Dependence of Current Carrying Capacity and AC Loss on Current Distribution in Coaxial Multi-Layer HTS Conductor

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Dependence of Current Carrying Capacity and AC Loss on Current Distribution in Coaxial Multi-Layer HTS Conductor

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***Abstract*—We had developed a simulation method of current distribution in coaxial multi-layer HTS conductor and investigated influence of the nonlinear voltage-current characteristic of HTS tape on current distribution. It had been reported that homogeneous current distribution, especially the same layer current, is effective in terms of reducing AC loss. There are, however, many sets of cable parameters to achieve homogeneous current distribution in such the coaxial multi-layer cables. Therefore, using our developed evaluation method, we numerically investigated the relationship between AC loss and the cable parameters such as twisting pitch, radius, and direction in coaxial three- and four-layer conductors. We evaluated both hysteresis loss and flux flow loss as AC loss using the Norris's model and V–I characteristic of HTS tape, respectively. The critical current of whole cable and current density of each tape are key parameters in terms of reducing AC loss. The larger twisting pitch is better for increasing the critical current of cable due to the greater number of usable tapes and the shorter tape-length per unit length of cable in longitudinal direction. Alternate twisting pitch, however, is ineffective for increasing the critical current due to small twisting pitch and small number of tapes for realizing homogeneous current distribution. There is no effect of the degradation of the critical current caused by magnetic field generated by the other layers on AC loss in the cable with the current carrying capacity of the order of at least 1 kA.**

***Index Terms*—AC loss, current distribution, HTS cable, twisting direction, twisting pitch.**

I. Introduction

POWER application of HTS cable is expected to be realized due to the improvement of HTS-tape performance such as critical current density. In HTS power cable, it is required to reduce AC loss as small as possible. For the reduction of AC loss in HTS cable, coaxial multi-layer conductor has been investigated both experimentally and analytically [1]–[5]. It has been revealed that homogeneous current distribution has an effect on reducing AC loss and is achieved by controlling cable parameters such as twisting pitch, radius, and direction [2]–[5].

We had developed a theoretical method based on magnetic flux conservation between adjacent layers to evaluate the cable parameters for homogeneous current distribution in coaxial multi-layer HTS cable. We have applied this method to evaluate current distribution at the operating current around critical current of cable by taking V–I characteristic of HTS tape into account. Since homogeneous current distribution can be realized by many sets of cable parameters, influence of manufacturing error of twisting pitch and radius on current distribution has been investigated to determine the suitable sets of cable parameters [5]. The suitable parameters for homogeneous current distribution in terms of minimizing AC loss, however, has not been discussed sufficiently yet. Therefore, we investigated the relationship between AC loss and the cable parameters using our developed theoretical method taking V–I characteristic of HTS tape into consideration.

We assumed three- and four-layer cables in analysis and calculated hysteresis loss and flux flow loss using various sets of cable parameters for homogeneous current distribution. Influence of critical current of whole cable and current density of each tape on total AC losses was investigated numerically using the following assumptions: 1) constant total volume of HTS tapes; and 2) constant total number of HTS tapes. In the assumption of constant total volume of HTS tapes, dependences of twisting direction and the magnitude of twisting pitch on total AC losses were investigated in terms of permissible maximum number of tapes. In the assumption of constant total number of HTS tapes, we investigated influence of the number of tapes for each layer and tape-length for each layer on total AC losses.

It is considered that HTS tapes are exposed to magnetic field generated by the operating current in the other layers and the critical current decreases according to the magnitude of the exposed magnetic field. The larger number of tapes is desirable for the layer exposed to large magnetic field to compensate the critical current in whole cable for the degradation of critical current of each tape. Therefore, we investigated influence of the J_c–B characteristics of HTS tape on total AC losses. We also investigated the suitable sets of cable parameters in four-layer cable to compare with those of three-layer cable.

II. Formulation

Many kinds of simulation methods have been adopted to evaluate current distribution in coaxial multi-layer cable [1]–[3]. In terms of cable design, it is very important to estimate the suitable cable parameters satisfied with required conditions such as AC loss and current carrying capacity. Therefore, we adopted our developed simulation method to investigate influence of cable parameters of twisting pitch, radius, and direction on AC loss and current carrying capacity.

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In a closed contour composed of kth and $k+1$th layers, Maxwell's equation is satisfied as follows:

$$\int \mathbf{E} \cdot dl = -\frac{\partial \Phi_{Total}}{\partial t} \tag{1}$$

where Φ_{Total} is the total magnetic flux through a loop composed of adjacent layers. The left-hand side of (1) is the Ohmic-voltage drop in the loop given by:

$$\int \mathbf{E} \cdot dl = R_k i_k - R_{k+1} i_{k+1} \tag{2}$$

where R_k is the equivalent resistance in the kth layer. Considering V–I characteristics of HTS tape and the magnetic flux in axial and azimuthal directions, we finally derived the following governing equation based on an equation of Kirchoff's circuit current in the loop of kth and $k+1$th layers:

$$\begin{aligned} &\mu_0 L_s \frac{r_{k+1} - r_k}{\pi(r_{k+1} + r_k)} \sum_{i=1}^{k} \frac{\partial i_i(t)}{\partial t} \\ &\quad + \mu_0 L_s \left(\frac{\varepsilon_k}{L_k} - \frac{\varepsilon_{k+1}}{L_{k+1}} \right) \sum_{i=1}^{k} \pi r_i^2 \left(\frac{\varepsilon_i}{L_i} \frac{\partial i_i(t)}{\partial t} \right) \\ &\quad + \mu_0 L_s \left(\frac{\varepsilon_k}{L_k} \pi r_k^2 - \frac{\varepsilon_{k+1}}{L_{k+1}} \pi r_{k+1}^2 \right) \sum_{i=k+1}^{n} \left(\frac{\varepsilon_i}{L_i} \frac{\partial i_i(t)}{\partial t} \right) \\ &= R_k i_k(t) - R_{k+1} i_{k+1}(t) \end{aligned} \tag{3}$$

where i_i is the current in the ith layer; r_k is the radius of the kth layer; L_i is the twisting pitch in the ith layer; n is the total number of layers and L_s is the length of conductor in the longitudinal direction, corresponds to L.C.M. of the twisting pitches. ε_i is defined as the parameter of twisting direction in the ith layer and it takes 1 or -1, corresponds to the clockwise and counterclockwise directions, respectively. Note that in this paper,"Z" and "S" correspond to the clockwise and counterclockwise directions, and "ZSZS" means that HTS tapes were twisted in the clockwise direction in the first and third layers, while the counterclockwise direction in the second and fourth layers. In (3), we assumed that total operating current is sinusoidal even if waveform of each layer current may be distorted by nonlinear characteristics such as flux flow resistance of a HTS tape. Therefore, we can obtain the following equations to solve the differential equation of (3):

$$\sum_{j=1}^{n} i_j(t) = i_t \sin \omega t \tag{4}$$

where i_t is the total operating current. We evaluated hysteresis loss using the Norris's model [6] and flux flow loss was calculated using the voltage-current characteristic of Bi2223 tape as follows:

$$V_j = V_c \left(\frac{i_j}{I_c} \right)^n \tag{5}$$

where I_c is the critical current; V_c is the voltage drop at the critical current of I_c; i_j and V_j are the operating current and voltage drop in jth layer; and n is n-value. In analysis, we adopted the cable parameters of coaxial three- and four-layer

TABLE I
PARAMETERS OF THREE- AND FOUR-LAYER CABLES

Conductor :		Silver-sheathed Bi2223 tape
thickness	[mm]	0.2
width	[mm]	4.0
critical current	[A]	50
n-value		10
Cable :		**Coaxial multi-layer conductor**
layer radius	[mm]	
1st layer		20.0
2nd layer		20.5
3rd layer		21.0
4th layer		21.5

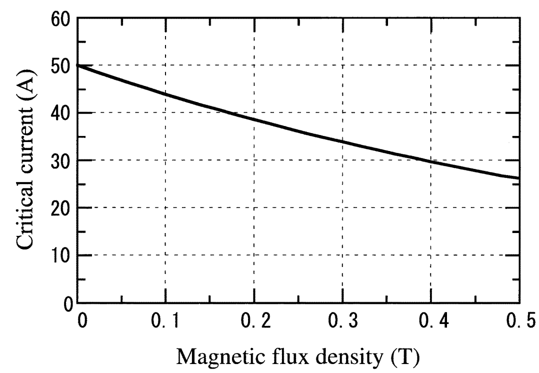

Fig. 1. Dependence of critical current of Bi2223 tape on magnetic flux density.

cables shown in Table I. In real cable, each layer is exposed to magnetic field generated by the other layers and critical current density of each tape may be decreased according to the magnitude of exposed magnetic field. Therefore, we considered a J_c–B characteristic shown in Fig. 1. Since length of HTS tape, depends on both twisting pitch and radius, is different for each layer, we took the effect of the difference of tape length into consideration in analysis. Equation (1) was solved numerically by the Runge–Kutta–Gill method.

III. Analysis and Discussions

Using (1), we calculated various sets of twisting pitch and direction for realizing the same layer current. Then we evaluated total AC loss for each set of cable parameters and investigate the suitable cable parameters in terms of AC loss.

A. Total Volume of HTS Tapes

It is very important for HTS-cable application to reduce not only AC loss but also cost of HTS cable. This means the total amount of HTS tapes is also one of the important parameter in design of HTS cable. Moreover, the dependences of twisting direction and the magnitude of twisting pitch on total AC losses in terms of permissible maximum number of tapes should be clarified. Therefore, we investigated the suitable cable parameters in three-layer cable based on the assumption of constant total volume of HTS tapes; it is assumed in analysis that the largest numbers of HTS tapes are wound for each layer.

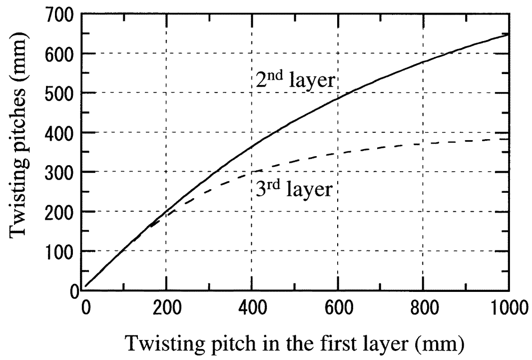

Fig. 2. Twisting pitches in a three-layer ZZZ cable for homogeneous current distribution.

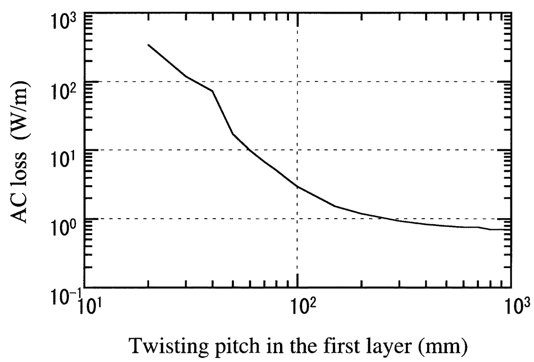

Fig. 3. Dependence of AC loss on the magnitude of twisting pitches in three-layer ZZZ cable at $i_t = 1$ kA.

Computed results of twisting pitches for realizing the same layer current in ZZZ cable at $i_t = 1$ kA are shown in Fig. 2. The twisting pitches of the second and third layers increase with that of the first layer. Since there are many sets of cable parameters for the same layer current, we investigated the relationship between the magnitude of twisting pitch and total AC losses. The calculated total AC losses at $i_t = 1$ kA as a function of L_1 are shown in Fig. 3. In Fig. 3, AC losses tend to decrease with L_1. This reason is that the number of tapes for each layer increases with the magnitude of twisting pitch; the number of tapes in the first, second, and third layers are 19, 20, and 20 at $L_1 = 100$ mm and 31, 31, and 31 at $L_1 = 800$ mm, respectively. Therefore, total critical current for each layer increases and total AC loss decreases with the twisting pitch in the first layer.

To investigated influence of twisting direction on the total AC loss, we compared total AC loss in the following four types of cable: 1) ZZZ; 2) ZSZ; 3) SZZ; and 4) ZZS. Note that computed AC losses in ZZZ and ZSZ cables become the same with those in SSS and SZS cables, respectively. In this analysis, we selected the twisting pitches of second and third layers at $L_1 = 800$ mm, because total AC loss tends to decrease with L_1 as shown in Fig. 3; flux flow loss becomes much larger than hysteresis loss at the smaller twisting pitch of L_1.

The calculated total AC losses as a function of total operating current are shown in Fig. 4. Total AC losses strongly depend on hysteresis loss at $L_1 = 800$ mm and total AC losses in the cable of ZZZ and SZZ became smaller than those of ZSZ and ZZS. The twisting pitches and the numbers of total HTS tapes in the second and third layers of ZZZ and SZZ are larger than

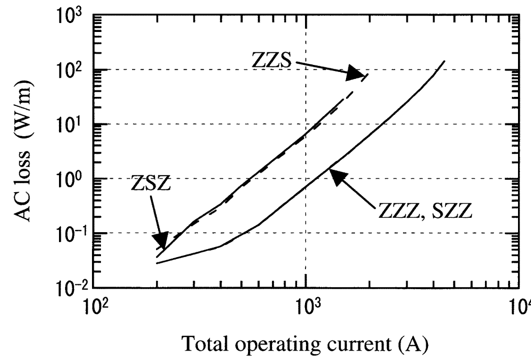

Fig. 4. Influence of twisting direction on AC loss at $L_1 = 800$ mm as a function of total operating current.

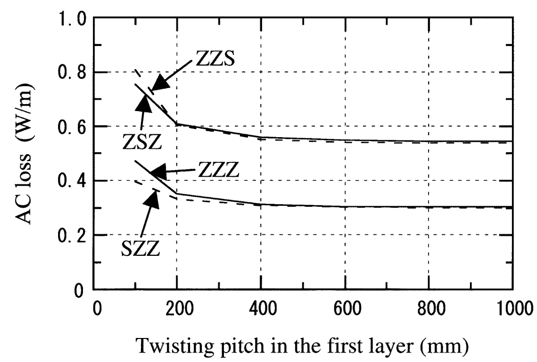

Fig. 5. Influence of twisting direction on AC loss in three-layer cable at $i_t = 300$ A as a function of twisting pitch in the first layer.

those of ZSZ and ZZS. Therefore, hysteresis losses in ZZZ and SZZ cables become smaller than ZSZ and ZZS cables, because the ratios of operating current to critical current in ZZZ and SZZ cables become smaller than those of ZSZ and ZZS cables. From these reason, current carrying capacities in ZZZ and SZZ cables become larger than those of ZSZ and ZZS cables. On an assumption of acceptable total AC loss of 1 W/m, the estimated current carrying capacities of i_t in ZZZ and SZZ are about 1070 A, while 520 A in ZSZ and ZZS cables. It can be considered from the AC loss evaluation that ZZZ and SZZ are desirable under the condition of a limited total volume of HTS tapes.

B. Total Number of HTS Tapes

As discussed above, AC loss strongly depends on the total number of HTS tapes. In this section, we investigated influence of only the magnitude of twisting pitch on AC loss in the four types of three-layer cables based on an assumption that i_t is 300 A and the number of HTS tapes for each layer is eight; total number of tapes is twenty-four. The purpose for this analysis is to investigate which of the factors, number of tapes and magnitude of twisting pitch, is more closely related to total AC loss. Computed AC losses at $i_t = 300$ A as a function of L_1 are shown in Fig. 5. In spite of the same number of HTS tapes, total AC loss differed with each type of cable. This may be caused by the difference in tape-length per unit length of cable in its longitudinal direction. The tape-lengths in ZSZ and ZZS cables are larger than those of ZZZ and SZZ cables, because of the shorter twisting pitch of ZSZ and ZZS cables than ZZZ and SZZ. At $L_1 = 800$ mm, the tape-lengths in the third layer per unit length

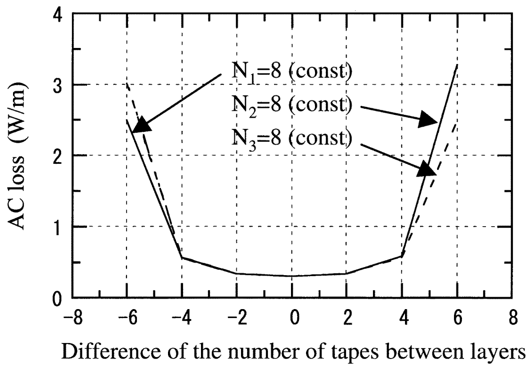

Fig. 6. Dependence of AC loss on the different number of tapes between layers in three-layer ZZZ cable with twenty-four tapes at $i_t = 300$ A.

of cable are 1.06 m, 2.23 m, 1.07 m, and 2.34 m in the cable of ZZZ, ZSZ, SZZ, and ZZS, respectively.

C. Influence of J_c–B Characteristic on AC Loss

Critical current of HTS tape decreases with the magnitude of exposed magnetic field generated by the other layers. Therefore, it is important to consider the effect of J_c–B characteristic of HTS tape on current distribution and AC loss. It is considered that number of tapes should be larger in the layer exposed to the larger magnetic field for reducing total AC loss, especially hysteresis loss, because the ratio of tape-current to the critical current should be as small as possible. This means that number of tapes for each layer should be controlled taking the magnitude of exposed magnetic field into consideration. Therefore, we calculated total AC loss in the above four types of cables as a function of the number of tapes for each layer. In this analysis, we assumed the maximum operating current of 300 A and total number of tapes in whole cable of twenty-four to investigate influence of the different number of HTS tapes for each layer on not total loss but hysteresis loss.

The computed results of total AC losses of ZZZ cable at $L_1 = 800$ mm are shown in Fig. 6. Horizontal axis shows the difference of the number of tapes against the average of eight. Minimum total AC loss was obtained in the cable with eight tapes for each layer and the AC loss increased with the difference of the number of tapes between layers. In ZZZ cable with the same layer current, the maximum magnetic fields exposed to HTS tapes at $i_t = 1$ kA are 1.86 mT, 3.44 mT, and 6.35 mT in the first, second, and third layers, respectively; critical-current degradations due to exposed magnetic field are 0.24 percent, 0.45 percent, and 0.82 percent in the first, second, and third layers, respectively. These results imply that total AC loss is almost independent of magnetic field at the total operating current of the order of at least 1 to 2 kA. The difference of the number of tapes between layers is much more important than the J_c–B characteristic of HTS tape for reducing AC loss.

D. Suitable Cable Parameters in Four-Layer Cable

We investigated the relationship between AC loss and cable parameters in eight types of four-layer cables to verify that the larger twisting pitch and the smaller difference of the number of tapes between layers, i.e., the larger critical current of whole cable and the greater homogeneity of current density of each tape, are effective for reducing AC loss. We assumed that total volume of HTS tapes was constant and maximum length of twisting pitch was 10 m. It was clarified in this analysis that minimum total AC losses were obtained in the cable of ZZZZ and SZZZ, while the larger AC loss in the cable of ZZSZ and ZSZS. Total AC loss was almost the same for $L_1 > 2500$ mm in ZZZZ cable and for $L_1 > 1900$ mm in SZZZ cable because total number of HTS tapes reaches the maximum. It is considered from the results of three- and four-layer cables that alternate twisting-direction of Z and S makes total AC loss larger.

IV. Conclusion

We analytically investigated dependence of AC loss and current carrying capacity on current distribution in coaxial multilayer cable. The magnitude of twisting pitch is very important and the larger twisting pitch can realize the lower AC loss. It may be considered that alternate twisting-direction is ineffective because of the larger AC loss due to the smaller number of tapes and twisting pitch. The difference of the number of tapes for each layer should be minimized; this implies that the same current density in all layers may be effective for minimizing AC loss. Total AC loss is almost independent of degradation of critical current due to magnetic field generated by the other layers at total operating current of the order of at least 1 kA.

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