Calculating AC losses in high-temperature superconducting cables comprising coated conductors

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Abstract

In this study, we present a new calculation model of AC loss in a high-temperature superconducting (HTS) cable comprising coated conductors. AC loss is calculated by an electric circuit (EC) model. A previous EC model had three circuit elements: resistance as a function of the layer current, inductances related to the circumferential and axial fields. The new EC model has only inductances, and resistance is eliminated. In both models, AC loss of the coated conductor in each layer of an HTS cable is calculated on the basis of the Norris equation for a thin strip. The differences between measurement and calculations using the previous and new models are 12% and 14%, respectively, when transporting 1 kA rms, which indicates that the new model is applicable for the calculation of AC loss in an HTS cable. These results indicate that layer current is dependent on inductances and not on resistance. The elimination of resistance simplifies AC loss calculation because it does not require repeated calculations for the convergence of the layer current. The calculation time was 1/20th of that of the previous model. In the new model, the Norris equation can be replaced with the calculation result obtained by the two-dimensional finite element method to obtain more accurate AC loss.

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Keywords: AC loss; Power transmission cable; Coated conductor; High-temperature superconductor; Electric circuit model

1. Introduction

HTS cables have been developed to transmit more power than conventional cables with low transmission loss and no electromagnetic emission. They also contribute to solving grid congestion problems in underground power
tunnels due to their compact form and low weight. However, AC loss occurs in HTS cables, which reduces the effectiveness of the power transfer system. Therefore, the study and reduction of AC loss in HTS cables is very important. The authors have previously reported the calculation of AC loss by an EC model and have demonstrated that the calculations are approximately equal to the measurements [1,2]. Moreover, the authors have also reported that the optimum helical pitches at the optimum helical directions can be calculated by the EC model to obtain the minimum AC loss. The EC model comprised three elements: resistance, and inductances caused by the axial and circumferential fields. Resistance is calculated on the basis of the Norris equation for a thin strip [3] and depends on the layer current. The Norris equation is applicable for an isolated single strip. The AC loss of a coated conductor in a monolayer cable is decreased when compared with that of a single isolated strip. The loss in an isolated coated conductor is primarily due to a perpendicular field, which is reduced in the gap between the strips [4-6]. The AC loss, including the interaction of coated conductors in an HTS cable, is calculated by the two-dimensional finite element method (2D FEM). Therefore, replacing the Norris equation with 2D FEM in the EC model is desirable for accurate calculation of AC loss in HTS cables. However, repeated calculations are required for the convergence of resistance. Therefore, calculation is very difficult using an EC model that includes 2D FEM because the calculation time to obtain a convergence of resistance increases remarkably. In the EC model, the resistance is not high in comparison to the reactance. Thus, the authors believed that omitting the resistance may eliminate the need for repeated calculations. In this paper, we present a new EC model that comprises only inductances and demonstrate the calculation method for AC loss using the new model. In addition, values calculated by the previous model are compared with the results of the new model. We also demonstrate that the new model calculates AC loss more quickly and easily.

2. Calculation

Figure 1 shows a schematic diagram of the structure of an HTS cable comprising coated conductors. The authors refer to the HTS cables studied by Mukoyama et al. of the Furukawa Electric Co., Ltd [7]. The length of the HTS model cable was 0.3 m. Each coated conductor was divided into 5 strips by laser processing, and the HTS layers comprised 85 strips. In Fig. 1, the helical directions of the second and third layers are drawn opposite to that of the first layer. The helical directions are the author’s assumption because the cable’s construction, including the helical direction and helical pitch, has not been disclosed. Table 1 shows the specifications of Mukoyama’s cable.

Figure 2 shows the new EC model for the HTS cable in which the current-dependent resistance of the HTS layers is eliminated. The coated conductors are helically wound on the G-FRP former for the construction of HTS layers. Therefore, the direction of layer current passing through each HTS layer is divided into an axial part and a circumferential part. The axial part of the layer current causes the circumferential field, while the circumferential part causes the axial field. The equation for the self-inductance and mutual inductance related to the field and the transport current , and are described elsewhere [1,2]. As shown in Fig. 2, the voltage per unit length, and is the transport current. The equation for the voltage and transport current are described elsewhere [1,2].

The resistance was a real value, while the reactance and were imaginary values. Thus, the voltage and layer current became complex values and . To solve and , repeated calculations were required for the convergence of resistance. In the new EC model, repeated calculations are not required, and...
Table 1. Specifications of Mukoyama’s cable [7]

| Layer number | Inner diameter | Tape numbers | Critical current | Calculated helical pitch |
|--------------|----------------|--------------|------------------|------------------------|
| 1            | 17.3           | 27           | 699              | 2.104 (S)              |
| 2            | 17.9           | 28           | 705              | 0.699 (Z)              |
| 3            | 19.2           | 30           | 778              | 0.121 (Z)              |

The simultaneous equations are easily solved by one calculation. Therefore, the calculation time is reduced by the new model.

The AC loss of a single isolated coated-conductor is estimated by the Norris equation for thin strips [3]. The self-field loss calculated by Norris equation is restricted at \( i_m < 1 \). Rather than using Norris equation, the self-field loss is approximated by applying the least-squares method (see the approximated equation of the self-field loss \( P_{NSm} \) in Ref. 1,2). The calculated self-field loss of a coated conductor in polygonal assemblies is reported to be smaller than that of a single isolated strip when calculated by the Norris equation [4-6]. However, as was observed in the experiment described in Section 3, the losses do not differ greatly. Therefore, the approximated equation of \( P_{NSm} \) would be acceptable for calculating the losses of the strip comprising HTS layers. Rather than using the Norris equation, the loss, including the interaction of adjacent coated-conductors in an HTS cable, can be calculated by 2D FEM. To calculate the loss using the EC model more accurately, replacing the approximated equation of \( P_{NSm} \) with the result of 2D FEM is desirable, which will be the focus of a future study. The self-field loss of the HTS model cable \( P_{EC} \) is obtained by the summation of \( N_m P_{NSm} \), where \( N_m \) is the number of strips comprising the HTS layers.

3. Results and discussion

The measurement results of the two types of three-layer cables have been reported by Amemiya et al. [4]. Here, only the results of cable 3C-A are discussed. This cable has the same parameters as that studied by Mukoyama et al. [7]. The specifications of Mukoyama’s cable are shown in Table 1. The helical direction and helical pitch of each layer have not been published. The values shown in Table 1 are the optimum values obtained by our calculation. In Amemiya’s cable, the coated conductors constituting each layer were arranged parallel to the cable axis, whereas in Mukoyama’s cable, the coated conductors were twisted helically on the former. Amemiya et al. ensured that the current passing through each layer was uniform by connecting each layer in series and measuring the loss. On the other hand, Mukoyama et al. produced uniform current through each layer by optimizing the helical pitch of each layer and measuring the loss. The variation in loss as a function of the transport current of Mukoyama’s cable is shown in Fig. 3. The solid circles are the measurement results of Mukoyama’s cable. The measurement results of Amemiya’s cable are approximately equal to those of Mukoyama’s cable. Therefore, we can deduce that Mukoyama’s cable design successfully fed a uniform current through each layer.

The optimum helical pitches of Mukoyama’s cable are calculated on the basis of the EC model (Table 1). The helical pitch of each layer is a measurable value in engineering. The symbols S and Z of the helical pitch denote the difference in the direction of winding of the coated conductors. In Fig. 3, the solid line is the calculation results of the new method, and the broken line is the results of the previous method. The measurement results of Mukoyama’s cable and the calculation results of the previous method match qualitatively. However, at 1 kA, transport current, these values differ quantitatively by 12%. The results of calculation and measurement are substantially equal by using a complex number in the previous method even though the relationship between voltage and current is nonlinear. The authors believe that the resistance \( R_m \) is sufficiently smaller than the reactance \( X_{lm} \), which is described by \( \omega L_m + L_{cm} \). \( R_m \) is less than 1/500 of \( X_{lm} \). Thus, the authors consider that \( R_m \) can be eliminated from the EC model.

The measurement results of Mukoyama’s cable and the calculation results of the new method match qualitatively. However, at 1 kA, transport current, these values differ quantitatively by 14%. This indicates that the new method can be further improved. This difference may be caused by the fact that the AC loss of one coated conductor was calculated by the Norris equation for a thin strip. The Norris equation can be used for a single isolated coated-conductor. The coated conductors are arranged adjacently in an HTS cable; thus, the interaction between each coated conductor must be considered.
The time for a single calculation is discussed below. In the previous method, the convergent calculation of the simultaneous equations for voltage and current was required to determine the layer current $I_m$ because the resistance was a function of the layer current $R_m(I_m)$. The new model can shorten the calculation time because $I_m$ is determined by solving the simultaneous equations, only once. When the calculation loop was run 100 times to calculate the optimum pitch, the new method analysis took 1/20 of the running time of the previous method. It is important to shorten the calculation time when analysing AC loss using 2D FEM. 2D FEM takes significantly more time to accurately calculate using several meshes. Therefore, by shortening the AC loss calculation time using the new method, it is also possible to shorten the calculation time drastically when adopting 2D FEM in the EC model.

4. Conclusions

In this study, a new calculation method that eliminates the resistance $R_m$ from the previous calculation method is suggested. The calculation results of the previous and new methods are substantially equal. Comparing the calculations with the measurement obtained in Mukoyama’s cable, the differences are 12% for the previous method and 14% for the new method when transporting 1 kA$_{rms}$. The calculation process of the new method is simple; it does not require repeated calculations. For example, when running the calculation loop 100 times to obtain the optimum helical pitch, the new method took 1/20 of the running time of the previous method. Therefore, calculation can be easily performed when adopting 2D FEM into the EC model. In future, AC loss should be analysed by considering the interaction between the coated conductors when using the EC model with 2D FEM.

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