論 文
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초전도 전류 발전기의 유도리액턴스 손실에 관한 연구

A Study on the Analysis of the Inductive Reactance Losses of a Superconducting Current Generator

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요 약

Case Western Reserve University에서 제작된 초전도 전류발전기의 유도성 리액턴스 손실에 관한 연구가 비교분석 되었다. 회전자속에서의 자장계산을 통하여 초전도 박막에서의 필라멘트 인덕턴스 뿐 아니라 회전자속 인덕턴스를 계산할 수 있게 되었다. 전류를 스위칭하는데 있어서 손실된 자기 에너지는 주로 초전도 전류발전기의 유도성 리액턴스 손실과 관련된 전압의 미세한 진폭 변동에 의한것 임을 보였다.

Abstract- The inductive reactance losses of a superconducting current generator built at Case Western Reserve University has been analyzed. The calculations of the field in the spot make it possible to estimate the spot inductance as well as the filament inductance on the foil. It is shown that the magnetic energy lost in switching the current is mainly due to the amplitude of the fluctuation in voltage associated with the inductive reactance losses of a superconducting current generator.

1. INTRODUCTION

The superconducting current generator has become of great interest to the designers of superconducting electric machinery[1, 2, 3] because of its compactness and ability to produce very large currents. Fig. 1 shows a highly idealized representation for such a device.

A cylindrical belt of superconducing material, such as Niobium, is made to rotate along its axis AA_1. Collecting leads(a, a_1, b, b_1) are welded on both rims of the belt and bunched at A and A_1. Several magnets($M_1, M_2, -, M_n$) are positioned around the belt.

An operational feature of the superconducting

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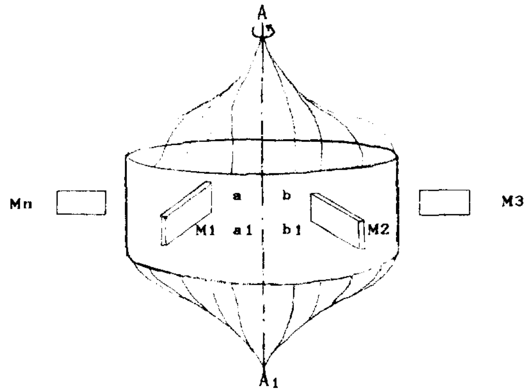

Fig. 1 Idealized superconducting current generator

current generator is the dependence of the pumping rate on the pump speed of rotation[4]. A fair amount of theoretical and experimental investigations[5, 6] that have been conducted on the flux pump have provided the basis for understanding the operation of the pump in broad lines. For an explanation in depth of the pump performance, however, it is essential to examine in details, the spatial and temporal behavior of the magnetic field distributions associated with the inductive reactance losses in and around the normal zones in the device.

The purpose of this paper is to examine, in some details, the inductive reactance losses associated with field pattern and to find means to reduce it for the better design.

2. FIELD DISTRIBUTION

The flux motion is assumed to take place in a nioblum sheet with a typical thickness of approximately 0.01cm. This is much larger than the London's penetration depth(of the order 10^{-6}cm) and yet thin enough to allow the use of a thin current sheet model.

The excitation magnets(Fig. 1) are assumed to produce flux spots of rectangular cross section.

The magnet field is taken to be normal to the niobium sheet in the region of the spot and parallel to the sheet outside the spot(Fig. 2).

The induced magnetic field leads to a compres-

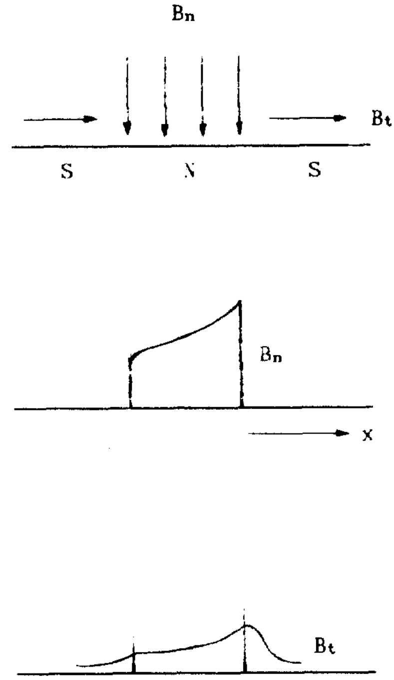

Fig. 2 (a) Direction of magnetic field in normal (N) and supercondcuting region of spot.
(b) Assumed distribution of B_n near the edge of spot.
(c) Distribution of B_t in and near the spot.

sion of the lines of force as shown in Fig. 2(c). The extent of this compression is found from the expression for the diffusion of the field which is referred to the Bullard-Cowling equation. This diffusion is expressed by

$$\frac{\partial \boldsymbol{B}}{\partial t}=\nabla\times(\boldsymbol{V}\times\boldsymbol{B})+\frac{1}{\mu_o\sigma}\nabla^2\boldsymbol{B} \qquad (1)$$

where μ_o is the permeability and σ the conductivity.

For dimensionless variables, let

$t=t_o\tau$; where t_o is a characteristic diffusion time, and τ is dimensionless

$(x,y)=(\varepsilon a,\eta a)=(\varepsilon,\eta)a$; where a is the width of the spot and ε & η are dimensionless

$\boldsymbol{V}=V_o\boldsymbol{v}$; where V_o is the peripheral speed of the cylindrical sheet and $\boldsymbol{v}$ is a unit vector in the direction of the sheet velocity.

Substitution of the above variable in Eq.(1) yields

$$\frac{(a/V_o)}{t_o}\frac{\partial \boldsymbol{B}}{\partial t}=\nabla\times(\boldsymbol{v}\times\boldsymbol{B})+\frac{1}{\mu_o\sigma V_o a}\nabla^2\boldsymbol{B} \tag{2}$$

In the above equation, the operator ∇ and ∇^2 are with respect to the new variable ε, η.

Since the velocity V is constant over the entire spot, it can be shown that Eq.(1) can be modified using vecter identities to

$$(\boldsymbol{v}\cdot\nabla)\boldsymbol{B}=\frac{\nabla^2\boldsymbol{B}}{\mu_o\sigma} \tag{3}$$

As mentioned above in the previous discussion, since the niobium sheet is thin, all current are surface current. Eq.(3) is hence to be solved in two dimensions only. The geometry of the spot makes it convenient to use a rectangular coordinate system as shown in Fig. 3 Introducing the dimensionless variables $\varepsilon=\frac{x}{a}$, $R=\mu_o\sigma V_o a$ and $\eta=\frac{y}{a}$, it is found that Eq.(3) becomes

$$\frac{\partial^2\boldsymbol{B}}{\partial\varepsilon^2}+\frac{\partial^2\boldsymbol{B}}{\partial\eta^2}-R\frac{\partial\boldsymbol{B}}{\partial\varepsilon}=0 \tag{4}$$

The above is a vector equation which has two

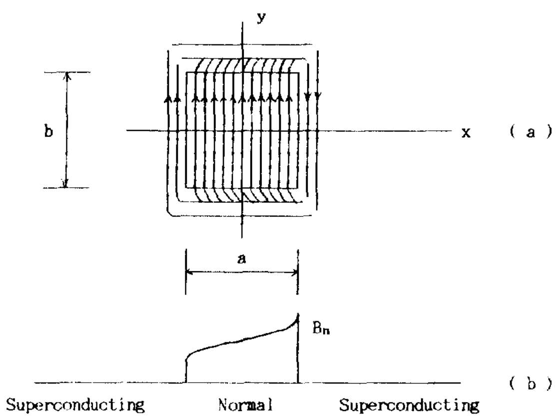

Fig. 3 (a) Path of induced current in and around spot.
(b) Magnetic field distribution in the spot.

component equation; one for the normal (to the sheet) component B_n and the other for the tangential component B_t which is parallel to $\boldsymbol{V}$.

The solution for Eq.(4) with help of $\nabla\cdot\boldsymbol{B}=0$ leads to

$$B_n=\frac{B_oR}{2\cosh R}e^{Rx/a} \tag{5}$$

$$B_t=B_x=-\frac{B_oR^2}{\mu_o 2a\cosh R}e^{Rx/a} \tag{6}$$

The surface current density in the spot is found from the Ampere's relation. Hence,

$$J_y=\frac{1}{\mu_o}\left(\frac{\partial B_x}{\partial z}-\frac{\partial B_z}{\partial x}\right)$$
$$=-\frac{1}{\mu_o}\frac{\partial Bn}{\partial x}$$
$$=-\frac{B_oR^2}{\mu_o 2a\cosh R}e^{Rx/a} \tag{7}$$

3. INDUCTIVE REACTANCE LOSSES IN PHASE TRANSITION

The determination of the field distribution in the spot makes it possible to evaluate the internal inductance of the spot 'L_i' and filament inductance 'L_f' on the foil. In particular, it is apparent that only the normal component of the magnetic field is linked with the current loops associated with the spot. Accordingly, if we define an internal inductance of the spot L_i, then

$$L_iI_e=\Phi_n \tag{8}$$

where Φ_n is the total flux of the normal component of the field linking with the spot and I_e is the total current in the spot, i.e.,

$$I_e=\int_{-a/2}^{a/2}J_y\,dx \tag{9}$$

By virtue of the conservation of charge the same total current also circulates outside the spot combining Eqs.(8) and (9) with Eqs.(5) and (7) one finds at once that

$$L_i=\int_{-b/2}^{b/2}\int_{-a/2}^{a/2}\frac{B_oR}{2\cosh R}e^{Rx/a}dxdy\Big/\int_{-a/2}^{a/2}\frac{B_oR^2e^{Rx/a}}{2\mu_o a\cosh R}dx$$
$$=\frac{\mu_o ab}{R} \tag{10}$$

The internal inductance of the spot is accordingly dependent on the effective speed and of course on the dimension of the spot.

The filament inductance of on the foil associated with the phase transition can be estimated from the following equation.

$$\frac{\partial \boldsymbol{J}}{\partial t}=\nabla\times(\boldsymbol{v}\times\boldsymbol{J}) \tag{11}$$

It is well known that the kinematic interpretation of eq.(11) is that the current lines are swept by the normal spot. Then the L_f can be derived approximately from the pattern of current found from eq.(11)

$$L_f=\frac{\phi}{I} \tag{12}$$

It is to be remembered that L_f increases with the time since the current filament is continuously swept by the spot. Then $\phi(t)$ can be expressed by

$$\phi=\phi_o\omega t/2n=\frac{\text{Ampere}\cdot\text{turn}}{\text{Reluctance}} \tag{13}$$

where ω is the angular velocity of the magnets and ϕ_o is the initial flux linkage.

Combining Eqs.(11), (12), and (13) and remembering that the ampere-turns for ϕ_o is I, one finds

$$L_f=\mu_o\frac{2ab}{h}\frac{\omega t}{2\pi} \tag{14}$$

where h represents the air-gap length.

The inductive reactance losses estimated by eqs. (7), (10), (14) are mainly associated with the magnetic energy loss in switching the current and the voltage drop.

For fixed dimension of the spot, L_f increases as the spot velocity increases, where as the L_i decreses. On the basis of the arguments given above, the stretching of the current sheet in the infinite strip is greater than that occuring in a finite strip. This means that the amplitude of the fluctuations in voltage will be higher for the cylindrical sheet than the for the finite strip. So, those results obserseved in this paper would lead to a premature quenching of the superconducting foil.

It is considered that one way to improve this phenomenon is to subdivide the belt into a number of strips of finite width.

4. CONCLUSION

The inductive reactance losses of a superconducting current generator has been analyzed by the help of the Bullard-Cowling equation with the field distribution on the foil. The calculation of the magnetic field in the spot make it possible to estimate the spot-indutance as well as the filament inductance on the foil. It is shown the reactance losses are dependent on the effective speed of the spot and on the dimension of the spot. As explained in the paper, the current lines are progressively compressed as the normal spot moves and the stretching of the curent filament in an infinite strip becomes greater than that occuring in a finite strip. This implies that the amplitude of fluctuations in voltage will be higher for the cylindrical foil than for the finite strip.

Terefore, it is suggested that the one way to prevent the premature quenching of the superconducting foil be to subdivide the belt into a number of strips of finite width.

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