AC loss analysis of single-layer CORC superconducting cable

Asato KOBUN*, Hideki NOJI

Advanced Course of Mechanical and Electrical Engineering, N.I.T., Miyakonojo College

*kobun64@miyakonojo.kosen-ac.jp

Abstract. The AC losses of a single-layer Conductor on Round Core (CORC) cables were calculated by three-dimensional finite element method (3D FEM). The cables are composed of REBCO superconducting tapes. A calculation model was created with a reference of parameters used for a fabrication of the cable, and the loss was calculated in two cases, one in which the current was passed through the cable and the other in which the perpendicular magnetic field was applied. When conducting current is passed through the cables, there is no difference in losses even if the superconducting tape is wound or not in a spiral shape, and both values agree with calculation results by Norris's analytical formula. Moreover, the losses calculated by 3D FEM are small in comparing with the measurement. When a perpendicular magnetic field was applied to the cable, the loss is smaller than the measurement. In addition, it was found that, by making the mesh smaller, the calculated loss becomes closer to the measurement even when a low magnetic field was applied.

Keywords: 3D FEM, AC loss, REBCO superconducting tape, CORC cable.

1. Introduction

Superconductivity is a phenomenon in which electrical resistance suddenly becomes zero at a certain temperature (i.e. critical temperature T_C) when certain metals, semiconductors, organic conductors, etc. are cooled to near absolute zero. When a direct current is applied to a cable made of this superconductor, the resistance is zero until a temperature of the cable is reached to T_C, so that the loss of the cable is maintained as zero. However, when an alternating current or an alternating magnetic field is applied, an alternating current (AC) loss occurs. Then, a development of the superconducting application device in which the loss is reduced as much as possible is in progress [1]. In this study, we chose CORC cables as the research object and investigated characteristics of the loss in this cable. Priviously, the losses were calculated by a method combining electrical circuit model and two-dimensional electromagnetic field analysis in our laboratory [2], but it was found that this calculation method couldn’t accurately calculate the loss. Therefore, we developed 3D FEM to calculate the losses as a new method.

The CORC superconducting cable is used for accelerators and storage of electric power, and a high magnetic field is applied in these application. The calculation was performed not only when AC trasnport current is passing through the cable but also when a magnetic field is applied vertically to the cable.

2. Method

We used COMSOL Multiphsics, a general-purpose physical simulation software based on the finite element method, to calculate the losses of a single-layer CORC cable composed of five REBCO superconducting tapes. The losses were calculated by 3D FEM analysis. The FEM is a kind of numerical analysis method, which regards an object as a collection of elements, divides it into fine elements called meshes. As governing equations applied to an entire model, Faraday's law (equation (1)) and Ampere's law (equation (2)) are used respectively. These formula are called as *H*-formulation [3]. In the equation (1), μ_0 represents the permeability of vacuum, *H* represents the magnetic field, and *E* represents the electric field. In equation (2), *J* is the current density. Since the *E*-*J* characteristics in the superconductor are expressed by the power-law characteristic which is inherent to the superconductor, the equation (3) is used in three dimensions. Here, E_C is a critical electric field (1×10^{-4} V/m) and J_C is a critical current density.

$$\mu_0\left[\frac{\partial H_x}{\partial t},\frac{\partial H_y}{\partial t},\frac{\partial H_z}{\partial t}\right]+\left[\frac{\partial E_z}{\partial y}-\frac{\partial E_y}{\partial z},\frac{\partial E_x}{\partial z}-\frac{\partial E_z}{\partial x},\frac{\partial E_y}{\partial x}-\frac{\partial E_x}{\partial y}\right]=0 \tag{1}$$

$$\left[J_x,J_y,J_z\right]=\left[\frac{\partial H_z}{\partial y}-\frac{\partial H_y}{\partial z},\frac{\partial H_x}{\partial z}-\frac{\partial H_z}{\partial x},\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}\right] \tag{2}$$

$$\left[E_x,E_y,E_z\right]=\left[E_c\left(\frac{J_x}{J_c}\right)^n,E_c\left(\frac{J_y}{J_c}\right)^n,E_c\left(\frac{J_z}{J_c}\right)^n\right] \tag{3}$$

The losses of CORC cables were calculated using the following equation (4). Here, *f* represents the frequency (f = 36 Hz), and *L* represents the length of the cable model (L = 40 mm).

$$Q=\frac{1}{L}\int_{\frac{1}{f}}dt\int_V\left(E_xJ_x+E_yJ_y+E_zJ_z\right)dV \quad [\mathrm{J/m} \tag{4}$$

Fig. 1 (a) and (b) show three-dimensional models of single-layer CORC cable; (a) the cable model whose helical pitch *HP* is 40 mm, (b) the cable model whose *HP* is infinity (no winding). This model was prepared based on the experimental data of Solovyov *et al*. [4].

(a) *HP* = 40 mm (b) *HP* = infinity

Fig. 1 Model of single-layer CORC cable

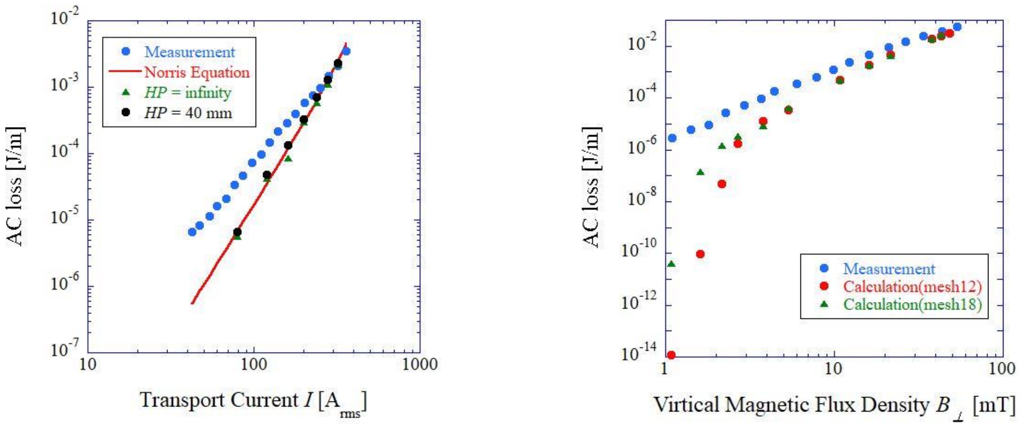
Table 1 Parameters of single-layer CORC superconducting cable

Tape width W	4 mm
Tape thickness T	1 μm
Cable diameter φ	8 mm
Number of tapes N	5
Critical current value I_c	565 A
Cable length L	40 mm
Pitch length HP	40 mm

3. Results and Discussion

3D FEM analysis was conducted for a single-layer CORC cable when AC current was supplied. The parameters for this cable are shown in Table 1 [4]. Fig. 2 shows the loss characteristics with respect to the applied current. In this figure, the blue circle is the measured value [4], the red line is the calculated value obtained by Norris equation [5], and the black circle is the calculated value of the cable shown in Fig. 1 (a), and the green triangle is the calculated value of the cable shown in Fig. 1 (b). As shown in Fig.2, both calculated values conducted by COMSOL almost agree with the calculation obtained by Norris equation, and are small in comparing with the measurement obtained by Solovyov *et al*. It is considered that the REBCO superconducting tapes composing the cable have an degradation of the critical current density at both ends of the tapes [4].

Fig. 3 shows the loss characteristics for the perpendicular AC magnetic field to the cable. In this figure, the blue circle is the measured value [4], the red circle and the green triangle are the calculated values of the cable models in which a number of meshes of the tape cross section is 12 and 18, respectively. The calculated values are close to the measurement result at high magnetic field, and are smaller than the measured value at low magnetic field. This is consid-



(a) (b)

Fig. 2 The characteristics of loss versus transport current (a) and of loss versus applied magnetic field (b).

ered to be an influence of the degradation of the critical current density at both ends of the tapes, as described above. It was also found that the calculation at low magnetic field becomes more accurate by increasing the number of meshes.

4. Summary

The results obtained by this study are summarized below. When AC current pass through the single-layer CORC superconducting cables, no difference was found in the losses of the cables with spirally winding tapes and no widing tapes. Both losses are coincided with the calculation obtained by Norris equation. Moreover, all calculation results became small in comparison with the measurement result.

When a perpendicular AC magnetic field was applied, the loss was smaller than the measurement result, as in the case where AC current was supplied. Due to make the mesh smaller, the calculated loss became close to the measurement result even when a low magnetic field is applied.

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