AC losses in multilayer power transmission cables comprising YBCO tapes

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Abstract AC losses in multilayer power transmission cables can be reduced by adjusting the helical winding pitch of each layer to make the layer's current distribution uniform. The optimum helical pitches can be estimated by a calculation using an electric circuit (EC) model based on an expression that calculates the losses in the superconducting tapes composing the cable. It is known that the losses in a monolayer cable depend on the cable parameters (i.e. the gap $2g$ between neighboring tapes, number N of the tapes, diameter $2r$ of the cable former and width w of the tape), and Malozemoff et al have reported a formula for calculating the monolayer cable losses that considers these parameters based on Mawatari and Kajikawa's analytical treatment. However, regarding Amemiya et al's measurement on the losses in monolayer cables, the numerical results of the losses calculated using the Norris formula for an isolated thin strip in N time are closer to the experimental results than those calculated using Malozemoff's expression. Then, to determine the losses in a three-layer cable that Mukoyama et al have reported, the losses are calculated by the EC model based on the Norris formula. The helical pitch of each layer is adjusted to make the layer's current distribution uniform in the cable reported by Mukoyama et al. At 1 kA_{rms}, the optimum helical pitches are calculated using the condition that the standard deviation of the layer currents is minimized, and the losses in the cable in the case of the optimum helical pitches are calculated. The mean error of the calculated values relative to the measured values is 23.7 %, which indicates that the calculation using the EC model is useful as a first approximation.

Electric circuit model

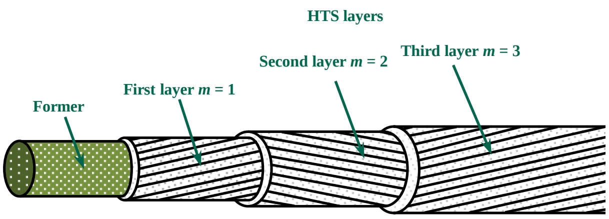

Fig. 1 Schematic diagram of three-layer HTS cable comprising YBCO tapes.

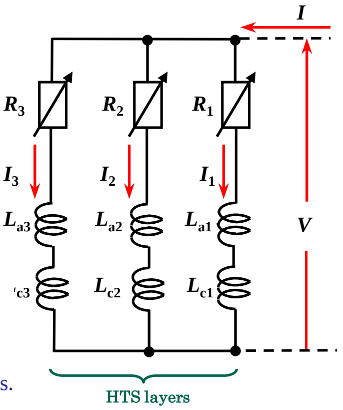

Fig. 2 Electric circuit model applied to three-layer HTS cable.

- **Resistance R_m**

P_{NS}

$$R_m(I_m) = \frac{\sqrt{(2\pi r_m)^2 + {p_m}^2}}{p_m} \frac{N_m P_m}{{I_m}^2} \quad (\Omega\text{m}^{-1})$$

r_m : the radius of the HTS layer
p_m : the helical pitch of the HTS layer
N_m : the number of the YBCO tapes
P_m : the loss of the YBCO tape
I_m : the r.m.s. value of the peak layer current

- **AC loss of the HTS cable P_{EC}**

$$\boxed{P_{EC} = \frac{1}{2}\text{Re}\left(\dot{V}\dot{I}_t^{\,*}\right) \quad (\text{Wm}^{-1})}$$

V : the complex number voltages
I_t : the transport current of the HTS cable
I_t* : the complex conjugate of I_t

In the EC model, the electromagnetic properties of each layer consist of resistance R_m and self-inductances L_{am} and L_{cm}. The interaction between the HTS layers is denoted by mutual inductances M_{am} and M_{cm}. Because the current in an HTS cable flows into a helicoid, the generated magnetic field is divided into the circumferential field and the axial field. The axial field inductances are L_{am} and M_{am}, and the circumferential field inductances are L_{cm} and M_{cm}. Using the loss P_m of the tapes constituting the cable, R_m is given as described above.

AC losses in monolayer cables

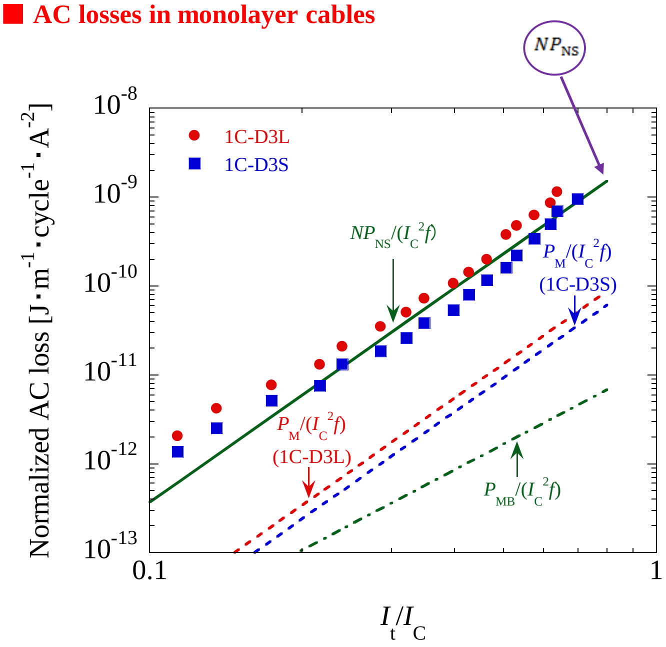

Fig. 4 Normalized loss as a function of normalized current for monolayer cables.

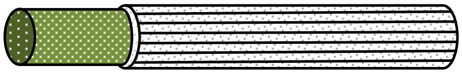

Fig. 3 Schematic diagram of monolayer HTS cable comprising YBCO tapes.

- **Norris formula for a thin strip**

$$\boxed{P_{NS} = \frac{{I_{C1}}^2 \mu_0 f}{\pi}\left((1-F)\ln(1-F) + (1+F)\ln(1+F) - F^2\right) \quad (\text{Wm}^{-1})}$$

I_{C1} : the critical current of the YBCO tape
μ_0 : the magnetic permeability of vacuum
f : the frequency f = 50 Hz
F : the normalized current of the YBCO tape I_{t1}/I_{C1}
I_{t1} : the transport current of an individual tape

The red solid circles show the measurement results for 1C-D3L, and the blue solid squares show the measurement results for 1C-D3S; both measurement results are taken from Reference **[**N. Amemiya, Z. Jiang, M. Nakahata, M. Yagi, S. Mukoyama, N. Kashima, S. Nagaya, Y. Shiohara, IEEE Trans. on Appl. Supercond. 17 (2007) 1712–1717**]**. The specifications of these cables are shown in Table 1. The green solid line is a calculation result based on the Norris formula. The red dotted line and the blue dotted line are calculation results for the cables 1C-D3L and 1C-D3S, respectively, based on the Malozemoff formula. These results differ because the cable parameters differ. The green dash-dot line is the calculation result based on the monoblock model.

Malozemoff formula for a monolayer cable

$$P_{\mathrm{M}} = \frac{\pi^3 I_{\mathrm{C}}^{\,2} \mu_0 f}{48} \frac{g^2}{2Nw^2} F^4 \quad (\mathrm{Wm^{-1}})$$

I_C : the critical current of a monolayer cable
$2g$: the gap between tapes
N: the number of the YBCO tapes
$2w$: the width of the YBCO tape

Monoblock model

$$P_{\mathrm{MB}} = \frac{I_{\mathrm{C}}^{\,2} \mu_0 f}{3\pi} \frac{d}{r} F^3 \quad (\mathrm{Wm^{-1}})$$

Table 1 Specifications of monolayer cables.

Cable name	1C-D3L	1C-D3S
Former diameter $2r$	20 mm	19.2 mm
Number of tapes N	18	18
Tape width $2w$	3.18 mm	3.18 mm
YBCO layer thickness d	1 µm	1 µm
Average gap between tapes $2g$	0.31 mm	0.17 mm
Total critical current I_C	819.5 A	861.1 A
Parameter g/w	0.098	0.053

As Fig. 4 shows, the calculation result based on the Norris formula is quantitatively closer to the measurement results. The calculation results based on the Malozemoff formula are smaller than the measurement results by one or more orders of magnitude. Moreover, the result based on the monoblock model is smaller than the results based on the Malozemoff formula. In these monolayer cables, the loss reduction by adjusting the cable parameters is not effective, but it is apparent that the electromagnetic characteristics of the tapes constituting the cable are not much different from those of the isolated tape. However, the calculation result based on the Norris formula does not fit the measurement results qualitatively; therefore, a formula that gives results in agreement with the measurement results both quantitatively and qualitatively is required.

■ AC losses in three-layer cables

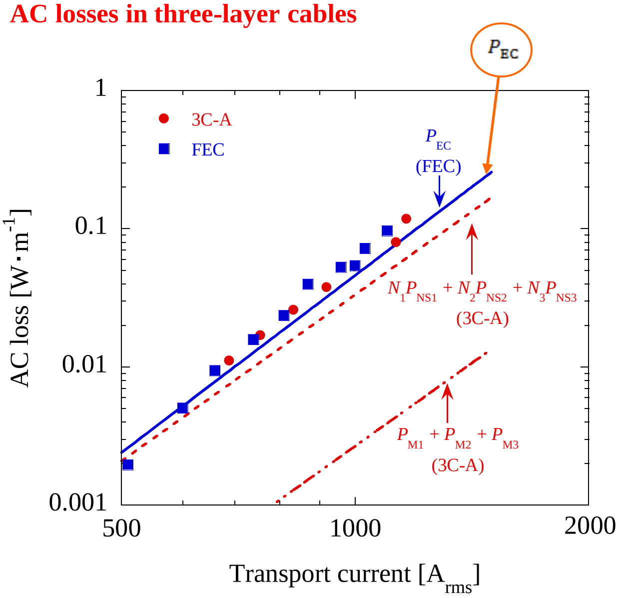

Fig. 6 AC loss as a function of transport current for three-layer cables.

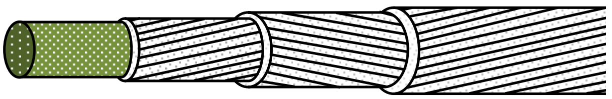

Fig. 5 Schematic diagram of three-layer HTS cable comprising YBCO tapes.

In Fig. 6, the red solid circles are the measurement results of the Amemiya cable, and blue solid squares are measurement results of the Mukoyama cable. P_{EC} is close to the two measurement results, and the mean error relative to the measurement results of the Mukoyama cable is 23.7 %. Except near It = 500 A_{rms}, the two measurement results are slightly larger than P_{EC}. This inequality may be due to the interaction between different layers (for example, the increase in the loss by the perpendicular field generated in the tape of the first layer causing a loss in the tape of the second layer).

Table 2 Specifications of three-layer cables.

Cable name	3C-A	FEC
Outer diameter	19.6 mm	19.6 mm
Inner diameter of layer 1 $2r_1$	17.3 mm	17.3 mm
Inner diameter of layer 2 $2r_2$	17.9 mm	17.9 mm
Inner diameter of layer 3 $2r_3$	19.2 mm	19.2 mm
Tape number of layer 1 N_1	27	27
Tape number of layer 2 N_2	28	28
Tape number of layer 3 N_3	30	30
Tape width $2w$	1.8 mm	1.8 mm
YBCO layer thickness d	1.4 µm	1.4 µm
Gap between tapes in layer 1 $2g_1$	0.21 mm	0.21 mm
Gap between tapes in layer 2 $2g_2$	0.20 mm	0.20 mm
Gap between tapes in layer 3 $2g_3$	0.21 mm	0.21 mm
Critical current of layer 1 I_{C1}	699 A	699 A
Critical current of layer 2 I_{C2}	705 A	705 A
Critical current of layer 3 I_{C3}	778 A	778 A
Parameter of layer 1 g_1/w	0.12	0.12
Parameter of layer 2 g_2/w	0.11	0.11
Parameter of layer 3 g_3/w	0.12	0.12
Calculated helical-pitch of layer 1 p_1	Not helical	865 mm (S)
Calculated helical-pitch of layer 2 p_2	Not helical	125 mm (Z)
Calculated helical-pitch of layer 3 p_3	Not helical	150 mm (S)

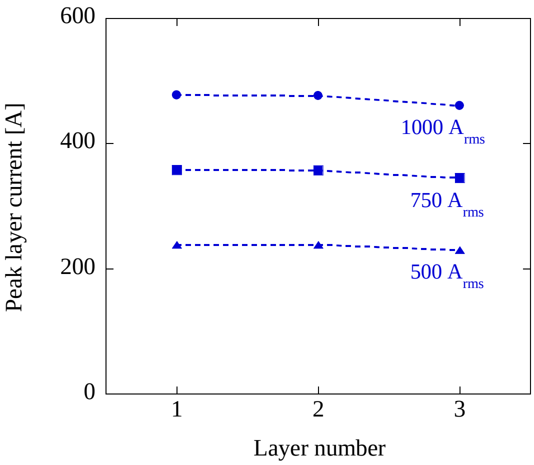

Fig. 7 Peak layer current as a function of layer number for the three-layer cable FEC.

The results of the layer currents calculated using the EC model are shown in Fig. 7. The dotted line in the figure is just a guide for the eyes. This figure shows that the layer currents are almost uniform for each transport current I_t. However, the third layer's current becomes slightly smaller compared to the other layer currents as I_t increases from 500 A_{rms} to 1000 A_{rms}. Compared with the loss $N_1P_{NS1}+N_2P_{NS2}+N_3P_{NS3}$ calculated from the Norris formula, P_{EC} is large, and it is thought that the inequality of the layer currents increases P_{EC} with the increase in transport current. The losses calculated from the Malozemoff formula are smaller by one or more orders of magnitude than the measurement results, although g_m/w of each layer in Table 2 is smaller than 0.405.