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Author(s)	Hoshino, T; Yamaji, N; Muta, I; Nakamura, T; Higuchi, N; Natori, N; Fuchino, S; Arai, K
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Measured-loss Analysis of Superconducting Power Transmission Cable

Tsutomu Hoshino, Norifumi Yamaji, Itsuya Muta, Taketsune Nakamura,
Graduate School of Engineering, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan

Noboru Higuchi, Naotake Natori, Shuichiro Fuchino and Kazuaki Arai
Electrotechnical Laboratory, Ibaraki 305-8568, Japan

Abstract-- **In the former work [6], the eddy current loss in the former due to pitch difference between current conductor and shield conductor was studied. The calculated value was negligible small which does not explain the measured value. The eddy current loss due to radial component of the magnetic field become comparable with the measured value.**

In this paper, the reason of the increased loss is revealed. The disturbance of the conductor pitch yields different strength of the axial magnetic field. The difference of the axial flux toward the radial direction as the radial component of the flux. The flux causes eddy current loss in the copper for stabilizer. It is well match with the measured value.

I. Introduction

Recently some electric power companies began to fabricate the single-phase power cable core with high Tc superconducting tapes. Their first target is 66 kV, 500 MVA class superconducting power transmission line cooled with sub-cooled liquid-nitrogen.

The authors made five 10 m-long Nb_3Sn superconducting power transmission cables in the 1980s [1,2]. Current tests of those cables were carried out cooled with liquid or supercritical helium. Cable conductors consist of two layers of helical-wound tapes, one for transport current and another for shield. Electrical insulation consists of wrapped plastic tapes. Countermeasure against thermal contraction is one of the major factors in the design of this type of the cables, especially when superconducting materials in use are brittle.

The latest cable "N" is designed to suppress the stress inside the cable caused by thermal contraction, with a compromise between ideal design and restriction of cable assembly. AC losses of the latest cable "N" are reduced to about 1/5 to 1/10 of that of the other cable. Nevertheless, they were ten times larger than those of material tapes were.

To investigate the causes of the higher AC losses in cable, cable "N" was disassembled after the AC loss measurement. The cable "N" is free from such degradation.

In this paper, we describe current distribution analysis of the cable and equivalent magnetic field analysis.

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T. Hoshino, hoshino@asl.kuee.kyoto-u.ac.jp, http://www.asl.kuee.kyoto-u.ac.jp; I. Muta, muta@kuee.kyoto-u.ac.jp

II. Design of the Cables

Cables are composed of two layers of conductors, one for the transport of current, the other for the shield current to reduce eddy current losses in the cooling channels [3] as shown in Fig. 1. The conductor tapes and insulator in the cable are to be helically wound at appropriate lay angles. For the conductor tapes, the most appropriate lay angles are defined by the following equation.

$$\tan\psi_2/R_2 = \tan\psi_1/R_1 \tag{1}$$

where R_1, R_2 are radius of shield and transport conductor, ψ_1, ψ_2 are lay angle of shield and transport conductor, respectively. If conductors are wound on this condition, the magnetic flux density at the center of the cable becomes zero. The eddy current losses inside the transport conductors can be eliminated. The dimensions of cable "N" are shown in Table I.

III. Analysis of Magnetic Field and Eddy Current Loss

A. *Axial component of the magnetic field*

Assuming that the shield conductor fed counter current of the transport conductor current, Ampère's law tells us

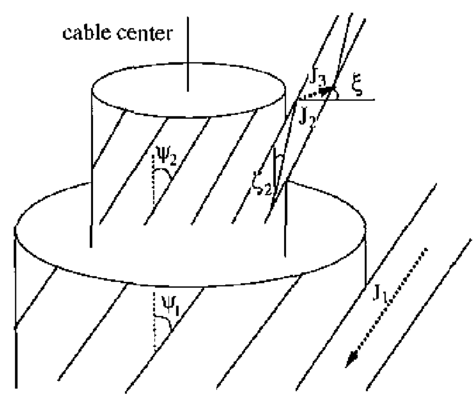

Fig. 1. Lay angles of the cable.

TABLE I Dimensions of Cable "N"

No. of layers	contents and materials	O.D.	winding direc. & pitch		tape size thickness × width (× pieces)
1	former, SUS corrugate tube with SUS mesh	27.0			
2-8	diameter adjuster, tyvek	28.6	LH	110 ~ 124	0.125 × 70
9	stabilizer performed OFHC tape	29.4	RH	250	0.3 × 6.5 × 13
10	-	30.0	LH	-	-
11	superconductor, Nb_3Sn tape	30.24	RH	-	0.12 × 6.45 × 13
12-21	insulator, tyvek	32.24	LH	112	0.125 × 70
22-75	-, every 6 layer		RH/LH	64 ~ 70	0.125 × 27 × 2
76-80	-		LH	-	-
81-85	-	45	LH	69	0.125 × 59
86	superconductor, NB_3Sn tape	45.34	RH	250	0.17 × 5 × 23
87	stabilizer performed OFHC tape	45.94	LH	-	0.3 × 6.5 × 19
88	-	46.54	RH	-	-
89-93	insulator, tyvek		LH	66	0.125 × 59
94-117	-, every 6 layer		RH/LH	70	0.125 × 27 × 2
118	-	52.6	RH	-	-
119-120	-				0.125 × 27 × 1/2

that there is no θ direction magnetic field in cylindrical coordinates (r, θ, z). The current $-I$ through the shield conductor flows inner surface along with the lay angle ψ_1. The (surface) current density J_1 was expressed as follows

$$I = -J_1 \cos\psi_1 (2\pi R_1 - N d_1) \tag{2}$$

where N_1 is the number of shield conductor tapes and d_1 is the gap between shield conductor tapes.

Define ζ_2 as the direction of outer surface current density J_2 through the transport conductor, ξ as the direction of inner surface current density J_3 through the transport conductor. The relation

$$J_2 \sin(\psi_2 - \zeta_2) = J_3 \cos(\psi_2 + \xi) \tag{3}$$

$$\begin{aligned} I &= J_2(2\pi R_{2o} - N_2 d_2)\cos\zeta_2 \\ &+ J_2(2\pi R_{2i} - N_2 d_2)\frac{\sin(\psi_2 - \zeta_2)}{\cos(\psi_2 + \xi)} \end{aligned} \tag{4}$$

is obtained. Where N_2 is the number of transport conductor tapes, d_2 is the gap between transport conductor tapes, R_{2o}, R_{2i} are outer and inner radius of transport conductor.

Analyzed magnetic field are described in the former work [6]. When the pitch of the transport conductor is not equal to that of the shield conductor, the axial magnetic field within the transport conductor described as follows:

$$\begin{aligned} H_{zi} &= J_2 \frac{\sin(\psi_2 - \zeta_2)}{\cos(\psi_2 + \xi)} \\ &\times \left\{ \cos\xi - \frac{N_2 d_2 \sin\psi_2 \sin(\psi_2 + \xi)}{2\pi R_{2i}} \right\} \end{aligned} \tag{5}$$

Then the eddy current loss P_e in the copper stabilizer is expressed as

$$P_e = \mu_0^2 d_s^3 w_s^3 N_s \omega^2 H_{zi} \cos\psi_s / \{32\rho(d_s^2 + w_s^2)\} \tag{6}$$

where ω is the angular velocity of the current, d_s, w_s, N_s, ψ_s, ρ are thickness, width, number, lay angle and resistivity of the stabilizer, respectively.

B. Radial component of the magnetic field

As shown in Fig. 2, I is the current through the transport conductor, l_1 and l_2 are the winding pitch of the transport conductor and the shield conductor respectively. The radial component of the magnetic field is described as follows,

$$H_z(r) = \begin{cases} -I/l_2 & (R_2 < r < R_3) \\ I/l_1 - I/l_2 & (R_1 < r) \end{cases} \tag{7}$$

where, R_1 is inner diameter of transport conductor, R_2 is outer diameter of shield conductor, R_3 is inner diameter of shield conductor. If there is pitch difference between region A and region B, there is difference of axial flux density. The difference of axial flux become radial component, because of continuity of the flux as shown in Fig. 2. The relations between flux are described as follows;

$$\Phi_{1r} = \Phi_{1A} - \Phi_{1B} \tag{8}$$

$$\Phi_{3r} = \Phi_{3A} - \Phi_{3B} + \Phi_{1r} \tag{9}$$

The flux Φ_{1r} and Φ_{3r} through the butt gap of superconducting tapes. Assuming that the radial flux distribution describes as a function of Gaussian distribution as follows

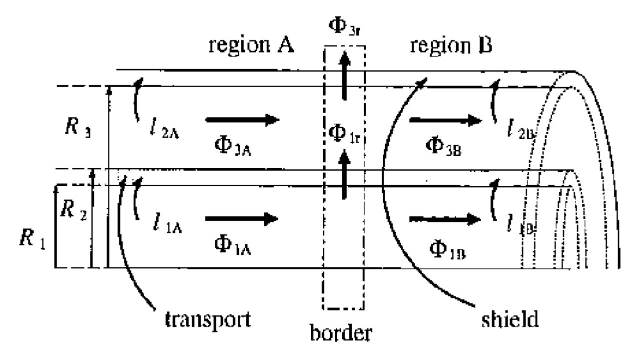

Fig. 2. Flux flow in the single phase cable.

TABLE II Measured Pitches of the Cable "N".

layer	2 m point A	2 m point B	4 m point A	4 m point B	6 m point A	6 m point B	8 m point A	8 m point B
outer layer of 1st insulator	121	—	120	—	120	—	120	—
1st layer of inner copper	248	249	251	249	250	250	255	250
2nd layer of inner copper	247	255	249	251	248	250	249	250
inner Nb_3Sn	249	246	248	247	250	249	254	246
10th layer of 2nd insulator	102	104	101	102	102	102	102	102
50th layer of 2nd insulator	64	—	63	—	64		64	–
outer layer of 2nd insulator	68	68	69	69	69	68	69	68
outer Nb_3Sn	248	253	252	253	246	250	250	247
1st layer of outer copper	251	248	253	251	252	250	249	251
2nd layer of outer copper	250	248	252	250	252	251	251	250
5th layer of 3rd insulator	67	67	66	67	67	67	67	66
outer layer of 3rd insulator	63	–	64	–	66	–	62	–

A: assemble, B: disassemble, units in mm.

$$f(z) = \frac{1}{R_1} \exp\left\{\frac{-\pi(z-z_0)^2}{R_1^2}\right\} \quad (10)$$

with length R_1 or R_3 which is same as conductor radius. Under the condition the flux density is less than lower critical field of Nb_3Sn, there is no radial component flux in the conductor. Using this formula, the eddy current loss in the inner copper layer is obtained. Similarly, the flux Φ_{3r} gives the eddy current loss in the outer copper layer.

IV. Evaluation of Eddy Current Loss

Measured pitches of the cable "N" are listed in TABLE II. The pitches were measured during assembly and disassembly after all tests. The pitch distribution of the conductor after all tests are shown in Fig. 3. Substituting the values of Nb_3Sn superconductor pitches to the equation (6) for each pitch section, the eddy current loss in the former due to axial flux is negligible small as shown in Fig. 4. Assuming that the resistivity of the copper for stabilizer is $\rho = 1.6 \times 10^{-10}$ Ωm, the eddy current loss in inner copper and outer copper obtained. Short sample AC loss values are also indicated. All values are converted to one meter cable base. (short sample AC loss of transport conductor) is proportional to (transport current)$^{3.37}$, and (short sample AC loss of shield conductor) is proportional to (transport current)$^{2.80}$. (eddy current loss) is proportional to (transport current)^2, but the eddy current loss in the copper is neglected (not indicated in the figure), as smaller than 10^{-3} W/m.

The measured pitches were distributed with the standard deviation listed in TABLE III. The pitch difference of the two superconducting layers are shown in Fig. 5. The axial flux shall change its direction to radial direction. The radial flux makes eddy current on the surface of the stabilizer and conductor and changes the direction ζ_2 of surface current J_2. Substituting the values of Nb_3Sn

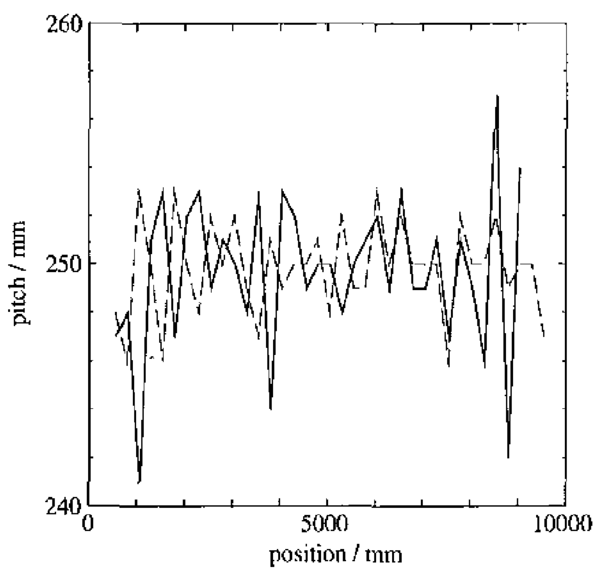

Fig. 3. Pitch distribution of cable "N", solid line: conductor pitch, broken line: shield pitch.

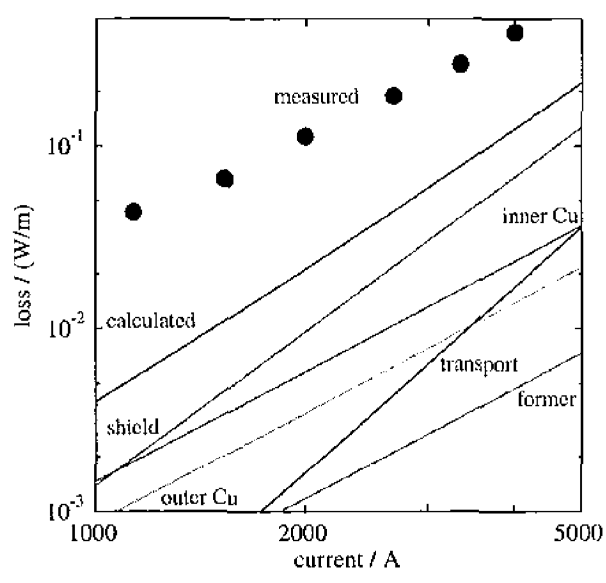

Fig. 4. Measured and calculated loss of cable "N".

TABLE III
THE STANDARD DEVIATION OF MEASURED PITCHES.

	assemble		disassemble
layer	set 1	set 2	set 1
1st layer of inner copper	2.39	1.93	0.55
2nd layer of inner copper	2.17	1.91	1.97
inner Nb_3Sn	2.04	2.03	1.94
outer Nb_3Sn	1.87	1.73	3.28
1st layer of outer copper	1.66	1.56	1.77
2nd layer of outer copper	1.56	1.75	1.44

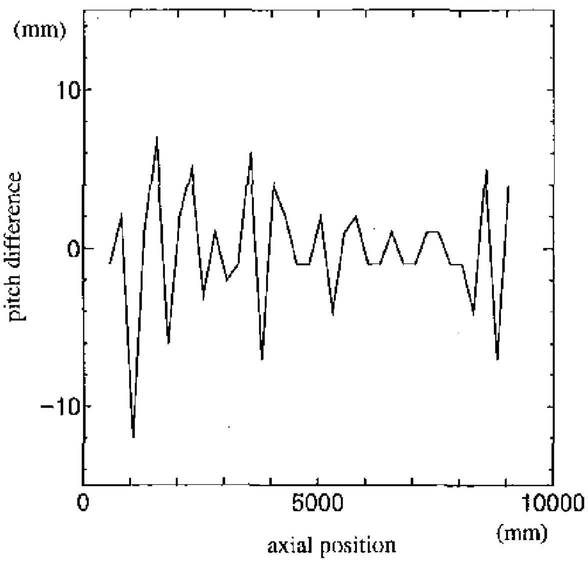

Fig. 5. Pitch Difference Distribution of the Superconducting Layers.

superconductor pitches to the equation (7), (10) for each pitch section, the eddy current loss in the copper layer due to radial flux obtained as shown in Fig. 4. In Fig. 6, the relationship between the current direction ζ_2 on the outer surface J_2 of inner superconductor and eddy current loss P_e. The loss was calculated as peak current density is 500 A/cm. The loss of 1.5×10^{-2} W/m corresponds to the 8.7 % deviation of ζ_2/ψ_2 which is comparable to the loss of short sample test.

V. CONCLUSION

The eddy current loss in the former and the stabilizer was calculated using the disassembled data of cable "N". The pitch effect of the difference between transport layer and shield layer was one-tenth order of the material tape loss. The pitch difference is not a dominant reason to increase the AC loss.

From a viewpoint of the current distribution, the current flow direction on the outer surface of the transport conductor affects remarkably on the eddy current loss. The difference of axial flux yields radial flux and change the current direction from lay angle of the conductor tape at 8.7 percent.

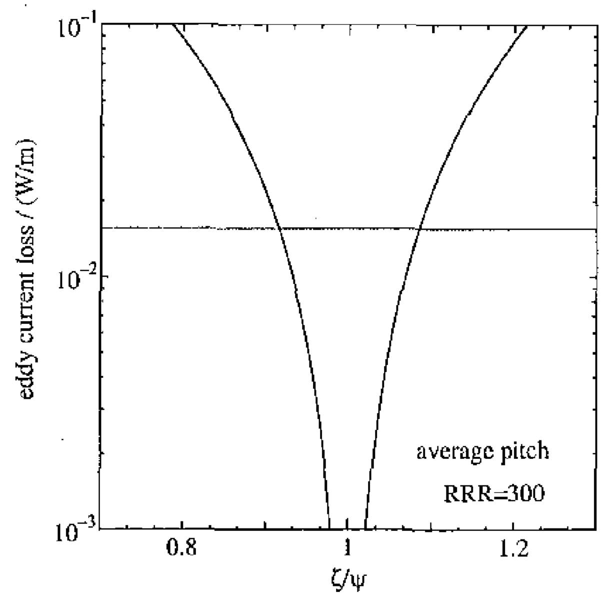

Fig. 6. Relationship between current direction on the outer surface of inner superconductor and eddy current loss.

The mechanism of the radial flux generation is revealed in this paper. The sum up calculated loss is 1/5 of the measured loss. The remaining (not evaluated) loss is the eddy current loss of the metals clad on superconducting tape. The remaining difference shows us to reduce way with manufacturing scheme.

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