Numerical and experimental investigations of current distribution at the joint between AC superconducting cable and normal conducting plate

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Numerical and Experimental Investigations of Current Distribution at the Joint between AC Superconducting Cable and Normal Conducting Plate

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Abstract —The effect of the configuration of the joint between an ac superconducting cable and a normal conducting plate on the current distribution and the joule loss is investigated by using the 3-D finite element method. It is shown that the concentration of current can be reduced by changing the configuration of joint. The effectiveness of the analysis is verified by measuring the current distribution on the surface of a copper plate and the quenching current.

I. Introduction

In ac superconducting electric machines, a superconducting cable is connected with a normal conducting plate. The joint of large capacity superconducting cable is not a big problem in the case of dc[1]. But in the case of ac excitation, quenching occurs at the joint due to the extreme concentration of current[2],[3]. The concentration of current and the joule loss in the normal conducting plate should be reduced by optimizing the shape and dimension of the connecting plate, in order to avoid quenching. As tetrahedral elements were used in [2], the FEM analysis at commercial frequency (50Hz) was difficult because the number of elements used must be increased due to the extreme skin effect. Even then, only the current distribution at low frequency (2Hz) could be analyzed. The experimental verification also was not carried out previously.

In this paper, the effect of the joint shape on the current distribution and the joule loss is investigated at 50Hz by using 3-D brick elements which are superior to tetrahedral elements from the viewpoints of accuracy and CPU time[4]. The optimal shape and dimension are discussed from the viewpoint of current distribution and joule loss. The current distribution on the surface of the copper plate was measured by using the newly developed method for measuring a very low signal at liquid helium temperature. The quenching current of the optimal joint was measured, and the effectiveness of the joint is shown.

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II. Analyzed Joints

The analyzed joints between the superconducting cables and the normal conducting plates are shown in Fig.1. Model A is the conventional joint in which the superconducting cable is connected at the middle of the copper plate as shown in Fig.1(a). As the current flows along the edge of the plate due to the considerable skin effect[1], the current in the plate enters the superconducting cable at a point b, and the extreme concentration occurs. Then, the joints shown in Fig. 1(b) and (c) are investigated. In model B, slits are put in the connecting plate as shown in Fig.1(b). In model C, the strands of the cable are divided into two parts and they are connected at each edge of the plate as shown in Fig.1(c). The effective value of the applied ac current (50Hz) is equal to 50A. For simplicity, the twist of strand is ignored, and the

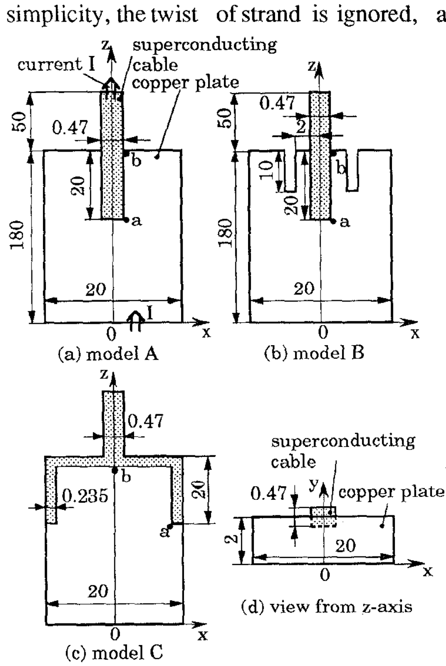

Fig.1 Analyzed joints.

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cross-section of the cable (diameter : 0.47mm) is approximated to be square (0.47 × 0.47mm), because the current distribution in the plate is not so much affected by the twist pitch[2]. The conductivity of the connecting terminal plate which is made of copper is 3.34×10^9 S/m (at 4.2° K). The conductivity of the superconducting cable is assumed as 100 times greater than that of copper[5].

III. Method of Analysis

Since the joint is composed of non-magnetic material, the quenching phenomenon is linear. Thus, the 3-D distributions of the forced current $\boldsymbol{J_o}$ fed to the conductor and the eddy current $\boldsymbol{J_e}$ induced in the conductor can be analyzed independently. The distribution of the total current is obtained by superposition. The basic equation for calculating the 3-D magnetic field is

$$rot(\nu rot\boldsymbol{A}) = \boldsymbol{J}_o + \boldsymbol{J}_e \tag{1}$$

where, **A** is the magnetic vector potential and ν is the reluctivity. $\boldsymbol{J_o}$ can be written as

$$\boldsymbol{J}_o = -\sigma\,\mathrm{grad}\phi_o \tag{2}$$

ϕ_o is the electric scalar potential which determines the forced current distribution. $\boldsymbol{J_e}$ is given by

$$\boldsymbol{J}_e = -\sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} + grad\phi_e\right) \tag{3}$$

where ϕ_e and σ are the electric scalar potential[6] which determine the eddy current and the conductivity.

As the current densities $\boldsymbol{J_o}$ and $\boldsymbol{J_e}$ satisfy the continuity condition, the following equations can be obtained[6]:

$$div\{-\sigma grad\phi_o\} = 0 \tag{4}$$

$$div\left\{-\sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} + grad\phi_e\right)\right\} = 0 \tag{5}$$

As ϕ_o can be calculated using Eq. (4), J_o is obtained from Eq. (2). The eddy current distribution can be calculated by Eqs. (1), (3) and (5) using the obtained forced current density J_o. The distribution of the total current is obtained by the superposition of J_o and J_e.

Galerkin's equations of the **A** - φ method for Eqs.(1), (3) and (5) can be written as follows [6]:

$$\boldsymbol{G_i} = \iiint gradN_i \times \nu rot\boldsymbol{A}dv - \iiint N_i\boldsymbol{J}_o dv + \iiint N_i\sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} + grad\phi_e\right)dv \tag{6}$$

$$G_{di} = \iiint gradN_i \cdot \sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} + grad\phi_e\right)dv \tag{7}$$

where, N_i is the interpolation function. The first order brick nodal elements[6] are used in the 3-D finite element analysis.

IV. Factors Affecting Current Distribution and Joule Loss

The current distribution is analyzed using the 3-D finite element method. The skin depth is 1.2mm at 50Hz. This area of skin depth is divided into four layers of brick elements. Table 1 shows the discretization data.

A. Construction of Joint

Fig.2 shows the current distributions near the surface of the connecting plate at ωt=0°. Zero time is taken as the instant when Jo becomes a maximum. The current distribution is considerably affected by the configuration of joint.

Fig.3 shows the distribution of the maximum value |Js| of the current density which flows into the superconducting

TABLE 1
Discretization data (model A)

Number of nodes	10,488
Number of elements	9,108
CPU time(s)	25,970

computer used : IBM3AT work station (49.7MFLOPS)

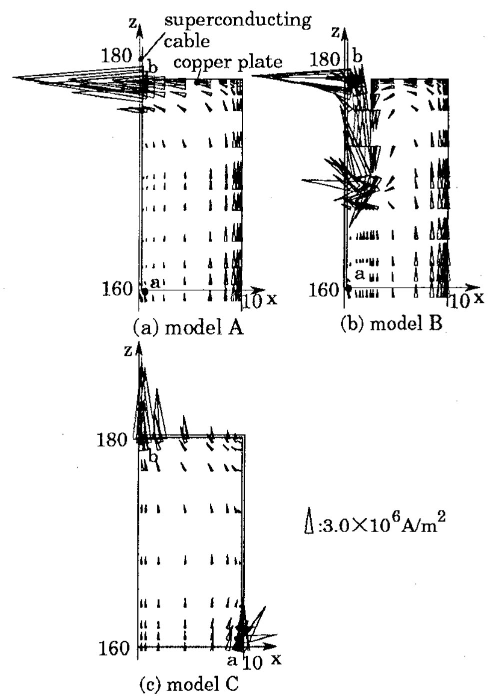

Fig.2 Effect of construction on current distribution (50Hz, y=2mm).

cable from the connecting plate along the line a-b shown in Fig.1. Most of the current in the plate in model A flows into the cable at the point b as shown in Fig.2(a). The current in model C shown in Fig.2(c) mainly flows into the cable at the two points a and b, because the superconducting cable is connected at both edges.

Fig.4 shows the maximum value $|Js|_{max}$ of current density along the line a-b and the total joule loss W obtained using the calculated current. The maximum value $|Js|_{max}$ in model C is about half that of model A. Moreover, the total joule loss W of model C is about 10% smaller than that of model A.

B. Frequency

Fig.5 shows the current distribution at 2Hz. Fig.6 shows the distribution of |Js| of the current density at the start of the superconducting cable. At 2Hz, |Js| at the point a is larger than that at the point b. On the other hand, when the frequency is increased, the current is concentrated near point b as shown in Fig.6 due to the skin effect. If the connecting plate is larger(100 × 60 × 10mm) as discussed in the reference[1], the skin effect is remarkable even if the frequency is low(2Hz). Therefore, the relationship between the joint dimensions and frequency should be investigated systematically.

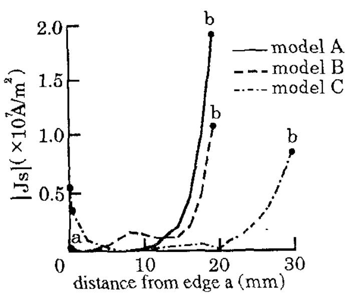

Fig.3 Current distribution flowing into superconducting cable along the line a-b (50Hz, y=2mm).

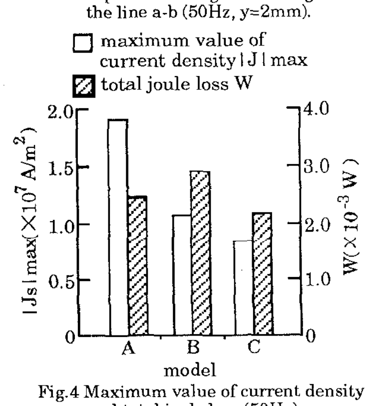

Fig.4 Maximum value of current density and total joule loss (50Hz).

V. EXPERIMENTS

The current distribution in a copper terminal plate shown in Fig.7 was measured. The outer diameter of the 7-strand superconducting cable is 0.47mm. This model is immersed in liquid helium. The eddy current densities at four points (x=4.7; z=1.5, 6.5, 11.5, 16.5) were measured using the modified probe method [7] shown in Fig.8. Pin holes were made in the insulation of the polymide film (thickness : 50μm) by a needle. The position of the needle was adjusted precisely using a manipulator. Electrically conductive adhesive was put, with lead-out wires into the pin holes as shown in Fig.8. The lead-out wires were twisted in order to avoid inductive pickup. The current density is calculated from the voltage drop between holes. As the measurement noise is extremely large (SN=-50dB), a new system for measuring very low signal (1~10ηV) was developed [8].

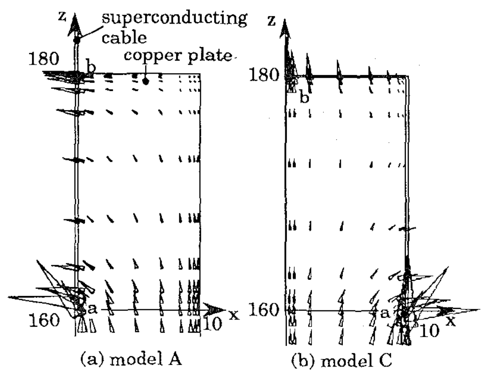

Fig.5 Current distribution (2Hz, y=2mm).

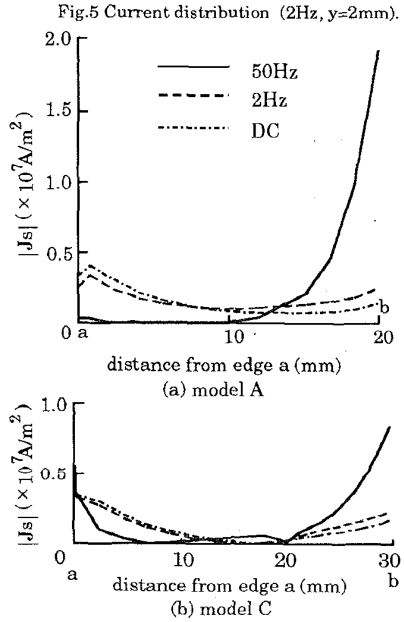

Fig.6 Effect of frequency on current distribution (y=2mm).

Fig.9 shows the comparison between measured and calculated values of x- and z-components, Jx, Jz, of current densities. The trend of the concentration of measured current due to the remarkable skin effect is similar to that calculated. The joints of models A and C were made, and the quenching currents at 50Hz were measured. Fig.10 shows the results. The critical current (dc) is also shown. The figure shows that the quenching current of model C is improved compared with that of model A. This tendency coincides with the results in Fig. 4.

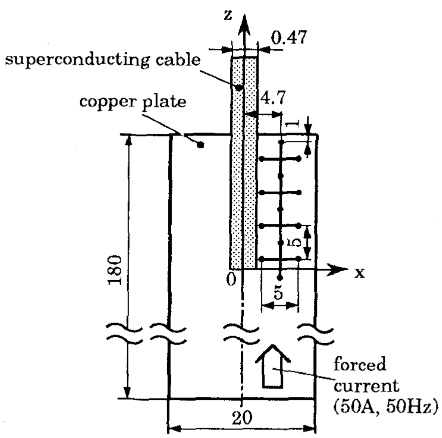

Fig.7 Measured model of joint.

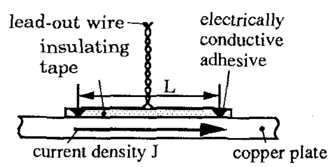

Fig.8 Modified prove method.

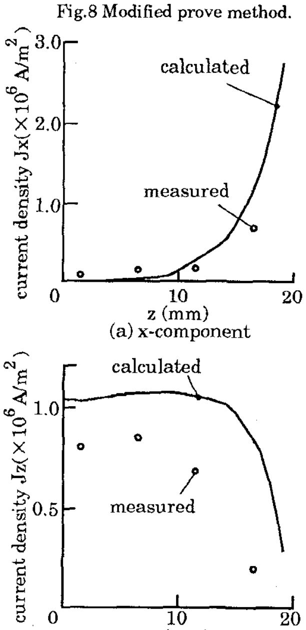

Fig.9 Distribution of current densities (50Hz, x=4.7mm, y=2mm).

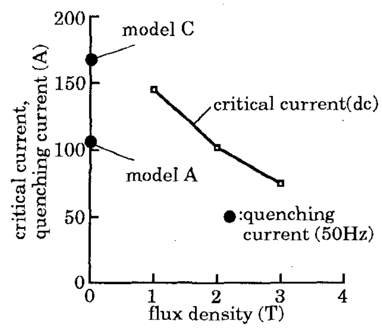

Fig.10 Measured values of quenching current.

VI. Conclusions

It is shown that the concentration of current and joule loss can be reduced by dividing the superconducting wire and connecting them at both edges of a copper plate. The effectiveness of this improved joint is verified by experiments. As the precise current distribution can be obtained using the method shown in this paper, the optimal configuration of the joint can be obtained using this method.

The following items should be investigated in the future:

(a)optimum configuration of the joint,

(b)relationship between the dimension and shape of the joint and frequency.

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