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AC loss calculation of REBCO cables by the combination of electric circuit model and 2D finite element method

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Abstract

This study investigates the losses in a two conducting-layer REBCO cable fabricated by researchers at Furukawa Electric Co. Ltd. The losses were calculated using a combination of my electric circuit (EC) model with a two-dimensional finite element method (2D FEM). The helical pitches of the tapes in each layer, P_1 and P_2, were adjusted to equalize the current in both cable layers, although the loss calculation assumed infinite helical pitches and the same current in each layer at first. The results showed that the losses depended on the relative tape-position angle between the layers (θ/θ'), because the vertical field between adjacent tapes in the same layer varied with θ/θ'. When simulating the real cable, the helical pitches were adjusted and the layer currents were calculated by the EC model. These currents were input to the 2D FEM to compute the losses. The losses changed along the cable length because the difference between P_1 and P_2 altered the θ/θ' along this direction. The average angle-dependent and position-dependent losses were equal and closely approximated the measured losses. As an example to reduce the loss in this cable, the angle and the helical pitches were fixed at $\theta/\theta' = 0.5$ and $P_1 = P_2 = 100$ mm (S-direction). The calculation with these conditions indicated that the loss is about one order of magnitude lower than the measurement.

Keywords: AC loss; HTS cable; REBCO tapes; 2D FEM; EC model

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1. Introduction

In recent researches about a reduction of AC losses in high-T_C superconducting (HTS) cables by a change of the cross-sectional configuration, these results have been reported such as effect of size of gaps (gap effect) [1], effect of removing lateral low-J_C edges (J_C distribution effect) [2] and effect of narrow width of HTS tapes (polygonal effect)

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Table 1. Specifications of Mukoyama's cable

Layer number m	Inner radius R_m [mm]	Tape numbers N_m	Critical current I_{Cm} [A]	Helical pitch P_m [mm] (direction)
1	16.099	16	730	340 (S)
2	16.349	16	730	280 (Z)

[3]. The author has reported that effect of relative tape-position angle between layers (relative tape-position angle effect) [4]. In the present study, it will be shown that the optimum relative tape-position angle is changed by the tape numbers in the cable. In order to calculate the losses in the cables, FEM analysis was particularly used because of the effectiveness of this method. On the other hand, the author have developed the EC model for calculating layer currents in cables [5]. It is considered that the combination of the EC model and 2D FEM performs loss calculation in the similar manner as a quasi-three-dimensional electromagnetic field analysis model. Previously, we conducted a successful 2D FEM analysis of monolayer and two-layer cables using the commercial software COMSOL [4]. In this study, we apply the combined-methods approach to the two-layer cables fabricated by Mukoyama et al. of the Furukawa Electric Co. Ltd [6] and thereby clarify their loss property, which has not yet been measured.

2. Calculation

Mukoyama's cable is a 1-m-long cable with opposing helical directions of the first and second conducting layers. The cable specifications are listed in Table 1. The EC model has been described elsewhere [5]. The layer currents calculated by the EC model are input as variables to COMSOL to calculate the loss. The 2D FEM analysis has been described elsewhere [4]. The critical current I_C in one tape of Mukoyama's cable was calculated as $I_C = 45.6$ A. Given the tape width w (4 mm) and thickness d of the superconductor in the tape (1 μm), the critical current density J_C was calculated as 1.14×10^{10} A/m^2.

3. Results and discussion

In Mukoyama's cable, the gaps between adjacent tapes g_m were comparatively large ($g_1 = 2.3$ mm and $g_2 = 2.4$ mm). Therefore, we considered that changing the relative tape position between the first and second layers would alter the losses. Assuming infinite helical pitches in both layers (namely, the tapes are lain straight along the cable length) to fix the θ/θ', we calculated the losses for different values of θ/θ'. Here, θ' is the occupation angle of one tape in the second layer, calculated as $2\pi/N_2$, and θ is the deviation angle between the perpendicular bisectors of the REBCO tape in the first and second layers. The angle θ/θ' has been described elsewhere [4]. This calculation also assumes equal layer currents. In a real HTS cable with infinite helical pitch, the outer layer current exceeds the inner layer current,

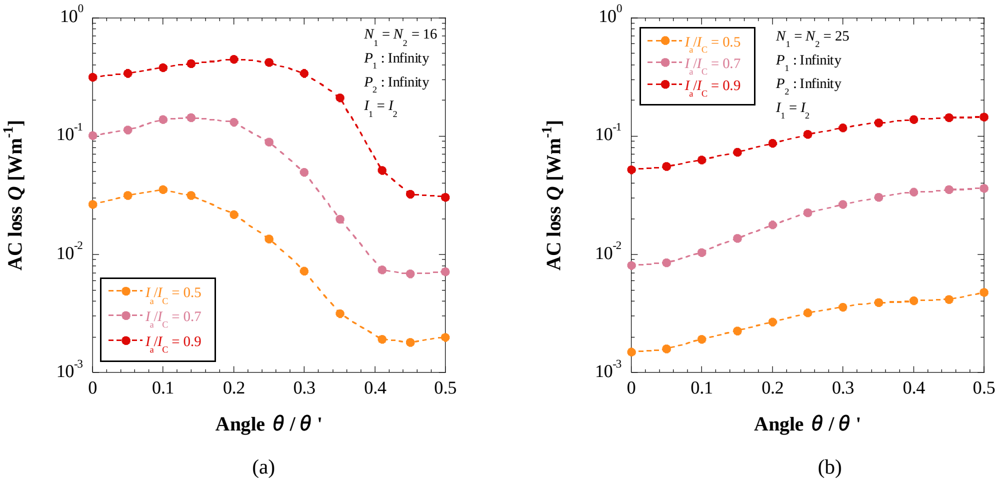

Fig. 1. AC losses in a two-layer cable versus the relative angle θ/θ', fixing $P_1 = P_2$ = infinity, $I_1 = I_2$, (a) $N_1 = N_2 = 16$, and (b) $N_1 = N_2 = 25$.