Numerical Study of the Current-Loss Properties of a Two-layered REBCO Power Cable Using 3D Finite Element Method

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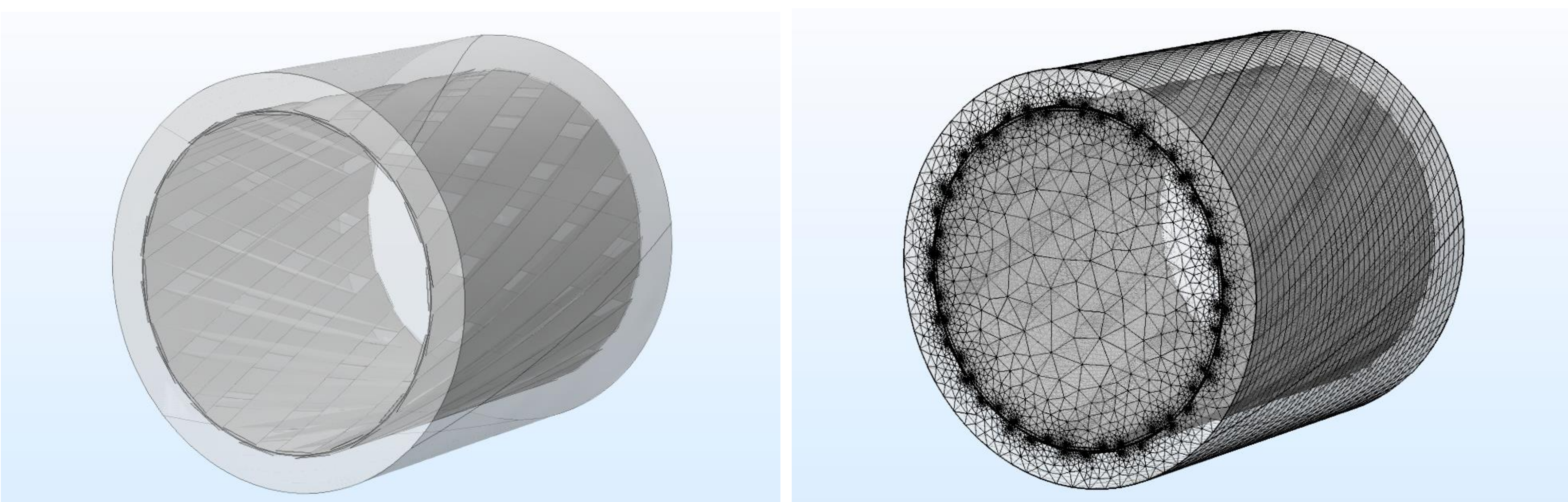
Abstract

This study investigates the loss properties of a two-layered REBCO power cable fabricated by the Furukawa Electric Co., Ltd. The losses are calculated using the three-dimensional finite element method (3D FEM) using COMSOL Multiphysics, which is based on the *H*-formulation. The calculated loss depended on the length *L* of the cable model that was made for the 3D FEM. The calculation converges to a value nearly equal to the measurement at $L \geqq 40$ mm. The property of the loss versus the transport current is investigated at $L = 40$ mm, and it is found that the calculation is almost equal to the actual measurement. The properties of the loss and the layer current versus the helical pitch of the first and second layers HP_1 and HP_2 are also investigated. The results proved that the loss depended on HP_1 and HP_2, and the helical pitches of the cable (HP_1 = 340 mm (S direction) and HP_2 = 280 mm (Z direction)) were optimal for obtaining the minimum loss. Moreover, the layer current obtained by the 3D FEM was almost equal to the current calculated by using the electric circuit model.

■Configuration of two-layered cable



(a) (b)

Fig. 1. 3D configuration of the two-layered cable (L = 40 mm, HP_1 = 340 mm (S), HP_2 = 280 mm (Z)): (a) without mesh and (b) with mesh.

Table 1. Specifications of two-layered cable

Tape width w	4 mm
Tape thickness	0.1 mm
Thickness of superconductor d	1 μm
Inner radius of first layer r_1	16.0 mm
Inner radius of second layer r_2	16.5 mm
Number of tapes in first layer N_1	16
Number of tapes in second layer N_2	16
Critical current of the tape I_C	45.6 A
Critical current of first layer I_{C1}	730 A
Critical current of second layer I_{C2}	730 A
Helical pitch of first layer HP_1 (direction)	340 mm (S)
Helical pitch of second layer HP_2 (direction)	280 mm (Z)

■Calculation method

The *H*-formulation applied to the cable model is as follows: Equation (1) is Faraday's law, and equation (2) is Ampere's law.

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

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

Here, μ_0 is the permeability of vacuum, and μ_r is the relative permeability (μ_r = 1).

Equation (3), which is an inherent power law, is applied to represent the electric field $\boldsymbol{E}$ in the superconductor as follows:

$$\left[E_x,E_y,E_z\right]=\left[E_C\left(\frac{J_x}{J_C}\right)^n,E_C\left(\frac{J_y}{J_C}\right)^n,E_C\left(\frac{J_z}{J_C}\right)^n\right]. \quad (3)$$

Here, n is the index value (n = 25); J_C is the critical current density ($J_C = 1.14 \times 10^{10}$ A/m^2); and E_C is the critical electric field ($E_C = 1 \times 10^{-4}$ V/m).

The loss P of the cable was calculated as follows:

$$P=\frac{f}{L}\cdot\int_{\frac{1}{f}}dt\int_V\left(E_xJ_x+E_yJ_y+E_zJ_z\right)dV\ \ [\mathrm{W/m}]. \quad (4)$$

Here, f is the frequency (f = 50 Hz), and L is the length of the cable model.

Although the layer current I_m of each layer was calculated using 3D FEM analysis, the I_m was calculated in the EC model for comparison with these values. In the EC model, the calculation was performed with the electrical resistance of the superconductor being zero.

Results and discussion

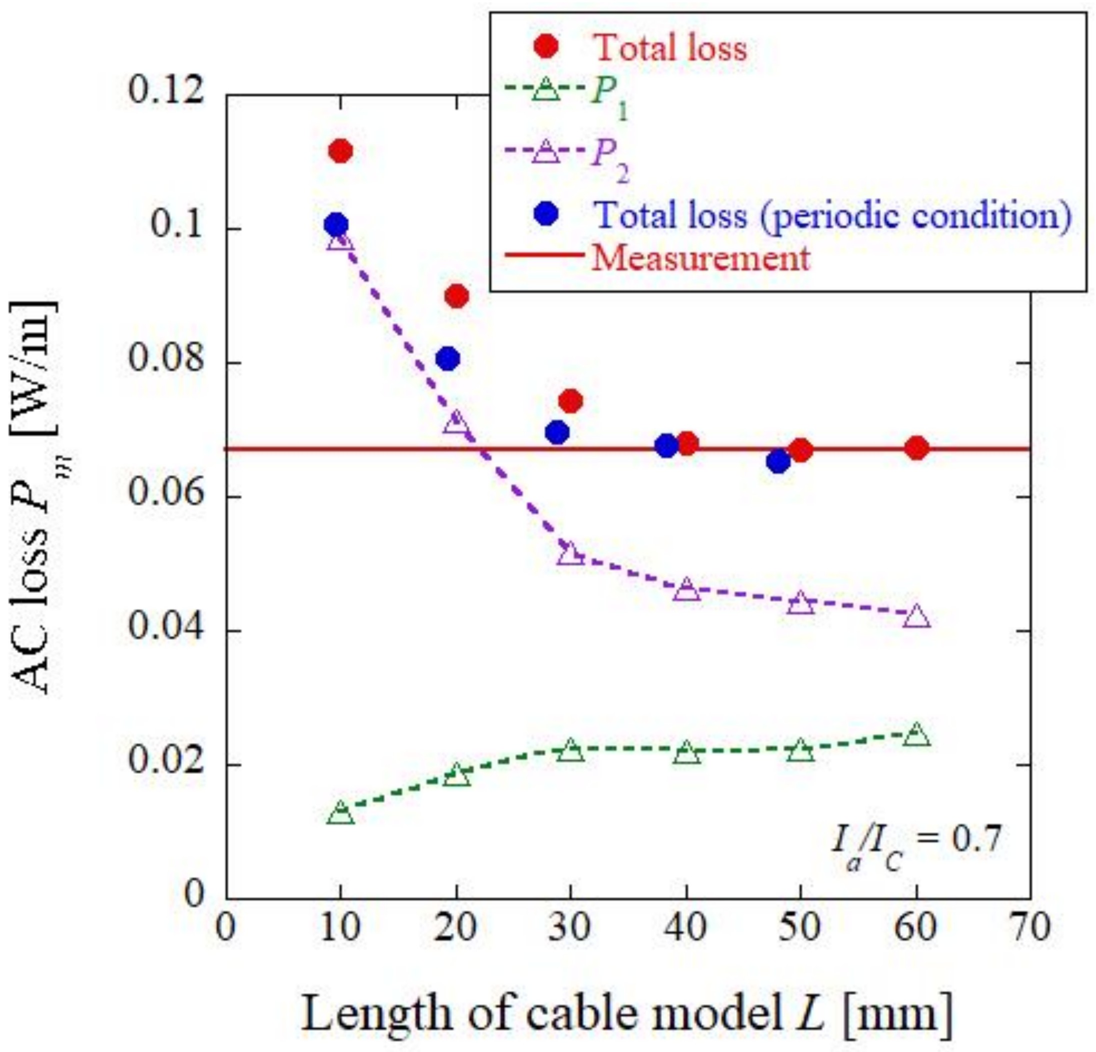


Fig. 2. Losses in the cable versus the length of the cable model when I_a/I_C = 0.7, HP_1 = 340 mm (S), and HP_2 = 280 mm (Z).

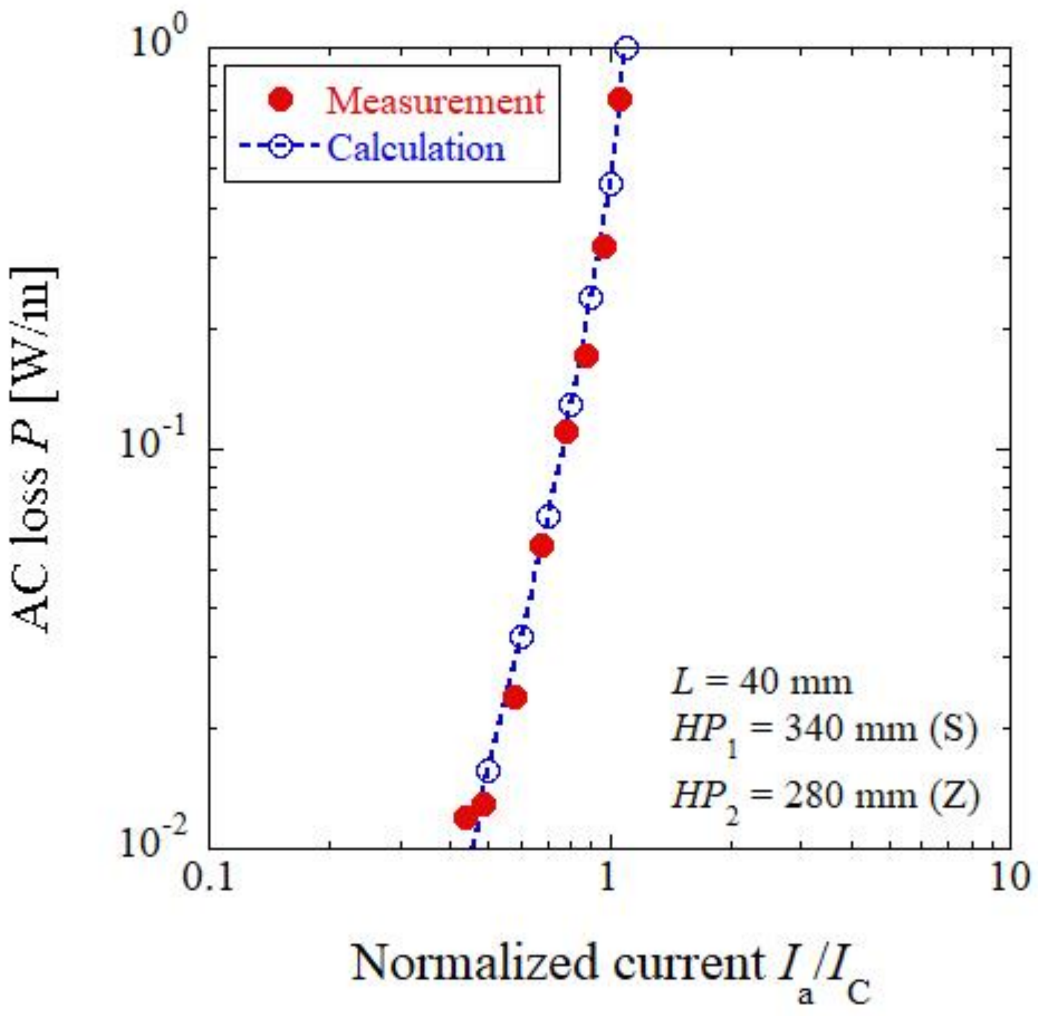
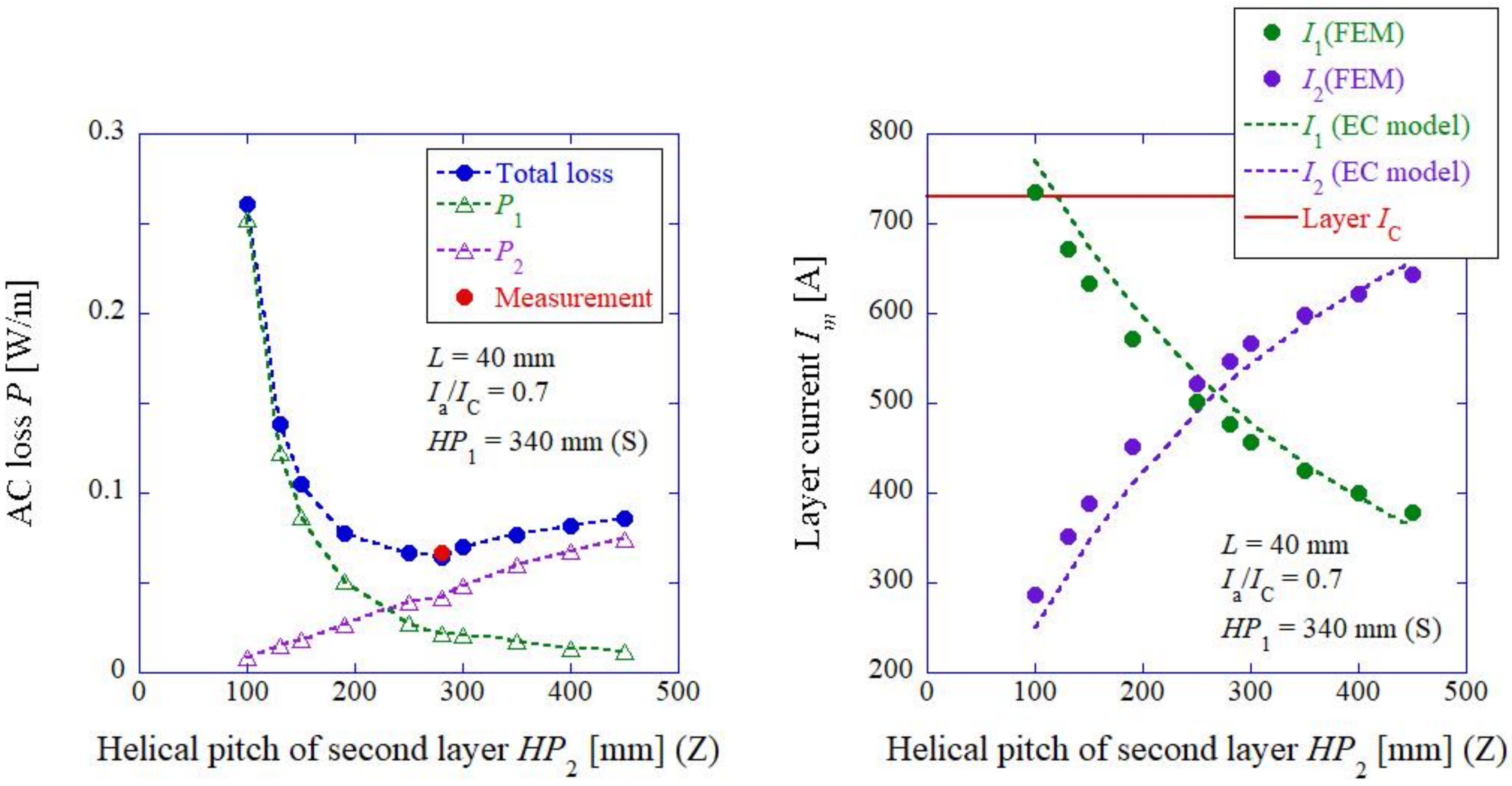


Fig. 3. Losses in the cable versus the normalized current I_a/I_C when L = 40 mm, HP_1 = 340 mm (S), and HP_2 = 280 mm (Z).

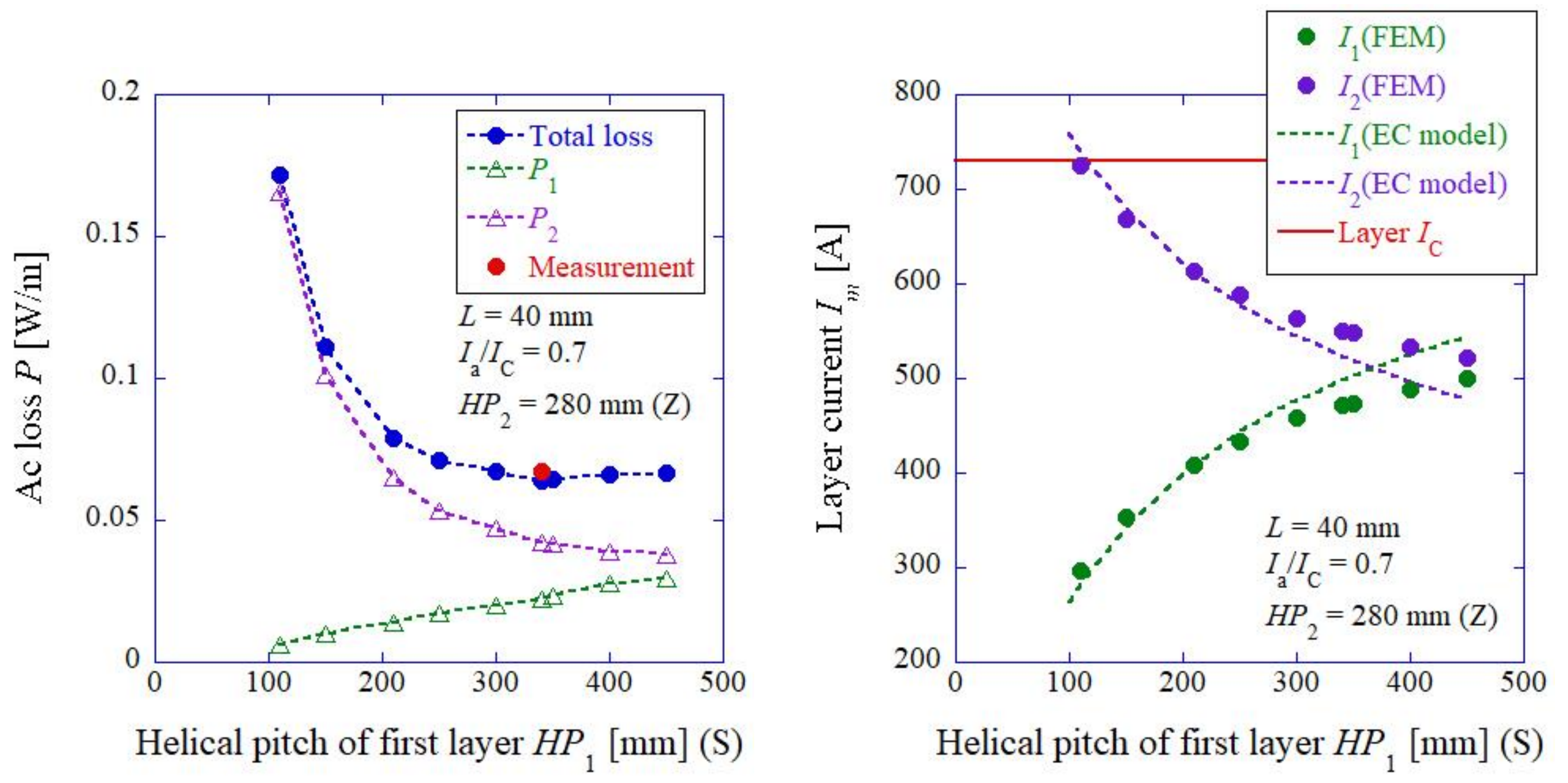
Fig. 2 shows the characteristics of the loss versus the length of the cable. Here, I_a is a current value. The solid red circles show the calculated value of the loss of the whole cable. The blue circles show the calculated loss of the whole cable when the periodic condition is taken into account, and the solid red line is the measured value. We can see that P_2 decreases as the length L of the cable model increases, and the loss of the entire cable decreases as P_2 decreases. Furthermore, when L ≧ 40 mm, the overall loss of the cable becomes consistent with the measured value. It is unknown why a cable model with the length L ≧ 40 mm is required for accurate calculations.

Fig. 3 shows the characteristics of the loss P versus the normalized current. In the following calculation, L is fixed at 40 mm. The red circles here are the measured values, and the blue circles are the calculated values. The calculated value almost agrees with the measured value, and the calculation was correctly performed.



(a) (b)

Fig. 4. Losses (a) and layer current (b) in the cable versus the helical pitches of the second layer HP_2 (Z) when L = 40 mm, I_a/I_C = 0.7, and HP_1 = 340 mm (S).



(a) (b)

Fig. 5. Losses (a) and layer current (b) in the cable versus the helical pitches of the second layer HP_1 (S) when L = 40 mm, I_a/I_C = 0.7, and HP_2 = 280 mm (Z).

Fig. 4 (a) shows the characteristics of the loss P versus the second layer helical pitch HP_2 (Z). When HP_2 is decreased from HP_2 = 450 mm, P_2 gradually decreases, and P_1 gradually increases. As a result, the overall loss P of the cable gradually decreases and reaches a minimum value near HP_2 = 280 mm. Measurement results were obtained under the minimum condition HP_2 = 280 mm. When HP_2 is further shortened from HP_2 = 280 mm, the value of P_1 rapidly increases from HP_2 ≦ 150 mm. Consequently, the value of P increases.

Fig. 4 (b) shows the characteristics of the layer current I_m versus HP_2 (Z) for each layer under the same fixed conditions as Fig. 4 (a). The green circles and purple circles show the layer currents I_1 (FEM) and I_2 (FEM) of the first and second layers, respectively, calculated using 3D FEM. The dotted green line and the dotted purple line show the layer currents I_1 (EC model) and I_2 (EC model) of the first and second layers, respectively, calculated using the EC model. The solid red line shows the critical current value (I_{C1} = I_{C2} = 730 A) of each layer. When HP_2 is shortened from HP_2 = 450 mm, I_2 (FEM) decreases and I_1 (FEM) increases. I_1 (FEM) and I_2 (FEM) become almost uniform near HP_2 = 250 mm. Near HP_2 = 250 mm, the loss P of the entire cable is minimized. If HP_2 is further shortened from HP_2 = 250 mm, I_2 (FEM) continues to decrease, and I_1 (FEM) continues to increase. When HP_2 = 100 mm, I_1 (FEM) exceeds the critical current value of the first layer; therefore, the value of P_1 rapidly increases, and the P value increases. The current values I_1 (EC model) and I_2 (EC model) calculated by the EC model are approximately equal to I_1 (FEM) and I_2 (FEM). The EC model has an extremely short calculation time; therefore, when designing a superconducting power cable, it can be used to calculate each layer's current to determine the optimal helical pitch and winding direction roughly.

The characteristics of the loss P and the layer current I_m versus the first layer helical pitch HP_1 (S) were also examined (Fig. 5 (a) and (b)). P became minimum around HP_1 = 340 mm, and the layer currents I_1 (FEM) and I_2 (FEM) calculated by 3D FEM were approximately equal to I_1 (EC model) and I_2 (EC model), respectively, calculated using the EC model.

Conclusions

To accurately calculate the loss of a superconducting power cable by 3D FEM, the length L of the cable model needed to be larger than a certain value. For a two-layered REBCO cable, the constant value was L = 40 mm. Using 3D FEM analysis on the L = 40 mm cable model, it was found that the calculated losses were in agreement with the measured values. Furthermore, the characteristics of the loss and the layer current for the helical pitches HP_1 and HP_2 were investigated. Consequently, it was found that this cable was fabricated using the optimal helical pitches to minimize the loss. Moreover, we found that the layer current calculated by the EC model was almost identical to that calculated by 3D FEM, and that the EC model could be used for the design of a superconducting power cable because of the superiority of the calculation time.