3D geometries, the cartesian components (J_x, J_y, J_z) are not suitable for representation purposes. A possible way to overcome this problem is to use the norm of \mathbf{J} . However, we will not be able to appreciate the two fronts of currents in opposite directions during the AC cycle. Therefore, we use the dot product between the current density vector and a tangential vector parallel to the winding direction (\mathbf{e}_t):

$$\frac{\mathbf{J} \cdot \mathbf{e}_t}{J_c(B_{\parallel}, B_{\perp})}. \quad (1)$$

In figure 2 we represent the current density behavior in the same saddle coil for an AC transport current with a peak value of 100 A and frequency $f = 50$ Hz, when the current is equal to zero, and after the first half period of the sinusoidal cycle. The current density penetration and behavior is very similar in the middle of the straight and circular sections. There is only a small difference between the inner and outer part of the curved section (indicated with green arrows in figure 2). This small difference is an effect of the self-field of the coil, which tends to be higher inside the coil than outside. According to these results, a 2D model that represents the middle of the straight section of the saddle coil can provide a good approximation of the current density behavior and a first estimation of the AC losses. However, these kinds of assumptions can only be validated with a 3D approach. For these reasons, several efforts have been made for the development of tools and methodologies that allow 3D modeling of HTS coils [19], [20], [21], [22], [23]. As part of these efforts, in 2014 the 3D H homogenization was introduced with the model of a racetrack coil [24]. However, the implemented approach requires the use of high resistivity layers in the homogenized domain, which make the building of the geometry and of the mesh more complex. Five years later, the 3D homogenized T-A formulation was proposed by Huang et al. [25], who used it to calculate the AC transport losses of HTS racetrack coils. In this work, we expand the current knowledge by using the 3D T-A homogenization for the simulation coils with complex shapes such as racetrack, saddle and twisted coils. The modeling approach is based on normal vectors that follow the shape of the 3D geometry. Therefore, this general definition allows an easy implementation of the model despite the complexity of the geometry.

ACKNOWLEDGMENT

This work was partly supported by the EU-funded Hi-SCALE COST Action CA19108.

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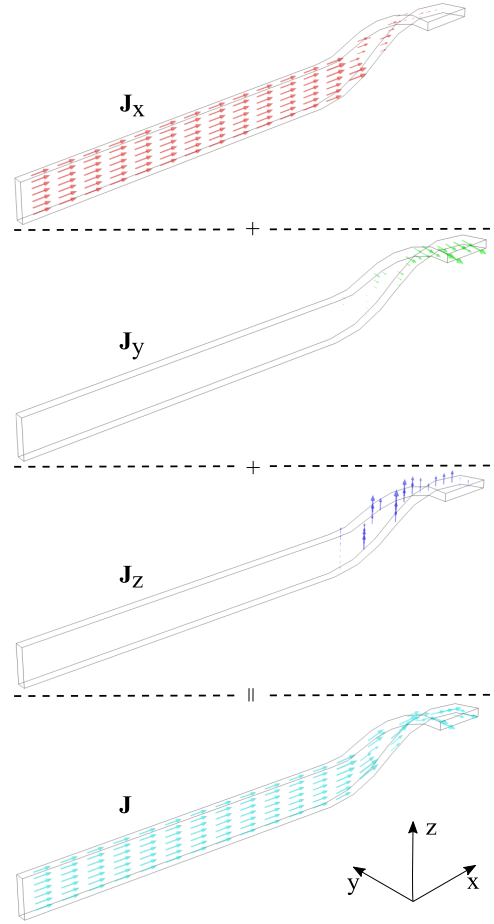


Fig. 1. Distribution of the current density components inside one-fourth of a saddle coil when the current reaches the maximum value. From top to bottom: x-component (J_x), y-component (J_y) and z-component (J_z). The total current density is depicted in light blue arrows at the bottom.

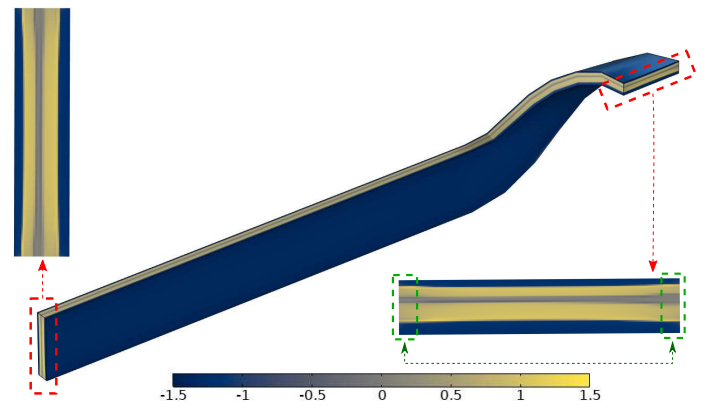


Fig. 2. Current density behavior in one-fourth of the saddle coil computed with the 3D T-A homogenization model, for AC transport current ($f = 50$ Hz and $I_{\text{peak}} = 100$ A) when the current is equal to zero, and after the first half period of the sinusoidal cycle. The current density is normalized with the critical current density by using equation (1) to reflect the two fronts of current (positive and negative) in the direction tangential to the winding.

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