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

Department of Electrical and Computer Engineering, Miyakonojo National College of Technology, Miyakonojo 885–8567, Japan

Hideki Noji, Shouta Kawano, Yoji Akaki, Tsugio Hamada

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.

Structure of HTS cable conductor

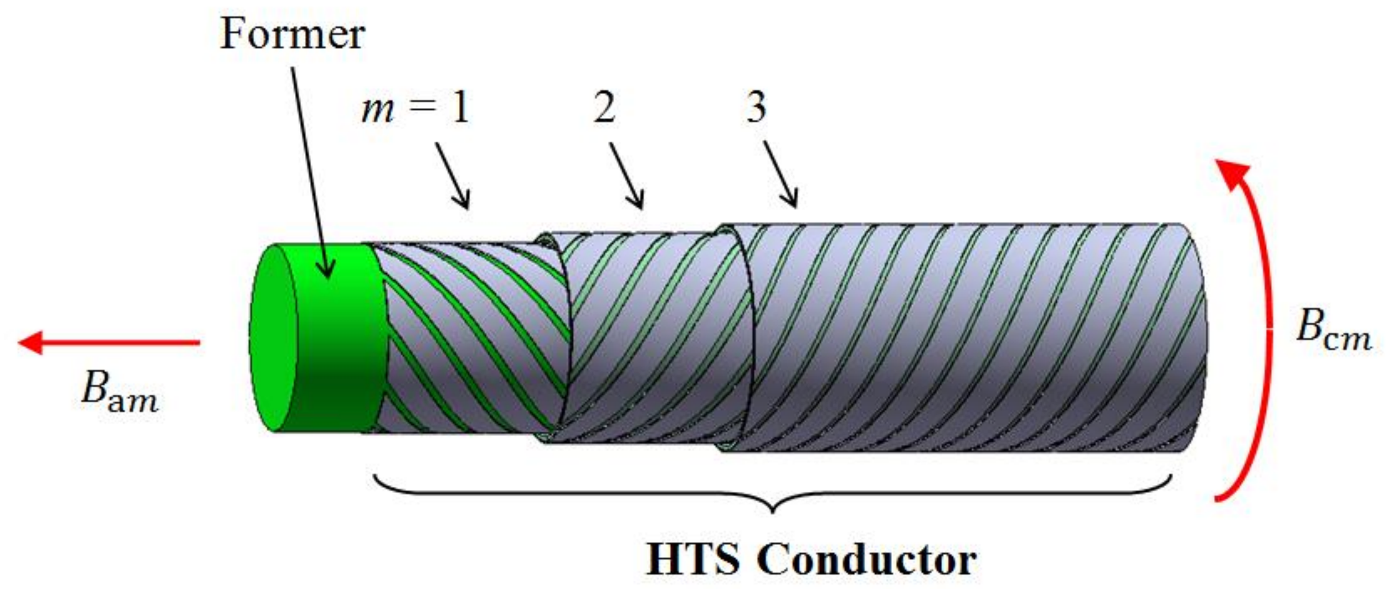


Fig.1 Structure of HTS cable conductor

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 [1]. 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.

[1] S. Mukoyama, M. Yagi, N. Hirano, N. Amemiya, N. Kashima, S. Nagaya, T. Izumi, Y. Shiohara, Physica C 463—465 (2007) 1150—1153.

Previous EC model

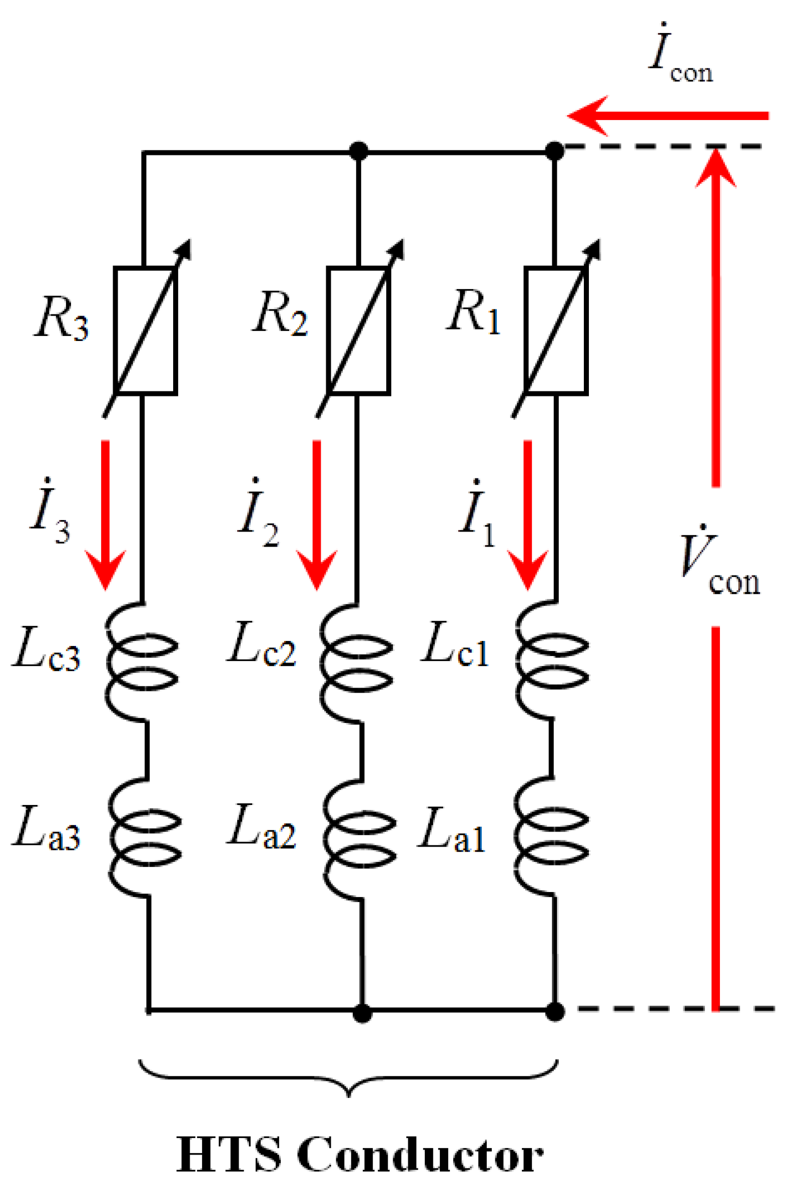


Fig.2 Previous EC model

R_m : Resistance as a function of layer current

L_{cm}, M_{cm} : Inductances caused by circumferential field

L_{am}, M_{am} : Inductances caused by axial field

$$\dot{V}_{con} = \{R_m + j\omega(L_{am} + L_{cm})\}\dot{I}_m + j\omega\sum_{l=1}^{3}(M_{aml} + M_{cml})\dot{I}_l \ ,$$

$$m = 1-3, l = 1-3, m \neq l, \text{and } \omega = 2\pi f$$

$$\dot{I}_{con} = \sum_{m=1}^{3}\dot{I}_m$$

The repeat calculations to get a convergence of resistance are required.

New EC model

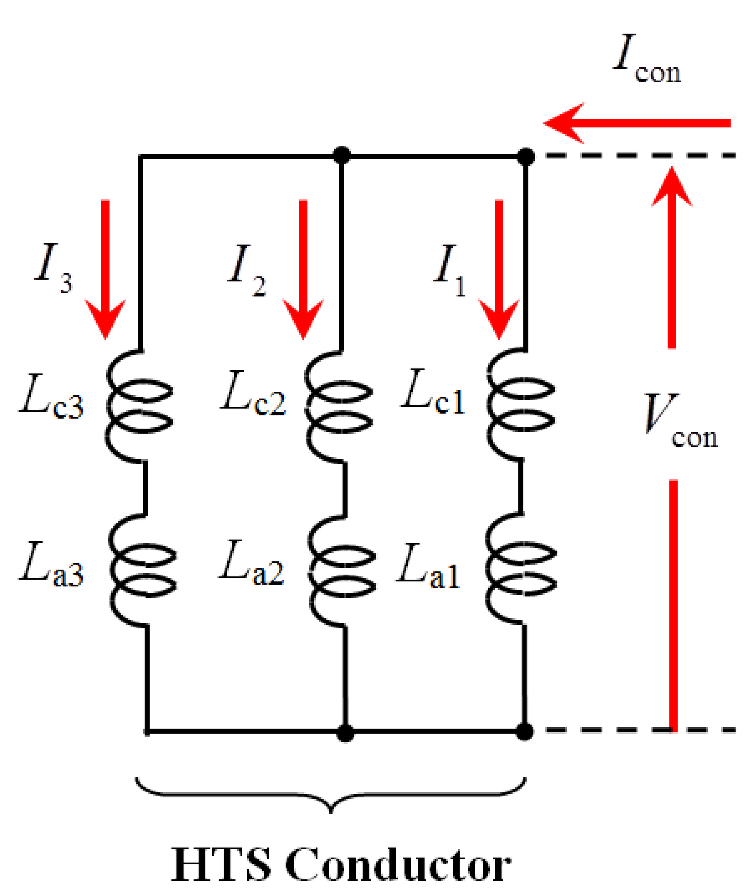


Fig.3 New EC model

$$V_{con} = \omega(L_{am} + L_{cm})I_m + \omega\sum_{l=1}^{3}(M_{aml} + M_{cml})I_l \ ,$$

$$m = 1-3, l = 1-3, m \neq l, \text{and } \omega = 2\pi f$$

$$I_{con} = \sum_{m=1}^{3}I_m$$

The layer current are obtained by solving one simultaneous equations. Using the layer current, AC loss of each layer in HTS cable conductor is obtained by Norris equation for thin strip.

Normalized current i_m $\quad i_m = \frac{\sqrt{2}I_m}{(N_m I_C)}$

Norris equation for thin strip

$$P_m = \frac{{I_C}^2\mu_0 f}{\pi}\{(1-i_m)\ln(1-i_m) + (1+i_m)\ln(1+i_m) - {i_m}^2\}$$

1. Calculation of AC losses

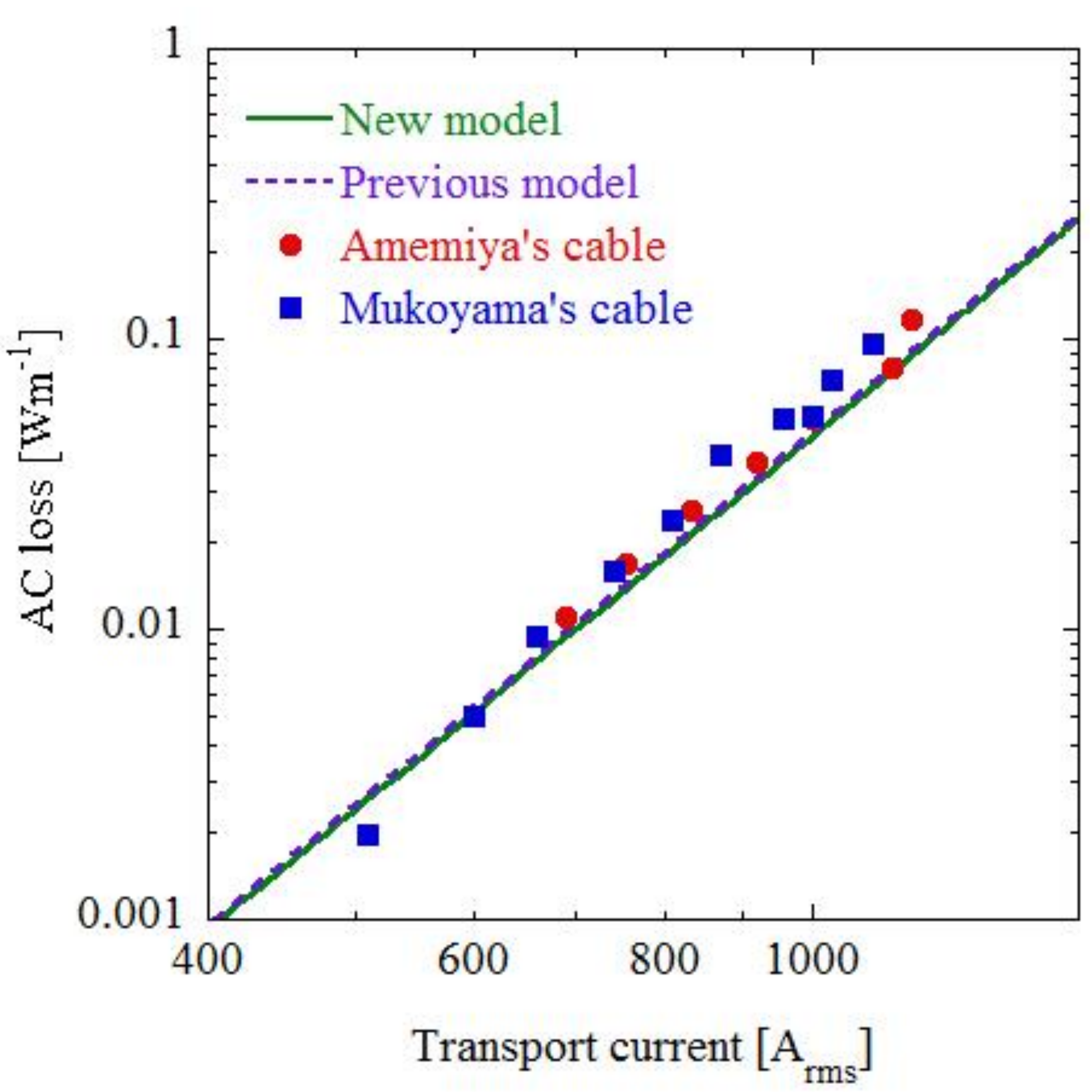


Fig.4 AC losses as a function of transport current for the HTS cable

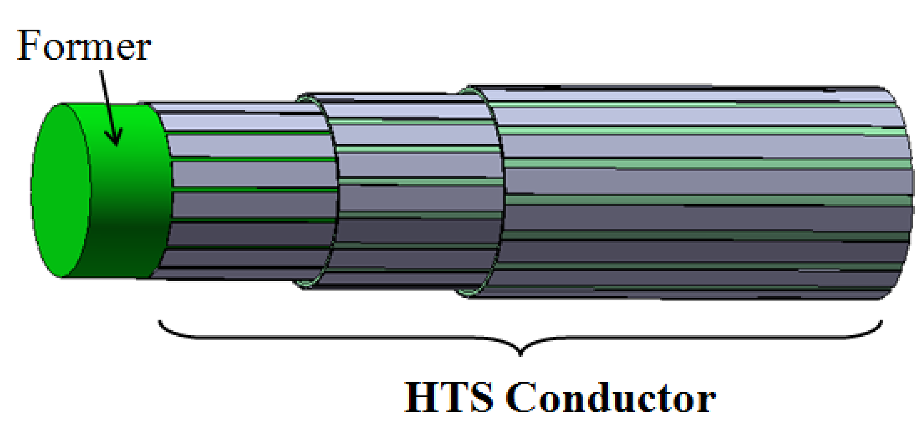


Fig.5 Amemiya's cable

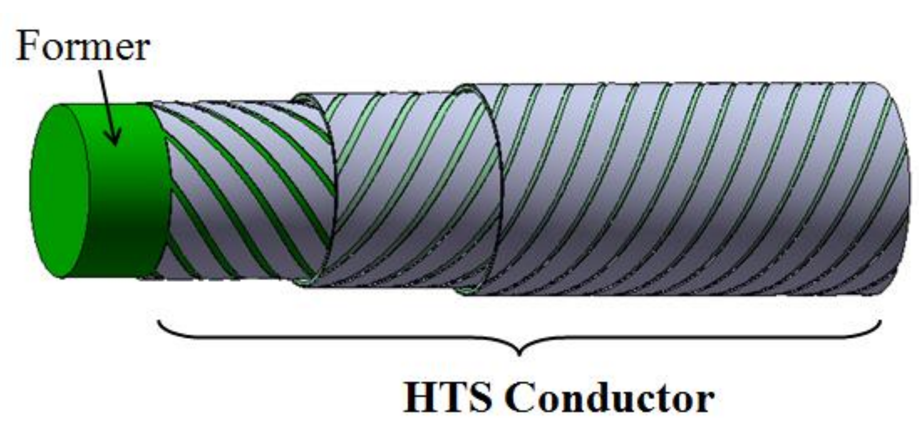


Fig.6 Mukoyama's Cable

Amemiya's and Mukoyama's cables have the same parameters [1, 2]. The specifications of the two cables are shown in Table 1. In Amemiya's cable, the HTS tapes constituting each layer were arranged parallel to the cable axis, whereas in Mukoyama's cable, the HTS tapes 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. made the current through each layer uniform by optimizing the helical pitch of each layer and measuring the loss.

[2] N. Amemiya, Z. Jiang, M. Nakahata, M. Yagi, S. Mukoyama, N. Kashima, S. 309 Nagaya, Y. Shiohara, IEEE Trans. Appl. Supercond. 17 (2007) 1712.

In Figure 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_{rms} 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 below.

$X_{Lm} = \omega(L_{am} + L_{cm})$ (Ω).

The values of R_m and X_{Lm} are shown in Table 2 for the optimum pitches in the previous method. R_m is less than 1/500 of X_{Lm}. Thus, the authors consider that R_m can be eliminated from the EC model.

Table 2 Resistance R_m and reactance X_{Lm} in the previous EC model

Layer m	Helical Pitch p_m [m]	Resistance R_m [Ω]	Reactance X_{Lm} [Ω]
1	1.384	1.471×10^{-7}	7.82×10^{-5}
2	0.707	1.42×10^{-7}	7.62×10^{-5}
3	0.112	1.38×10^{-7}	8.07×10^{-5}

Table 1 Specifications of two cables

Cable name	Amemiya's cable	Mukoyama's cable
Outer diameter	19.6 mm	19.6 mm
Inner diameter of layer 1 $2r_1$	17.3 mm	17.3 mm
Inner diameter of layer 2 $2r_2$	17.9 mm	17.9 mm
Inner diameter of layer 3 $2r_3$	19.2 mm	19.2 mm
Tape number of layer 1 N_1	27	27
Tape number of layer 2 N_2	28	28
Tape number of layer 3 N_3	30	30
Critical current of layer 1 I_{C1}	699 A	699 A
Critical current of layer 2 I_{C2}	705 A	705 A
Critical current of layer 3 I_{C3}	778 A	778 A
Calculated helical-pitch of layer 1 p_1	Not helical	865 mm (S)
Calculated helical-pitch of layer 2 p_2	Not helical	125 mm (Z)
Calculated helical-pitch of layer 3 p_3	Not helical	150 mm (S)

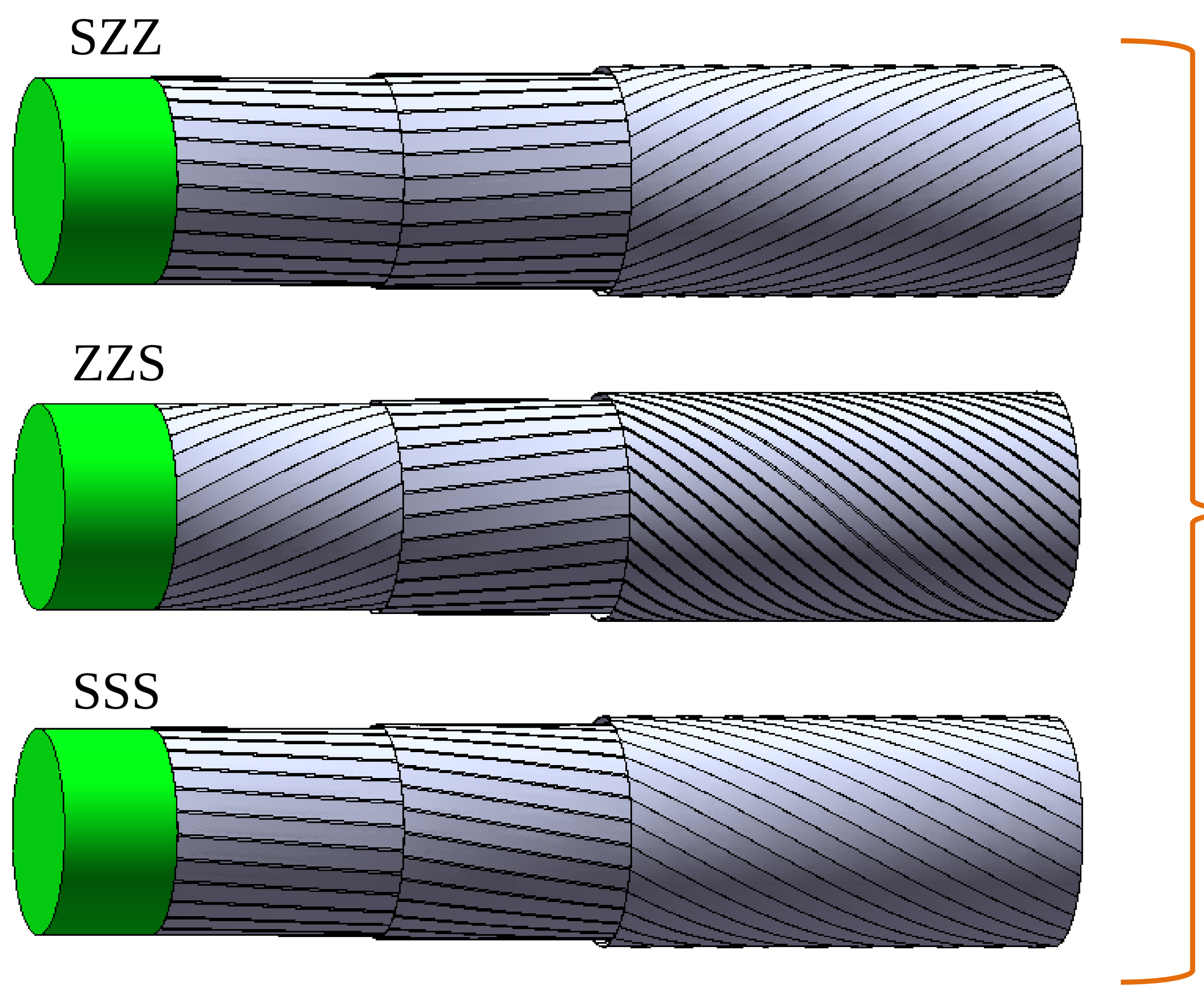
The measurement results of Mukoyama's cable and the calculation results of the new method match qualitatively. However, at 1 kA_{rms} transport current, these values differ quantitatively by 14%. This indicates that the new method can be further improved. This difference may be caused by the fact that 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.

2. Design of HTS cable conductors

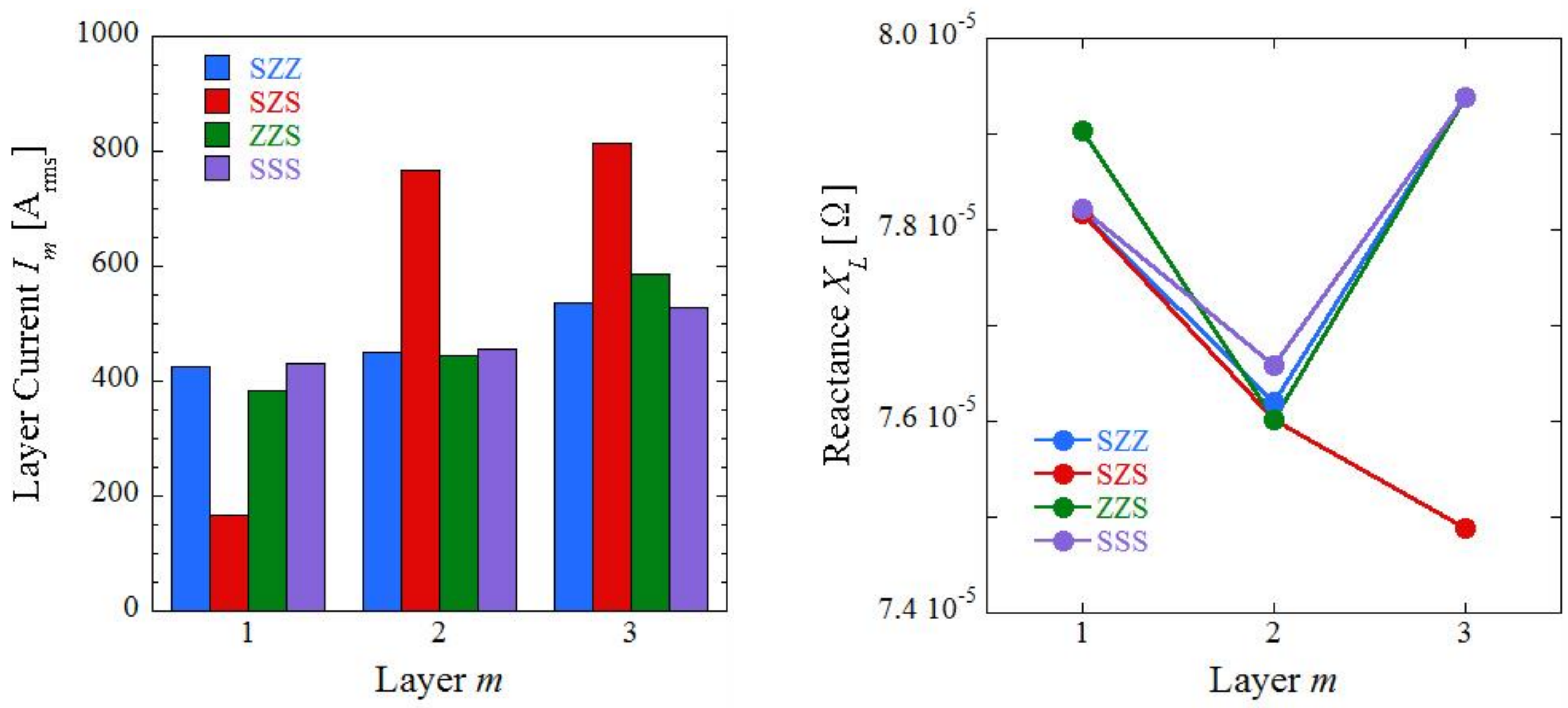
Table 3 Minimum AC losses and optimum helical pitches

Helical direction	Minimum AC loss [Wm^{-1}]	p_1 [m]	p_2 [m]	p_3 [m]
SZZ	0.0463	2.104	0.699	0.121
SZS	0.253	2.104	2.109	0.186
ZZS	0.0512	0.324	2.109	0.121
SSS	0.0458	1.144	0.414	0.121



AC losses are able to be reduced for helical directions SZZ, ZZS and SSS.

Fig.7 Helical directions of HTS cable conductors



(a) Current distributions of each layer

(b) Reactance of each layer X_{Lm}

Fig.9 Comparison of properties for different helical directions of HTS cable conductors

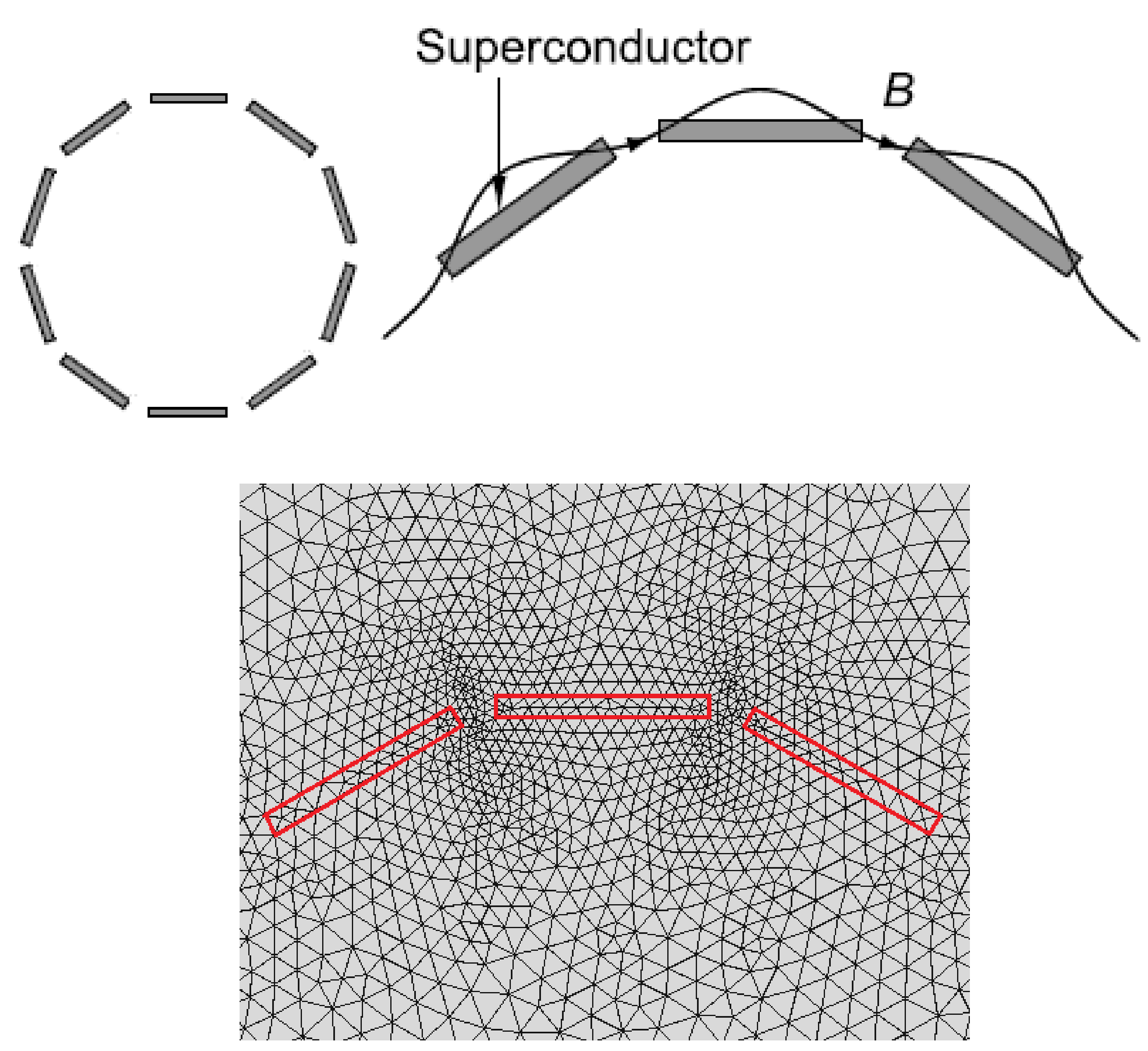


Fig.10 Computation of AC losses by FEM

Figure 9 (a) shows the current distributions of each layer for four helical directions. The current distributions of each layer are uniform when the helical directions are SZZ, ZZS, and SSS. However, it also shows that a large current flows in the outer layer and a drift current occurs when the helical direction is SZS. Figure 9 (b) shows the reactance of each layer X_{Lm} for the four helical directions. The reactance of SZZ, ZZS, and SSS is large at the outer layer; however, the reactance of SZS is small at the outer layer. At SZS, a large current flows in the outer layer because the reactance is smaller in the outer layer; consequently, the reactance cannot equalize the currents. Therefore, the AC loss is increased at SZS.

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 analyzed by considering the interaction between the coated conductors when using the EC model with 2D FEM (see Figure 10).