Cryogenics 49 (2009) 34–38

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Numerical study on self-field losses of 30 m BSCCO HTS transmission cable

H. Noji *

Department of Electrical and Information Engineering, Miyakonojo National College of Technology, 473-1 Yoshio-cho, Miyakonojo 885-8567, Japan

ARTICLE INFO

Article history:
Received 31 January 2008
Received in revised form 30 September 2008
Accepted 1 October 2008

Keywords:
Self-field loss
Superconducting power cable
BSCCO tapes
Electric circuit model

ABSTRACT

The self-field losses of the one phase of high-T_C superconducting (HTS) transmission cable are calculated by the electric circuit (EC) model. The one phase of HTS cable is constructed by the former of fine-strands copper rod, HTS conductor with four superconducting layers, the insulation made by polypropylene laminated paper, and HTS shielding with two superconducting layers, which was fabricated by Sumitomo Electric Industries (SEI). The length of the cable is 30 m. Each HTS layer comprises BSCCO tapes. The current-dependent resistance of HTS layers in EC model is estimated on the base of Norris expressions for ellipse. The calculated losses are compared with the experimental results measured by 4-terminal method by SEI. The calculation of alternating current (AC) losses, a summation of the self-field losses in HTS layers and the eddy-current losses in the former, is almost equal to the measurement at wide transport-current range below the lowest value of the layer critical current. This result indicates that the numerical calculation by EC model is quite reliable. The minimum AC loss is also calculated by obtaining the optimum helical-pitch lengths of HTS layers at transporting 1 kA_{rms}. The minimum loss is 36% lower than the loss of HTS cable designed by SEI at the transport current value. In HTS cable with the optimum helical-pitch lengths, the calculation of the layer currents are not uniform in HTS conductor but are almost uniform in HTS shielding, which is contradict to SEI's one. It is considered that the numerical calculation by EC model is useful to obtain the optimum helical-pitch lengths in HTS cable with the minimum AC loss.

1. Introduction

It has been reported that the self-field losses of the multiple high-T_C superconducting (HTS) tapes are strongly affected by the arrangements of the tapes. For example, Muller indicates the results of calculation that the self-field losses of the tape composed of z-stack of infinitely long superconducting slab are changed by the thickness of a strip d, the strip width $2a$ and the stacking spacing D [1]. In his report, it is shown that the self-field losses of the coplanar array of multiple HTS tapes are smaller than that of a single isolated slab. He has expressed that for small D ($D < a$) the z-stack behaves similar to an infinite superconducting slab (Norris expression for ellipse). The electromagnetic behavior of the twisted wires is more complicate. Amemiya et al. have reported a theoretical model for the electromagnetic field analysis of twisted multifilamentary HTS cable to reveal the magnetic field penetration process in them [2]. They have indicated the results of calculation that the self-field losses of mono-layer YBCO cable composed of twisted multifilament are changed by the space between YBCO tapes b [3]. In their report, it is shown that the self-field losses of YBCO tape are smaller than that of a single isolated strip. They has expressed that for large b ($b = 50$ mm) YBCO tape in the cable behaves similar to an infinite superconducting strip (Norris expression for thin strip).

On the other hand, the author has reported the self-field losses of z-stack of 15 HTS tapes [4]. In this research, the self-field losses of the z-stack were measured by the 4-terminal method and calculated by the electric circuit (EC) model based on the self-field losses of a single isolated HTS tape. The measurement and calculation are almost equal, and both values are also nearly equal to the Norris expression for ellipse. In the case of this z-stack, D is sufficiently small ($D = 0.2$ mm and $a = 1.25$ mm). The author and co-researchers have also reported the self-field losses of 4-layer HTS cable consisted of helical winding BSCCO tapes [5]. In this research, the self-field losses are calculated by EC model based on the losses of a single isolated BSCCO tape (Norris expression for ellipse). The calculation is acceptably equal to the measurement obtained by 4-terminal method. In recently, the author has reported the self-field losses of 2-layer HTS cable consisted of helical winding YBCO tapes [6]. YBCO cable was fabricated by Furukawa Electric Corporation (FEC) [7,8]. The self-field losses are calculated by EC model based on the losses of a single isolated YBCO tape (Norris expression for thin strip). Numerically calculated losses are compared with experimental results measured by FEC. The calculations are almost equal to the measurements at wide transport-current range

* Tel.: +81 986 47 1312; fax: +81 986 47 1208.
E-mail address: noji@cc.miyakonojo-nct.ac.jp

0011-2275/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cryogenics.2008.10.002

below the critical current (I_C) of YBCO cable. Considering these results, EC model based on the self-field losses described by Norris expression is not exact but it might be qualitatively acceptable to analyze the self-field losses of multiple HTS tapes.

The self-field losses of HTS cable have become of interest to design the cable structure with minimum loss. As proving a reliability of the calculation by EC model, it is necessary to collect more results comparing with the measurements of alternating current (AC) losses in HTS cables and the calculations. In this study, a 30 m, 3-core BSCCO HTS cable fabricated by Sumitomo Electric Industries (SEI) is chosen [9]. AC losses of the one phase of BSCCO HTS cable have been measured by 4-terminal method by SEI in 2002. AC loss (a summation of the self-field losses in HTS layer and the eddy current loss in the former) is calculated by EC model based on Norris expression for ellipse. The calculation method and results of AC losses in BSCCO HTS cable are presented.

2. Calculation

Fig. 1 shows a schematic diagram of the one phase of HTS cable, and Table 1 shows the main parameters of HTS cable. The one phase of HTS cable is constructed by the former of fine-strands copper rod, HTS conductor with four superconducting layers, the insulation made by polypropylene laminated paper (PPLP), and HTS shielding with two superconducting layers. HTS layers are formed by winding BSCCO tapes on the former. Fig. 2 shows EC model for the one phase of HTS cable. The self-field loss of BSCCO tape is calculated by Norris equation for ellipse. Norris expression for ellipse is described as

$$w_m = \frac{I_C^2 \mu_0 f}{\pi}\left\{(1-i_m)\ln(1-i_m) + (2-i_m)\frac{i_m}{2}\right\}\ (\mathrm{W\,m^{-1}}). \tag{1}$$

Here, i_m $(m = 1–6)$ is a normalized current of BSCCO tape and is given by $i_m = \hat{I}_m/(N_m I_C)$. $\hat{I}_m$ is a peak layer current transporting to HTS layers. This value is equal to the absolute value of complex layer-current $\dot{I}_m$. N_m is the number of BSCCO tapes constructing HTS layers, and I_C is the critical current of the tapes. f is a frequency of electric source ($f = 50$ Hz). I_C of BSCCO tape comprising HTS conductor is estimated as 44.4 A that is calculated by I_C of HTS conductor divided by $N_1 + N_2 + N_3 + N_4$ (=2.4 kA/54). On the other hand, I_C of BSCCO tape comprising HTS shielding is estimated as 50.0 A that is calculated by I_C of HTS shielding divided by $N_5 + N_6$ (=2.7 kA/54). I_C of HTS conductor and HTS shielding are measured by SEI. I_C of BSCCO tape comprising HTS conductor and HTS shielding are supposed to be equivalent. The self-field losses calculated by Norris expressions is restricted at $i_m < 1$. Instead of Eq. (1), the self-field loss for ellipse is approximated as follows:

$$w_m = 6.807 \times 10^{-6} I_C^2 \cdot i_m^{3.371}\ (\mathrm{W\,m^{-1}}). \tag{2}$$

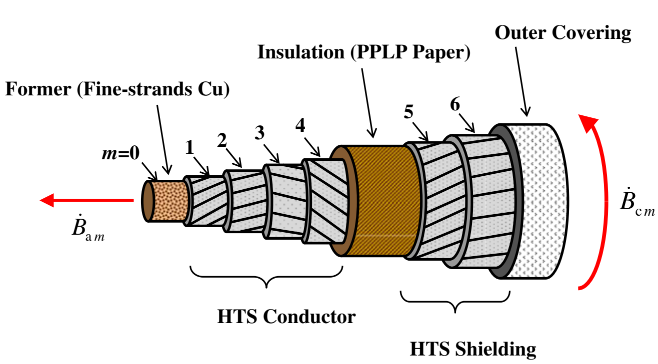

Fig. 1. A schematic diagram of the one phase of BSCCO HTS cable.

Table 1
Main parameters of 30 m BSCCO HTS transmission cable.

Layer, m	Radius, r_m (mm)	Helical direction	Helical pitch length, P_m(SEI) (mm)	Helical pitch length, P_m(min) (mm)	Number of tapes, N_m	Layer, I_C (kA)
1	8.65	S	130	905	13	0.58
2	9.10	S	305	1000	13	0.58
3	9.55	Z	400	915	14	0.62
4	10.00	Z	115	195	14	0.62
5	18.05	S	350	525	27	1.35
6	18.50	S	530	1000	27	1.35

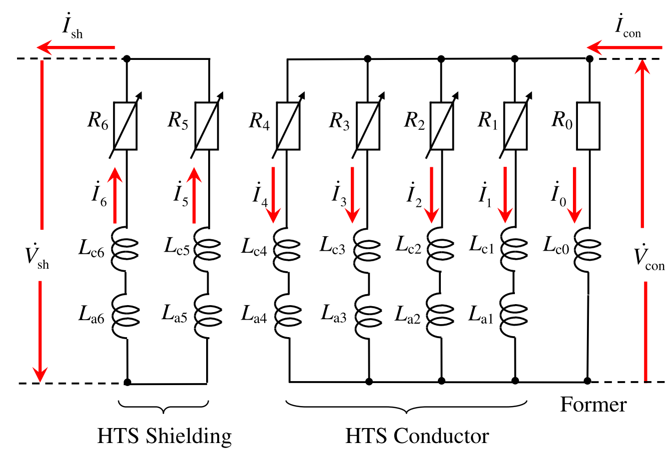

Fig. 2. EC model applied to the one phase of BSCCO HTS cable. The description of mutual inductances is omitted to avoid congestion.

Eq. (2) is obtained by the least-squares method applying to the Eq. (1). As mentioned above, Eq. (1) is restricted at $i_m < 1$. During the calculation of simultaneous Eqs. (8) and (9) described below, i_m is happened to be higher than 1 and w_m becomes to be an infinity in Eq. (1). Then, the calculation procedure is stopped before a convergence to the answer. Eq. (2) is useful to avoid the error of calculation. The current-dependent resistance, $R_m(I_m)$, is given by

$$R_m(I_m) = \frac{\sqrt{(2\pi r_m)^2 + P_m^2}}{P_m} \cdot \frac{N_m w_m}{I_m^2}\ (\Omega\,\mathrm{m^{-1}}), \tag{3}$$

where P_m is a helical pitch of HTS layer, r_m is a radius of HTS layer, and I_m is the r.m.s. value of $\hat{I}_m$ $(m = 1–6)$. I_m is obtained by $\hat{I}_m/\sqrt{2}$. Eq. (3) is obtained as follows. Supposing that the electromagnetic properties of BSCCO tapes in layer m are equivalent, the current passing through a tape in layer m is obtained by $\frac{I_m}{N_m}$. The resistance of BSCCO tape is obtained by $\frac{N_m^2 w_m}{I_m^2}$. Then, a combined value of the parallel connecting equivalent resistances of BSCCO tapes in layer m is obtained by $\frac{N_m w_m}{I_m^2}$. A tape length wound helically on the cylinder of radius r_m by helical pitch P_m is obtained by $\sqrt{(2\pi r_m)^2 + P_m^2}$. A tape length by unit length toward axis direction of HTS conductor is described as $\frac{\sqrt{(2\pi r_m)^2 + P_m^2}}{P_m}$. The resistance is proportional to the tape length. Therefore, the current-dependent resistance, the resistance of HTS layer, $R_m(I_m)$ is given by Eq. (3). A resistance of the former R_0 is obtained as follows. Supposing that the former is just a copper cylinder, R_0 is described as

$$R_0 = \frac{\rho_{Cu}}{\pi r_0^2}\ (\Omega\,\mathrm{m^{-1}}), \tag{4}$$

where ρ_{Cu} is a resistivity of copper at liquid nitrogen temperature ($2.15 \times 10^{-9}\ \Omega$ m) and r_0 is a radius of the former (8.00 mm). R_0 is calculated to $1.07 \times 10^{-5}\ \Omega\,\mathrm{m^{-1}}$.