AC loss Calculation of Two-layer REBCO Superconducting Cable by 3D Electromagnetic Field Analysis

Ryo OKADOME and *Hideki NOJI*
Advanced Course of Mechanical and Electrical Engineering, N.I.T., Miyakonojo College,
Miyazaki 885-8567, Japan

Abstract. Three dimensional (3D) electromagnetic field analysis is a method for analyzing the electromagnetic field stereoscopically when an alternating current (AC) is passed through a superconducting cable. In this research, we calculated the AC loss of a two-layer REBCO superconducting cable made by Furukawa Electric Co., Ltd. by 3D electromagnetic field analysis with general-purpose software COMSOL Multiphysics. The result of the calculation was agreed with the experimental result of Furukawa Electric. We also calculated AC loss by changing helical pitches and winding directions of each layer of the two-layer REBCO superconducting cable, and designed a cable with the minimum loss.

Key words: *3D electromagnetic field analysis, REBCO tapes, Superconducting power cable, AC loss*

1. Introduction

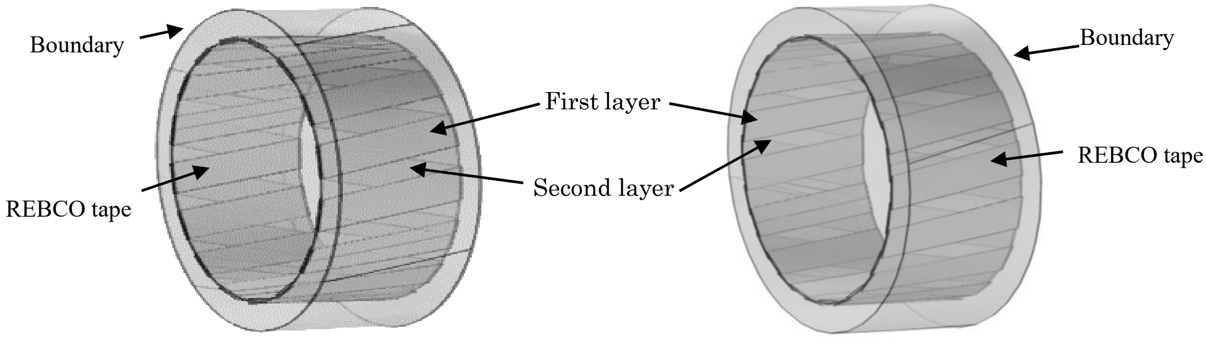
"Superconductivity" was discovered by Dutch physicist Kamerlingh Onnes in 1911. Superconductivity is a phenomenon in which electric resistance becomes zero at a certain temperature (critical temperature T_C) when cooling certain metals and semiconductors to absolute zero [1]. The property is applied to linear motor car and magnetic resonance imaging (MRI), and it is becoming familiar to us. This is also applied to the field of power transmission. When electric current of more than the capacity is passed through the conventional transmission line, electric wire may generate heat and fire due to electric resistance. In conventional transmission lines, metals with low electric resistance were used, but about 5% of the electricity generation amount was still heat generation due to electric resistance, that is, energy loss. A superconducting cable utilizes the characteristic of superconducting "zero electrical resistance" for power transmission, and when this is realized, the heat generated by the electrical resistance disappears and theoretically the energy loss becomes zero. When the superconducting cables are used for power transmission cables, it is possible to reduce the power loss for power transmission and the cost of the entire power transmission infrastructure as compared with the existing power transmission system. In addition, the superconducting cable is large capacity and compact, they are easy to underground in urban areas. However, the electric resistance of the superconducting cable is zero only in the case of direct current (DC) power transmission. When an electric current is passed through the electric wire, a magnetic field is generated around it, and in the case of AC transmission, the direction of the magnetic field frequently changes. Then, energy dissipation occurs due to a movement of the pinned magnetic flux inside the superconductor, resulting in energy loss. Therefore, when AC transmission is performed by the superconducting cable, the loss occurs. In our laboratory, we are conducting studies aiming at reducing such AC loss toward practical application of superconducting cables.

We newly introduced 3D electromagnetic field analysis which analyzes the electromagnetic field of superconducting cable three-dimensionally. So far, our laboratory has calculated the AC loss of superconducting cable by quasi-3D electromagnetic field analysis combining two-dimensional electromagnetic field analysis and electric circuit model [2]. However, in 3D electromagnetic field analysis, the result that AC loss increases when a helical pitch of the single layer superconducting cable is shortened was obtained, but the result could not be taken into consideration by the quasi-3D electromagnetic field analysis. Therefore, in this study, AC losses of two-layer REBCO superconducting cable is calculated by 3D electromagnetic field analysis using COMSOL. Then we try to design a low-loss cable.

2. Calculation

COMSOL used for calculation is simulation software which analyzes models using the finite element method (FEM). In the FEM, a target is regarded as an aggregate of elements, divided into elements, and each element is analyzed to approximate the whole analysis result. An example of three-dimensional model of a two-layers REBCO superconducting cable is shown in Fig.1.

Equations (1) and (2) are expressions of Faraday's law and Ampere's law. Equation (3) is an equation of the resistivity expressed by an exponential law inherent to superconductivity, and equation (4) is an equation of Ohm's law. These equations are introduced into our model. Then, the electromagnetic field when a sinusoidal current is applied to the superconducting cable is three-dimensionally analyzed and AC loss is calculated by an equation (5).



(a) Tape-on-tape (b) Tape-on-gap

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

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

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

$$\left[\rho_{scx},\ \rho_{scy},\ \rho_{scz}\right]^T=\left[\frac{E_c}{J_c}\left(\frac{J_x}{J_c}\right)^{n-1},\ \frac{E_c}{J_c}\left(\frac{J_y}{J_c}\right)^{n-1},\ \frac{E_c}{J_c}\left(\frac{J_z}{J_c}\right)^{n-1}\right]^T \tag{3}$$

$$\left[E_x,\ E_y,\ E_z\right]^T=\left[\rho_{scx}J_x,\ \rho_{scy}J_y,\ \rho_{scz}J_z\right]^T \tag{4}$$

$$Q=f\cdot\int_{\frac{1}{f}}dt\iint_S E(J)\cdot J dS \quad [\mathrm{W/m}] \tag{5}$$

3. Results and discussion

3.1 AC loss of SZ winding two-layer REBCO cable

3D electromagnetic field analysis was performed on a 3D model of SZ winding in which the winding directions of the two layers are opposite to each other. Parameters of the cable were referenced to the two-layer REBCO superconducting cable made by Furukawa Electric Co., Ltd. [3]. The parameters are shown in Table 1.

First, using the model shown in Fig.1, the AC loss characteristic for a normalized current of the two-layers cable was calculated. The result is shown in Fig.2. Here, the energizing current Ia is normalized by the critical current I_C. As shown in Fig. 1 (a), the tape on tape is a calculation result of a model in which the next tape from the tape of the first layer and the second layer overlaps at the model end portion, and the tape on gap is a calculation result of a model in which the tape portion and the gap portion between the two layer overlaps at the model end portion, as shown in Fig. 1 (b). In addition, the red circle is the measurement value of Furukawa Electric Co., Ltd. [3]. From Fig.2, it is understood that AC losses calculated by COMSOL and measured by Furukawa Electric are close to each other. From this fact, we think that the program of 3D electromagnetic field analysis can be correctly created using COMSOL. Moreover, both of the calculated values of AC losses of the tape-on-tape and tape-on-gap models remained almost unchanged. The structure of the SZ winding two-layers cable is periodic with respect to the length direction. The length L_{pe} of this cable for one cycle is obtained by equation (6) [4].

$$L_{pe}=\frac{1}{N}\cdot\frac{P_1P_2}{P_1+P_2} \tag{6}$$

Here, N is the number of tapes in each layer, P_1 and P_2 are the helical pitches of the first layer and the second layer, respectively. As shown in Figs.1 (a) and (b), a calculation time can be shortened by performing AC loss calculation in the model of only one period section.

Next, AC loss and layer current characteristics when P_2 was changed by fixing P_1(S) to 340 mm were calculated. The results are shown in Fig.3. Furthermore, AC loss and layer current characteristics when P_1 was changed by fixing P_2(Z) to 280 mm were calculated. The results are shown in Fig.4. From Fig.3 (a), it can be seen that the AC loss of the first layer, Q_1, increases as P_2 decreases. This is because, as shown in Fig. 3 (b),

Table 1 Parameters of two-layer REBCO 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 P_1	340 mm
Helical pitch of second layer P_2	280 mm

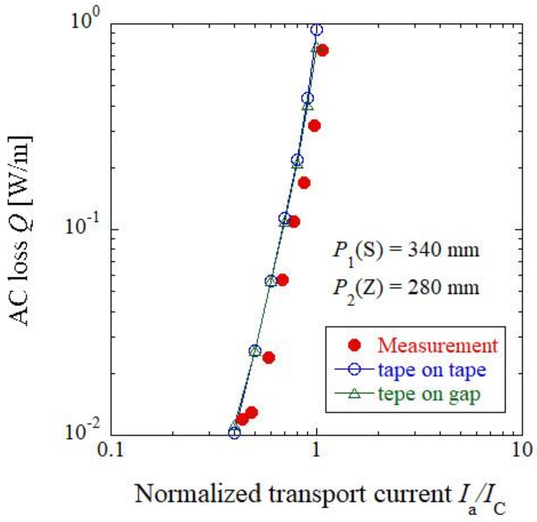
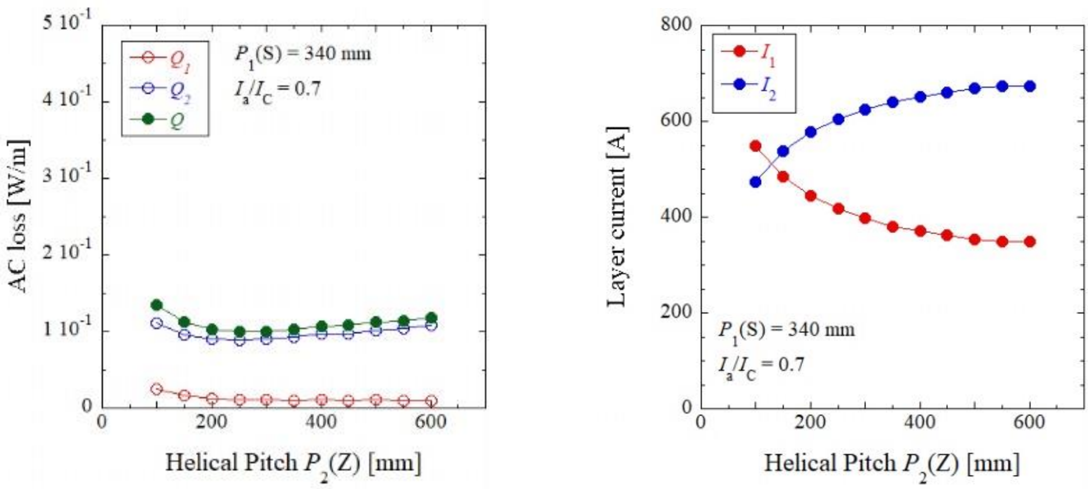


Fig.2 AC loss characteristic against normalized current.



(a) AC loss characteristic against P_2 (Z). (b) Layer current characteristics against P_2(Z).

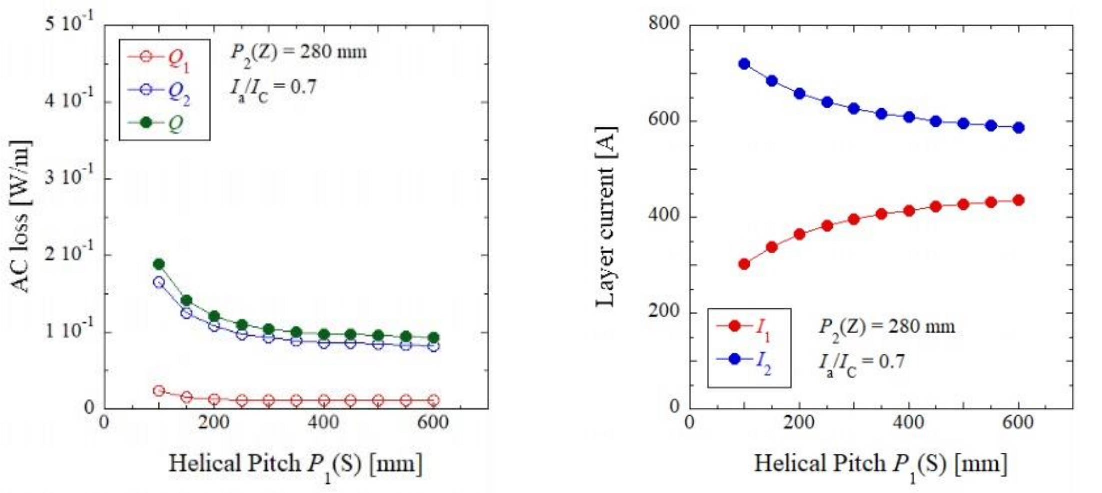
Fig.3 AC loss and layer current characteristics against P_2(Z) when P_1(S) = 340 mm.

as P_2 is shortened, the layer current of the first layer, I_1, increases. In addition, as can be seen from Fig.3 (a), the AC loss of the second layer, Q_2, decreases as P_2 decreases, but it increases as P_2 decreases to the minimum around P_2 = 280 mm. As shown in Fig.3 (b), as P_2 is shortened, the layer current of the second layer, I_2, decreases and then Q_2 decreases, but if P_2 becomes too short, Q_2 sharply increases and total loss, Q, increases as a result. Since Q_2 accounts for most of Q, the characteristics of Q_2 and Q are almost the same, and Q is the minimum loss at P_2(Z) = 280 mm. Furthermore, it can be seen from Fig.3 (b) that I_1 and I_2 become uniform in the vicinity of P_2(Z) = 130 mm.

When P_1 becomes shorter as shown in Fig.4 (b), I_1 decreases and then the loss tries to decrease, but as the helical pitch becomes shorter, a tendency of increasing AC loss works, Q_1 hardly changes. When P_1 becomes too short, Q_1 sharply increases as shown in Fig.4 (a). Also, it can be seen that Q_2 increases as P_1 decreases. This is because, as shown in Fig.4 (b), as P_1 is shortened, I_2 increases. Since Q_2 accounts for most of Q, the characteristics of Q_2 and Q are almost the same. From the results in Figs.3 and 4, it was found that the minimum loss of the cable is about 0.1 W/m at I_a/I_C = 0.7.

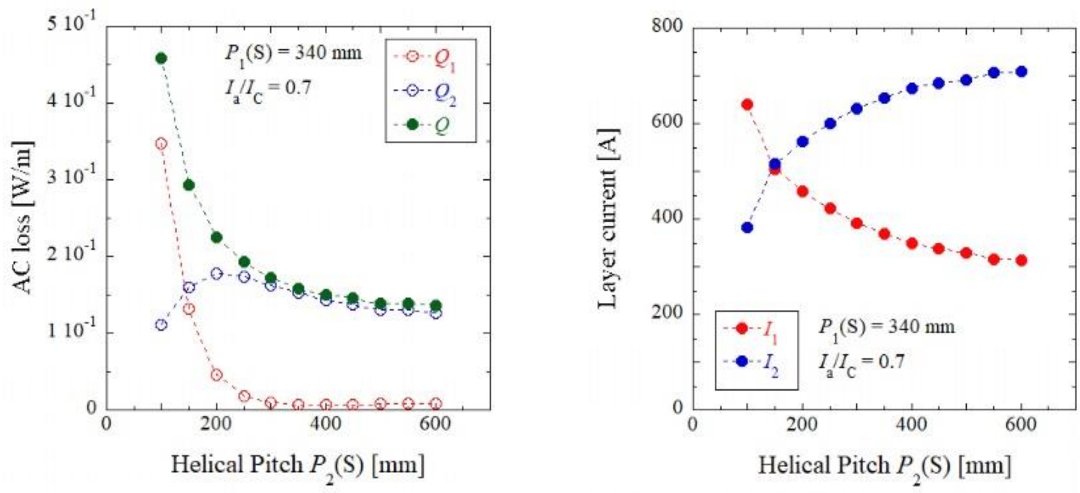
3.2 AC loss of SS winding two-layer REBCO cable

In the SS winding, the winding directions of the two layers are the same. First, the AC loss and layer current characteristics when P_1 of the cable was fixed at P_1(S) = 340 mm and P_2 was changed were calculated. The results are shown in Fig.5. From Fig.5 (a), it can be seen that Q_1 increases as P_2 decreases. This is because, as shown in Fig.5 (b), as P_2 is shortened, I_1 increases. In addition, as shown in Fig.5 (a), as P_2 is shortened, I_2



(a) AC loss characteristic against P_1(S). (b) Layer current characteristics against P_1(S).

Fig.4 AC loss and layer current characteristics against P_1(S) when P_2(Z) = 280 mm.



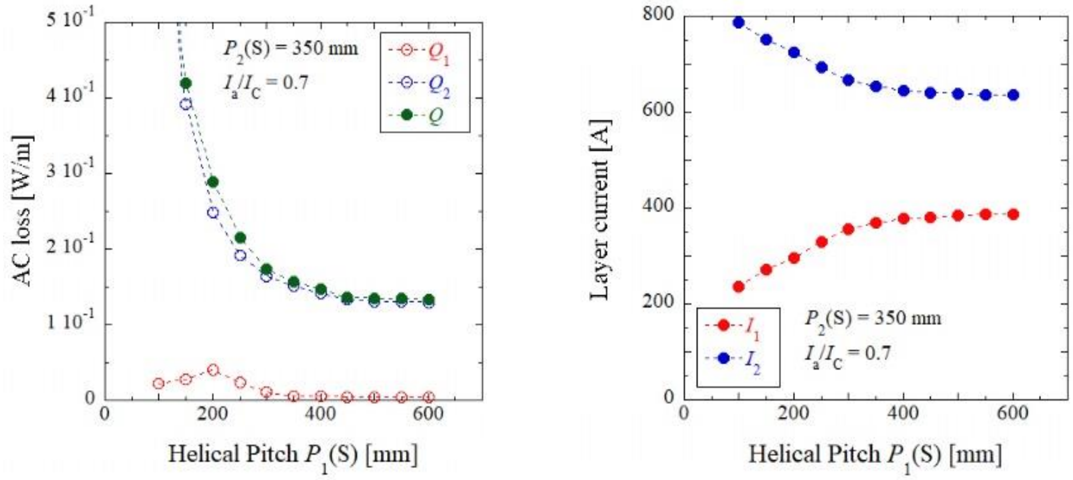
(a) AC loss characteristic against P_2(S). (b) Layer current characteristic against P_2(S).

Fig.5 AC loss and layer current characteristics against P_2(S) when P_1(S) = 340 mm.

decreases as shown in Fig.5 (b), but if the helical pitch is shortened, the AC loss increases, so Q_2 gradually increases. After that, since I_2 abruptly decreases around P_2(S) = 200 mm, Q_2 decreases. In addition, it is found that Q increases as P_2 decreases, and I_1 and I_2 become substantially uniform around P_2(S) = 150 mm.

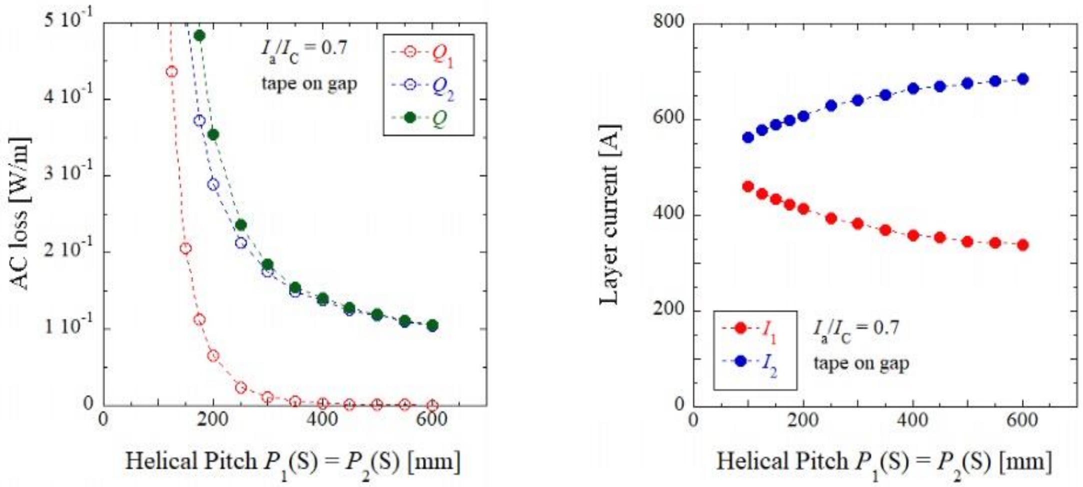
Furthermore, based on the results in Fig.5, P_2 would be set as close as possible to an equal between I_1 and I_2. P_2 was fixed to P_2(S) = 350 mm, which did not increase much compared to P_2(S) = 600 mm, and the loss and current characteristics were calculated by changing P_1. The results are shown in Fig.6. From Fig.6 (a), it is found that Q_2 increases as P_1 is shortened. This is because, if P_1 is shortened as shown in Fig.6 (b), I_2 increases. In addition, when P_1 is shortened, as shown in Fig.6 (b), I_1 decreases and the tendency of increasing the loss by decreasing the helical pitch works so that Q_1 gently increases. Since I_1 abruptly decreases around P_1(S) = 300 mm, Q_1 decreases.

Finally, the AC loss and the current characteristics in the case where REBCO tapes were arranged on the tape-on-gap with P_1(S) = P_2(S) were calculated. The results are shown in Fig.7. As can be seen from Fig.7 (a), when the helical pitch is shortened, Q_1 and Q_2 abruptly increase around P_1(S) = P_2(S) = 200 mm. This is because the tendency of rapidly increasing the loss works when the helical pitch becomes too short. Further, from Fig.7 (b), it can be seen that when the helical pitches are shortened, I_1 decreases and I_2 increases. Furthermore, when P_1(S) = P_2(S) = 600 mm, Q is about 0.1 W/m as shown in Fig.7 (a). When the helical pitches become infinite, that is REBCO tapes are aligned parallel to the cable length direction, the calculated loss is 0.07 W/m which is the minimum loss in this study.



(a) AC loss characteristic against P_1(S). (b) Layer current characteristic against P_1(S).

Fig.6 AC loss and layer current characteristics against P_1(S) when P_2(S) = 350 mm.



(a) AC loss characteristic against P_1(S) = P_2(S). (b) Layer current characteristic against P_1(S) = P_2(S).

Fig.7 AC loss and layer current characteristics against P_1(S) = P_2(S).

4. Summary

The calculated value of AC loss of two-layer REBCO superconducting cable obtained by 3D electromagnetic field analysis agreed with the experimental value of Furukawa Electric. In addition, the AC loss of the two-layer cable was calculated with P_1(S) = P_2(S), placing REBCO tapes on the tape-on-gap and aligning parallel to the cable length direction, Q is equal to 0.07 W/m at I_a/I_C = 0.7 which is the minimum loss in this study.

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References

[1] T. Yamaji, PHP Science World, pp21-23.
[2] G. Kawasaki and H. Noji, Proceedings of NUM 2016 (Viet Nam), 4 pages (2016).
[3] S. Mukoyama, M. Yagi, H. Hirano, et.al, Physica C 445–448 (2006) 1050–1053.
[4] K. Takeuchi, N. Amemiya, T. Nakamura, et.al, Supercond. Sci. Technol. 24 (2011) 085014.