An effective design for induced current reducing of a single-phase multi-layer HTS coaxial cable with former

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Abstract: High temperature superconducting (HTS) cables require a former layer to bypass fault currents and support superconducting tape. The former layer of the HTS cable does not conduct current in steady-state operation due to the resistance difference with the conducting layer. However, in practice, an induced current flows through the former layer due to the mutual interaction with the conducting layer. Therefore, the current distribution in the cable should be uniform and the induced current in the former layer must be minimized. This paper deals with an effective design of a single-phase multi-layer HTS coaxial (SMHTSC) cable with former layer. The optimal combination of the pitch length and the winding direction in the conducting layer and the shield layer was selected for uniform current distribution of the SMHTSC cable and minimization of induced current in the former layer. The current distribution of the SMHTSC cable was analyzed based on the numerical calculation results obtained using the impedance matching method. The results and discussions of the current distribution on the SMHTSC cable with and without former layer were compared and presented.

1. Introduction

High-temperature superconducting (HTS) cables offer a compact design and very low loss compared to conventional copper cables, and hence the HTS cables are being actively studied and developed worldwide as promising power cables for urban areas [1]-[2]. The HTS cables generally require a former located at the center of the cable, which not only acts as a support for robustly winding the superconducting tape, but also serves as a pathway to bypass the fault current. The choice of this former has a great impact on the structure and design of a cable [3]. In addition, the HTS power cables typically consist of a multi-layer structure of HTS tape wires spirally wound over coaxial former. The characteristics of multi-layers are defined by mainly two structural parameters: the pitch length, and the winding direction. The winding direction can be clockwise or anti-clockwise. The characteristics of the structural parameters play an important role in maintaining a uniform current distribution and may be influenced by the manufacturing process, so an their optimum design is required. The non-uniform current distribution consequently increases the total power loss in the cable and also reduces the cable current capacity [4]-[6].

This paper presents an effective design method of a single-phase multi-layer HTS coaxial (SMHTSC) cable with former layer. The SMHTSC cable structure is composed of a former layer, a conducting layer and a shield layer. Each layer except the former has a unique impedance that is affected by the pitch length and winding direction, and has a current distribution according to the impedance. However, when the former layer exists, the current distribution of the conducting layer is changed by the interaction with the former layer, and the induced current also flows in the former layer. Therefore, it is necessary to determine the pitch length and the winding direction so that the current distribution of the conducting...
layer becomes uniform and the former induced current is also minimized. The impedance matching method was used to iteratively calculate various combinations of the pitch length and the winding direction in the SMHTSC cable with and without the former layer. The pitch length and the winding direction of the SMHTSC cable, which represents the uniform current distribution in the conducting layer, were selected through the design process using the impedance matching method. By selecting the appropriate pitch length and winding direction, the induced current of the former layer was minimized to less than 27.3 A and the current distribution of the SMHTSC cable was uniformed. This study result will be useful for the development of other types of multi-layer HTS coaxial cables with former layer.

2. Numerical analysis of the SMHTSC cable

2.1. Configuration of the SMHTSC cable

Two SMHTSC cables with and without former layers are wound in the same pitch length and winding direction. Figure 1 shows the structure of a SMHTSC cable with two conducting layers and one shield layer and no former layer. Figure 2 shows the structure in which the former layer is added to the SMHTSC cable. The radius of the two conducting layers is determined by the cross-sectional area of the former layer. For the former layer, the radius is designed not to rise above a certain temperature even when the fault current is flowing. Also, in the case of shield layer, the insulation thickness is selected considering the withstand voltage, and the radius is determined accordingly. The specifications of SMHTSC cable are shown in table 1.

![Figure 1. Structure of SMHTSC cable without former layer](image1)

![Figure 2. Structure of SMHTSC cable with former layer](image2)

| Table 1. Specifications of SMHTSC cable model. |
|-----------------------------------------------|
| **Items**                                    | **Value**           |
| Voltage/capacity                             | 23 kV/50 MVA        |
| Rated current                                | 1,250 A             |
| Total cable length                           | 1000 mm             |
| Number of conducting layers                  | 2                   |
| Number of shield layer                       | 1                   |
| Radius of former layer                       | 8 mm                |
| Inner radius of conducting layer             | 9 mm                |
| Outer radius of conducting layer             | 10 mm               |
| Radius of shield layer                       | 15 mm               |
2.2. Modelling of the SMHTSC cable

Figure 3 shows the equivalent circuit of the SMHTSC cable. Each layer can be represented by the resistance \( R_i \), the self-inductance \( L_i \) and the mutual inductance between the coupled two layers \( M_{ij} \). The self-inductance of the layer and the mutual inductance between the \( i \)th and \( j \)th layers can be calculated as shown in (1) and (2) using the magnetic field energies stored per unit volume. In addition, the inductance and mutual inductance of the former layer can be calculated as shown in (3) and (4). The impedance matrix is derived from the equivalent circuit connected to the source and the load as shown in figure 2 using (5) [7].

\[
L_i = \frac{\mu_0 r_i^2}{l_{pi}} + \frac{\mu_0}{2\pi} \ln \frac{D}{r_i} \\
M_{ij} = \frac{a_i a_j \mu_0 r_i^2}{l_{pi} l_{pj}} + \frac{\mu_0}{2\pi} \ln \frac{D}{r_j} \quad (r_j > r_i) \\
L_f = \frac{\mu_0}{8\pi} + \frac{\mu_0}{2\pi} \ln \frac{D}{r_f} \\
M_f = \frac{\mu_0 r_f^2}{3l_{pf}} + \frac{\mu_0}{2\pi} \ln \frac{D}{r_f}
\]

where, \( \mu_0 \) is the magnetic permeability of free space, \( D \) is the outermost radius of the electrical shielding, \( a_i \) is the winding direction of clockwise, \( a_j \) is the winding direction of anti-clockwise, \( f \) is the former layer of SMHTSC cable.

\[
\begin{bmatrix}
V
\end{bmatrix} =
\begin{bmatrix}
R_f + R_{load} & R_{load} & R_{load} & 0 \\
R_{load} & R_1 + R_{load} & R_{load} & 0 \\
R_{load} & R_{load} & R_2 + R_{load} & 0 \\
0 & 0 & 0 & R_{load}
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
I_4
\end{bmatrix} + j\omega
\]

\[
\begin{bmatrix}
L_f & M_{f1} & M_{f2} & M_{f3} \\
M_{f1} & L_1 & M_{12} & M_{13} \\
M_{f2} & M_{12} & L_2 & M_{23} \\
M_{f3} & M_{13} & M_{23} & L_3
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
I_4
\end{bmatrix}
\]

where, \( R_1 \) and \( R_2 \) denote the equivalent resistances that cause AC losses, and \( R_{load} \) is the equivalent resistance of load. The SMHTSC cable was simulated under the rated current load condition, with the resistances \( R_1, R_2, \) and \( R_{load} \) of 0.015 \( \mu \Omega \), 0.021 \( \mu \Omega \) and 18.4 \( \Omega \), respectively.
2.3. Analysis of the current distribution

The current distribution in the conducting and shield layers of the SMHTSC cable is analysed for various combinations of pitch length and winding direction. Table 2 shows the range of the pitch length and increase value for each layer without the former layer. The winding direction consists of clockwise and anti-clockwise directions. The pitch length and winding direction of the SMHTSC cable should be chosen to uniformly control the current distribution among each conducting layer and the shield layer. Figure 4 shows the flowchart of the impedance matching method. By using the impedance matching method, the current distribution of each layer and the induced current of the former layer are repeatedly calculated and the appropriate pitch length and winding direction can be selected.

Table 2. The range of the pitch length variation.

| Items                        | Value          |
|------------------------------|----------------|
| Range of pitch length        | 150 mm to 650 mm |
| Increase value of pitch length | 10 mm          |

![Figure 4. Flowchart of the impedance matching method](image)

3. Calculation results and discussions

3.1. Comparison of the SMHTSC cables with and without former layer

Table 3 shows the results of repeatedly calculated current distributions for various combinations of the pitch length and winding direction in a former-less SMHTSC cable. As shown in table 2, the pitch length was changed from 150 mm to 650 mm at intervals of 10 mm, and the current ratio of the conducting...
layer was calculated from 70% to 90% at maximum while changing the winding direction. As a result, many current ratios were calculated, but only three cases of current ratios of 70%, 80% and 90% were considered to analyse the influence of the SMHTSC cable former layer.

### Table 3. Calculation results of the current distribution in the SMHTSC cable without former layer.

| Cases | Pitch length [mm] | Current of conducting and shield layers [A] | Winding direction (F= clockwise, R= anti-clockwise) | Current ratio of conducting layer [%] |
|-------|-------------------|---------------------------------------------|--------------------------------------------------|-------------------------------------|
| Case 1 | 300/320/620       | 516.2/733.7/1157.9                          | R/F/R                                            | 70                                  |
| Case 2 | 280/290/570       | 557.9/692.0/1156.1                          | F/R/F                                            | 80                                  |
| Case 3 | 250/300/430       | 592.4/657.5/1145.2                          | R/F/R                                            | 90                                  |

The inductance value changes according to the pitch length of each layer irrespective of the presence or absence of the former layer, and the current distribution of each layer changes accordingly. Therefore, the current distribution was analysed by adding the former layer to the SMHTSC cable having the same pitch length, winding direction, and radius as in the case of no former, and the results are shown in table 4. As shown in table 4 the SMHTSC cable without the former layer had a higher current ratio of the conducting layer than with the former layer. The SMHTSC cable with the former layer has a high induced current in the former layer. Therefore, in the case of the SMHTSC cable with former layer, the current distribution and the induced current should be analysed considering the effect of the former layer and the current ratio of the conducting layer.

### Table 4. Calculation results of the current distribution in the SMHTSC cable with former layer.

| Cases | Pitch length [mm] | Current of conducting and shield layers [A] | Winding direction (F= clockwise, R= anti-clockwise) | Induced current of former layer [A] (Loss of former layer) | Current ratio of conducting layer [%] |
|-------|-------------------|---------------------------------------------|--------------------------------------------------|----------------------------------------------------------|-------------------------------------|
| Case 1 | 300/320/620       | 419.7/701.4/994.3                           | R/F/R                                            | 128.8 (0.2 W/m)                                          | 59                                  |
| Case 2 | 280/290/570       | 455.0/497.1/1216.2                          | F/R/F                                            | 97.8 (0.1 W/m)                                          | 65                                  |
| Case 3 | 250/300/430       | 475.9/637.0/972.9                           | R/F/R                                            | 136.9 (0.2 W/m)                                          | 74                                  |

3.2. **An effective design of the SMHTSC cable with former**

There are eight combinations of SMHTSC cables according to the winding direction. Like the pitch length, the winding direction also affects the current distribution of each conducting layer and the induced current in the former layer. In this case, the minimized induced current was the least when the winding directions of the conducting layer and the shield layer are F, R and F, respectively, as shown in figure 5. Therefore, the direction of winding of F, R, F was selected and applied to analyse the SMHTSC cable with the former layer. The calculation result of the minimum induced current according to the pitch length is shown in figure 6. As can be seen in figure 6, in the SMHTSC cable with the former layer, the induced current in the former layer can be minimized by adjusting the pitch length of each layer to an appropriate range. In particular, the pitch length change of the inner conducting layer has a greater effect on the induced current of the former layer than the other layers. Therefore, in order to effectively design a SMHTSC cable with former layer, it is necessary to select the pitch length of the inner conducting layer of 150 mm. Table 5 shows the calculated results for the pitch length range of 150 mm to 650 mm of the SMHTSC cable with former layer. The SMHTSC cable with former layer has a uniform current distribution of 98% in the conducting layer and an induced current of 27.3 A in the former layer and the copper loss of the former layer was minimized to 8.4 mW/m. It was confirmed that the current distribution of the former layer and the conducting layers could be improved through the adjustment of the pitch length and the winding direction.
Figure 5. Calculation results of the induced current for the combinations of winding direction

Figure 6. Calculation results of the induced current due to the pitch length combinations

Table 5. Calculation results of the effective design of the SMHTSC cable with former layer.

| Items               | Pitch length | Winding direction (F= clockwise, R= anti-clockwise) | Current of each layer |
|---------------------|--------------|-----------------------------------------------------|-----------------------|
| Former layer        | -            | -                                                   | 27.3 A                |
| Inner conducting layer | 150 mm     | F                                                   | 605.8 A               |
| Outer conducting layer | 170 mm     | R                                                   | 616.7 A               |
| Shield layer        | 650 mm       | F                                                   | 1237.3 A              |
4. Conclusions
This paper presents an effective design process for a SMHTSC cable with former layer. The influence of the former layer was analysed by comparing a SMHTSC cable with or without former layer. Both cables have the same pitch length and winding direction selected. The SMHTSC cable without the former layer showed a higher current ratio of the conducting layer than with the former layer. The SMHTSC cable with the former layer has a high induced current in the former layer. The pitch length and winding direction of each layer were chosen to reduce the induced current in the former layer. The induced current of the former layer was the smallest when the winding directions of the conducting layers and the shield layer were F, R and F, respectively. When the pitch lengths of the conducting layers and the former layer of the SMHTSC cable with the former layer were 150 mm, 170 mm and 650 mm, a 98% uniform current distribution in the conducting layers and an induced current of 27.3 A in the former layer were exhibited. The copper loss of the former layer was minimized to 8.4 mW/m. Even if the cable size and the number of layers are changed, the proposed SMHTSC cable design method can balance the current distribution of the conducting layer and minimize the induced current of the former layer. The results of this study can be used effectively to design other types of multilayer HTS coaxial cables.

Acknowledgments
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