AC transport-current properties of four-layer REBCO superconducting power cable

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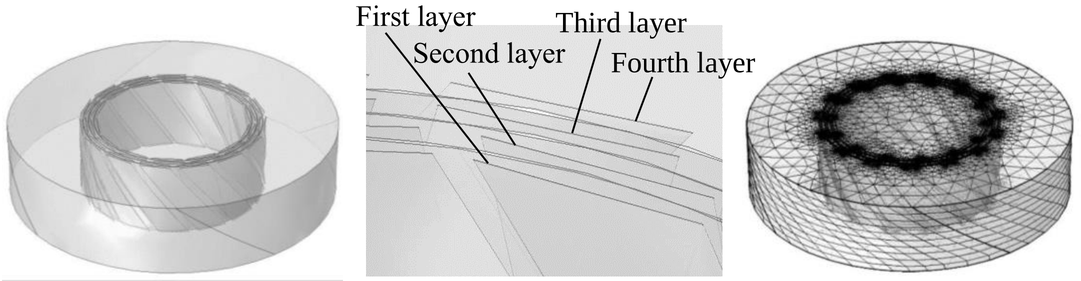
Abstract. The characterisitecs of AC loss and layer current were calculated by applying an alternating current to the four-layer REBCO superconducting cable by three-dimensional finite element method (3D FEM). The REBCO cable manufactured by Fujikura Ltd. is targeted for calculation, but a winding direction and a winding pitch of the superconducting tape of each layer are not disclosed. Therefore, the winding direction was fixed to SSZZ (left rotation for the first and second layer, right rotation for the third and fourth layer) from the inner layer to the outer layer. Using an electric circuit (EC) model, the winding pitches at which each layer current was as uniform as possible were determined and fixed as the initial value for calculation. As a result of calculating the loss, the calculated value is larger than the experimental value, and each layer current is different from the value calculated by the EC model. When the length of the cable model for calculation is increased, the calculated loss is significantly reduced and approaches the measurement result, and each layer current approaches the value calculated by the EC model.

Keywords: AC loss, REBCO superconducting cable, 3D FEM, EC model

1. Introduction

Superconductivity is a phenomenon in which the electrical resistance becomes zero when a specific metal or compound is cooled to an extremely low temperature. If an electrical resistance is present, an energy loss called Joule heat occurs when the current flows, but no electrical Joule heat is generated even if the current flows because the electrical resistance is zero in the superconducting state. Because of such characteristics, the superconductor can flow current without waste, so it is suitable for use as a power transmission cable. When AC power transmission is carried out, a direction of the current always changes, so the magnetic field also changes its direction frequently [1]. Then, energy dissipation occurs due to the movement of the pinned magnetic flux under the influence of the alternating magnetic field, so that an electrical resistance occurs. However, since the value of the electric resistance is small, the superconducting cable can transmit electric power with lower loss than the conventional copper cable. For practical application of superconducting cables, calculation of AC transport-current characteristics of the cables by 3D FEM is performed for the purpose of reducing AC loss.



(a) Overall view (b) Enlarged view (c) Mesh model

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

2. Calculation

The winding direction of the four-layer superconducting cable is fixed to SSZZ, and an EC model is used to determine the winding pitch of each layer [2]. The EC model is to obtain the current distribution of each layer of the cable by considering a mutual and a self inductances in a length direction of the cable. In this research, 3D superconducting cable model is created using COMSOL, and 3D FEM is performed to calculate the AC transport-current characteristics. As governing equations applied to the cable model, Faraday's law (1) and Ampere's law (2) are used. This governing equation is called *H*-formulation [3].

$$\mu_0(\partial \boldsymbol{H}/\partial \mathrm{t}) + \boldsymbol{\nabla} \times \boldsymbol{E} = 0 \tag{1}$$

$$\boldsymbol{J} = \boldsymbol{\nabla} \times \boldsymbol{H} \tag{2}$$

Here, μ_0 is the permeability of vacuum, $\boldsymbol{H}$ is the magnetic field, and $\boldsymbol{E}$ is the electric field. Furthermore, the electric field $\boldsymbol{E}$ in the superconductor has a current density $\boldsymbol{J}$ characteristic inherent to the superconductor as shown in equation (3).

$$\boldsymbol{E} = E_{\mathrm{C}}(\boldsymbol{J}/J_{\mathrm{C}})^n \tag{3}$$

Here, E_C is a critical electric field ($E_C = 1 \times 10^{-4}$ V/m), J_C is a critical current density, and n is an index value (n = 25). The values of $\boldsymbol{H}$, $\boldsymbol{E}$, and $\boldsymbol{J}$ are determined by simultaneous equations (1)-(3), and AC loss P is calculated using equation (4).

$$P = \frac{f}{L}\int_{\frac{1}{f}} dt \int_V \boldsymbol{E} \cdot \boldsymbol{J} \; dV \quad [\mathrm{W/m}] \tag{4}$$

Where f is a frequency (f = 60 Hz) and L is the length of the cable model.

3D model of the four-layer REBCO superconducting cable is shown in Fig.1. The length of the model shown in Fig.1 is L = 10 mm, but L is extended to 40 mm to calculate the loss P and each layer current I_m.

3. Result and discussion

Table 1 shows the configuration parameters of the four-layer REBCO superconducting cable. Here, the width and thickness of the tape, the inner diameter of each layer, the number of tapes, and the critical current were determined with reference to the REBCO cable having four-layer conductor and two-layer magnetic shield which is manufactured by Fujikura Ltd. [4]. However, since the information on the winding direction and the winding pitch is not disclosed, the winding direction is fixed to SSZZ, and the winding pitch HP_m is calculated by EC model so that

Table 1 Configuration parameters of four-layer REBCO superconducting cable

Width of tape	4 mm
Thickness of tape	1 μm
Inner diameter of the first layer	20.5 mm
Inner diameter of the second layer	22.0 mm
Inner diameter of the third layer	23.5 mm
Inner diameter of the fourth layer	25.0 mm
Number of tapes in the first and second layer	14
Number of tapes in the third and fourth layer	15
Overall critical current	14 kA
Critical current per tape	240 A

the current of each layer is as uniform as possible. As a result, a cable model was prepared with HP_1 = 100 mm (S direction), HP_2 = 310 mm (S direction), HP_3 = 290 mm (Z direction), and HP_4 = 100 mm (Z direction). At first, L was set to 10 mm to reduce calculation time. Then, as a result of calculating the loss with the trasnport current as I = 3 kA_{rms}, the calculated value became about 5 times larger than the measured value.

The winding direction and the winding pitch were fixed, and the L was extended from 10 mm to 40 mm. Each layer loss P_m with respect to L is shown in Fig.2, and each layer current I_m is shown in Fig.3. In Fig.2, P_m indicates the calculated loss of the m-th layer, and P indicates the calculated value of total loss. The measured value (indicated as measurement in Fig. 2) is obtained by Fujikura Ltd. [4]. In Fig. 3, $I_{m(\mathrm{FEM})}$ and $I_{m(\mathrm{EC})}$ indicate calculated values of the layer current in the m-th layer obtained by 3D FEM and EC model.

As can be seen in Fig. 2 and Fig. 3, it is understood that P decreases toward the experimental value as L increases, and each layer current converges closer to the value calculated by EC model. In order to calculate the loss correctly, it is necessary to make the each layer current converge to a constant value by increasing L to some extent. While the increasing L improves an accuracy of the calculation, it has a disadvantage that the calculation time becomes very long due to the increase in the number of meshes, so that the L can not be simply increased.

4. Conclusion

In order to accurately calculate AC loss of the superconducting cable, it is necessary to prepare a cable model of $L \geqq 40$ mm. However, if L is increased, the number of meshes increases and the calculation time becomes very long. Therefore, it is necessary to aim to find out how to calculate the loss acclately without spending calculation time.

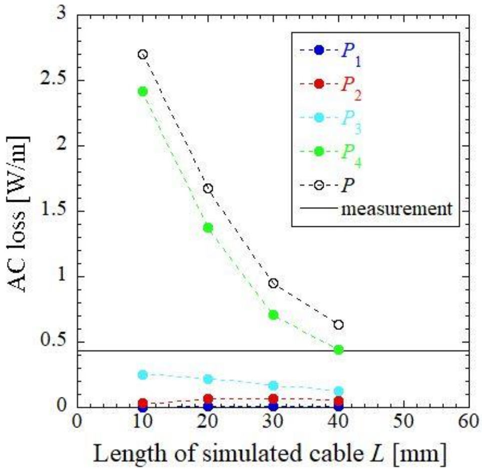


Fig. 2 The characteristics of layer loss versus length of cable model.

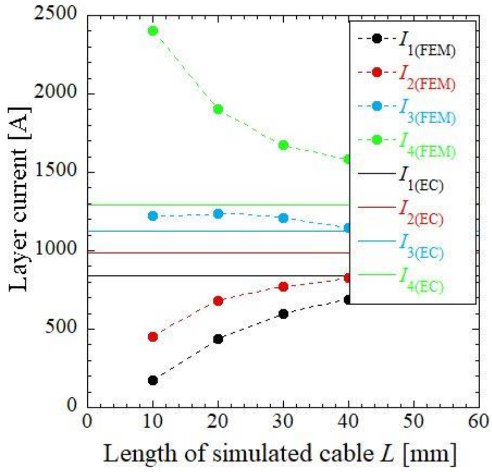


Fig. 3 The characteristics of layer current versus length of cable model

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