

## Electromagnetic Behavior of High- $T_c$ Superconducting Fault Current Limiters under the Quench State

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**Abstract** - In this paper 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 which are currently developed by Superconductor Power System Lab in Korea Electric Power Research Institute. 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<sup>2</sup> and also the maximum Joule heat was 2,030 W/m<sup>2</sup> in this region. We think that the new and the modified structure must be considered for an uniform distribution of the electromagnetic field.

**Key Words** : Electromagnetic behavior, Superconducting fault current limiter, Quench state, Finite element method

### 1. Introduction

For the design of electric machines, an electromagnetic analysis is very important for the performance determination of electric apparatus such as the insulation between wires, the distribution of the current density, the distribution of the magnetic flux and the Joule heat generation. Until now, diverse prototypes of superconducting power applications such as fault current limiters, power cables, SMES, transformers and generators have been developed for the large-scale power application of superconducting technology. These superconducting power applications should be coordinated with the electric power-delivery system in order to improve the stability, the controllability, and total efficiency in a future power system [1]-[4].

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 [5]. There has been numerous constructions and tests of a 100 kVA level SFCL formed by a spiral-type structure. The SFCL of meander-line type has been researched mainly by Korea Electric Power

Research Institute (KEPRI). Now the 5.5 KVA prototype of meander line type SFCL has been built and tested by KEPRI [6].

The SFCL is based on the superconducting/normal (S/N) transition of high- $T_c$  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.

The contents of this work are organized as follows: (1) numerical formulations for finite element techniques are shortly described; (2) by using the numerical formulation a discretization of the analysis region and mesh generation in the analysis region of an SFCL is presented; (3) calculated

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results including the electromagnetic field, the distribution of Joule heat and the current density will be reported and discussed; (4) a short summary and conclusion is provided.

## 2. Analysis Model and FEM Formulation

### 2.1 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  $\mu\text{m}$  thick  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  (YBCO) thin films grown on two-inch diameter  $\text{Al}_2\text{O}_3$  substrates. The critical current density was 3  $\text{MA}/\text{cm}^2$  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.

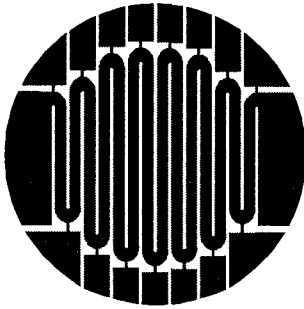


Fig. 1 The pattern of superconducting fault current limiting elements

### 2.2 FEM Formulation

The FEM analysis of SFCL under the quench state is based on Maxwell's equation ,

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

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

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

where  $\epsilon$ ,  $E$ ,  $B$ ,  $H$ ,  $D$ , and  $\rho$  are the volume charge density, 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,

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

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

$$\nabla \cdot \epsilon \nabla \phi = -\rho \quad (5)$$

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

The equation (6) can be described from Gauss-Green formula using Galerkin's method [7],

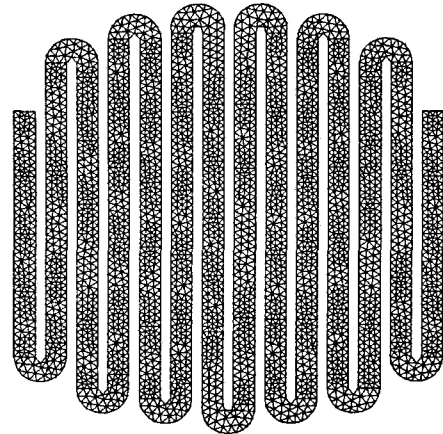


Fig. 2 Generation patterns of triangular mesh for electromagnetic analysis of plane section of an SFCL.

$$\int (\epsilon \frac{\partial \phi}{\partial x} n_x + \epsilon \frac{\partial \phi}{\partial y} n_y) W_j dl - \int_s (\epsilon \frac{\partial \phi}{\partial x} \frac{\partial W_j}{\partial x} + \epsilon \frac{\partial \phi}{\partial y} \frac{\partial W_j}{\partial y} - Q W_j) dS = 0 \quad (7)$$

where  $W_j$  is the weighting function. When  $\phi(x, y)$  is defined as the potential distribution of triangular 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,

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

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

## 3. Numerical Results of Field Analysis

### 3.1 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 3,650. 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.

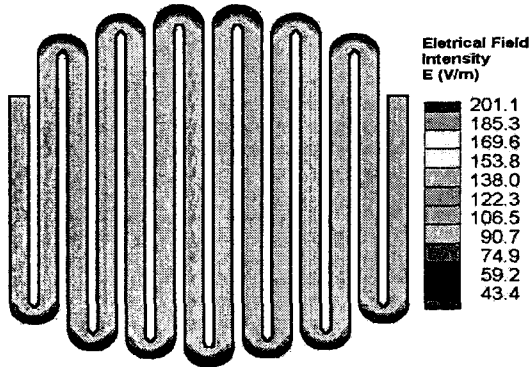


Fig. 3 Distribution of electric field intensity for an SFCL under the quench state.

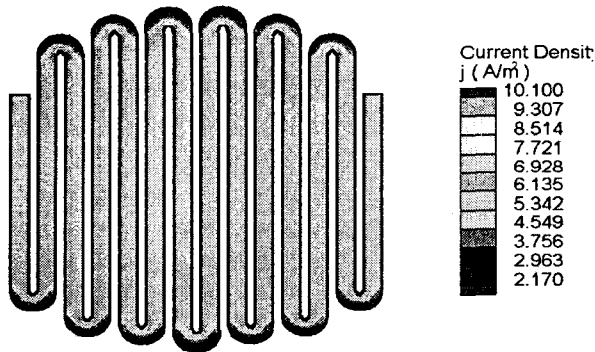


Fig. 4 Distribution of current density for an SFCL under the quench state.

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.

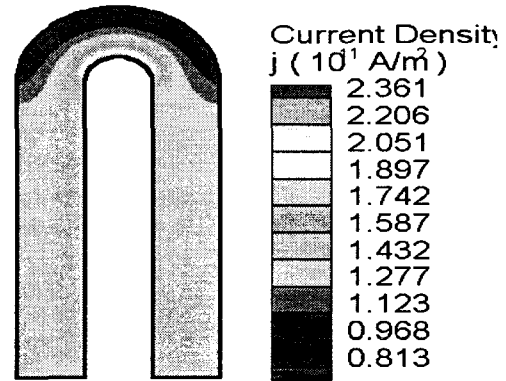


Fig. 5 Distribution of current density for an SFCL under the quench state.

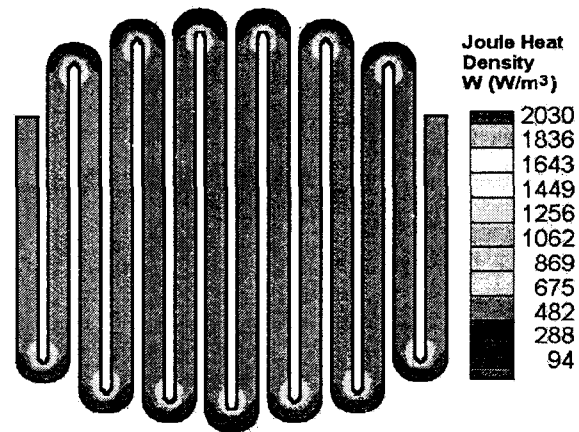


Fig. 6 Distribution of Joule heat density of an SFCL under the quench state.

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/m<sup>2</sup> and the value of current density in straight line was uniform with the value of 5.35 A/m<sup>2</sup>. The non-uniform concentration of current density rapidly generates Joule heat. Fig. 5 shows the distribution of current density for an SFCL under the quench state about one part of the inner curved lines. We confirmed the high concentration of the current density in the inner curved line more obviously. This unbalanced concentration of current density should

result the melting of superconducting line and non-uniform quench-propagation when over voltage was applied.

Fig. 6 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/m<sup>2</sup>. This maximum Joule heat was gradually decreased and closed to the small volume in the same manner shown in Fig. 3 and Fig 4.

### 3.2 Field Analysis of Central Cross Section of SFCL

Fig. 7 shows the triangular mesh generation for the electromagnetic analysis of the cross section of an SFCL under the quench state. The total number of mesh element is triangular element of 3650 as the same case of a plane section of an SFCL. Applied source voltage was 220 V, source frequency was 60 Hz, and the resistance of superconductors under the quench state was modeled by 20  $\Omega$ /m. The width of strip line in an SFCL was 2 mm and the gap between each strip was 1 mm respectively. In total, 14 strips were modeled.

Fig. 8 shows distribution of magnetic potential for the cross section of an SFCL under the quench state. We knew that the distribution of magnetic potential was concentrated to an input port and an output port of an SFCL and also the level of concentration of magnetic potential was significantly high in each strip. It can be attributed to the mutual coupling of magnetic field generated from each superconducting strip. The maximum value of magnetic potential was  $7.530 \times 10^{-9}$  Wb/m. Considering the correlation between the distribution of the magnetic field and the quench propagation, this non-uniform magnetic field would also result the unbalanced quench propagation.

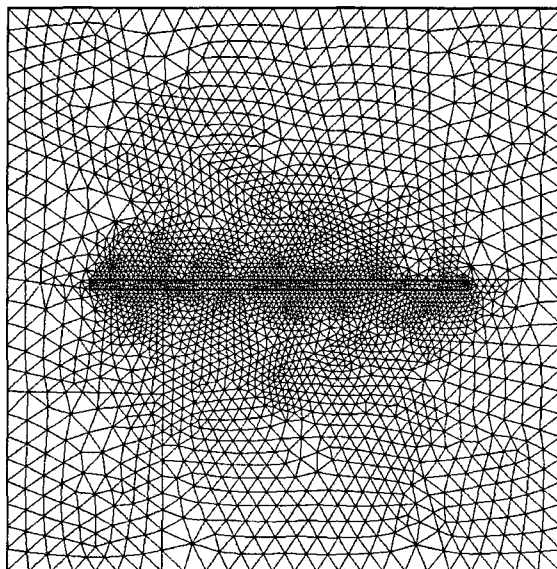


Fig. 7 Generation patterns of triangular mesh for the electromagnetic analysis of the cross section of an SFCL.

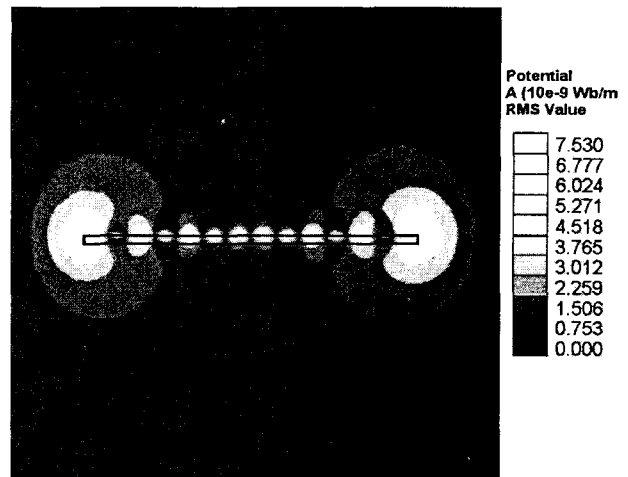


Fig. 8 Distribution of magnetic potential for the cross section of an SFCL under the quench state.

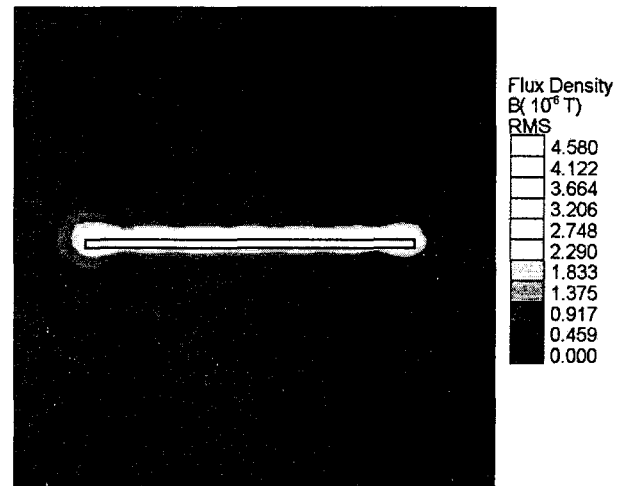


Fig. 9 Distribution of magnetic flux density for the cross section of SFCL under the quench state.

Fig. 9 shows the distribution of the magnetic flux density derived from the result in Fig. 8. The concentration of the magnetic flux density was generated through an input port and an output port. The maximum value of magnetic flux density was  $4.580 \times 10^{-6}$  T. However the distribution of the magnetic flux was nearly uniform unlike the result of Fig. 8.

### 4. Summary and Conclusion

As a result of the numerical analysis, 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. In the meantime, the spiral-line type-SFCL has the

restrictions in the serial connections for the increase of the power capacity because of their non-inductive structure. 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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