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3D finite element analysis of eddy current loss of HTS tapes – External field analysis

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Abstract

The eddy current losses in the matrix of two twisted filaments Bi-2223 HTS tapes in applied external AC magnetic field was calculated using 3D FEM software. The highest eddy current loss in the matrix was experienced when magnetic field is applied perpendicular to the wide side of the rectangular model. Numerically calculated eddy current losses are plotted as the function of frequency, filament twist pitch, matrix conductivity and magnetic field amplitude. Longer filament twist pitch models have higher eddy current losses in transverse magnetic field. In longitudinal magnetic field shorter filament twist pitch have higher eddy current losses. Increases in the applied external field amplitude, frequency and matrix conductivity contributes to higher eddy current losses. Numerical calculation results shows that the contribution of eddy current loss at commercial frequency is not minimal. The numerical results presented are for uncoupled filaments HTS tapes.

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Keywords: Eddy current loss; AC losses; Twist pitch; HTS; Aspect ratio; FEM; Numerical calculation; External field; 3D modeling

1. Introduction

Superconductors are developed for power engineering applications such as transformers, power transmission cables; AC/DC lines, fault current limiters (FCL) motors and generators. Superconductors have to meet several requirements in order to compete with the presently used materials. Additionally, AC losses should be low enough to justify the extra investment in the superconductor and the cryogenic system. Therefore, it is necessary to accurately predict the AC losses of HTS tapes that will be in used for superconducting applications.

For most applications of HTS for example in AC superconducting wires, transformers and magnets, the conductors carry AC current in the presence of external magnetic field. When some applications operate at sub-critical currents, the losses due to the external magnetic field are the dominating losses. Consequently, investigating AC losses in external magnetic field is important.

Numerical calculation results of eddy current losses in self field by using finite element method software, Maxwell 3D® from Ansoft Corporation [1] were reported in Ref. [2]. Additionally, Maxwell 3D software has advantage of using both voltage and current excitations. In this paper numerical calculation results of eddy current losses in applied AC external magnetic field are presented. AC losses in applied magnetic field consist of hysteresis loss, eddy current loss, and coupling loss. At this moment, there is no provision to calculate hysteresis loss AC solver of in Maxwell 3D software.

Electric field is induced when external time-varying magnetic fields penetrates into a normal conductor, which in turn drives currents. These are known as eddy currents.

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In multifilamentary HTS tapes, the induced eddy current flows partly through the superconductor and through the matrix. When current flows from one filament to another, the currents couple with the filaments together into a single large current loop. The loop current encountered resistance along its path through the matrix and the ohmic loss is called the coupling loss, and therefore we can estimate the coupling loss as the eddy current loss. The eddy current losses referred to in this paper are the total losses due to the induced current in the matrix, which includes the inter-filamentary coupling current.

Numerical calculation software's were used also to calculate AC losses [3–6]. Most of these papers are for the excellent academic work of 2D FEM software, developed by these groups.

Twisted filament problems can only be solved by 3D software principally. This is because the filaments are not always placed at the same position inside the conductor geometry. The shielding current in the matrix at specific position is not the same, depending on the location of the filament. Clearly, twisted multifilamentary or other complex geometrical problems in HTS tapes could only be solved with 3D software accurately.

Recently, more authors are using 3D FEM software for the analysis of AC loss in HTS tapes [7–9]. Grilli et al. [7] introduces the difficulties of 3D simulation and summarizes published work on 3D FEM calculations. For example, effect of aspect ratio on the coupling loss in straight filament models. Additionally, 3D self field results were compared with 2D published results for straight filament. Only the effect of transport current was compared. A corner shape 3D model of straight filament was presented which is applicable for superconducting current limiters. The second result presented is of 8 twisted tapes wound around a cylinder for AC power cable application. But no result was presented for HTS tapes with twisted filaments. In external field, the published results is for straight filament, to verify the existence of coupling of two filaments at different frequency and field amplitude.

Duron et al. [8] discusses the behavior of strip lines of YBCO/Au fault current limiter (FCL) using 3D simulation software. This paper analyzes the effect of shapes of the superconducting strips using 3D software and a optimum shape was proposed for the superconducting strips in the wafer.

Costa et al. [9] analyze the coupling between two filaments via resistive matrix of different geometry (changing aspect ratio). The solution presented here is only for straight filament. With proper symmetry applied the end effects was not discussed. The field direction is only in one direction with the rectangular shape. Although the field directions could be compensated by discussing the different aspect ratio, this analysis is different from what we are reporting in this paper.

The main purpose of this paper is to estimate not only the coupling current loss due to the existence of the superconducting filament but also the ordinary eddy current loss of the tape by the external ac magnetic field. For all the numerical calculation reported in this paper we assumed that the critical current is constant, and not depending on the twist pitch, and model. This means that the filament is always superconducting.

We have arranged the paper in the following sequence. The simulation setup and information on the models used is discussed in Section 2. In Section 3, the numerical results are discussed and the conclusion in Section 4.

2. Simulation setup

2.1. End effects

The size of the rectangular model was thickness of 0.2 mm and width of 4 mm which is typical for HTS tapes. Circular model was of diameter 1 mm. The filament diameter was 10 μm, and kept constant for all calculations.

The length of each model depends on the twist pitch in the numerical calculation. The calculated length was set at five times longer than the twist pitch for each model. The calculated losses of the 3rd segment will correspond to the expected losses in an infinitely long tape. Fig. 1 shows a circular model with two filaments. Fig. 2 shows the rectangular with two filaments. The calculated loss will not reflect the expected loss in long tapes due to the end effects. However, the actual losses sometimes depend on the end effect for finite length of the tape.

2.2. Governing equation

Eddy current losses in the 3rd segment were calculated according to Eq. (1).

$$P = \int_{\mathrm{vol}} \frac{J \cdot J^*}{2\sigma} \mathrm{d}V \tag{1}$$

unit calculated is Watt, where J is the eddy current density, J^* is the complex conjugate of the eddy current density, σ is the conductivity.

We are presenting in this paper, the numerical result only for the matrix which was calculated through Eq. (1).

2.3. The models for calculation

We have used 5 mm twist pitch for the calculation of the effect of frequency, magnetic field amplitude and conductivity for both circular and rectangular models. For the calculations on the effect of twist pitch, the length of each model increases accordingly. The appropriate symmetry conditions have been applied on the three symmetry planes.

The models of the numerical calculation structures are shown in Fig. 3. Losses are caused by the external magnetic field directed perpendicular or parallel to the simulated model. Longitudinal magnetic fields are termed parallel field in this paper, i.e. the fields parallel to the length of model. In rectangular model two expressions are used for perpendicular field; perpendicular to the wide side and