AC loss calculation of REBCO superconducting cable-conductor by quasi-3D electromagnetic field analysis

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A calculation of AC losses of REBCO superconducting cable-conductor composed of two superconducting layers was conducted by quasi-three dimensional (3D) electromagnetic field analysis. A method of the analysis has been developed by our laboratory and is composed of a combination of an electric circuit model and 2D electromagnetic field analysis. A result of the analysis for two layers cable-conductors indicates that the calculation of AC loss is almost agreed with the measurement obtained by Furukawa Electric Co. Ltd. As reducing the loss, the cable-conductor is redesigned to obtain uniform layer current by optimizing helical pitches under conditions of same helical pitch and helical direction, and minimizing a relative position angle of REBCO tapes between the layers. The result shows that the calculation of the redesigned cable-conductor is about one order of magnitude smaller than the measurement.

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Key Words : *Superconducting calbe, REBCO tapes, AC loss, quasi-3D electromagnetic field analysis*

1. Introduction

Recently, an increase of electric energy demand by improving a convenience of life has been a problem in Japan. In particular, it is predicted that a power shortage is going to be occurred in large city, Tokyo. And it is at the same time, a global warming by CO_2 which can be emitted by thermal power plant etc. is also big social problem. A superconducting power cable is possible to solve these problems, because the cable can transmit large current compactly in comparing with a conventional copper cable and can reduce an alternating current (AC) loss significantly. In the copper cable, all of the electrical energy generated by the power plant don't reach the factories and houses because electrical resistance of copper cable loses some energy as a joule heat. In Japan, it has been calculated that about 5% of the transmission loss is occurring. In the superconducting cable, the electrical resistance is nearly equal to zero, and then it is possible to significantly reduce the power-transmission loss. If all of the copper cables has been exchanged by the superconducting cable, the loss of about 3.1 billion kW can be saved in this country. This electric energy is equivalent to the amount of power that 2.6 million people use in their life in a year.

In our laboratory, we have been studied for a practical use of the superconducting cable. Our aim is to design the superconducting cable with lower AC loss in conditions of higher transmission current and the same diameter of the copper cable.

2. Quasi-3D electromagnetic field analysis

So far, we have been used an electric circuit model to calculate the AC loss of the superconducting cable in our laboratory. In the model, the loss obtained by Norris equation [1] was used as a basis of the loss of a superconducting tape constructing the cable [2]. The model was made by considering an electromagnetic property in a direction of cable length and a current distribution in each superconducting layer in the cable can be calculated easily by the model. However, the electromagnetic property in a direction parallel to a cross section of the cable has been not considered in the model. In recent years, it was found by an electromagnetic field analysis of cross section that there is some cable structures reducing the loss [3-5]. Therefore, we made an analysis program of 2D electromagnetic field in cross section of the cable by a finite element method and developed the way to combine the program with the electric circuit model [6]. This new method is called quasi-3D electromagnetic field analysis. The 2D electromagnetic field analysis was performed by commercial software COMSOL. In this paper, we apply the quasi-3D electromagnetic field analysis to REBCO cable-conductors with two and three superconducting layers and show results of AC loss calculation for both cable conductors. These calculation are compared with the measurement obtained by Furukawa Electric Co., Ltd., and it is discussed an effectiveness of the calculation method.

2.1 2D electromagnetic field analysis

As mentioned above, the 2D electromagnetic field analysis was performed by the finite element method. By this method, an analysis object region is divided in mesh division and an electromagnetic field is calculated for each mesh division, and an analysis result of the whole region is obtained.

Figure 1 shows an appearance of superconducting AC cable [7]. In the cable, it consists of three cable-cores for conducting three-phase alternating current. The cross section of the cable core is described by 2D model, and the following governing equation is applied to the model:

$$\nabla \times E(J) = -\mu \frac{\partial H}{\partial t}, \quad (1)$$

$$\nabla \times \mathrm{H} = \mathrm{J}, \quad (2)$$

$$E = E_\mathrm{C} \left(\frac{J}{J_\mathrm{C}}\right)^n. \quad (3)$$

Equation (1) is Faraday's law of electromagnetic induction, and (2) is Ampere's law. Equation (3) is a relational expression between electric field E and current density J in superconductor, and an empirical formula (exponential law) is used for a resistivity of superconductor. Here, E_C is the critical electric field (= 1×10^{-4} V/m), and J_C is the critical current density. In addition, the following formula is used as a boundary condition:

$$\oint H \cdot dl = 2\pi H_\varphi = \sum I \rightarrow H_\varphi = \frac{\sum I}{2\pi r}. \quad (4)$$

Here, H_φ is a magnetic field tangential to the boundary. From the above equation, AC loss is obtained by using the following equation:

$$P = f \cdot \int_{\frac{1}{f}} dt \int_S E(J) \cdot J \; dS \qquad [\mathrm{Wm}^{-1}]. \quad (5)$$

Here, f is a frequency of AC transport current, usually $f = 50$ Hz.

Figure 2 shows a 2D model of two layers cable-conductor consisting of 32 REBCO tapes. Layer current flowing to each layer depend on a winding direction and a winding pitch of the REBCO tapes. The layer current can be calculated by the electric circuit model as described below and are incorporated into the 2D electromagnetic field analysis.

Fig. 1 Appearance of superconducting AC cable.

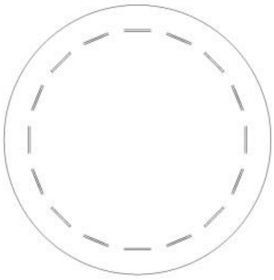


Fig. 2 2D model of two layers cable-conductor.

3. Analytical results of two layers cable-conductor

3.1 AC loss when the relative position angle is changed

AC losses were calculated for the cable cross - section model shown in Fig. 2. For the configuration parameters of the cable, it was referred which made to the two layers REBCO cable-conductor manufactured by Furukawa Electric Co., Ltd. [8]. Table 1 shows its parameters.

Table 1 Specifications of two layers cable-conductor.

Parameter name	Value
Tape width	4 mm
Tape thickness	0.1 mm
Thickness of superconductor	1 μm
Radius of former	16 mm
Radius of first layer's superconductor	16.099 mm
Radius of second layer's superconductor	16.349 mm
Number of tapes in first layer	16
Number of tapes in second layer	16
Critical current of tape	45.6 A

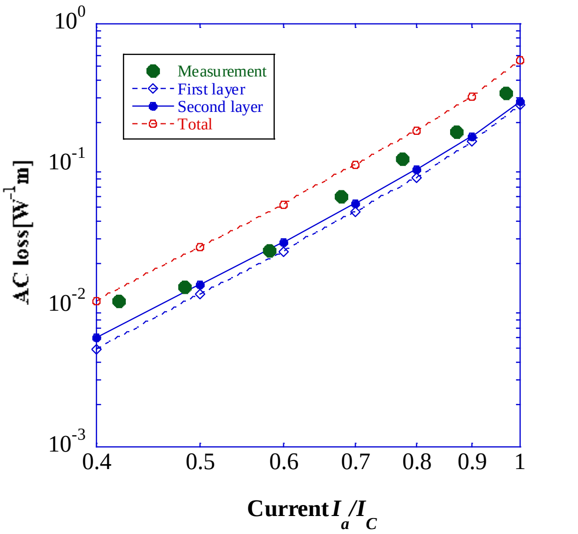


Fig. 4 AC loss characteristics of two layers cable-conductor with uniform layer current.

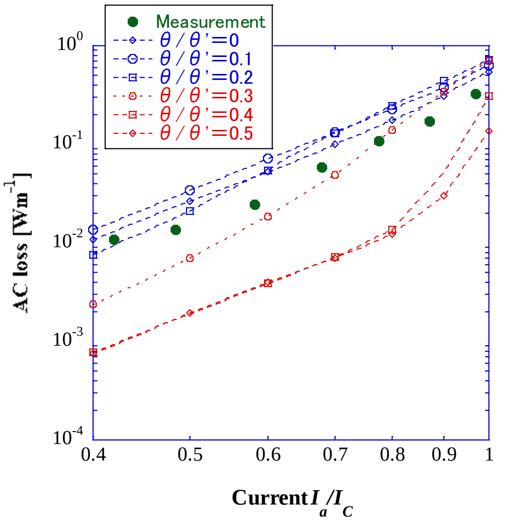


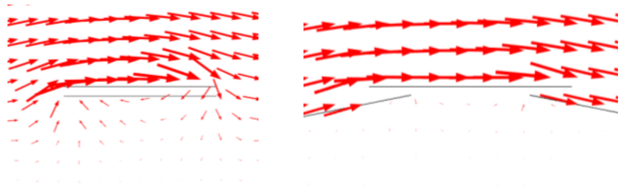
Fig. 6 AC loss characteristics of two layers cable-conductor with relative position angle changed

In the model shown in Fig. 2, the positon in the rotational direction of REBCO tapes of the first layer and the second layer, that is, the relative position overlaps (This is regarded as the relative position angle $\theta/\theta' = 0$). The change in the AC losses with respect to this relative position angle is calculated. Figure 5 is an explanatory diagram of the relative position angle. Assuming that the angle between adjacent REBCO tapes in the same layer is θ' and the angle between adjacent tapes in the first layer and the second layer is θ, the relative position angle is defined as θ/θ'. As shown in Fig. 5 (a), there is no deviation of the relative position angle ($\theta/\theta' = 0$). As shown in Fig. 5 (b), the relative position angle deviates the most ($\theta/\theta' = 0.5$).

Figure 6 shows the calculation of AC loss with respect to the normalized current I_a/I_C when the relative position angle θ/θ' is changed from 0 to 0.5. When the relative position angle θ/θ' exceeds 0.5 and approaches 1, the AC loss characteristic returns to the original deviation-zero state ($\theta/\theta' = 0$), so it is omitted here. The green real circle in Fig. 6 is the measurement of Furukawa Electric Co., Ltd. previously shown in Fig. 4. From this result, it can be seen that the AC loss decreases as the relative position angle θ/θ' increases. Figure 7 shows the

(a) $\theta/\theta'=0$ (b) $\theta/\theta'=0.5$

Fig. 5 Explanation of relative position angle.



(a) $\theta/\theta'=0$ (b) $\theta/\theta'=0.5$

Fig. 7 Magnetic field profile of cable cross section.

magnetic field profile of the cross section of the cable-conductor when the relative position angle θ/θ' is 0 and 0.5. As is clear from Fig. 7, when $\theta/\theta' = 0$, the perpendicular magnetic field (the magnetic field in the direction perpendicular to the tape surface) applied to the end portion of the superconducting tape is strengthened by the first layer and the second layer. When $\theta/\theta' = 0.5$, the perpendicular magnetic field is small and most of the magnetic field is applied parallel to the tape surface.

In superconducting tape, especially REBCO tape with extremely thin thickness d ($d = 1$ μm), it is known that the AC loss increases with the application of the perpendicular magnetic field and reducing the vertical magnetic field is most important in designing a cable having the minimum loss.

In an actual cable, since the winding direction and winding pitch of each layer are different, this relative position angle changes in the length direction of the cable. Then, AC loss was calculated in consideration of these directions and pitches.

3.2 Results of quasi-3D electromagnetic field analysis

The two layers REBCO cable-conductor manufactured by Furukawa Electric Co., Ltd. is reported as follows. In the winding direction, the first layer is the S direction and the second layer is the Z direction (winding in the opposite direction), the

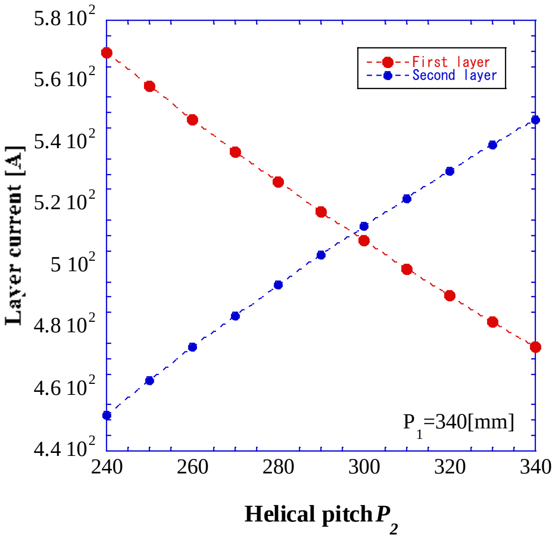


Fig. 9 Each layer current for cable-conductor designed with minimum loss.

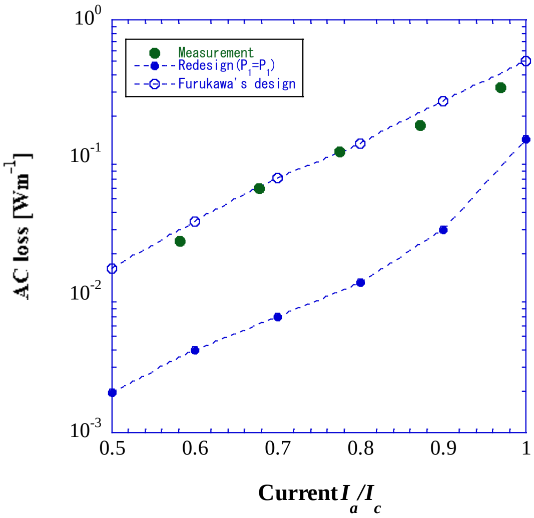


Fig. 10 AC loss characteristics by quasi three-dimensional electromagnetic field analysis.

winding pitch is $P_1 = 340$ mm for the first layer and $P_2 = 280$ mm for the second layer [8]. By using the electric circuit model, P_1 was fixed at $P_1 = 340$ mm and P_2 was changed in the vicinity of 280 mm to obtain the each layer current. Figure 8 shows the results. From this figure, it is found that the current is almost uniform around $P_2 = 280$ mm. In addition, From the results in Fig. 6, it can be seen that $\theta/\theta' = 0.5$ should be maintained anywhere in the length direction of the cable in order to design a cable having the minimum AC loss. In order to realize this, it is necessary to find the condition that the winding direction and the winding pitch of each layer are same and the current of each layer is uniform. Therefore, next, the winding direction was the same and the current of each layer was calculated under the condition of $P_1 = P_2$. The result is shown in Fig. 9. From this result, it was found that the current in each layer became substantially uniform in the vicinity of $P_1 = P_2 = 100$ mm.

In configuration parameters of the cable conductor fabricated by Furukawa Electric Co., Ltd., winding directions are opposite to each other and winding pitches are $P_1 = 340$ mm and $P_2 = 280$ mm. From these information, the layer current were calculated by the electric circuit nmodel and were substituted for 2D electromagnetic field analysis. Furthermore, since the relative position angle changes in the cable length direction due to the difference in winding direction and winding pitch, the AC loss distribution in the cable length direction was ocuured. The AC loss distribution was averaged over the 1 m section to find the average loss and compared with the measurement. The result is shown in Fig. 10. The green real circle is the measurement, and the blue white circle is the average loss. It is understood that the two values agree roughly. Furthermore, the AC loss when the cable configuration parameters were wound in the same way and $P_1 = P_2 = 100$ mm was calculated. The result is shown by a blue circle in Fig. 10. From this figure, it was found that by designing the cable configuration parameter having the minimum loss, the cable can reduce the loss by about one order of magnitude as compared with that produced by Furukawa Electric Co., Ltd.

4. Conclusion

It was confirmed that the calculation result of the AC loss by quasi-3D electromagnetic field analysis coincided with the measurement result for the two layer REBCO cable-conductor manufactured by Furukawa Electric Co., Ltd.

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