Ac loss analyses of superconducting power transmission cables considering their three-dimensional geometries

Authors
Naoyuki Amemiya, Ryohei Nishino, Katsutoku Takeuchi, Masahiro Nii, Taketsune Nakamura
Department of Electrical Engineering
Kyoto University
Kyoto-Daigaku-Katsura, Nishikyo, Kyoto 615-8510, Japan

Masashi Yagi
Furukawa Electric Co., Ltd.
Yawata-Kaigandori, Ichihara 290-8555, Japan

Takeshi Okuma
Superconductivity Research Laboratory
International Superconductivity Technology Center
Shinonome, Koto, Tokyo 135-0062, Japan

Corresponding author.
Naoyuki Amemiya
Postal address: Department of Electrical Engineering, Graduate School of Engineering, Kyoto University
Kyoto-Daigaku-Katsura, Nishikyo, Kyoto 615-8510, Japan
Phone: +81 75 383 2220
FAX: +81 75 383 2224
E-mail address: amemiya@kuee.kyoto-u.ac.jp

Abstract
Numerical electromagnetic field analyses of superconducting power transmission cables consisting of coated conductors were made considering their three-dimensional spiraled structures. Thin strips of superconductor were wound spirally around a round former to represent a layer in a cable. The analyses were made for two-layer cables where the spiral pitch of the inner layer and that of the outer layer are different. A non-uniform lateral critical current density distribution, a trapezoidal distribution with shoulders, was assumed across each coated conductor. The calculated ac losses were compared with measured ones. The influence of the relative positions between the inner-layer coated conductors and the outer-layer coated conductors on the current distribution across each coated conductor as well as ac losses was discussed. The influence of the current distribution between layers, determined by the spiral pitches, on the ac losses was also studied.

Keywords:
ac loss; coated conductor; power transmission cable; high Tc superconductor

WT-16-INV
ISS 2011

1. Introduction

Ac losses in coated conductors in a superconducting power transmission cable are dominated by the magnetic field component normal to its superconductor layer [1], which is generated by the distortion of the magnetic field enclosing a layer consisting of coated conductors [2–5]. It should be noted that the ac losses in coated conductors in a particular layer are influenced substantially by the magnetic fields generated by the current in other layers [5]. Considering that the magnetic field is distorted at the gaps between coated conductors, the ac losses in the particular layer could be influenced by the relative positions of gaps in the adjacent layers. Since most of superconducting power transmission cables are with spiraled multi-layer structure with different spiral pitches in different layers, the relative positions of the gaps in the adjacent layers vary along the cable axis. Furthermore, we pointed out that the lateral critical current density (J_c) distribution remarkably influences the ac losses in superconducting power transmission cables [6].

Objective of this paper is to clarify the ac loss characteristics of multi-layer superconducting power transmission cables through electromagnetic field analyses by using a model in which the 3D spiral structure of the two-layer cables can be considered [7]. The following points are focused on:

1) the comparison between calculated and measured ac losses;
2) the ac loss distribution along conductor (cable) axis and current distributions across the width of each coated conductor at various positions along the coated conductor (cable) axis;
3) the impact of the lateral J_c distribution on lateral current distribution as well as ac losses;

4) the influence of current distribution between layers determined by the spiral pitches on the ac losses of cables.

2. Numerical model

The numerical model is based on the thin-strip approximation (1D model) of the superconductor layer of a coated conductor: the magnetic field component tangential to the superconductor layer of each coated conductor is neglected, and only the normal magnetic field component is taken into account, which dominates the ac loss in the coated conductor. The current vector potential $\boldsymbol{T}$ is used for the formulation instead of current density $\boldsymbol{J}$,

$$\boldsymbol{J} = \nabla \times \boldsymbol{T} \, . \tag{1}$$

The governing equation derived from Faraday's law is

$$\nabla \times (\rho \nabla \times \boldsymbol{T}_1) \cdot \boldsymbol{n}_1 + \frac{\mu_0 t_\mathrm{s}}{4\pi} \frac{\partial}{\partial t} \sum_{\text{source points}} \int_{S_\mathrm{e}} \frac{(\nabla \times \boldsymbol{T}_2) \times \boldsymbol{r} \cdot \boldsymbol{n}_2}{r^3} \mathrm{d}S = 0 \, . \tag{2}$$

Here, $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$ are the current vector potentials at the field point and source point, respectively; $\boldsymbol{n}_1$ and $\boldsymbol{n}_2$ are the normal vectors of the conductor's wide face at the field point and source point, respectively; $\boldsymbol{r}$ is the vector from the source point to the field point; ρ is the resistivity; and t_s is the thickness of the superconductor layer in coated conductors. We assumed that t_s is 2 μm in all analyses. While the three-dimensionality of the geometry can be considered by using $\boldsymbol{r}$, the mathematical analysis region on a coated conductor wide face is a two-dimensional one [7]. The spiral geometries of coated conductors in the inner and outer layers are shown in Fig. 1. Here, we use the (X, Y, Z) coordinates whose X axis agrees with the cable axis. The center line of each coated conductor can be parameterized using the real number u and positive integer m as

$$X = u, Y = \frac{D}{2}\cos\left(\frac{2\pi u}{p} + \frac{2\pi m}{N}\right), Z = \frac{D}{2}\sin\left(\frac{2\pi u}{p} + \frac{2\pi m}{N}\right), \qquad (3)$$

where D is the diameter of the layer, p is the spiral pitch of the layer, and N is the number of coated conductor in the layer. The superconducting property is given by the power law E–J characteristic,

$$E = E_0\left(\frac{J}{J_c}\right)^n, \qquad (4)$$

where E_0 and n were fixed at 10^{-4} V/m and 30, respectively. The J_c-B characteristic was considered in the calculation shown in *3.1* but was not considered in other calculations.

An arbitrary lateral J_c distribution can be considered in the numerical model, but the trapezoidal J_c distribution with shoulders as shown in Fig. 2 was used in this paper. Ac loss power density can be calculated from current density and equivalent resistivity deduced from the power law E–J characteristic. The current in each coated conductor is given by using the boundary condition. In all calculations, the frequency of the current was 50 Hz. The details of the numerical model are shown in [7].

3. Results of analyses

3.1. Comparison between calculated and measured ac losses

To validate the numerical model, the ac losses calculated by using the model were compared with the measured ac losses in a two-layer cable. The specifications of the cable whose ac losses were measured and calculated are shown in Table 1. The cable consists of 5 mm-wide coated conductor, whose lateral J_c distribution can be approximated by the trapezoid with shoulders of 0.8 mm [6]. The critical current of the entire cable is 3860 A. Assuming that the critical current density depends on the magnetic flux density normal to the superconductor layer, we used the following J_c-B_n characteristic, which was obtained by fitting to a measured J_c-B_n curve,

$$J_c = \frac{B_c}{B_c + B_n} J_{c0}, \qquad (5)$$

where B_n is the magnetic flux density component normal to the superconductor layer, J_{c0} is the critical current density at zero external magnetic field, and the constant B_c is 0.4 T. The load rate, the peak of the transport current divided by the critical current (I_t / I_c), of the inner layer and that of the outer layer were assumed to be identical. In Fig. 3, the calculated ac losses are compared with the measured one. The calculated values reasonably agree with the measured ones.

3.2. Ac loss distributions along coated conductor axes

Ac losses were calculated in a two-layer cable whose specifications are listed in Table 2. The cable consists of 4 mm-wide coated conductors with various shoulders of the trapezoidal lateral J_c distribution of each coated conductor. The critical current of each coated conductor is 100 A. The load rate was fixed at 0.6 for each layer.

The calculated ac losses for various shoulders are listed in Table 3. With increasing shoulder, the ac loss in the inner layer as well as that in the outer layer increases. In Fig. 4, the ac loss power densities are plotted along the coated conductor axes shown in Fig. 1. The ac loss power densities vary along the coated conductor axes (cable axis). In this figure, the axial position *x* of 0 mm corresponds to the tape-on-tape position, where the outer-layer coated conductor is just on the inner-layer coated conductor, and *x* of 5.56 mm for the inner layer and *x* of 5.88 mm for the outer layer correspond to the tape-on-gap position, where the outer-layer coated conductor is just on the gap between the inner-layer coated conductors. Since the number of coated conductor of the inner layer and that of the outer layer are different, the relative positions between the inner-layer coated conductors and the outer-layer coated conductors vary along the cable axis. This should be the reason for this variation. The magnetic field component normal to the superconductor layer, which dominates the ac loss characteristics of coated conductors, is generated near the edge of coated conductor or at the gap between coated conductors. Therefore, the relative positions between the inner-layer coated conductors and the outer-layer coated conductors can critically influence the ac loss characteristics of coated conductors in two-layer superconducting cables. In Figs. 5, 6, 7 and 8, the lateral current distributions are shown at the tape-on-tape position, at an intermediate position, at the tape-on-gap position, and at a positions corresponding to the loss peaks in Fig. 4, respectively. In Fig. 5, the current distributions in the inner layer and in the outer layer are almost same at the tape-on-tape position. Therefore, it can be naturally understood that the ac loss in the inner layer and that in the outer layer are almost same at 0 mm in Fig. 4. In Fig. 7, there are humps in the current distributions. These humps are caused by the normal magnetic field component generated at the gap between coated conductors in another layer. In Fig. 6, asymmetric current distributions are observed, due to the asymmetrically located gaps in another layer.

3.3. Influence of spiral pitches on current distributions between layers and ac losses

Here, we consider cables consisting of two conductor layers and one shield layer whose specifications are listed in Table 4. The spiral pitches and radius of the inner conductor layer, those of the outer conductor layer, and those of the shield layer determine the current distribution between layers. In the following argument, r_1, r_2, and r_s are the radius of the inner layer, that of the outer layer, and that of the shield layer, respectively. p_1, p_2, and p_s are the spiral pitch of the inner layer, that of the outer layer, and that of the shield layer, respectively. I_1 and I_2 are the inner layer current and the outer layer current, respectively. From the azimuthal magnetic flux enclosing a layer and the axial magnetic flux enclosed by a spiraled layer, the voltage V_1 which appears in the loop consisting of the inner layer and the shield layer and the voltage V_2 which appears in the loop consisting of the outer layer and the shield layer can be given as

$$\begin{aligned} V_1 &= -\mu_0\left(\frac{1}{2\pi}\ln\frac{r_s}{r_1}+\frac{\pi r_1^2}{p_1^2}-2\frac{\pi r_1^2}{p_1 p_s}+\frac{\pi r_s^2}{p_s^2}\right)\frac{\mathrm{d}I_1}{\mathrm{d}t} \\ &\quad -\mu_0\left(\frac{1}{2\pi}\ln\frac{r_s}{r_2}+\frac{\pi r_1^2}{p_1 p_2}-\frac{\pi r_1^2}{p_1 p_s}-\frac{\pi r_2^2}{p_2 p_s}+\frac{\pi r_s^2}{p_s^2}\right)\frac{\mathrm{d}I_2}{\mathrm{d}t} \\ &\equiv -L_1\frac{\mathrm{d}I_1}{\mathrm{d}t}-M_{12}\frac{\mathrm{d}I_2}{\mathrm{d}t} \end{aligned} \quad , \qquad (6)$$

$$\begin{aligned} V_2 &= -\mu_0\left(\frac{1}{2\pi}\ln\frac{r_s}{r_2}+\frac{\pi r_1^2}{p_1 p_2}-\frac{\pi r_2^2}{p_2 p_s}-\frac{\pi r_1^2}{p_1 p_s}+\frac{\pi r_s^2}{p_s^2}\right)\frac{\mathrm{d}I_1}{\mathrm{d}t} \\ &\quad -\mu_0\left(\frac{1}{2\pi}\ln\frac{r_s}{r_2}+\frac{\pi r_2^2}{p_2^2}-2\frac{\pi r_2^2}{p_2 p_s}+\frac{\pi r_s^2}{p_s^2}\right)\frac{\mathrm{d}I_2}{\mathrm{d}t} \\ &\equiv -M_{21}\frac{\mathrm{d}I_1}{\mathrm{d}t}-L_2\frac{\mathrm{d}I_2}{\mathrm{d}t} \end{aligned} \quad . \qquad (7)$$

Considering that $V_1 = V_2$, the ratio between the inner-layer current I_1 and the outer-layer current I_2 can be given as

$$\frac{I_1}{I_2}=\frac{L_2-M_{12}}{L_1-M_{21}}=\frac{\dfrac{\pi r_2^2}{p_2^2}-\dfrac{\pi r_1^2}{p_1 p_2}-\dfrac{\pi r_2^2}{p_2 p_s}+\dfrac{\pi r_1^2}{p_1 p_s}}{\dfrac{1}{2\pi}\ln\dfrac{r_2}{r_1}-\dfrac{\pi r_1^2}{p_1 p_2}+\dfrac{\pi r_1^2}{p_1^2}+\dfrac{\pi r_2^2}{p_2 p_s}-\dfrac{\pi r_1^2}{p_1 p_s}} \ . \qquad (8)$$

First, the calculated current distributions are listed in Table 5. In the cable S, more current flows in the inner layer; in the cable M, the current is almost uniformly distributed; in the cable L, more current flows in the outer layer. Then, these calculated imbalanced currents were supplied to the inner and outer layers to calculate the ac losses.

The critical current of each coated conductor is 100 A, and the lateral J_c distribution is the trapezoid with 0.3 mm – shoulder. The calculated ac losses are shown in Table 5. It should be noted that the minimum ac loss appears in the cable S, in which the current distribution is not uniform, and more current flows in the inner layer. In general, more ac loss is generated in the outer layers. Therefore, a moderate suppression of the current in the outer layer might reduce the ac loss in the outer layer, which dominates the ac loss in the entire cable.

4. Conclusion

Numerical electromagnetic field analyses were made for two-layer power transmission cables consisting of coated conductors with spiral geometry. The model for numerical electromagnetic field analyses, considering the spiral geometry of coated conductors in a two-layer cable, was validated successfully by comparing the calculated ac losses with the measured ones. The ac loss in a cable distributes along the cable axis, because the relative positions between inner-layer coated conductors and outer-layer ones vary along the axis. The spiral pitches of layers in a cable influence the current distribution between layers, and, hence, influence the ac loss of the cable. It should be noted that the uniform current distribution would not always minimize ac losses.

Acknowledgement

This work was supported by the New Energy and Industrial Technology Development Organization as the M-PACC (Materials and Power Applications of Coated Conductors) Project.

References

[1] Z. Jiang, N. Amemiya N, M. Nakahata, Numerical calculation of AC losses in multi-layer superconducting cables composed of coated conductors, Supercond. Sci. Technol. 21 (2008) 025013–025020.

[2] S. Fukui, J. Ogawa, N. Suzuki, T. Oka, T. Sato, O. Tsukamoto, T. Takao, Numerical analysis of AC loss characteristics of multi-layer HTS cable assembled by coated conductors, IEEE Trans. Appl. Supercond. 19 (2009) 1714–1717.

[3] R. Inada, Y. Nakamura, A. Oota, Numerical analysis for AC losses in single-layer cables composed of rectangular superconducting strips with various lateral Jc distributions, J. Phys.: Conf. Ser. 97 (2008) 012324–012329

[4] A.P. Malozemoff, G. Snitchler, Y. Mawatari, Tape-width dependence of AC losses in HTS cables, IEEE Trans. Appl. Supercond. 19 (2009) 3115–3118

[5] N. Amemiya, Q. Li, K. Ito, K. Takeuchi, T. Nakamura, T. Okuma, Ac loss reduction of multilayer superconducting power transmission cables by using narrow coated conductors, Supercond. Sci. Technol. 24 (2011) 065013.

[6] N. Amemiya, Q. Li, K. Takeuchi, T. Nakamura, M. Yagi, S. Mukoyama, Y. Aoki, N. Fujiwara, Effects of lateral-tailoring of coated conductor for ac loss reduction of superconducting power transmission cables, IEEE Trans. Appl. Supercond. 21 (2011) 943–946

[7] K. Takeuchi, N. Amemiya, T. Nakamura, O. Maruyama, T. Ohkuma, Model for electromagnetic field analysis of superconducting power transmission cable comprising spiraled coated conductors, Supercond. Sci. Technol. 24 (2011) 085014.