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# STUDY ON CAUSE OF QUENCHING AT THE JOINT BETWEEN MULTIFILAMENTARY SUPERCONDUCTING CABLE AND NORMAL CONDUCTING CABLE USING 3-D FEM

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***Abstract* - - In order to investigate the cause of quenching at the joint between a multifilamentary superconducting cable and a normal conducting cable, the 3-D current distribution is analyzed. It is found that the cause of quenching is the extreme concentration of current in the joint due to the pronounced skin effect at liquid helium temperature. The mechanism of the concentration of current which is affected by the twist pitch and skin depth is also clarified quantitatively by numerical analysis.**

## I. INTRODUCTION

In ac superconducting electric machines, the superconducting cable is connected with the normal conducting cable through a connecting plate[1]. When the ac current is increased, quenching occurs at the joint. As a result, the rated current of the superconducting electric machine is limited to a smaller value than that of the ac superconducting cable itself[1]. Since the superconducting cable is made of twisted multifilaments, it was difficult to analyze the 3-D current distribution at the joint. Therefore, the cause of quenching was not clear.

In this paper, a new method for calculating the distribution of the applied current and eddy current in such a joint between the multifilamentary superconducting cable and the normal conducting cable is introduced. The effects of frequency, twist pitch of the superconducting cable and slit in the connecting plate on the concentration of current are examined. The cause of quenching is discussed in detail using the current distribution obtained.

## II. ANALYSIS

### *A. Analysis Model*

The joint which was analyzed between the superconducting cable and the normal conducting cable is shown in Fig.1. The conductivity of the connecting plate is $5\times10^9$S/m (at 4.2°K). The superconducting cable is composed of triply-stacked strands which are immersed in solder to stabilize the cable. The diameter of the cable is 4.5mm and the twist pitch is 31.5mm[1]. The conductivity $\sigma_m$ of the solder is $3\times10^8$S/m. The volume fraction $\lambda$[2] ofthe superconductor is 0.47. The effective value of the applied ac current is equal to 4500A.

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### *B. Method of Analysis*

*1) Modelling of Multifilamentary Cable*

Since the magnetic field analysis of the triply-stacked superconducting cable is complicated, the cable is approximated by a conductor which is filled with $100\lambda$% superconducting filaments and $(1-\lambda)\times100$% solder as shown in Fig.2.

The conductivity $\sigma_\perp$ perpendicular to the filament is calculated to be $1.08\times10^8$S/m using the following equation[2]:

$$\sigma_\perp = \frac{1-\lambda}{1+\lambda}\sigma_m \tag{1}$$

The infinite conductivity $\sigma_{/\!/}$ parallel to the filament cannot be treated as such in the numerical calculation. $\sigma_{/\!/}$ is assumed to be $1.08\times10^{13}$S/m in order to avoid round-off error[3].

If the coordinates are transformed from x-y-z to u-v-w as shown in Fig.2, the u-, v- and w-components $J_u$, $J_v$ and $J_w$ of the current density are calculated by Eq.(2).

$$\begin{Bmatrix} J_u \\ J_v \\ J_w \end{Bmatrix} = \begin{bmatrix} \sigma_\perp & 0 & 0 \\ 0 & \sigma_\perp & 0 \\ 0 & 0 & \sigma_{/\!/} \end{bmatrix} \begin{Bmatrix} E_u \\ E_v \\ E_w \end{Bmatrix} \tag{2}$$

where $E_u$, $E_v$ and $E_w$ are the u-, v- and w-components of the electric field strength E.

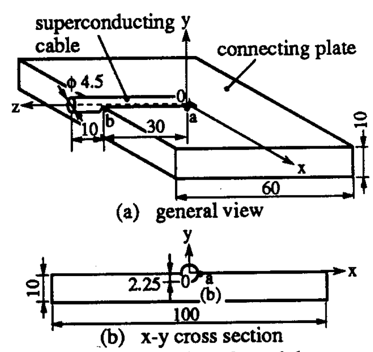



Fig. 1 Analyzed model.

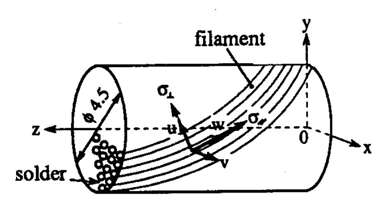



Fig. 2 Modelling of twisted multifilamentary cable.

*2) Superposition of Forced Current and Eddy Current*

Since the joint is composed of non-magnetic material, the phenomenon is linear. Thus, the 3-D distributions of the forced current fed to the conductor and the eddy current induced in the conductor can therefore be analyzed independently. The distribution of the total current is obtained by superposition.

The basic equation for calculating the 3-D magnetic field is

$$\mathrm{rot}\,(\nu\,\mathrm{rot}\mathbf{A}) = \mathbf{J_0} + \mathbf{J_e} \quad (3)$$

where, $\mathbf{A}$ is the magnetic vector potential and $\nu$ is the reluctivity. $\mathbf{J_e}$ is the eddy current density which is given by

$$\mathbf{J_e} = -\sigma\,(\frac{\partial \mathbf{A}}{\partial t} + \mathrm{grad}\,\phi_e) \quad (4)$$

where $\phi_e$ and $\sigma$ are the electric scalar potential[4] and the conductivity. $\mathbf{J_0}$ is the forced current density, and it can be written as

$$\mathbf{J_0} = -\sigma\,\mathrm{grad}\,\phi_0 \quad (5)$$

$\phi_0$ is the electric scalar potential which determines the forced current distribution.

As the current densities $\mathbf{J_0}$ and $\mathbf{J_e}$ satisfy the continuity condition, the following equations can be obtained:

$$\mathrm{div}\,\{-\sigma\,(\frac{\partial \mathbf{A}}{\partial t} + \mathrm{grad}\,\phi_e)\} = 0 \quad (6)$$

$$\mathrm{div}\,\{-\sigma\,\mathrm{grad}\,\phi_0) \quad (7)$$

As $\phi_0$ can be calculated using Eq.(7), $\mathbf{J_0}$ is obtained from Eq.(5). The eddy current distribution can be calculated by Eqs.(3), (4) and (6) using the forced current density $\mathbf{J_0}$ so obtained. The distribution of the total current is obtained by the superposition of $\mathbf{J_0}$ and $\mathbf{J_e}$.

The current distribution is analyzed using a 3-D finite element method[3]. Fig.3 shows the boundary conditions for numerical analysis. It is assumed that the current is perpendicular to the cross sections of the connecting plate and the superconducting cable on the boundaries.

## III. FACTORS AFFECTING CURRENT DISTRIBUTION

*A. Frequency*

The effect of frequency on the current distribution is investigated. As the skin depth $\delta$ is only 0.9mm at 60 Hz, an extremely fine mesh is required near the surfaces of the connecting plate and the superconducting cable. Therefore, the current distributions are calculated at 2Hz, which gives a larger skin depth of 5mm.

Fig.4 shows the current distribution at a cross section (z=29.8mm) of the connecting plate at $\omega t$=0°. Zero time is taken as the instant when $\mathbf{J_0}$ becomes a maximum. Fig.5 shows the current distributions near the surface of the connecting plate in the case when the twist pitch L of the superconducting cable is equal to 31.5mm. In the dc case in Fig.5(a), the forced current is equal to $\sqrt{2}$x4500A. In the ac case in Fig.5(b), the distribution at $\omega t$=0° is shown.

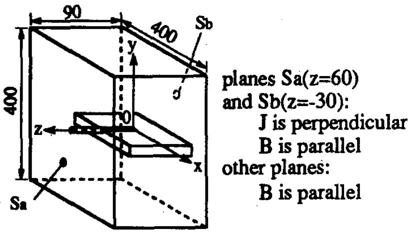



Fig.3 Boundary conditions.

Fig.6 shows the distribution of the maximum value of the x-component $|J_x|$ of the current density which flows into the superconducting cable from the connecting plate along the line a-b (x=2.25mm, y=0mm) shown in Fig.1. In the dc case, $J_x$ 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 the point b as shown in Fig.5 due to the skin effect, because the conductivity is very high at liquid helium temperature.

Fig.7 shows the maximum value of the z-component $|J_z|$ of the current density near the surface (r=2.21mm) of the superconducting cable. $\theta$ is the angle measured from the x-axis. The concentration of current under ac excitation at the lower part (180°<$\theta$<360°) of the cable, which is in contact with the connecting plate, is much greater than that under dc excitation. The reason will be discussed in Section B.

*B. Twist Pitch*

The effect of the twist pitch L of the superconducting cable on the current distribution is investigated. The skin depth $\delta$ is equal to 5mm at 2Hz. If $\delta$ is less than L/2, the current which flows into the cable at the lower part (180°<$\theta$<360°) may not transfer to the upper part (0°<$\theta$<180°) as shown in Fig.8. The current distribution is therefore analyzed for three kinds of twist pitches of 10, 17

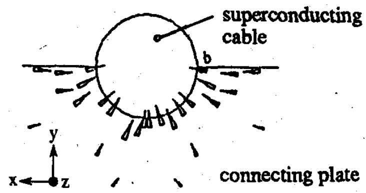
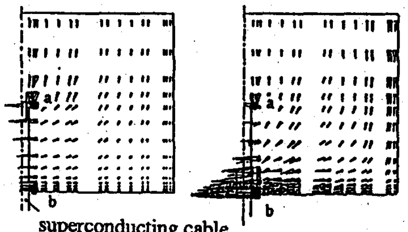



Fig. 4 Current distribution at cross section of connecting plate (2Hz, z=29.8mm, L=31.5mm).




(a) dc (b) ac (2Hz)

Fig. 5 Effects of frequency on current distribution (y= -0.3mm, L= 31.5mm).

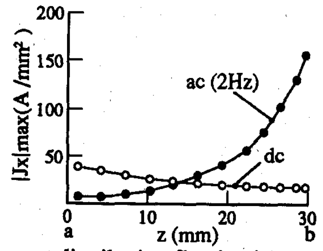



Fig. 6 Current distribution flowing into superconducting cable along the line a-b (L= 31.5mm).

and 50mm corresponding to $\delta/L$=0.5, 0.3 and 0.1 respectively.

Fig.9 shows the same distributions as Fig.7 for various twist pitch L. When L is large, the current concentrates at the lower part (180°<θ<360°) of the cable. This happens because most of the current which flows into the superconducting cable at the lower part (180°<θ<360°) does not transfer to the upper part (0°<θ<180°) of the cable within the short path (less than L/2).

As the filament of the cable is twisted in the direction shown in Fig.8, $|J_z|$ near θ=180° is larger than that near θ=0° at z=30.5mm as shown in Fig.7.

### *C. Slit in Plate*

In order to reduce the concentration of current, a slit is put in the connecting plate. The effects of the size and position of the slit on the current distribution are investigated. As the current distribution in the plate is not so much affected by the twist pitch L, the analyzed region is reduced to 1/2 of that shown in Fig.3 by assuming that L is infinity.

Fig.10 shows the effects of slit size and position on the current distribution near the surface of the plate. Fig.11 shows the distribution of the maximum value of $|J_x|$ along the line a-b shown in Fig.1. In the case of Fig.10(c), the concentration of $|J_x|$ is smaller than those of Figs.10(a) and (b) due to the slit.

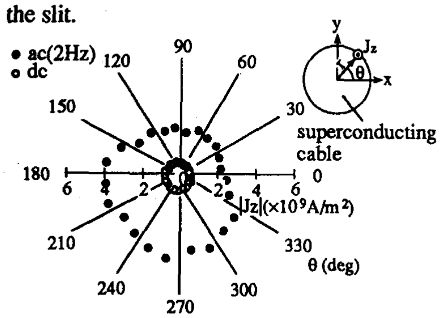



Fig. 7 Current distribution in superconducting cable ($r$= 2.21mm, $z$= 30.5mm, $L$=31.5mm).

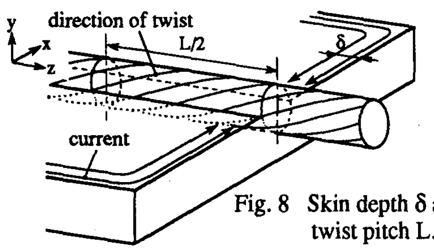



Fig. 8 Skin depth δ and twist pitch L.

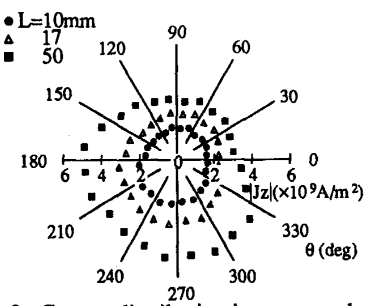



Fig. 9 Current distribution in superconducting cable (2Hz, $r$= 2.21mm, $z$= 30.5mm).

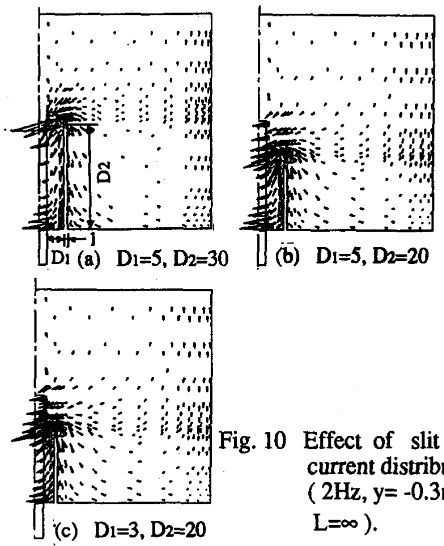



Fig. 10 Effect of slit on current distribution (2Hz, y= -0.3mm, L=∞).

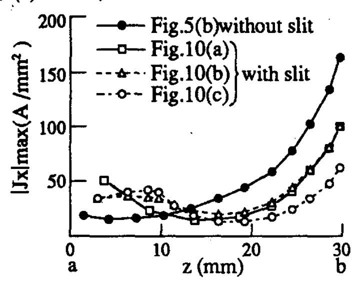



Fig. 11 Effect of slit on current flowing into superconducting cable (2Hz, L=∞).

## IV. CONCLUSIONS

It is found that the cause of quenching is the extreme concentration of current at the edge of the connecting plate. It is shown that a slit in the plate has a remarkable influence in reducing the concentration of current.

The following items should be investigated in the future:

(a) more precise and practical modelling of triply-stacked superconducting cable,
(b) the optimal shape of connecting plate,
(c) experimental verification.

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