AC losses calculation in superconducting solenoids: comparison of **H**-formulation with **T-A** formulation

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***Abstract*—The finite-element method (FEM) model based on H-formulation has been widely applied for estimating the AC losses of high temperature superconducting (HTS) coils made of REBCO coated conductors. The T-A formulation has emerged as a computationally more efficient alternative for modeling HTS coils of 2D. However, due to the use of the infinitely thin-strip approximation for the superconducting layer of REBCO tapes, it cannot take into account the currents induced by the magnetic field component parallel to the wide face of the tapes. This field component is significant in solenoidal coils, particularly in their central part. In this contribution, we compare the AC losses of superconducting solenoids made of REBCO tapes, calculated with the H and T-A formulations, with the aim of evaluating the computational speed and the accuracy of both formulations.**

Keywords—AC losses, HTS solenoid,* H*-formulation,* T-A *formulation

I. Introduction

In recent years, high temperature superconducting (HTS) tapes have been widely used in scientific research and other fields due to their high current-carrying capacity and good in-field behavior [1]-[2]. The application RE-Ba-Cu-O (REBCO, RE is rare earth) of second-generation (2G) HTS material is promising in electrical engineering and high field applications [3]-[4]. Superconducting solenoids are a geometry of interest for applications such as superconducting motors, superconducting transformers and superconducting magnetic energy storage (SMES) [5]-[7]. The prediction of their electromagnetic behavior and AC losses is of high importance for the design and protection of HTS devices.

Numerous computational approaches have been proposed over the last two decades [8]-[10]. Among them, the **H**-formulation has been widely used due to its ease of implementation and reasonable computational efficiency [11]. However, when it comes to dealing with large-scale applications, the **H**-formulation has too long computation times. Comparatively, the **T-A** formulation proposed by Zhang *et al*. [12] shows much faster calculation speed (at least for 2D problems) thanks to the approximation of the superconducting layer as an infinitely thin strip. However, this approximation has an important limitation: it cannot consider the penetration of the magnetic field component parallel to the wide face of the superconducting layer. In certain geometries, such as solenoids, this component can play an important role. Therefore, it is important to assess the impact of such an approximation. For this purpose, the AC losses of a superconducting solenoid are calculated and compared with the results obtained with the **H**-formulation. The **H**-formulation simulates the entire cross-section of the superconducting layer, takes into account all the relevant magnetic field components, and can be used as reference.

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II. Geometry of Superconducting Solenoid

A. Configuration of Superconducting Solenoid

A one-layer superconducting solenoid is simulated. Fig. 1 shows the schematic view of the superconducting solenoid and the definition of the main parameters. The *gap* is the distance between two wires, r_1 is the distance from coil to central axis, W_{tape} and d_{tape} are the width and length of the tapes that make up the superconducting solenoid, respectively. The outer boundary is far larger than r_1, thus the air region radius is set 10 times of the outer radius. The values of main parameters are shown in Table Ⅰ.

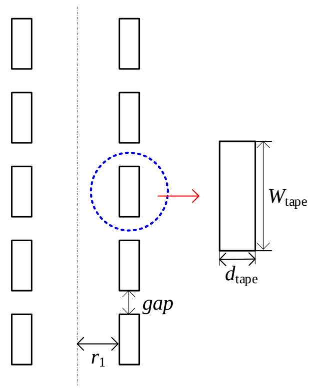

Fig. 1. Schematic view of superconducting solenoid

TABLE I. Main Parameters of Superconducting Solenoid

Parameters	Value
r_1	150/mm
gap	1/mm
W_{tape}	4/mm

Parameters	Value
d_{tape}	1/μm

B. Numerical Models

The **H**-formulation is used to perform the 2D axisymmetric model of superconducting solenoid and calculate the magnetic field [13]. The model solves Faraday's equation written in terms of the magnetic field

$$\mu_0 \mu_r \frac{\partial \mathbf{H}}{\partial t} + \nabla \times (\nabla \times \rho \mathbf{H}) = 0 \tag{1}$$

where ρ is the resistivity, μ_0 is the vacuum permeability, μ_r is the relative permeability of the corresponding material.

The **T**-**A** formulation calculates magnetic field using the magnetic vector potential **A** to calculate the magnetic field everywhere, and the current potential **T** to calculate the current density in the superconductor. Faraday's equation is written as [15],

$$\nabla \times (\rho \nabla \times \mathbf{T}) = -\frac{\partial (\nabla \times \mathbf{A})}{\partial t} \tag{2}$$

When the calculation of magnetic field is finished, the AC losses are calculated by integrating the $J{\cdot}E$ over the superconducting region and averaging it over a cycle. It should be noted that the first quarter of the sinusoidal cycle must be avoided, because it is not representative of the AC regime due to the occurring transient. Therefore, the cyclic AC losses can be computed on the second half of the first cycle as Eq. (3) [16],

$$Q = 2 \int_{1/2f}^{1/f} \int_{\Omega} J \cdot E d\Omega dt \tag{3}$$

where f is the frequency of the AC source and Ω is the superconducting region.

III. AC Loss

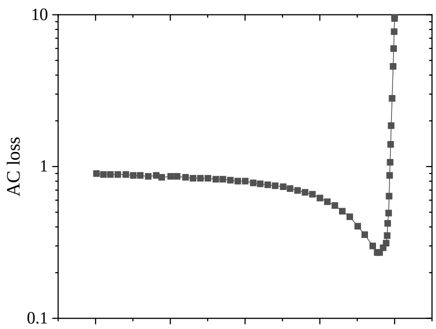

Fig. 2. Estimation of AC-losses in individual turns of the solenoid. Data replotted from [17]

The estimated losses of the individual tapes are presented in Fig. 2, which is replotted from reference [17]. The tapes at the top and the bottom of the coil (right part of the plot) present the highest AC losses, due to the field component perpendicular to the flat face of the tape. The tapes in the center of the solenoid have very similar and low loss values. This is because the field is very uniform and directed essentially parallel to their flat face. Despite their low individual loss value, these tapes may contribute significantly to the total losses of the solenoid, due to their large number. Therefore, it is important to determine their (low) loss value accurately and understand if the dissipation is caused by the field component parallel or perpendicular to the tape. This can be done by comparing the results of the **H** and **T**-**A** formulations, since the latter can only account for the losses caused by the perpendicular field component.

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