Analysis on Current Distribution of Four-Layer HTSC Power Transmission Cable with a Shield Layer

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Abstract - The inductance difference between conducting layers of high-T_C superconducting (HTSC) power transmission cable causes the current sharing of each conducting layer to be unequal, which decreases the current transmission capacity of HTSC power cable. Therefore, the design for even current sharing in HTSC power transmission cable is required. In this paper, we investigated the current distribution of HTSC power cable with a shield layer dependent on the pitch length and the winding direction of each layer. To analyze the effect of the shield layer on the current sharing of the conducting layers of HTSC power cable, the current distribution of HTSC power cable without a shield layer was compared with the case of HTSC power cable with a shield layer. It could be found through the analysis from the computer simulations that the shield layer of HTSC power cable could be contributed to the improvement of current distribution of conducting layers at the specific pitch length and the winding direction of conducting layer. The result and discussion for the current distribution calculated for HTSC power transmission cable with a shield layer were presented and compared with the cable without a shield layer.

Keywords - Current distribution, High-T_C superconducting power transmission cable, Inductance difference, Pitch length, Shield layer, Winding direction.

1. Introduction

As power transmission capacity due to power demand increases, high T_C superconducting (HTSC) power transmission cable is expected to be a countermeasure to overcome the limitation of conventional power transmission cable. The multi-layer structure of HTSC power transmission cable designed for larger current transmission makes the self inductance of each layer and the mutual inductance between two layers different. These inductance differences in conducting layers cause non-uniform current distribution, which results in exceeding the critical current of a specific layer and thus, lower power transmission capacity. The method to raise the contact resistance of each layer is effective for the uniform current distribution of each layer. However, this method increases the additional power loss and causes the efficiency of the HTSC power cable system to decrease. Another method to adjust the pitch length and the winding direction of each layer is complicated, which makes it difficult for the cable designer to find a simple solution for the uniform current distribution [1-3].

In this paper, we suggested that the shield layer could be contributed to the even current distribution of HTSC power transmission cable. For confirmation of it, we investigated the dependence of the current distribution in the HTSC power transmission cable with a shield layer designed with the same pitch length in all layers on the pitch length and the winding direction. From the numerical analysis, the pitch length where the current distribution difference between the layers was a minimum value could be found in the case of HTSC power cable with a shield layer designed with a specific winding direction. On the other hand, the pitch length with the minimum difference in the current distribution of HTSC power cable without a shield layer did not exist irrespective of the winding direction of each layer.

2. Numerical Modeling for Calculation

HTSC power cable for analysis in this paper consists of four conducting layers and one shield layer as shown in Fig. 1(a), which are wound on the former with the same winding pitch and the repeated winding direction (clockwise and anti-clockwise). Fig. 1(b) displays the equivalent circuit for HTSC power cable. Each layer can be represented by the resistance for contact and ac loss (R_i), the self inductance (L_i) and the mutual inductance between the coupled two layers (M_{ij}). The self inductance of the ith layer and the mutual inductance between the ith layer and jth layer can be calculated as demonstrated in Equations (1) and (2) using the magnetic field energies stored per

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volume [4].

$$L_i = \mu_0 \frac{\pi r_i^2}{l_{pi}^2} + \mu_0 \frac{\ln(D/r_i)}{2\pi} \quad (1)$$

$$M_{ij} = M_{ji} = \frac{a_i a_j \mu_0}{l_{pi} l_{pj}} \pi r_i^2 + \frac{\mu_0}{2\pi} \ln(D/r_j) \, (r_j > r_i) \quad (2)$$

Here, D is the outermost radius of the electrical shielding. The matrix equation with a complex form for the analysis of the steady state current distribution can be derived from the equivalent circuit connected with the source voltage and the load in Fig. 1(b) as follows:

$$\begin{bmatrix} E_{In} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{load}+R_1 & R_{load} & R_{load} & R_{load} & 0 \\ -R_1 & R_2 & 0 & 0 & 0 \\ 0 & -R_2 & R_3 & 0 & 0 \\ 0 & 0 & -R_3 & R_4 & 0 \\ 0 & 0 & 0 & 0 & -R_{SC} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_s \end{bmatrix} + j\omega \begin{bmatrix} L_1 & M_{12} & M_{13} & M_{14} & M_{1S} \\ L_1+M_{21} & -M_{12}+L_2 & -M_{13}+M_{23} & -M_{14}+M_{24} & -M_{1S}+M_{2S} \\ -M_{21}+M_{31} & -L_2+M_{32} & -M_{23}+L_3 & -M_{24}+M_{34} & -M_{2S}+M_{3S} \\ -M_{31}+M_{41} & -M_{32}+M_{42} & -L_3+M_{43} & -M_{34}+L_4 & -M_{3S}+M_{4S} \\ -M_{S1} & -M_{S2} & -M_{S3} & -M_{S4} & -L_S \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_S \end{bmatrix} \quad (3)$$

Where E_{In} and R_{load} is source voltage and load resistance, respectively. By solving the matrix equation of (3), the current distribution of each layer was calculated.

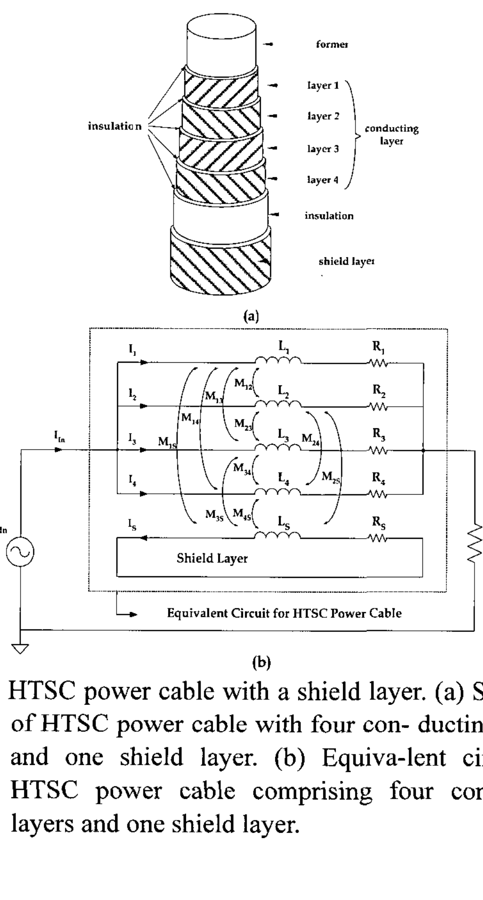


Fig. 1. HTSC power cable with a shield layer. (a) Structure of HTSC power cable with four con- ducting layers and one shield layer. (b) Equiva-lent circuit of HTSC power cable comprising four conducting layers and one shield layer.

3. Calculation Results and Discussions

Fig. 2 displays the current distribution according to cable length for two cases: HTSC cable without a shield layer and HTSC cable with a shield layer. The winding direction of each layer was set to SZSZ for the former and to SZSZS for the latter. The pitch length of HTSC power cable for calculation was chosen to be 0.90 m and the resistance for contact and ac loss in each layer was assumed to be identical, which is usually 10μΩ. Other design parameters for HTSC power cable for the analysis of current distribution are presented in Table 1.

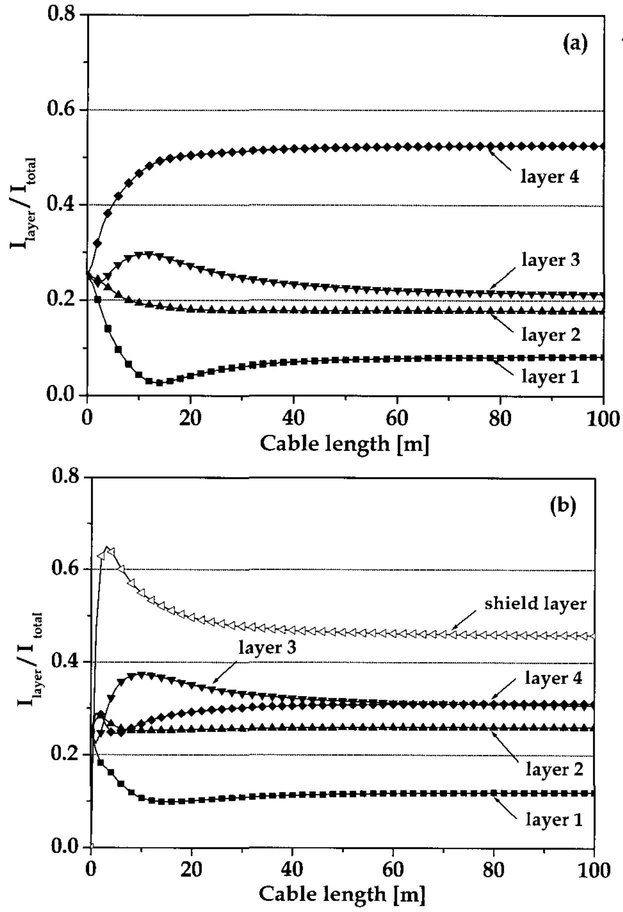


Fig. 2. Current distribution dependent on cable length in two cases: (a) HTSC power cable without a shield layer (SZSZ) (b) HTSC power cable with a shield layer (SZSZS).

As the cable length increased, the current distribution difference in case of the HTSC cable with a shield layer was smaller than that of the HTSC cable without a shield layer. From these results, the shield layer could be observed to affect the current distribution of the conducting layers.

For further analysis for the effect of the shield layer on the current distribution in conducting layers, the current distribution according to the pitch length and the winding direction were investigated for two cases: HTSC cable without a shield layer and HTSC cable with a shield layer. Although one layer can be designed to have a different pitch length from other layers through the adjustment of the pitch length, in this paper, we considered the case that the pitch length in all layers were adjusted with the same value.

Table 1. Design Parameters of HTSC Transmission Cable

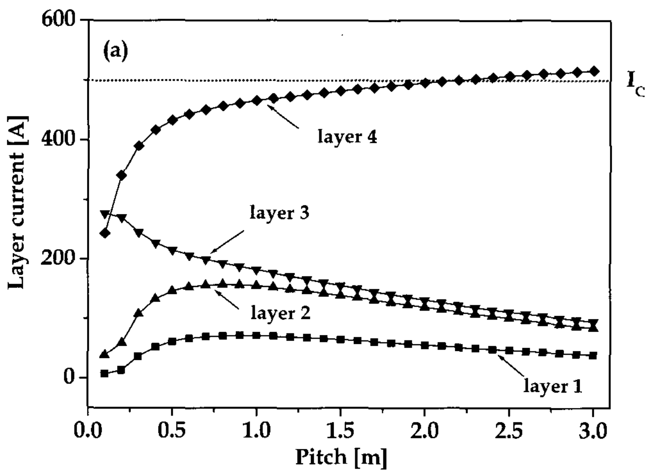
Specification	Value	Unit
Number of conducting layers	4	
Number of shield layers	1	
Former radius	20	mm
Thickness of tape	0.18	mm
Thickness of filamentary region	0.12	mm
Thickness of insulation between layers	0.1	mm
Thickness of insulation between conducting layers and shield layer	0.97	mm
Critical current in each layer	500	A

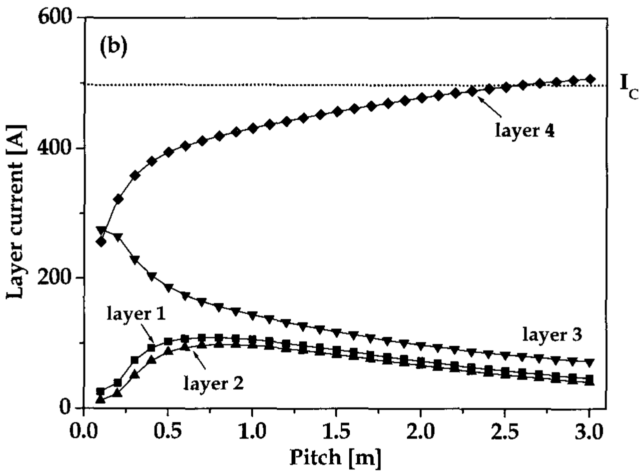
The length of HTSC power cable for calculation was chosen to be 100 m and the resistances for contact and ac loss in each layer were assumed to be identical, which is usually 10μΩ. For the conducting layers, eight combinations according to the winding direction exist. In case that HTSC power cable has a shield layer, there are again two combinations according to the winding direction of one shield layer for each combination of eight. Therefore, 16 cases can be obtained.

Fig. 3 shows the current distribution according to the pitch length of layers in case of HTSC power cable without the shield layer. As seen in Fig. 3, the design of the pitch length with higher than 2.2, 2.6, and 3.0 m at each winding direction (SZSZ, SZZS, SSSZ) leads the current of the 4^{th} layer to exceed its critical current. In addition, the difference of current distribution between layers was larger as the pitch length of layers increased. In other words, the current distribution in each layer in case of HTSC cable without the shield layer was not much improved in all pitch length ranges. Although not shown in this paper, five other combinations according to winding direction in cases without the shield layer showed the similar inclination to these three cases (SZSZ, SZZS, SSSZ) for the current distribution of each layer due to the pitch length. Conversely, in the current distribution of each layer according to the pitch length and the winding direction of HTSC power cable with the shield layer, all the conducting layers except for the shield layer did not exceed the critical current of each layer in three cases (SZSZS, SZZSZ, SSSZS) among the sixteen combinations as indicated in Table 2.

Table 2. Combination of Winding Direction of Multi-Layer Htsc Power Cable With one Shield Layer

	Conducting Part				Shield Part	Combination
Layer Number	1	2	3	4	5	
Winding Direction	+	+	+	+	+	SSSSS
	+	+	+	+	-	SSSSZ
	+	+	+	-	+	SSSZS
	+	+	+	-	-	SSSZZ
	+	+	-	+	+	SSZSS
	+	+	-	+	-	SSZSZ
	+	+	-	-	+	SSZZS
	+	+	-	-	-	SSZZZ
	+	-	+	+	+	SZSSS
	+	-	+	+	-	SZSSZ
	+	-	+	-	+	SZSZS
	+	-	+	-	-	SZSZZ
	+	-	-	+	+	SZZSS
	+	-	-	+	-	SZZSZ
	+	-	-	-	+	SZZZS
	+	-	-	-	-	SZZZZ





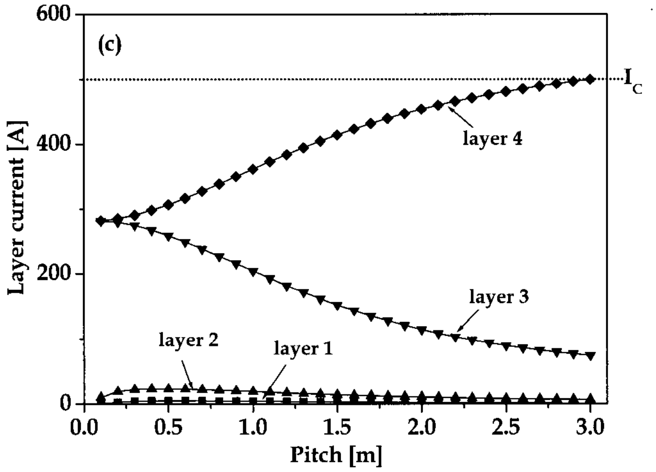
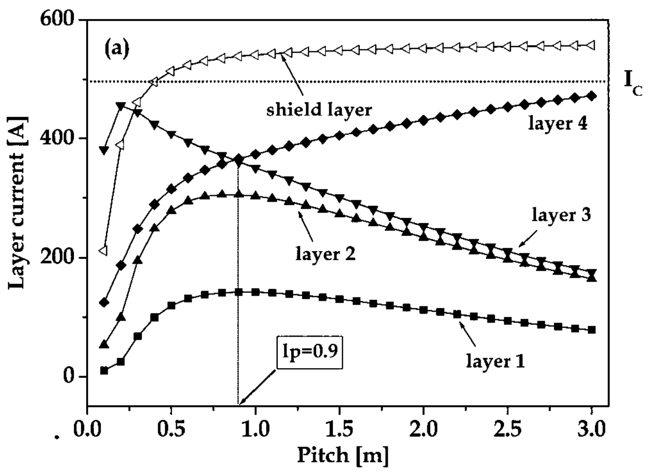
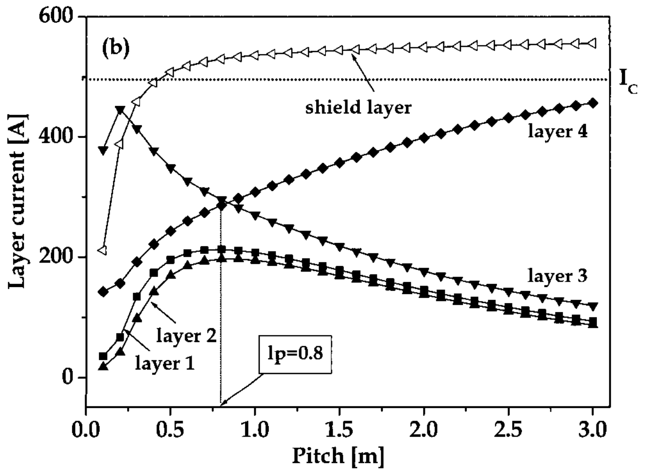


Fig. 3. Current distribution dependent on pitch length without a shield layer. (a) SZSZ. (b) SZZS. (c) SSSZ.

Fig. 4 shows the current distribution of each layer in three cases. Unlike multi-layer HTSC power cable without the shield layer, the pitch length that the current distribution difference between the maximum current conducting layer and the minimum current conducting layer was a minimum value that could be observed (indicated with vertical dotted line). As the pitch length increased, the current of layer 3 decreased sharply. On the other hand, the current of layer 4 increased even more, which determines the uniformity of the current distribution in all the conducting layers. At the pitch length where the amplitude of the currents conducting both layer 3 and layer 4 approached the equal value (l_p = 0.9, 0.8, 1.6), the current distribution difference between the conducting layers was the least value according to the pitch length in three winding direction cases (SSSZS, SZSZS, SZZSZ). In other cases except for these three cases, the currents in the conducting layers of 3 and 4 increased continuously as the pitch length increased, like the HTSC power cable without a shield layer as indicated in Fig. 3. Among three cases with the pitch length for the least current distribution difference in multi-layer HTSC power cable with one shield layer, the case with the winding direction of SZZSZ showed the smaller current difference of the three cases.





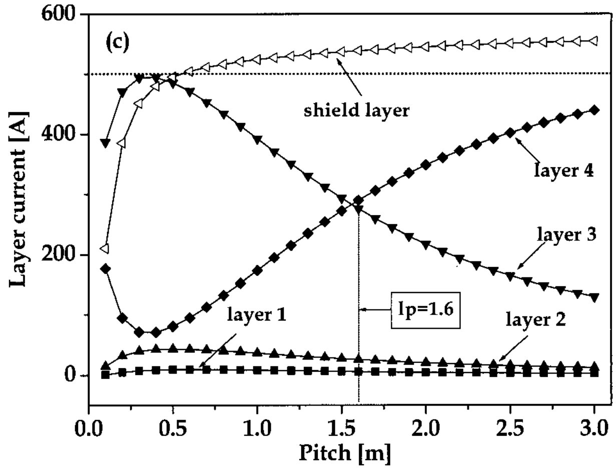


Fig. 4. Current distribution as a function of pitch length in all conducting layers with the shield layer. (a) SZSZS. (b) SZZSZ. (c) SSSZS.

It was confirmed using the above analysis that the current distribution of conducting layers could be improved through the adjustment of the pitch length and the winding direction if the shield layer could be designed with HTSC tapes of larger critical current.

4. Conclusions

In this paper, we suggested that the shield layer of HTSC power cable, which was originally required for the protection from the electromagnetic phenomenon like the conventional power cable, could be contributed for the improvement of the current distribution of each layer in HTSC power cable with different inductances. To confirm it, we investigated the current distribution of conducting layers in HTSC power cable dependent on the pitch length and the winding direction of each layer for two cases: four-layer HTSC power cable with a shield layer and four-layer HTSC power cable without a shield layer. Through the analysis from the computer simulations, the current distribution in all conducting layers of HTSC cable could be improved in case that HTSC power cable with the shield layer was designed with the specific pitch length of all layers for each winding direction. It was expected that the results and discussions for HTSC power cable with the shield layer in this paper could be useful for the cable designer to strive to solve the problem of non-uniform current distribution in HTSC power cable.

Acknowledgement

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