The analysis of the AC loss of the YBCO superconducting cable.

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In this study, a calculation method of the AC loss of the YBCO superconducting cable is suggested. The AC loss is calculated on the basis of an electric circuit model. A previous model is comprised of three circuit elements: resistance as a function of the layer current, inductances related to the circumferential field and the axial field. A new model is comprised of only inductances, and resistance is eliminated. The differences between a measurement and calculations using the previous model and the new model are 12 % and 16 % at transporting 1 kA_{rms}, which shows the new model is applicable to calculate the AC loss. Moreover, a calculation time has shortened one-twentieth by the new model in comparison with the time using the previous model.

Keywords: Superconducting cable, AC loss, Electric circuit model.

1. Introduction

A shortage of power supply is predicted in the metropolis due to the increasing demand for convenience. Global warming is also a serious issue due to CO_2 emissions from thermal power plants. Therefore, the superconducting power transmission cable (superconducting cable) is desired to be put to practical use as soon as possible because it can decrease an AC loss compared with the conventional cable. Using the superconducting cable in the duct of the conventional cable, it enables to solve the shortage of power supply economically because the superconducting cable makes it possible to transmit high-capacity electricity in a small space. It is also possible to reduce emissions of CO_2 without wasting generated power.

The superconducting cable composed of YBCO tapes is shown in Fig.2. Decreasing the AC loss is necessary to realize the superconducting cable. It is for that purpose that the AC loss is to be calculated numerically using parameters of composition of the superconducting cable. The AC loss is calculated to analyse currents distributions in the cable conductor. In the superconducting cable, big currents flow in the outer layer by skin effect. This phenomenon is called drift. This drift is known to increase the AC loss. Helically arranging each layer of the superconducting tapes which comprised the superconducting cable and then adjusting helical pitch to restrain drift currents, current is distributed uniformly to decrease the AC loss.

The previous method of analysis of currents distributions in the superconducting cable was done by an equivalent circuit (shown in Fig. 2). This equivalent

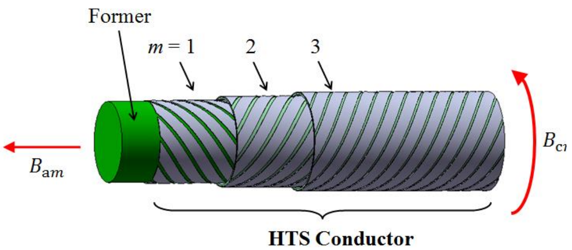

Fig. 1. Structure of the superconducting cable

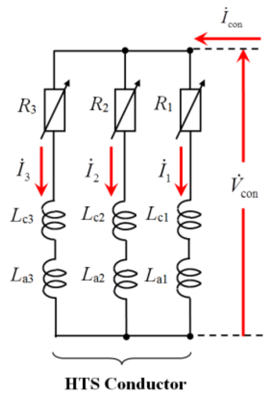

Fig. 2. Previous EC model

circuit is called Electric Circuit model (EC model). The previous EC model is comprised of three circuit elements: resistance as a function of the layer current R_m, inductances related to the circumferential field B_{cm} and the axial field B_{am} (shown in Fig. 2). Simultaneous equations of the voltage generated in the superconducting cable are Eq. (1) and (2). These simultaneous equations were calculated repeatedly until the current values of each layer are to converge. And then the AC loss was calculated. These Eq. (1) and (2) are a case of three layers.

$$\dot{V}_{\text{con}} = \{R_m + j\omega(L_{\text{am}} + L_{cm})\}\dot{I}_m + j\omega \sum_{l=1}^{3}(M_{\text{am}l} + M_{\text{cm}l})\dot{I}_l ,$$
$$m = 1-3, l = 1-3, m \neq l, \text{and } \omega = 2\pi f \quad (1)$$
$$\dot{I}_{\text{con}} = \sum_{m=1}^{3} \dot{I}_m \quad (2)$$
This method, however, requires a long time because of repeating calculation. Also, it shouldn't be possible to represent voltage drop at the superconducting cable by using a complex number like Eq. (1) because it is a nonlinear. In this thesis, a calculation method using the EC model with three devices is called the previous method.

In this study, a new calculation method of the AC loss is suggested. This new method uses a new EC model which is comprised of only inductances, and resistance is eliminated. By the new method, the AC loss was calculated quickly and easily without the convergence calculation. Using this new model, the AC loss is calculated and the structure of the superconducting cable which has the minimum AC loss was determined.

2. Calculation method

The AC loss is calculated by using MATLAB which is a numerical analysis software. A result of calculation using the new model is compared with a result of calculation using the previous model and measurement of the AC loss. And the optimum helical pitches of the superconducting tapes with the minimum AC loss are calculated using the new model.

2.1 Calculation method of the AC loss

The new EC model is shown in Fig. 3. The new EC model comprises the inductances related to the circumferential field B_{cm} and the axial field B_{cm}, and the resistance as a function of the layer current R_m is eliminated. Using this new model, the AC loss was calculated shortly without the convergence calculation. This calculation method is called the new method.

The new method is shown below. The EC model shown in Fig. 3 comprises the self-inductance and the mutual-inductance. In this study, equations of the self-inductances related to the axial field L_{am} (m=1-3) and the mutual-inductance related to the axial field M_{aml} (l=1-3) are given below.
$$L_{\text{am}} = \mu_0 \pi \frac{{r_m}^2}{{p_m}^2} \quad (3)$$
$$M_{\text{am}l} = D_m D_l \mu_0 \pi \frac{(\min\{r_m, r_l\})^2}{p_m p_l} \quad (4)$$
In the equation, p_m and r_m are the helical pitch and the radius at m layer. p_l and r_l are the helical pitch and the radius at l layer. The helical pitch is the length of the axial direction of a conductor when the superconducting tape is coiled once around the former. D_m and D_l in Eq. (4) is the factor of the helical direction when S wind is 1

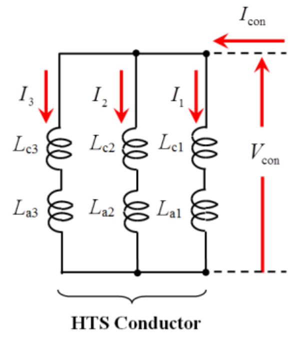

Fig. 3. New EC model

and Z wind is -1. In Fig. 1, layer 1 is S wind, layer 2 and 3 are Z wind. μ_0 is the permeability in vacuum.

Equations of the self-inductances related to the circumferential field L_{cm} and the mutual-inductance related to the circumferential field M_{cml} are given below.
$$L_{cm} = \frac{\mu_0}{2\pi} \ln\left(\frac{r_s}{r_m}\right) \quad (5)$$
$$M_{cml} = \frac{\mu_0}{2\pi} \ln\left(\frac{r_s}{\max\{r_m, r_l\}}\right) \quad (6)$$
Here, r_s is the radius of the virtual magnetic field on the calculation. A simultaneous equation of the voltage generated V_{con} in the superconducting cable and the layer current I_m is given by Eq. (3) to (6).
$$V_{\text{con}} = \omega(L_{am} + L_{\text{cm}})I_m + \omega \sum_{l=1}^{3}(M_{\text{am}l} + M_{\text{cm}l})I_l ,$$
$$m = 1-3, m \neq l, \text{and } \omega = 2\pi f \quad (7)$$
$$I_{\text{con}} = \sum_{m=1}^{3} I_m \quad (8)$$
Here, I_{con} is the rms value of the transmission current. The layer current is calculated by the simultaneous equations (7) and (8). The value of the normalized current value flowing in the superconducting tape is shown in Eq. (9).
$$i_m = \sqrt{2} I_m / (N_m I_{\text{C}}) \quad (9)$$
When the superconducting cable comprises the YBCO superconducting tapes, the AC loss generated in one superconducting tape P_m is calculated by Eq. (10).
$$P_m = \frac{{I_{\text{C}}}^2 \mu_0 f}{\pi}\{(1-i_m)\ln(1-i_m) + (1+i_m)\ln(1+i_m) - {i_m}^2\} \quad (10)$$
In the equation, f is frequency of a power source. When the AC loss is influenced by interaction between superconducting tapes which comprise the superconducting cable, the AC loss generated in one superconducting tape P_m is calculated using the finite element method.

The generated AC loss of a superconducting cable P is calculated by Eq. (11).
$$P = \sum_{m=1}^{3} N_m P_m \quad (11)$$

2.2 The design method of the superconducting cable with a minimum AC loss

Configuration parameters are a radius of each layer r_m, the number of the superconducting tapes of each layer, directions of the superconducting tapes and helical pitch p_m of the superconducting tapes. r_m and N_m

are determined by the environment that are used. But the directions of the superconducting tapes and helical pitch p_m can be changed freely by the designer of the superconducting cable. The transmission current needs to be determined first because the optimum helical pitch depends on the transmission current. In this study, the transmission current is 1 kA_{rms}. There are four combinations of helical directions (SZZ, SSZ, SZS and SSS) at three-layered superconducting cable. The minimum helical pitch of layer m is given in Eq. (12).

$$p_{m\,\min} = \frac{4r_m}{\sqrt{\left(\frac{2\pi r_m}{N_m w_{id}}\right)^2 - 1}} \qquad (12)$$

Here, w_{id} is the width of the superconducting tape. The optimum helical pitch, which can be obtain a minimum AC loss, is decided by changing $p_{m\,\min}$ to $p_{m\,\min}+2$ [m] in increments of 5 mm at all combinations of SZZ, SSZ, SZS and SSS.

3. Study result

3.1 AC loss

The AC losses for the transmission currents are shown in Fig. 4. A solid line is the calculation result using the new method and a broken line is the calculation result using the previous method. In Fig. 4, circle marks are the result of measurement of Amemiya's cable, using a four-terminal method. The cable was made by Professor Amemiya's group at Yokohama National University. And also square marks are the result of measurement of Doctor Mukoyama's cable which was made by Mukoyama's group at Furukawa Electric Co., Ltd., using the four-terminal method. Amemiya's cable and Mukoyama's cable comprise the same YBCO superconducting tapes and they also consist of the same parameters of composition expect for the arrangement of the superconducting tapes on the former. For Amemiya's cable, the superconducting tapes are arranged parallel to the axis of cable. In this cable, each layer is connected in series so uniform currents are flown in the all layers. On the other hand, for Mukoyama's cable, the superconducting tapes are arranged in the helical on the former. The helical direction and the helical pitch of each layer aren't published.

The results of the measurement of AC losses of Amemiya's cable and Mukoyama's cable match. These results suggest that the superconducting tapes are arranged in the helical on the former, so the all the layers of transmission currents become uniform.

The result of measurement of Mukoyama's cable and the result of a calculation of the previous method (shown as the broken line) are matched qualitatively. But at 1 kA_{rms} of a transmission current, these values are different quantitatively by 12 %. It means that there is still room for improvement in the previous method. The results of a calculation and a measurement are substantially equal by using complex numbers, even though the relationship between voltage and current is a nonlinear.

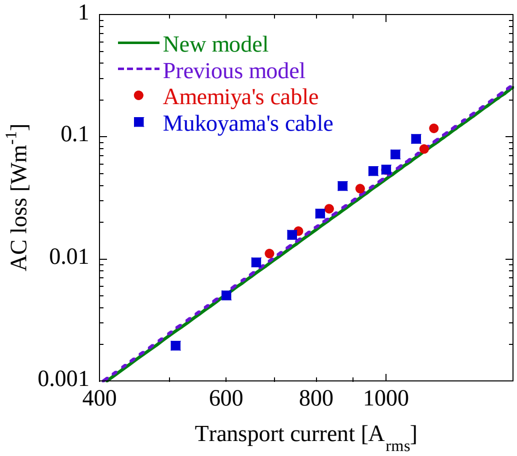

Fig. 4. The AC loss of the transmission currents

Table 1 Resistance R_m and Reactance X_{L_m}

Layer m	Helical Pitch p_m [m]	Resistance R_m[Ω]	Reactance X_{L_m} [Ω]
1	1.384	1.47E-07	7.82E-05
2	0.707	1.42E-07	7.62E-05
3	0.112	1.38E-07	8.07E-05

It is believed that the resistance R_m is sufficiently smaller than the reactance $X_{\mathrm{L}m}$, Eq. (13).

$$X_{L_m} = \omega(L_{am} + L_{cm}) \qquad (13)$$

The values of R_m and $X_{\mathrm{L}m}$ are shown in Table 1 at the optimum pitch. R_m is less than 1/500 of $X_{\mathrm{L}m}$.

The result of the measurement of Mukoyama's cable and the result of the calculation of the new method (shown as the solid line) match qualitatively. But at 1 kA_{rms} transmission current, these values are different quantitatively by 16 %. It means that there is still room for improvement in the new method. The cause of this difference is believed that the AC loss of one superconducting tape was calculated by Norris expression for a thin strip Eq. (10). This Norris expression for a thin strip can be used for a single isolated superconducting tape.

The superconducting tapes are arranged adjacently at the superconducting cable, and thus the interaction between each superconducting tape needs considering. The AC loss is calculated by using the finite element method to analyse the magnetic field distribution. The AC loss can be calculated more exactly by using the EC model to analyse currents distributions of each layer and using the finite element method to analyse the AC loss of each superconducting tape.

The time of a calculation is discussed below. In the previous method, the convergent calculation of the simultaneous equations, Eq. (1) and (2), is needed to determine the layer current I_m because the resistance as a function of the layer current. On the other hand, the new model can be shortened the time to calculate because the layer current I_m is determined by solving the simultaneous equations Eq. (7) and (8) once. When the loop calculation was run 100 times to calculate the optimum pitch, the new method analysis was completed 1/20 of running time of the previous method. It is important to shorten the time to calculate when analysing the AC loss using the finite element method. It takes a longer time to use the finite element method to calculate accurately by using a number of meshes. Therefore, shortening the time of calculating the AC loss by using the new method, it is also possible to shorten the time of calculation drastically when adopting the finite element method in to the EC model.

3.2 Structure of the superconducting cable

Table 2 shows the calculated values of the minimum AC losses and the optimum pitches. From Table 2, it is clear that the AC loss can decrease when the helical directions are SZZ, ZZS and SSS. But the AC loss with the helical directions of SZS can't decrease. Fig. 5 shows the current distributions of each layer when the helical directions are SZZ and SZS. The current distributions of each layer are uniform when the helical directions are SZZ. However, it also shows that a large current flows in the outer layer and a drift current has occurred when the helical directions are SZS. Fig. 6 shows the reactance X_{Lm} of SZZ and SZS. The reactance X_{Lm} is calculated by Eq. (13). The reactance of SZZ is large at the outer layer but the reactance of SZS is small there. At SZS, a large current flows in the outer layer because the reactance is smaller in the outer layer, so it can't make currents of the all layers even. Therefore, the AC loss couldn't be uniform at SZS.

4. Conclusion

In this study, eliminating the resistance R_m from the previous calculation method, the new calculation method is suggested. The results of calculations using the previous method and the new method are substantially equal. The process of calculation of the new method is simple because it doesn't include a repeat calculation. Therefore, it can be easily calculated when adopting the finite element method in to the EC model.

In the future, the AC loss needs analysing in consideration of the interaction between the superconducting tapes using the EC model with the finite element method because the results of calculation using the previous method and the new method have quantity errors.

Table 2 AC loss and optimum pitch

Helical direction	AC loss [Wm^{-1}]	p_1 [m]	p_2 [m]	p_3 [m]
SZZ	0.0452	0.809	0.947	0.112
SZS	0.225	0.069	0.072	0.077
ZZS	0.0452	0.114	0.522	0.077
SSS	0.0452	0.839	0.367	0.117

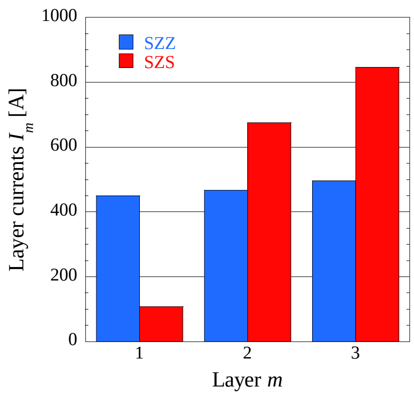

Fig. 5. Current distribution of SZZ and SZS

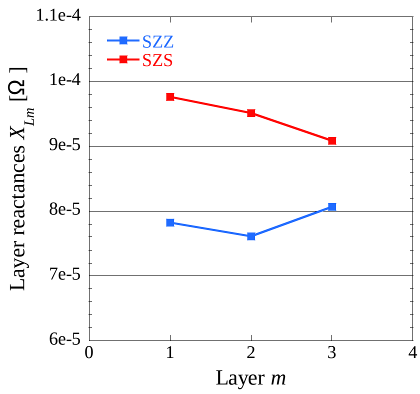

Fig. 6. Reactance of SZZ and SZS

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