Study of AC loss properties of two-layer REBCO superconducting power cable

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Abstract. In this study, three-dimensional finite element method (3D FEM) was conducted using COMSOL, and the calculated loss was compared with the measured loss of the two-layer REBCO superconducting cable manufactured by Furukawa Electric Co., Ltd. As a result, the calculated value was almost equal to the measured value when a length of cable model *L* is 40 mm. It was found that the calculated value gets closer to the experimental value as the *L* is increased. The reduction method of the loss proposed by the previous research was tested to verify the effect. The method is that it is keeping a same helical pitches and a same winding direction of first and second layer, and keeping a same relative position of the superconducting tapes between the layers (tape-on-gap). Due to the method, the loss is minimized when there is no helical pitch and the minimum value becomes larger than the measured value. As a result, it was found that the method has no effect to reduce the loss.

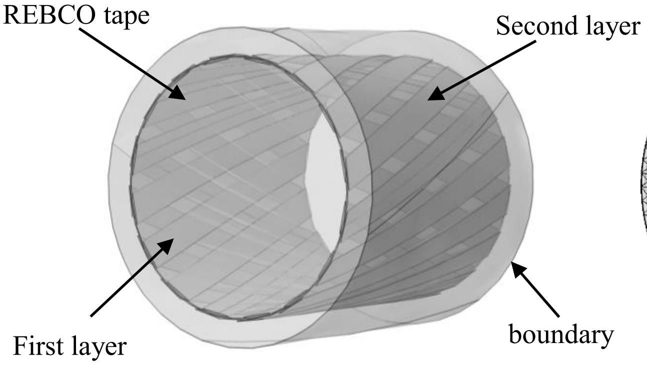
Keywords: 3D FEM, REBCO superconducting power cable, AC loss

1. Introduction

"Superconductivity" is a phenomenon in which the electrical resistance becomes zero at the critical temperature when certain metals and semiconductors are cooled [1]. This phenomenon is applied to a power transmission. Copper is used for conventional power transmission lines, but about 5% of the amount of power transmission is consumed by electrical resistance, resulting in energy loss. A superconducting cable utilizes the characteristic of zero electrical resistance for power transmission, and if this application is realized, heat generation will be eliminated, and theoretically, energy loss will be zero. The superconducting cable can reduce the cost of the entire transmission infrastructure by reducing power loss during transmission. Furthermore, because of the large capacity and compactness of this cable, undergrounding in urban areas is easy. However, the electrical resistance of the superconducting cable becomes zero only in the case of direct current transmission, and a loss occurs when performing alternating current (AC) transmission with the superconducting cable. In our laboratory, we have aimed at reducing AC loss for achieving a practical application of the cables.

2. Calculation

COMSOL used in this study is simulation software that analyzes a model using FEM. FEM is a method in which an object is regarded as a collection of elements, divided into elements, each element is analyzed, and an overall analysis result is obtained approximately. An example of 3D model of a two-layer REBCO superconducting cable used for calculation here is shown in Fig. 1.



(a) Model of superconducting cable

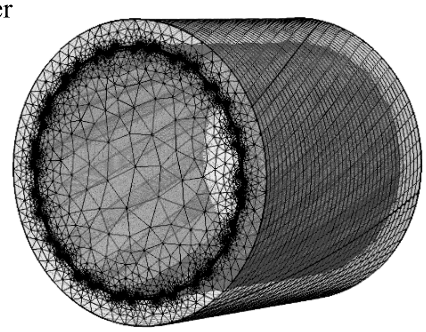

(b) Mesh of model

Fig. 1 3D model of two-layer REBCO superconducting cable.

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

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

$$\left[\rho_{scx},\rho_{scy},\rho_{scz}\right]=\left[\frac{E_C}{J_C}\left(\frac{J_x}{J_C}\right)^{n-1},\frac{E_C}{J_C}\left(\frac{J_y}{J_C}\right)^{n-1},\frac{E_C}{J_C}\left(\frac{J_z}{J_C}\right)^{n-1}\right] \quad (3)$$

$$\left[E_x,E_y,E_z\right]=\left[\rho_{scx}J_x,\rho_{scy}J_y,\rho_{scz}J_z\right] \quad (4)$$

$$P=\frac{f}{L}\cdot\int_{\frac{1}{f}}dt\int_V\left(E_xJ_x+E_yJ_y+E_zJ_z\right)dV \quad [\mathrm{W/m}] \quad (5)$$

The equation (1) is Faraday's law, the equation (2) is ampere's law, the equation (3) is the resistivity represented by the power law inherent in the superconductor, and the equation (4) is Ohm’s law. These equations are introduced into the model and the electromagnetic field when a sinusoidal current is applied to the cable is analyzed three-dimensionally. Then, the AC loss is calculated by equation (5).

3. Calculation results

First, we calculated the loss of the cable in which the winding direction of each layer is SZ (oposite direction between the layers). The parameter of the cable was referred to the value of the cable manufactured by Furukawa Electric Co., Ltd. [2]. The cable parameters are shown in Table 1.

Fig.2 is the calculation result of the loss characteristic to the applied current of the cable. Here, a trasnport current I_a is standardized by the critical current I_C. The length L of the cable model is L = 40 mm, and the measured value is an experimental result of Furukawa Electric Co., Ltd. [2]. It can be seen from Fig. 2 that the calculated value and the measured value almost coincides with each other.

Table 1 Parameters of superconducting cable

Tape width	4 mm
Tape thickness	1 μm
Radius of first layer	16.0 mm
Radius of second layer	16.5 mm
Number of tapes in each layer	16
Critical current of one tape I_C	45.6 A
Helical pitch of first layer HP_1	340 mm (S)
Helical pitch of second layer HP_2	280 mm (Z)

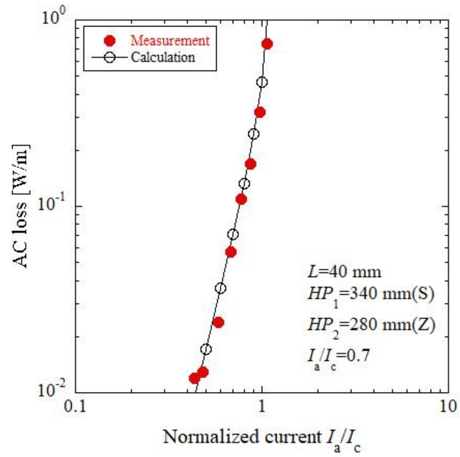
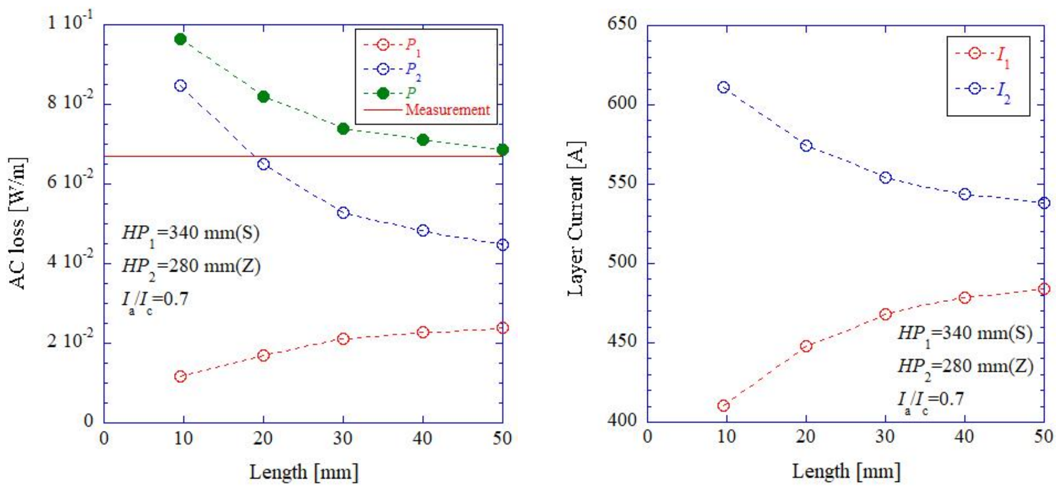


Fig. 1 AC loss characteristic versus current.

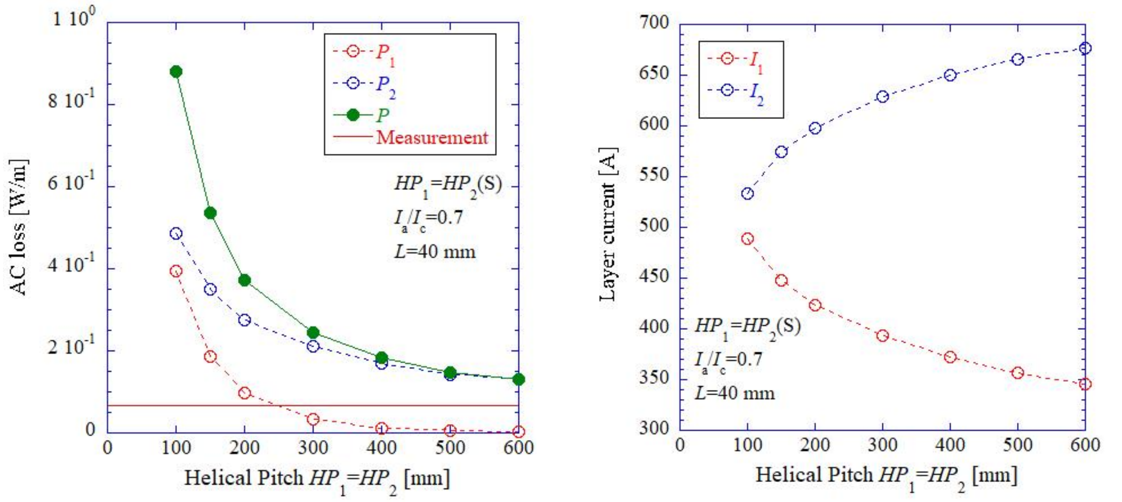
Fig. 3 shows loss characteristics and layer-current characteristics with respect to L. In Fig. 3(a), P_1 is the loss of the first layer, P_2 is the loss of the second layer, and P is the loss of the entire cable. In Fig.3 (b), I_1 is a first layer current, and I_2 is a second layer current. It can be seen from Fig. 3 that P decreases with an increase of L and approaches the measured value. This is considered as a reasen that I_1 and I_2 converge to a constant value with an increase of L. In comparing the calculation time, it takes about 6 hours for L = 40 mm and about 68 hours for L = 50 mm. We decided to use a cable model with L = 40 mm, which has a calculated value approximately equal to the measured value and a short calculation time.

Next, we tried the cable construction method that was able to reduce the loss in the previous research [3], and verified the effect. In the cable construction method, the winding direction of each layer is fixed as the same winding direction (SS), the same helica pitch ($HP_1 = HP_2$) and the same relative position of the superconducting tapes between the first and second layer (tape-on-gap). The helical pitch is changed while keeping it as the same. The loss was calculated while trying this cable configuration method. Fig. 4 shows loss characteristics and layer current characteristics when the helical pitch is changed. It can be seen from Fig. 4(a) that the loss of



(a) AC loss characteristics (b) Layer current characteristics

Fig. 3 AC loss characteristics and layer current characteristics versus length of cable model.



(a) AC loss characteristics (b) Layer current characteristics

Fig. 4 AC loss and layer current characteristics versus helical pitch (HP_1 = HP_2).

each layer increases rapidly from around HP_1 = HP_2 = 300 mm as the helical pitch is shortened. It is considered that this is because when the helical pitch becomes too short, the loss increases rapidly. As can be seen in Fig. 4(b), when the helical pitch is shortened, the layer current of the first layer decreases, the layer current of the second layer increases, and the layer current approaches uniform. As shown in Fig. 4(a), when the helical pitch is increased, the loss of the entire cable is P = 0.13 W / m, which is larger than the measured value of 0.067 W / m. Finally, it was found that the cable configuration method proposed in the prior research has no loss reduction effect.

4. Summary

The AC loss of the two-layer REBCO superconducting cable calculated by 3D FEM was almost equal to the measured value of Furukawa Electric Co., Ltd. It was found that the calculated value of the loss depends on the length of cable model L, and converges to a certain value at $L \geqq$ 40 mm. Moreover, it was found that the cable configuration method proposed in the previous research had no loss reduction effect, but rather became larger than the measured value.

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