Dependence of AC loss on helical pitch of three-layer REBCO superconducting cable

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Abstract. AC loss calculation of three-layer REBCO superconducting cable was performed by three dimensional (3D) electromagnetic field analysis. For the calculation, parameters of the cable made by Furukawa Electric Co., Ltd. were referred, but winding direction and helical pitch of each layer were unknown. Therefore, in order to find the optimum cable configuration, calculations are made with various winding directions and helical pitches, and their dependencies on the loss is observed. Conditions of the calculation for the winding direction were only SZZ (left rotation for the first layer, right rotation for the second layer and right rotation for the third layer) and SSS (left rotation for all layer). It was confirmed that the helical pitch for the first layer, P_1, does not affect on the loss, that the loss increases only when the helical pitch for the second layer, P_2, is short, and that the loss decreases as the helical pitch for the third layer, P_3, becomes shorter.

Keyword: *3D electromagnetic field analysis, AC loss, REBCO superconducting cable.*

1. Introduction

Superconductivity is a phenomenon in which the electric resistance becomes zero when a specific metal or compound is cooled to an extremely low temperature. In the presence of electrical resistance, an energy loss of Joule heat occurs when current flows, but if a conductor changes to a superconducting state, the electrical resistance becomes zero, so that Joule heat does not occur even if current flows. Because of such a characteristic, the superconductor can flow current without an energy loss, 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, as the magnetic flux that was pinned in the superconductor moves the energy dissipation is occurred, so the electric resistance is generated. 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 the practical application of superconducting cables, we have studied on the calculation method of the AC loss to reduce it.

Previously, in our studies, the AC loss was calculated by a method combining an electric circuit model and two-dimensional electromagnetic field analysis [2]. However, by means of this method, it was impossible to calculate accurately when compared with the measurement value of the loss of the superconducting cable. This is because the shorter helical pitch of the superconducting tapes causes the larger loss, which was confirmed by the calculation of the loss of single-layer cable by 3D electromagnetic field analysis. However, according to the conventional method, the increase of the loss due to short helical pitch couldn't be incorporated in the calculation. Therefore, as a new calculation method, the loss calculation of the superconducting cable is performed by 3D electromagnetic field analysis.

2. Calculation

In this research, using COMSOL Multiphsics that is general purpose physical simulation software based on the finite element method, a model of 3D superconducting cable was created and the electromagnetic field analysis is performed to calculate AC loss. The finite element method is a type of numerical analysis method, in which a target is regarded as a collection of elements, divided into elements, and each element is analyzed to approximately obtain the whole. As a governing equation applied to the whole model, Faraday's law of equation (1), Ampere's law of equation (2) and Ohm's law of equation (3) were used [3].

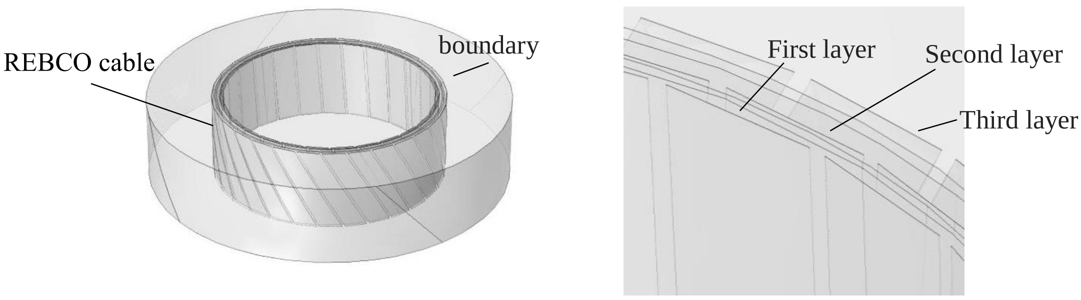
$$\mu\frac{\partial \boldsymbol{H}}{\partial \mathrm{t}}+\boldsymbol{\nabla}\times\boldsymbol{E}=0 \tag{1}$$

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

$$\boldsymbol{E}=\rho_{\mathrm{sc}}(\ \mathrm{J}\ )\boldsymbol{J} \tag{3}$$

The resistivity ρ_{sc} is obtained by equation (4) which is an exponential law specific to superconductivity.

$$\rho_{\mathrm{sc}}=\frac{E_{\mathrm{C}}}{J_{\mathrm{C}}}\left(\frac{J}{J_{\mathrm{C}}}\right)^{n-1} \tag{4}$$



(a) Overall view (b) Enlarged view

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

Three dimensional representation of these equations results in Faraday's law as equation (5), Ampere's law as equation (6), Ohm's law as equation (7) and superconductor's resistivity as equation (8).

$$\mu_0\left[\frac{\partial H_x}{\partial t},\frac{\partial H_y}{\partial t},\frac{\partial H_z}{\partial t}\right]^T+\left[\frac{\partial E_z}{\partial y}-\frac{\partial E_y}{\partial z},\frac{\partial E_x}{\partial z}-\frac{\partial E_z}{\partial x},\frac{\partial E_y}{\partial x}-\frac{\partial E_x}{\partial y}\right]^T=0 \tag{5}$$

$$[J_x,J_y,J_z]^T=\left[\frac{\partial H_z}{\partial y}-\frac{\partial H_y}{\partial z},\frac{\partial H_x}{\partial z}-\frac{\partial H_z}{\partial x},\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}\right]^T \tag{6}$$

$$[E_x,E_y,E_z]^T=[\rho_{scx}J_x\ ,\rho_{scy}J_y\ ,\rho_{scz}J_z]^T \tag{7}$$

$$[\rho_{scx},\rho_{scy},\rho_{scz}]^T=\left[\frac{E_c}{J_c}\left(\frac{J_x}{J_c}\right)^{n-1},\frac{E_c}{J_c}\left(\frac{J_y}{J_c}\right)^{n-1},\frac{E_c}{J_c}\left(\frac{J_z}{J_c}\right)^{n-1}\right]^T \tag{8}$$

From the above equations, AC loss is calculated using the following equation (9).

$$\mathrm{Q}=f\cdot\int_{\frac{1}{f}}dt\iint_S E(J)\cdot J\ dS\quad[\mathrm{W/m}] \tag{9}$$

Here, 3D model of three-layer REBCO superconducting cable is shown in Fig.1.

3. Result and discussion

Table1 shows the configuration parameters of three-layer 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 by a reference of the three-layer cable made by Furukawa Electric Co., Ltd. [4]. However, information on the helical pitch and the winding direction is not disclosed, so each pitch was initially as P_1 = 775 mm (S direction), P_2 = 920 mm (Z direction) and P_3 = 110 mm (Z direction), and AC loss was calculated. Fig.2 shows the AC loss characteristic with respect to the applied current, I_a. From this figure, the loss calculated by 3D electromagnetic field analysis is larger than the value measured by Furukawa Electric. Each layer loss was calculated with respect to I_a as shown in Fig. 3(a), and each layer current was also calculated with respect to I_a as shown in Fig. 3(b).

From Fig. 3(a), it is found that the total loss of the cable, Q, is almost the loss of the third layer, Q_3. In addition, from Fig. 3(b), it can be seen that the layer current is not uniform. Therefore, in order to find the optimum helical pitch where layer current coincides with each other and Q becomes low, the loss and the layer current are calculated as changing the helical pitch of each layer. First, P_1 and P_2 were fixed, P_3 was changed to calculate the losses and the layer current as shown in Fig. 4 (a) and (b). The normalized current, I_a/I_C, is set to 0.7. Here, I_C is the critical current of the cable. From Figs. 4(a) and (b), it can be seen that as P_3 becomes shorter, Q becomes lower, and each layer current is closing. However, there is a minimum pitch for the third layer, P_{3min}, to configure the cable, and when calculating its value, P_{3min} is obtained as 77 mm. Therefore, when P_3 becomes P_{3min} or less, almost no decrease in the total loss is observed. The minimum pitch of each layer is

Table 1 Configuration parameter of three-layer REBCO superconducting cable.

Width of tape	1.8 mm
Thickness of tape	1 μm
Inner diameter of first layer	17.3 mm
Inner diameter of second layer	17.9 mm
Inner diameter of third layer	19.2 mm
Number of tapes in first layer	27
Number of tapes in second layer	28
Number of tapes in third layer	30
Critical current of first layer	699 A
Critical current of second layer	705 A
Critical current of third layer	778 A

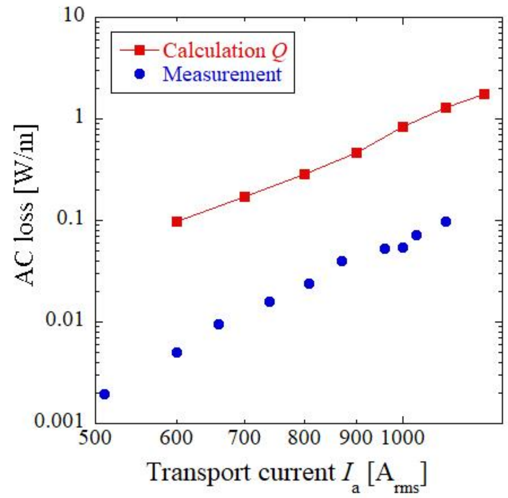


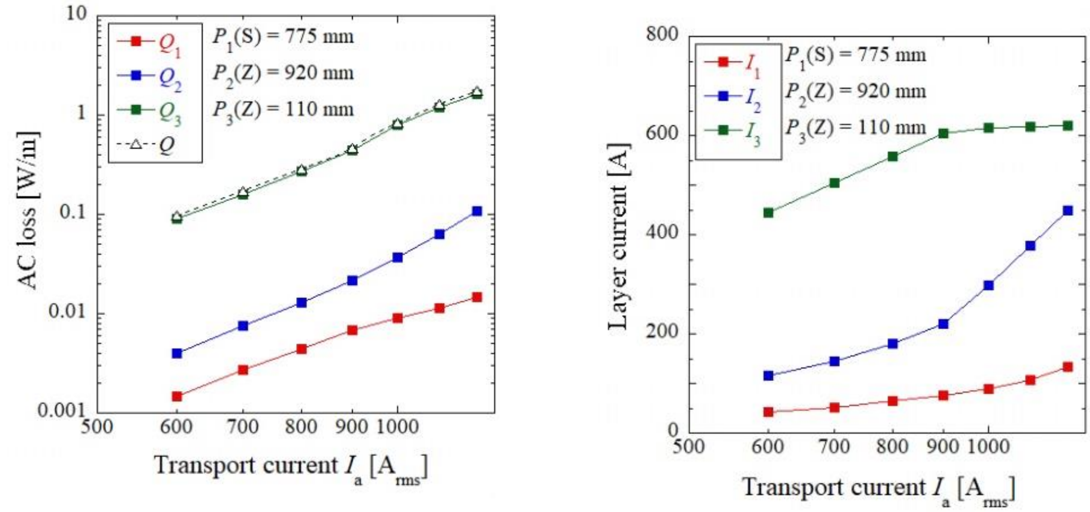
Fig.2 AC loss characteristic of three-layer REBCO superconducting cable with respect to applied current.

calculated by using equation (10) [5].

$$P_{m\ \min} = \frac{4r_m}{\sqrt{\left(\frac{2\pi r_m}{N_m w_{id}}\right)^2 - 1}} \tag{10}$$

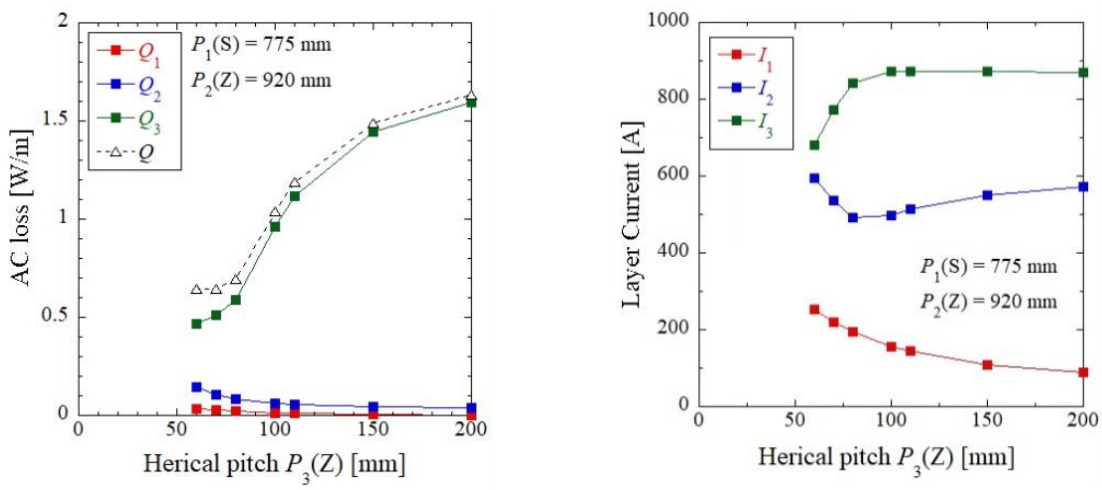
From the result of the characteristic of Q with respect to P_3, P_3 was fixed to 80 mm and P_2 was changed. Fig. 5 (a) and (b) show the losses and the layer current with respect to P_2. From Figs.5(a) and (b), Q becomes the minimum in the vicinity of P_2 = 920 mm which is equal to the original setting parameter, but there is no big change unless P_2 is too short. However, when P_2 is made very short, it is understood that the current of the first layer, I_1, is bigger than the current of the second layer, I_2, and Q becomes very large. From the result of the characteristic of the losses with respect to P_2, since Q is not so much changed unless it is too short, P_2 was fixed at 920 mm and P_1 was changed. Fig. 6 (a) and (b) show the characteristics of the losses and the layer current with respect to P_1, respectively. As shown in these figures, I_1 approaches to I_2 when P_1 is shortened and the current of the third layer, I_3, slightly increases. Each layer loss shows similar characteristics. However, Q is almost unchanged as changing P_1. From Figs. 6(a) and (b), it is found that Q is not decreased less than the measured value obtained by Furukawa Electric, even when the helical pitch of each layer is changed when the winding direction of the cable is SZZ.

Next, the winding direction was changed to SSS and the loss is calculated with changing P_3 when P_1 and P_2 were fixed to P_1 = 775 mm, P_2 = 920 mm. The characteristics of the losses and the layer current with respect to P_3 are shown in Figs. 7(a) and (b). From these figures, it is understood that as P_3 is shorter, I_2 and I_3 are getting closer. However, Q decreases until P_3 decreases to $P_{3\min}$ = 77 mm and increases when P_3 is further shortened. From the result of the characteristic of Q with respect to P_3, P_3 was fixed to 80 mm. The losses and the layer current were calculated with changing P_2 as shown in Figs. 8(a) and (b). I_1 becomes larger than I_2 only when P_2 is 100 mm. Q becomes very large at the short P_2, but basically, at the longer P_2, Q is almost no change.



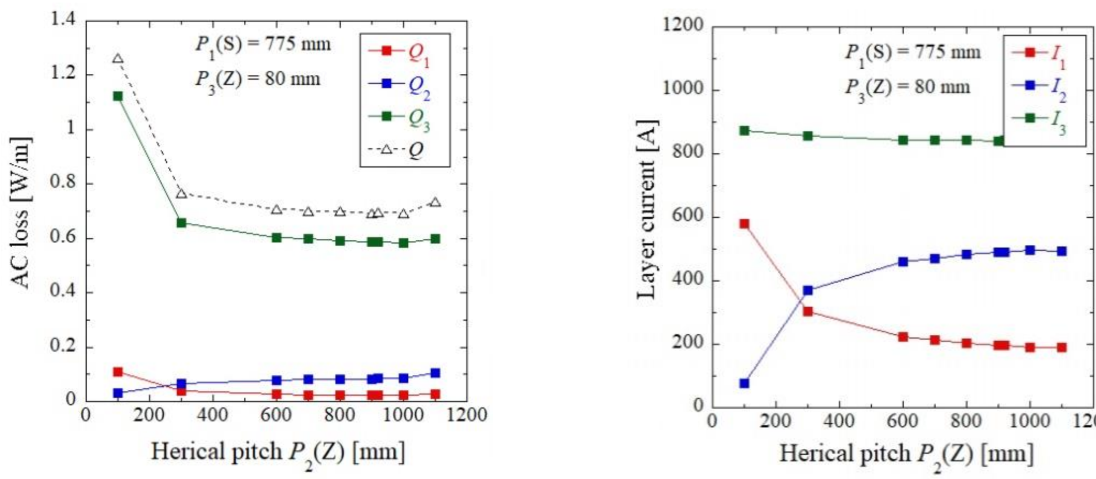
(a) The characteristic of layer loss. (b) The characteristic of layer current.

Fig. 3 The characteristics of layer loss and layer current with respect to applied current.



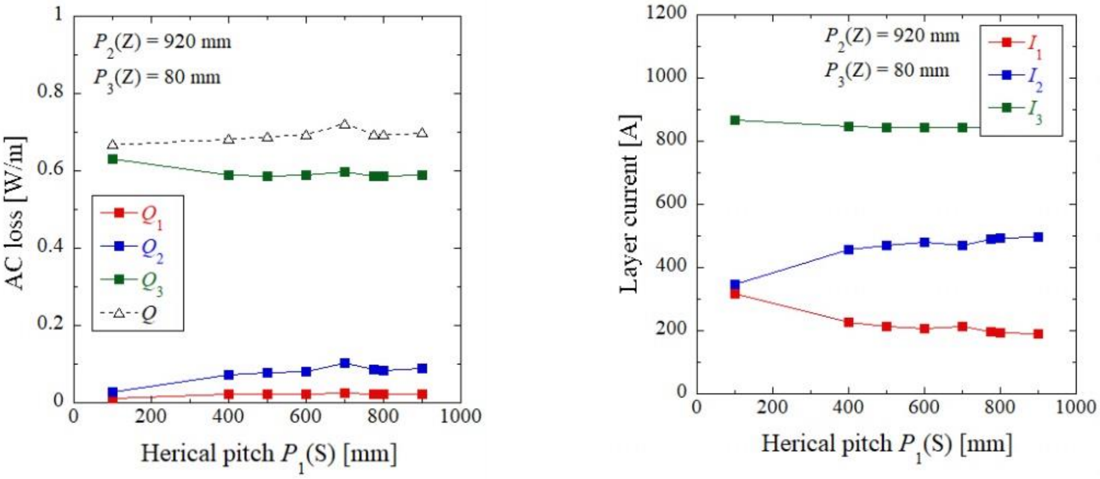
(a) The characteristic of layer loss. (b) The characteristic of layer current.

Fig. 4 The characteristics of losses and layer current with respect to P_3 (SZZ direction).



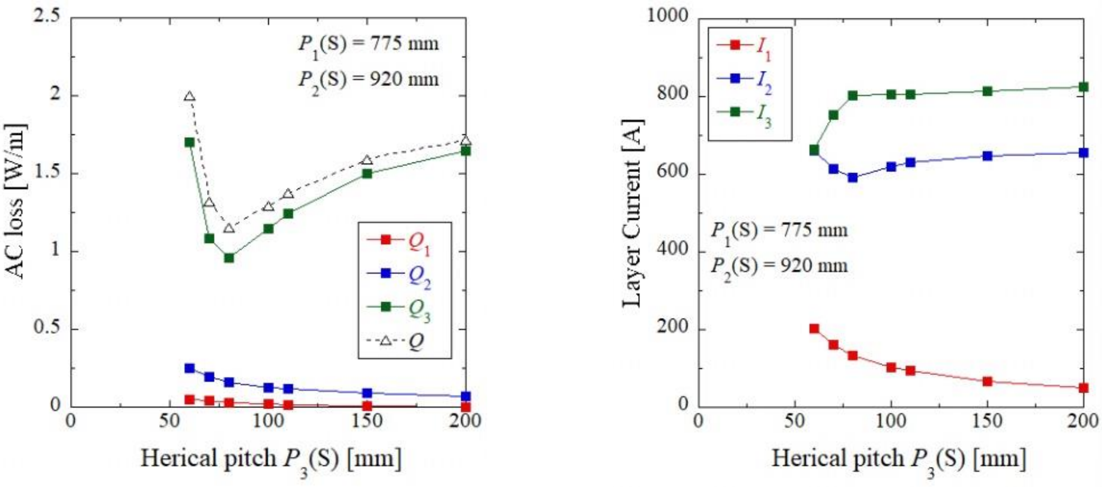
(a) The characteristic of layer loss. (b) The characteristic of layer current.

Fig. 5 The characteristics of losses and layer current with respect to P_2 (SZZ direction).



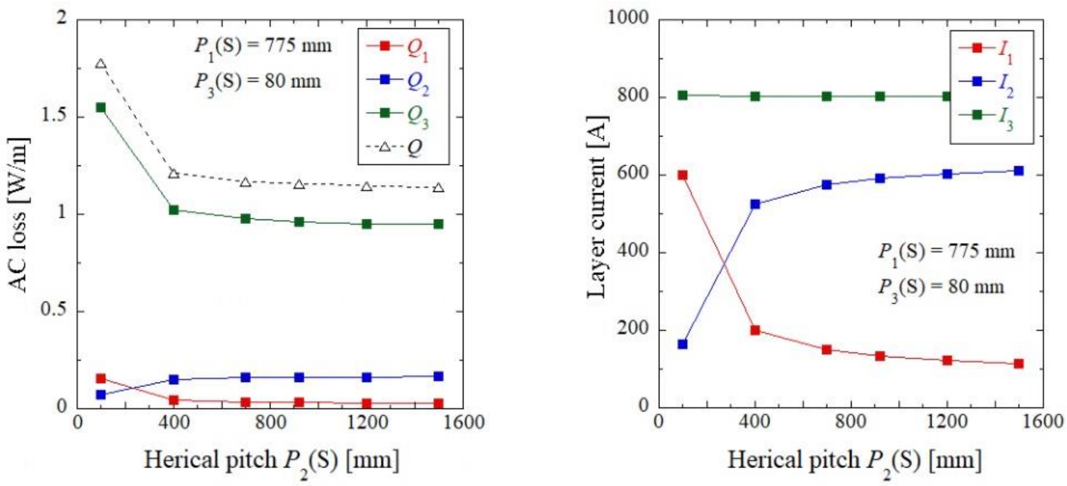
(a) The characteristic of layer loss. (b) The characteristic of layer current.

Fig. 6 The characteristics of losses and layer current with respect to P_1 (SZZ direction).



(a) The characteristic of layer loss. (b) The characteristic of layer current.

Fig. 7 The characteristics of losses and layer current with respect to P_3 (SSS direction).



(a) The characteristic of layer loss. (b) The characteristic of layer current.

Fig. 8 The characteristics of losses and layer current with respect to P_2 (SSS direction).

4. Conclusion

When the winding direction was SZZ and P_3 was changed, the loss decreases as P_3 becomes close to $P_{3\text{min}}$. When P_2 was changed, the loss increases as P_2 is less than 300 mm. Even if P_1 is changed, the loss hardly changes. When the winding direction is SSS, the characteristics of Q respect with to P_2 and P_3 were almost same dependency as in SZZ. Although we have conducted the above research, as a future prospect, we will calculate the losses with changing P_1 when the winding direction is SSS. Moreover, the characteristics of the losses and the layer current respect with to P_1, P_2 and P_3 will be also calculated when the winding directions are SZS and SSZ. We aim to find the winding direction and helical pitch to calculate the loss that coincides with the measured value of Furukawa Electric.

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