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박막형 초전도 한류기의 퀜치상태의 전자기 특성

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Elecctromagnetic characteristics of superconducting fault current limiters under the quenching

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Abstract - we analyzed the electromagnetic behavior of a superconducting fault current limiter (SFCL) under the quench state using FEM. The analysis model used in this work is 5.5 KVA meander-line type SFCLs. Meshes of 3,650 triangular elements were used in the analysis of this SFCL. Analysis results showed that the distribution of current density was concentrated to inner curved line in meander-line type-SFCL and the maximum current density was 14.61 A/m^2 and also the maximum Joule heat was 2,030 W/m^2 in this region. We think that the new and the modified structure must be considered for an uniform distribution of the electromagnetic field.

1. Introduction

A superconducting fault-current limiter (SFCL) is the most promising in commercialization among the superconducting power applications. The most typical structures among the resistive fault-current limiters are the SFCL of a meander-line type and that of a spiral-type. The spiral-type SFCL has been developed mainly by Siemens in Germany [1]. There has been numerous constructions and testings of a 100 kVA level SFCL formed by a spiral-type structure. The SFCL of meander line type has been researched mainly by Korea Electrical Power Research Institute (KEPRI). Now the 5.5 KVA prototype of meander line type SFCL has been built and tested by KEPRI [2-3].

The SFCL is based on the superconducting /normal (S/N) transition of high-*Tc* superconductors. In other words, the widely-known resistive SFCL relies on the switch-like onset of resistivity during a quenching process caused by exceeding the critical current of superconductors. This S/N transition of superconductor results in the limitation of a fault current passed through the device and the SFCL works as a limiting device with a fast limiting speed.

The important thing is the current redistribution, the variation of the electromagnetic field, and the Joule-heat growth in an SFCL occurred at this point. Therefore the understanding of an electromagnetic behavior in an SFCL under the quench state is necessary for the optimum design of an SFCL. Unfortunately, there have not been many studies done for the electromagnetic analysis of an SFCL.

In this work, we analyzed the electromagnetic behavior of the SFCL of meander-line type which had the same dimension as KEPRI's SFCL using Finite Element Method (FEM). The analysis results were reported in terms of the redistribution of current density, the electric field intensity, the concentration of Joule heat, the magnetic flux and the magnetic potential.

2. Anaysis model and FEM formulation

A. Analysis Model

Fig. 1 shows the model geometry of the SFCL of meander-line type designed by KEPRI for our electromagnetic field analysis. This SFCL was fabricated using 0.3 μm thick $YBa_2Cu_3O_{7-x}$ (YBCO) thin films grown on two-inch diameter Al_2O_3 substrates. The critical current density was 3 MA/cm^2 and the critical temperature was 90 K. Total length of the meander line was 42 mm. The width of the meander line was 2 mm and the gap between each meander line was 1 mm. The resistance of an SFCL at room temperature and under the quench state was 32 ohm and 20 ohm respectively.

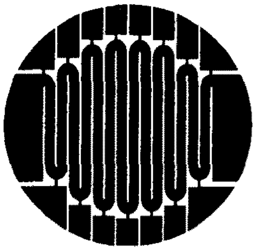

Fig. 1 The pattern of superconducting fault current limiting elements

B. FEM Formulation

The FEM analysis of SFCL under the quench state is based on Maxwells equation

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad (1)$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \qquad (2)$$

$$\nabla \cdot \vec{D} = \rho \qquad (3)$$

where ε, E, B, H, D, and ρ are the permittivity, the electric field intensity, the magnetic flux density, the magnetic field intensity, the electric flux density and the volume charge density, respectively. The electric field intensity can be written as follow,

$$\vec{E} = -\nabla \phi \qquad (4)$$

where ϕ is the electric potential. The governing equation can be expressed using (3) and (4),

$$\nabla \cdot \varepsilon \nabla \phi = -\rho \qquad (5)$$

$$\frac{\partial}{\partial x}\left(\varepsilon \frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon \frac{\partial \phi}{\partial y}\right) = -Q \qquad (6)$$

The equation (6) can be described from Gauss-Green formula using Galerkins method [7].

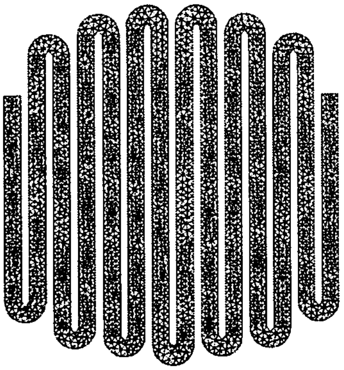

Fig.2 Generation patterns of triangular mesh for electromagnetic analysis of plane section of an SFCL.

$$\int \left(\varepsilon \frac{\partial \phi}{\partial x} n_x + \varepsilon \frac{\partial \phi}{\partial y} n_y\right) W_j \, dl - \int \left(\varepsilon \frac{\partial \phi}{\partial x} \frac{\partial W_j}{\partial x} + \varepsilon \frac{\partial \phi}{\partial y} \frac{\partial W_j}{\partial y} - Q W_j\right) dS = 0 \qquad (7)$$

where W_j is the weighting function. When $\phi(x,y)$ is defined as the potential distribution of trianglular element, analytic region is divided into finite triangle element, and equation (7) is carried out for all the triangles of the field region, the following matrix equation is obtained, solving which the unknown potential is determined.

$$\phi_e \phi(x,y) = [N]^T \cdot \phi^e \qquad (8)$$

where $[N]^T$ is shape function for 2-D triangular element, ϕ^e is the node potential function for each element and ϕ_e is the edge potential function in triangular element.

3. Numerical Results

A. Field Analysis of Plane Section of SFCL

Fig. 2 shows the generation of the triangular mesh for the electromagnetic analysis of an SFCL under the quench state. The total number of mesh element was triangular element of 3650. Applied source voltage was 220 V, source frequency was 60 Hz, and the resistance of superconductors under the quench state was modeled by 20 ohm. The curvature diameter of the outer curved line within the superconducting meander line was 6 mm and that of the inner curved line in the superconducting meander line was 4 mm.

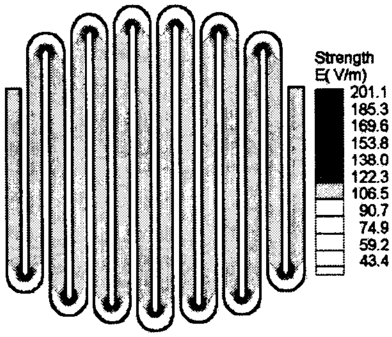

Fig.3 Distribution of electric field intensity for an SFCL under the quench state.

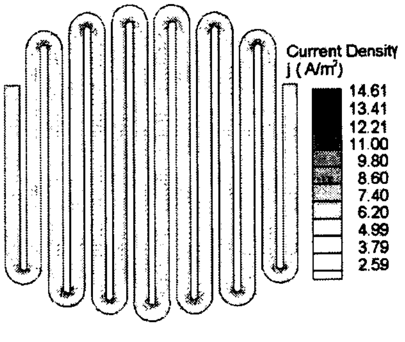

Fig.4 Distribution of current density for an SFCL under the quench state.

Fig. 3 shows the distribution of the electric field intensity for an SFCL under the quench state. We knew that the distribution of the electric field intensity of an SFCL was mainly concentrated to the inner curved line in the superconducting meander line under the quench state. The maximum intensity of the electric field in the inner curved line was 201.1 V/m in the meander line of an SFCL, and the distribution of the electric field intensity was rapidly decreased and closed to zero V/m as they approached the outer curved line in the SFCL. However, the electric field intensity was nearly uniform throughout the entire region of the straight line of an SFCL and the field intensity in this region was 106 V/m. This non-uniform distribution of the electrical field intensity should result the high concentration of a current density and the unbalanced propagation of hot spot originated from the generation of Joule heat in the inner curved line.

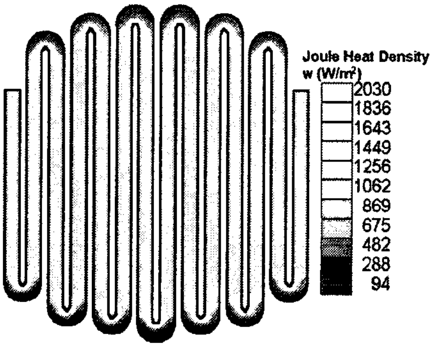

Fig.5 Distribution of Joule heat density of an SFCL under the quench state.

Fig. 4 shows the distribution of current density derived from the result of Fig. 3 for an SFCL of meander line type under the quench state. The current distribution of an SFCL showed the high concentration in the inner curved line and that of an SFCL was gradually decreased and closed to zero in the outer curved line. The maximum value of current density in the inner curved line was 14.61 A/m2 and the value of current density in straight line was uniform with the value of 5.35 A/m2. The non-uniform concentration of current density rapidly generates Joule heat. This unbalanced concentration of current density should result the melting of superconducting line and nonuniform quench propagation when over voltage was applied.

Fig. 5 shows the distribution of Joule heat density derived from Fig. 4. The maximum Joule heat generated from the inner curved line of superconductors was 2,030 W/m2. This maximum Joule heat was gradually decreased and closed to the small volume in the same manner shown in Fig. 3 and Fig 4.

3. Conclusion

As a result of the numerical analsis, we have made the following conclusions. First, the uniform electromagnetic field can not be achieved in the case of the meander-line type-SFCL because of the concentration of electric field in the inner curved line and the concentration of magnetic field in the input and output ports. The concentration of the electric field induced on the concentration of current density and it resulted the local generation of hot spot. Therefore, it must be considered to the design of a new type or a modified type of an SFCL with the uniform field distribution.

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