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3D finite element analysis of eddy current losses of HTS tapes—Self field analysis

Tosin Famakinwa [a,*], Qing Ming Chen [b], Satarou Yamaguchi [a]

[a] Department of Electrical Engineering, Graduate School of Engineering, Chubu University, 1200 Matsumoto cho, Kasugai, Aichi 487-8501, Japan
[b] Ansoft Corporation, Benex S-1, 5F Shin-Yokohama 3-18-20, Kohoku Ward, Yokohama City 222-0033, Japan

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Abstract

The eddy current losses in the matrix of twisted filament HTS tapes have been calculated using 3D commercially available finite element method (FEM) analysis tool of Ansoft Maxwell 3D®. At various reference points, numerical calculations were compared with analytical expressions to validate the numerical results. Numerical calculation of eddy current losses are plotted as a function of conductivity, frequency, transport current amplitude, and filament twist pitch in both rectangular and circular tape models. Circular model of same twist pitch and volume have lesser eddy current losses than rectangular tape model. Simulations results show that the eddy current losses are inversely proportional to the square of the filament twist pitch. Eddy current losses remain almost constant for the calculated frequency.

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Keywords: Eddy current loss; AC losses; Twist pitch; HTS; Aspect ratio; Self field; FEM; 3D numerical simulation

1. Introduction

Superconductors are developed for power engineering applications such as transformers, power transmission cables; AC or DC lines, motors and generators. For HTS application to be viable, it has to meet several requirements in comparison with the presently used materials. Additionally, AC losses should be low enough to justify the extra investment in the superconductor and the cryogenic system. It is necessary to accurately predict the AC losses of HTS tapes that will be in used for superconducting applications. Since the discovery of HTS many researchers are working on how to reduce AC losses and accurately predict losses.

The goal of this paper is to present the first report on numerically calculation results of eddy current losses in the matrix of HTS tapes of both rectangular and circular cross-section using 3D FEM software from Ansoft Corporation [1]. The non-linear behavior of the Bi2223 used as filament in HTS tapes was not taken into account. This work is one of the first Maxwell 3D calculations for publication. This first paper describes the self field case and the second paper will describe the external field.

The AC losses in HTS could be dissociated into hysteresis loss, eddy current losses, resistive loss which appears near the critical current for self field and coupling current loss in multi-filamentary HTS tapes. Eddy current losses is the loss occurring as a result of induced current in the matrix by the transport current or applied external field. When induced current flows from one filament to another, the currents couple the filaments together into a single large magnetic system. This coupled current encountered a resistance along the current path through the silver or alloyed

* Corresponding author. Tel.: +81 9035866018; fax: +81 568519725.
E-mail address: tosin@isc.chubu.ac.jp (T. Famakinwa).

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matrix. In this situation the ohmic loss in the matrix is often called coupling loss. Using numerical calculation code we have calculated the total eddy current losses which are generated by the induced current flowing in the matrix without the coupling of the filaments.

Many recent published articles on AC losses shows noteworthy progress in the reduction of AC losses in HTS tapes [2–8,10,12–17]. Numerical analysis has been used by several authors too, for example [2–5]. Most of these published articles used 2D FEM calculation results [2–5]. However, Grilli et al. [9] used 3D FEM software to analyze coupling current loss for tapes with different aspect ratio. This work by Grilli et al. [9], was limited only to a straight filament model and external field as the current source.

On the hand, in this paper we present the solution for twisted filament problems with transport current while in the next paper we will present for external field as the current source.

Eddy current losses in twisted multi-filamentary HTS tapes are due to the rate of change of magnetic field or current source, resistivity, and width of the matrix, filaments size and the critical current density of the conductor. Such a solution could only be calculated accurately with 3D FEM software.

To the best of our knowledge so far there has been no published work on the dependency of the eddy current losses on the filament twist for AC transport current (self field). One reason is that, it is difficult to differentiate between losses in the matrix and the superconducting filament experimentally. Additionally, the main purpose of filament twisting is to reduce coupling loss in applied external field. AC loss in external field is reduced by twisting of the filament, shorter filament twist pitch have lower losses. Another reason is that a FEM twisted filament solution is only feasible with 3D FEM software which is now becoming readily available.

For all the numerical calculation reported in this paper we assumed that the critical current is constant not depending on the twist pitch, and model. This means that the filament is always superconducting. We present only the result of the loss in the matrix of the simulated HTS tape.

We have arranged the paper in the following sequence: First we give a brief overview of the 3D software in Section 2. In Section 3 we discussed the verification of software accuracy. Section 4, the numerical calculation result is presented and the conclusion in Section 5.

2. Numerical formulation

2.1. Solver

The eddy current field simulator computes time-varying magnetic fields that arise from AC currents and external time-varying magnetic field due to the imposed current source. The distribution of the magnetic field **H** and the current density **J** are calculated by the solver. The magnetic flux density **B** is automatically calculated from the **H** magnetic field. Other derived quantities such as the skin depth, ohmic loss, impedance can be calculated from these basic field quantities.

The magnetic field is assumed to have the following form:

$$\mathbf{H}(x,y,z,t) = \mathbf{H}(x,y,z)\cos(\omega t + \theta(x,y,z)) \quad (1)$$

$$\omega = 2\pi f \quad (2)$$

where $\mathbf{H}(x,y,z)$ is a vector that has been calculated at each point of space, f is the frequency of the source that controls the current and voltage externally, $\theta(x,y,z)$ is the phase difference and a function of space.

2.2. Governing equations

The eddy current solver in Maxwell 3D, computes time-varying magnetic fields that arise from AC total current source in conductors and time varying external magnetic fields represented by boundary conditions. In a user-subroutine, the current source was chosen. For the numerical calculation reported in this paper the source is AC total current and it is directly connected to the superconducting filament. The magnitude and phase of the AC external source current is inputted. After specifying all the currents sources and all the necessary boundary conditions, the eddy current field simulator computes the magnetic field using Maxwell equations.

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (3)$$

where $\mathbf{J} = \sigma\mathbf{E}$ and $\mathbf{B} = \mu_0\mu_r\mathbf{H}$.

J is the current density field. It is related to the induced electric field **E**, **B** is the magnetic flux density, computed using the relationship above, while μ_0 is the permeability of vacuum, μ_r is the relative permeability and ε is the permittivity of free space. The full relationship between **H** and **J** is given by

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial}{\partial t}\varepsilon\mathbf{E} \quad (4)$$

where ε is the permittivity of vacuum.

2.3. Solution process

To solve for the magnetic field $\mathbf{H}(x,y,z,t)$, the solver computes directly from the imposed currents source using

$$\nabla \times \left(\frac{1}{\sigma + j\omega\varepsilon}\nabla \times \mathbf{H}\right) = j\omega\mu\mathbf{H} \quad (5)$$

The solver combines the solutions and solves for the magnetic field $\mathbf{H}(x,y,z,t)$, producing a continuous field solution through out the model. In an adaptive analysis it refines automatically the tetrahedral with the highest error and continues solving until stopping criterion is met. In a non-adaptive solution the process stops after one field solution, see Fig. 1.