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Pitch Calculation of 4-layer HTS Power Transmission Cable for Balanced Sharing Current

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Abstract-- **A typical HTS power transmission cable has multi-layer conductor structure to increase the current capacity. The tapes of the innermost layer are wound on a round former, and adjacent tapes of another layer are separated by a thin insulating film. However, usually the current is not evenly distributed among the layers because of inductance difference of each layer, and the inductance is provided by the winding pitch of each layer's tape. Consequently a method to make the current distribution more uniform is a adjusting the tape winding pitch, hence reduce the AC loss. This paper describes a current distribution by adjusting a tape winding pitch of each layer. Also, this paper shows recommendations for future cable conductor prototypes.**

1. INTRODUCTION

An HTS (High Temperature Superconductor) power transmission cable consists of a core and outer parts, a cryostat filled with liquid nitrogen. The core is the most important part, which roles of carrying the current. Generally, the core contains many superconducting tapes. The tapes are wound on a round former, which is in a long pipe or a hose shape. A thin insulating film separates the adjacent tapes. The total current flows in the four inner layers, and the two outer layers role of magnetic shield. Fig. 1 shows an example of the core part of an HTS power transmission cable. The size of a HTS cable can be small compared with the conventional cable that uses normal conductor and has the same power transmission capacity, because the HTS cable has a high current density in low temperature. Moreover, it has a possibility that the operation cost of the cable can be reduced because of its low transmission loss.

The most important technology to realize the economical cable is in reducing AC loss of the HTS cable [1]. Making uniform current distribution is as important as the AC loss. If the layers do not share the current evenly, and number of tapes. Also it is known that AC lo ss of a cable is minimum

Mainly self and mutual inductances between the layers when the layers share current evenly[2]. of cable determine the current distribution, and the inductances of the layers are given by the geometry, winding pitches and directions.

The inductances of the layers are calculated by very complicated equations that are associated with multi -layers structure. It is not easy to find a design specification, which has a good combinations of the layer pitches and winding directions by an analytical method.

In this paper, the developed computer program is used to investigates the effect of the winding pitches of an HTS cable with 4 conductor layers and two shield layers.

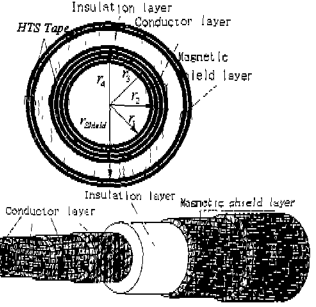

Fig. 1. Schematic view of the windings in an HTS power transmission cable

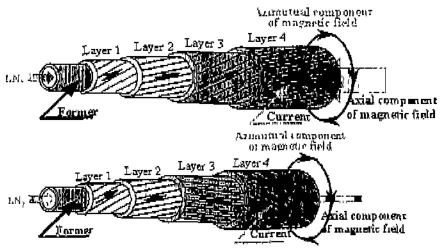

Fig. 2. Schematic view of the magnetic field in an HTS power transmission cable according to the winding type. (a) Winding type 'SSSS' (b) Winding type 'SSZZ'

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2. NUMERICAL MODELING

2.1. Analysis Model

The HTS cable for analysis has four conductor layers and two shield layers. Radius of the former is 12.9[mm] and the total operating current is 1260[A]. Table 1 shows the specifications of the analytical model.

TABLE I
HTS POWER TRANSMISSION CABLE DATA

Number of conductor layers	4
Number of shield layers	2
Winding direction	SSZZ+SS
Thickness of HTS tape	0.26 [㎜]
Width of HTS tape	4.04 [㎜]
Critical current of HTS tape	65 [A]
Former diameter	25.5 [㎜]
Thickness of Kapton insulation	0.1 [㎜]
Thickness of insulation layer	4.51 [㎜]
Diameter of magnetic shield layer	38.54 [㎜]
Winding pitch	200～600 [㎜]
Operating Current	1260 [A]
Total cable length	250 [m]

2.2. Analysis theory

2.2.1. Inductance calculation

Fig. 1 shows the schematic view of the winding in an HTS power transmission cable. For a single layer configuration the magnetic flux density, ***B***, is deduced by the use of Ampere's law. This is separated in an axial field and a tangential field as Fig. 2. The self inductance is obtained by calculating the enclosed magnetic field energy and the self inductance, ***L*** [H/m], leading to :

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

where, l_{pi} is the winding pitch of the layer given from the winding angle $\alpha(\tan\alpha = 2\pi r_i / l_{pi})$, r_i is the radius of the layer and, μ_0 is the vacuum permeability ($4\pi \times 10^{-7}$ [H/m]), D is the distance between the layer and the center of the return path.

The mutual inductances per unit length between an inner layer i and an outer layer j, $M_{ij}(=M_{ji})$, is given by formula (2) and (3) [3];

$$W_m = W_{mi} + W_{mb} + W_{mo} = \frac{1}{2} L_i I_i^2 + \frac{1}{2} L_j I_j^2 + M_{ij} I_i I_j, \qquad (2)$$

$$M_{ij} = M_{ji} = \frac{a_i a_j \mu^0}{l_{pi}\, l_{pj}} \pi r_i^2 + \frac{\mu_0}{2\pi} \ln\left(\frac{D}{r_j}\right) \ (r_j > r_i), \qquad (3)$$

where, L_i and L_j are the self inductances of layers i and j. I_i and I_j are the currents in layers i and j. a_i and a_j are constants (+1 or -1) taking into account the relative winding directions.

Also, the self and mutual inductances can be calculated by another approximate analysis method. The mutual inductance M_{ij} between an inner layer i and an outer layer j is given by

$$M_{ij} = M_{zij} + M_{\theta ij} \quad [H/m], \qquad (4)$$

where, M_{zij} is mutual inductance by the axial direction current component and $M_{\theta ij}$ is mutual inductance by the radial direction current component. In the case of $i=j$, self inductance of the th layer can be found by this formula [4].

The two inductance components are given by the following equations;

$$M_{zij} = \frac{\mu_0}{2\pi}\left(\ln\frac{2\ell_{total}}{r_j} - 1\right), \qquad (5)$$

$$M_{\theta ij} = \mu_0 \pi r_i^2 \left(\frac{\tan\alpha_i}{2\pi r_i}\right)\left(\frac{\tan\alpha_j}{2\pi r_j}\right), \qquad (6)$$

$$= \frac{\mu_0}{4\pi}\left(\frac{r_i}{r_j}\right)(\tan\alpha_i)(\tan\alpha_j)$$

where, l_{total} is the total cable length, r_i is radius of ith layer and α_i is pitch angle of ith layer, respectively.

2.2.2. The equivalent electrical circuit model by the impedance of cable

Fig. 3 shows the equivalent circuit for a cable with layers. The equivalent circuit for the magnetic shield layer is also represented in the same manner, except that the voltage for the shield layers differ from that of the conductor layers. As shown in the figure, an R-L circuit represents each layer in the cable. This means that we assume the current is distributed uniformly among conductors in one layer.

The equivalent circuits of the conductor layers and shield layers are merged in a matrix equation as follows;

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ e_{s1} \\ e_{s2} \end{bmatrix} = \begin{bmatrix} R_1 + j\omega L_1 & j\omega M_{1,2} & j\omega M_{1,3} & j\omega M_{1,4} & j\omega M_{1,s1} & j\omega M_{1,s2} \\ j\omega M_{2,1} & R_2 + j\omega L_2 & j\omega M_{2,3} & j\omega M_{2,4} & j\omega M_{2,s1} & j\omega M_{2,s2} \\ j\omega M_{3,1} & j\omega M_{3,2} & R_3 + j\omega L_3 & j\omega M_{3,4} & j\omega M_{3,s1} & j\omega M_{3,s2} \\ j\omega M_{4,1} & j\omega M_{4,2} & j\omega M_{4,3} & R_4 + j\omega L_4 & j\omega M_{4,s1} & j\omega M_{4,s2} \\ j\omega M_{s1,1} & j\omega M_{s1,2} & j\omega M_{s1,3} & j\omega M_{s1,4} & R_{s1} + j\omega L_{s1} & j\omega M_{s1,s2} \\ j\omega M_{s2,1} & j\omega M_{s2,2} & j\omega M_{s2,3} & j\omega M_{s2,4} & j\omega M_{s2,s1} & R_{s2} + j\omega L_{s2} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_{s1} \\ I_{s2} \end{bmatrix}$$

$$(I_{total} = I_1 + I_2 + I_3 + I_4) \qquad (7)$$

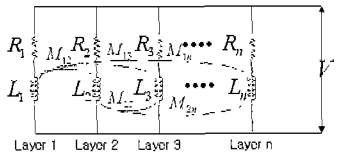


Fig. 3. Equivalent circuit of the power transmission cable with layers

where, V_n is voltage drop of the conductor layers and e_{s1}

to e_{s2} are voltage drops of the shield layers[V/m]. The R_i in the equation are contact resistances between the conductors and the terminal bushing, if the cable is in a normal operating condition. ω is the angular frequency ($2\pi f$) and j is the imaginary unit. I_1 to I_4 are currents of the four conductor layers, and I_{s1} to I_{s2} are currents of the shield layers [A]. The total operation current of the cable is sum of the currents of the four conductor layers.

The current will begin to redistribute when the current in a layer reaches the critical current. Thereby the critical current of the layers also can play a direct role.

Since, we are not calculating a particular cable, but calculating characteristics of HTS cables with various pitches, all the calculations are done for unit length of the cable and the resistances are ignored. The voltage of the shield layers is set to zero, because on the end of the cable, the shield layers of the three phases are connected together with the ground.

The above matrix equation is to obtain currents of the layers, so it is necessary to know the voltages of the layers, which is not known. Thus, we used an arbitrary value for the voltage and calculate the currents by multiplying the inverse matrix of the impedance matrix and voltage matrix. The calculated total current may be different from a design goal, but we can use the ratio for our purpose.

2.2.3. The AC loss in a multi-layer HTS power transmission cable

The AC loss is induced by flowing alternating current or penetrating a external magnetic field. We can classify the AC loss; one is self field loss by only self magnetic field and the other is external field loss by only external magnetic field.

In this paper, self field loss is calculated by Norris formula [5];

$$Q_i = \frac{\mu_0 f I_{ci}^{\,2}}{2\pi}\{(2-F_i)F_i + 2(1-F_i)\ln(1-F_i)\} \quad [W/m], \qquad (8)$$

where, f is the frequency, $F_i = I_{pi} / I_{ci}$ is the ratio of the peak current and the critical current.

Magnetization loss by an external field is calculated by formula [6];

$$\begin{aligned} Q_i &= \frac{2f B_{i//}^2}{\mu_0}\frac{\beta_i}{3}S_i \quad \beta_i < 1, \qquad (9)\\ &= \frac{2f B_{i//}^2}{\mu_0}\left(\frac{1}{\beta_i} - \frac{2}{3\beta_i^3}\right)S_i \quad \beta_i > 1 \end{aligned}$$

$$\beta_i = \frac{B_{i//}}{}$$

where, b is the thickness of the HTS tape, J_c is the critical current density, $B_{i//}$ is the parallel magnetic component in the HTS tape.

3. CALCULATION RESULT AND DISCUSSION

3.1. Calculation program

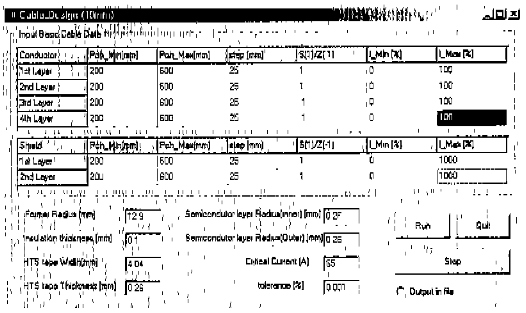
We developed a calculation program to explore current distribution among layers and AC loss of cable as shown Fig. 4.

3.1.1. Structure of the calculation program

The input data in this program are basic specification of the HTS tape and the cable. Fig. 4 shows the execution window of the software. When we input the necessary data and press the "Run" button, the software calculates currents and AC losses for all of the cases within the pitch ranges given in the execution window. All results that satisfy the given condition (minimum and maximum currents for layers) are written in a file. Fig. 5 shows the flowchart.

3.1.2. Calculation result

For the conductor layers, there are eight possible combinations of the direction; ssss, sssz, sszs, szss, zsss, sszz, szzs and szsz. For each combination, there are again 4 combinations of the shield layer direction; ss, sz, zs and zz. Therefore, we have 32 cases to calculate. But, we already selected 'SSZZ+SS' type among 32 possible combinations of the direction as the investigating model.



Input Basic Cable Data

Conductor	Pch_Min[mm]	Pch_Max[mm]	step [mm]	S(1)/Z(-1)	I_Min [%]	I_Max [%]
1st Layer	200	600	25	1	0	100
2nd Layer	200	600	25	1	0	100
3rd Layer	200	600	25	1	0	100
4th Layer	200	600	25	1	0	100

Shield	Pch_Min[mm]	Pch_Max[mm]	step [mm]	S(1)/Z(-1)	I_Min [%]	I_Max [%]
1st Layer	200	600	25	1	0	1000
2nd Layer	200	600	25	1	0	1000

Former Radius (mm) 12.9
Insulation thickness (mm) 0.1
HTS tape Width(mm) 4.04
HTS tape Thickness (mm) 0.26
Semiconductor layer Radius(inner) (mm) 0.2F
Semiconductor layer Radius(Outer) (mm) 0.26
Critical Current (A) 65
tolerance (%) 0.001

Fig. 4. Program execution window

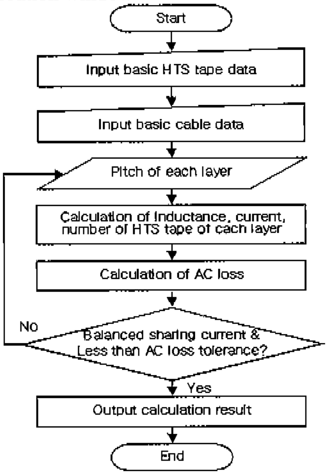


Fig. 5. Program flow chart

Although, there are a tremendous number of possible combinations, not many combinations make useful results.

We are trying to make the current sharing among the conductor layers as even as possible, so the best result is obtained when the currents of the four conductor layers are 25% of the total current.

This is not exactly true, because a number of conductors in layers are different and the critical currents of the four layers can be different due to the magnetic field. However, the difference is small and we ignored that.

When the pitch of the 1st layer is fixed and pitches of other layers are changed gradually, we find current distribution aspect of each layer in the cable. In the case of 'SSZZ+SS', Fig. 6 represents current distribution aspect of layers when the pitch of the first layer is longer.

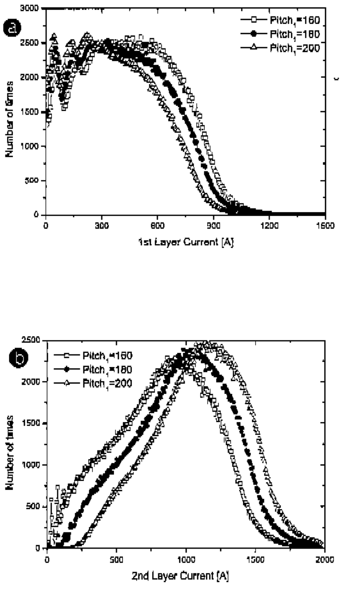
Generally, as longer pitch of th layer, the inductance of the layer decreases then the current of the layer flows more increases[7].

In a separate way of this, as shorter pitch of 1st layer, Fig. 6 represents that a number of combinations to flow higher operation current increases.

Also, in the case of 4th layer, operation current is not changed nearly for changing the pitch of the 1st layer. Considering of total operation current of the cable is 1260[A], we can confirm that longer pitch of the 1st layer has a bad effect for uniform current distribution of cable.

Fig. 7 shows the AC loss aspect of Layers according to changing the pitch of 1st layer. This results display combination to have a small mount of AC loss in the most of layer, as shorter pitch of 1st layer, likewise

Fig. 8 shows pitch distribution aspect of each layer for balanced current distribution, according to changing the pitch of the 1st layer. We also found out that decreasing pitch of 1st layer enlarges a range of other's layer pitch for balanced current distribution in cable.



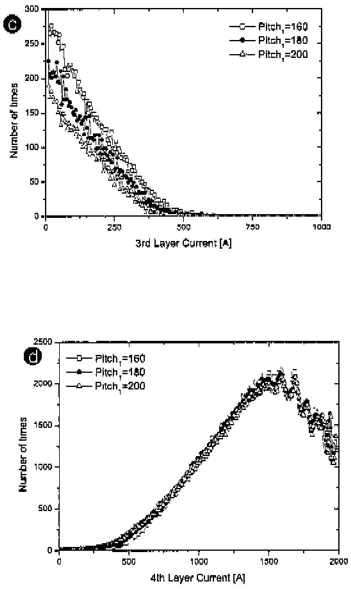
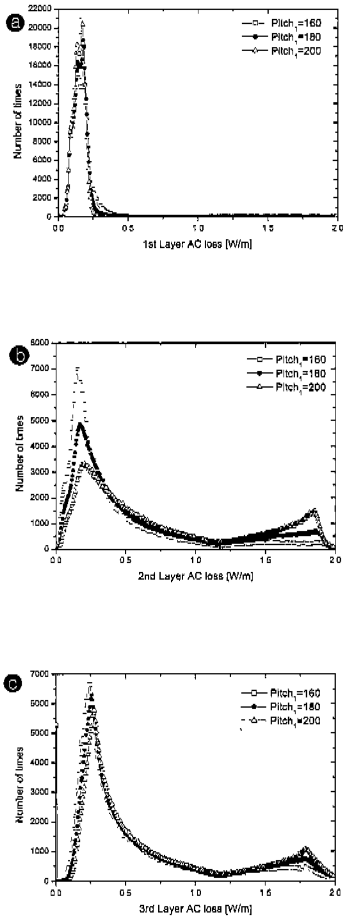


Fig. 6. Current distribution aspect of each Layer according to changing pitch of 1st layer. (a) 1st layer, (b) 2nd layer, (c) 3rd layer, (d) 4th layer



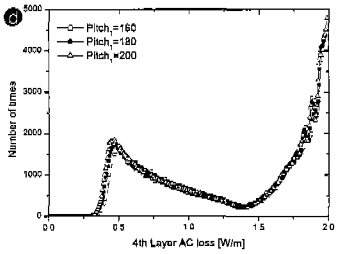


Fig. 7. AC loss aspect of each layer according to changing pitch of 1st layer. (a) 1st layer, (b) 2nd layer, (c) 3rd layer, (d) 4th layer

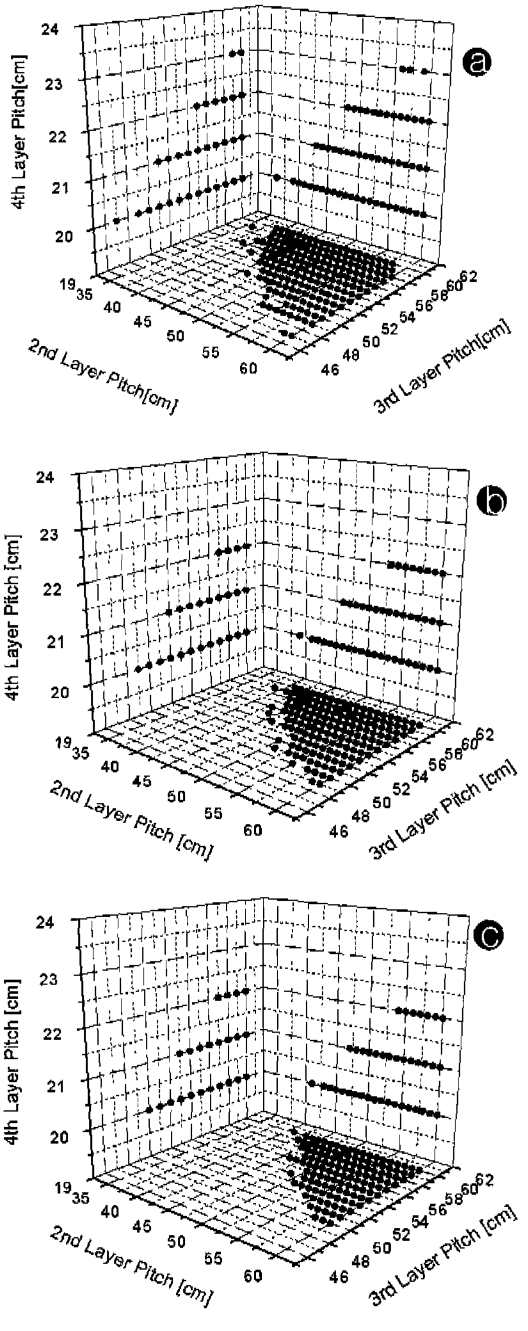


Fig. 8. Pitch distribution aspect of each Layer according to changing pitch of 1st layer. (a) 1st layer pitch = 16[cm], (b) 1st layer pitch = 18[cm], (c) 1st layer pitch = 20[cm]

4. CONCLUSION

In this paper, we can calculate inductance of each layer for the 4-layer HTS power transmission cable that consists of 4 conductor layers and 2 magnetic shield layers.

Dealing with this, our paper is referred to current distribution and AC loss of cable by an analytic method. We selected 'SSZZ+SS' type as the investigating model. Then we find out a variable relation of current distribution, the AC loss, the pitches of other layers for cable according to adjusting pitch of 1st layer.

Based on the facts that have been investigated, we conclude that a shorter pitch of 1st layer in cable design has a better effect for uniform current distribution and AC loss.

From these facts, we can recommend for future cable conductor prototypes and really they may be confirmed by producing cable.

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