3D Homogenized T-A Formulation for Modeling HTS Coils

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***Abstract*—The estimation of losses in high-temperature superconductors (HTS) is a key part of the design of superconducting devices. These losses will influence the cooling requirements and the thermal stress distribution in the superconducting coils. Due to the complex behavior of the superconductor, there are no analytical expressions able to predict accurately the losses in HTS tapes/wires in coils under operating conditions such as AC transport current and AC external applied magnetic field. For this reason, 2D finite element models are typically used to estimate losses and analyze the electromagnetic behavior of superconducting devices. These models are not able to consider end-effects or analyze complex 3D geometries. We present in this work the T-A homogenization in 3D for the analysis of superconducting coils. This modeling approach reduces computation time in comparison with the currently available 3D H homogenization. First, we validate the technique against measurements and axisymmetric solutions by modeling circular coils. Then, this technique is used to study the AC losses and the electromagnetic behavior of a racetrack coil.**

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

I. Introduction

The electrical properties of high-temperature superconductors have inspired several applications in different fields [1], [2], [3], [4]. The estimation of losses is fundamental for the design and construction of these applications since they strongly influence the cooling power requirements.

There are several analytical solutions available to estimate losses in tapes and stacks of tapes [5], [6], [7]. However, these expressions are only valid under specific operating conditions and can not be directly used in more complex cases such as AC transport current and externally applied magnetic field in HTS coils. Therefore, finite element models (FEM) are typically used to estimate losses and analyze the electromagnetic behavior of superconducting devices.

There are two main formulations of Maxwell's equations that are commonly used to model superconductors by using FEM. The first one is based on the magnetic field strength (**H**) and has already been used to study numerous applications [8], [9]. The second one was introduced in [10] and is based on the current vector potential (**T**) and magnetic vector potential (**A**). This T-A formulation is mostly used to analyze superconducting layers by applying a thin strip approximation. This approach reduces degrees of freedom and computation time.

Most of the FEM-based models used to study superconducting devices are 2D. These models are usually a representation of the cross-section of very long or axisymmetric arrangements. For this reason, they do not consider end effects and can not be used to study complex 3D geometries. We present in this work the 3D T-A homogenization. First, we make a small review of the T-A formulation and homogenization in 2D to set the basis that allows extending the same concepts in 3D. Then, the modeling technique is used to analyze the circular coils presented in [11]. This study allows us to validate the modeling approach against axisymmetric solutions and measurements. Finally, the technique is used to analyze a racetrack coil. These simulations are compared with the estimation of losses presented in [12] by showing that the 3D T-A homogenization can reproduce the same results with a significant reduction of computation time in comparison with the currently available 3D H homogenization.

II. T-A formulation and homogenization

The first applications of the T-A formulation to study superconducting devices by using FEM were introduced in [10], [13]. These works presented the T-A formulation as an efficient approach to model HTS tapes with a high aspect ratio. An approximation is typically done in the T-A formulation by considering that the superconducting layer in the tapes under study (for instance rare-earth barium copper oxide/REBCO tapes) has a very large width-to-thickness ratio. Therefore, we can collapse the thickness of the tape by transforming it into a superconducting sheet.

The homogenization technique assumes that the superconducting tapes that are wound in coils can be represented by an anisotropic bulk that is able to reproduce the overall electromagnetic behavior of the coil [14]. This allows reducing degrees of freedom and computation time. The technique was implemented in 2D by using the T-A formulation in [15], [16]. Therefore, we follow a similar approach to extend the homogenization into the 3D analysis of superconducting coils.

III. Validation of the Modeling Approach and Study of a Racetrack Coil

The first analyzed case with the 3D T-A homogenization is the circular coils presented in [11]. This geometry can be studied with an axisymmetric model. Therefore, we can compare not only losses but also the normalized current density distribution and overall electromagnetic behavior between the 3D T-A homogenization and the 2D T-A formulation (as shown in figure 1). In addition to this comparison, we can validate the model with the measurements presented in [11].

Once the modeling technique is validated, we can proceed to analyze more complicated geometries that can not be investigated in 2D. Therefore, we study the racetrack coil presented in [12]. This kind of coils is typically used in superconducting electrical machines for wind turbine applications [17]. We use in these simulations the same geometry and material properties presented in [12]. The T-A 3D homogenization is in good agreement with the H 3D homogenization and achieves a reduction in computation time between $87.43\,\%$ and $88.26\,\%$.

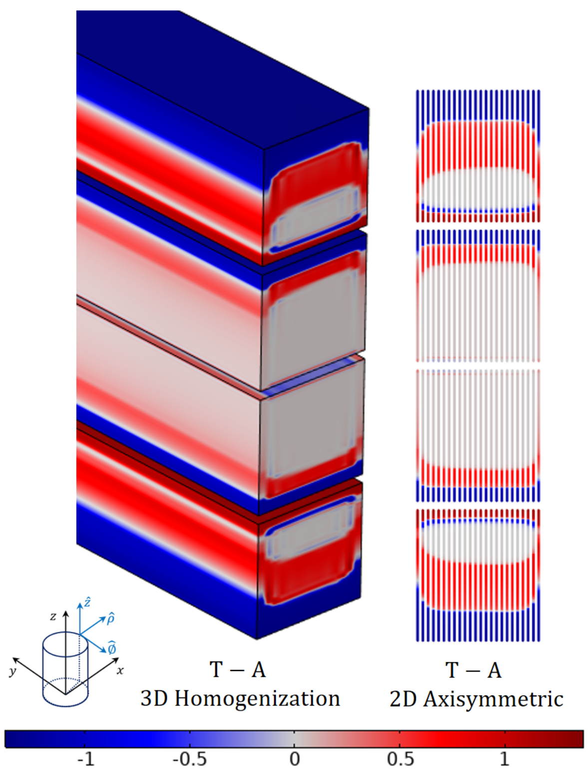

Fig. 1. Normalized current density behavior in four circular coils stacked one on top of the other for transport current (55 A peak) without externally applied magnetic field. A comparison between the T-A 3D homogenization and T-A 2D axisymmetric solution is done when the current is equal to zero after the first sinusoidal cycle.

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