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A Study on Transient Numerical Simulation on Heat Transfer Characteristics in the Resistive SFCL

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Abstract-- **A transient numerical simulation was conducted to have variation of temperature on an element of resistive Superconducting Fault Current Limiter (SFCL) under quench condition. It is very important engineering information for an optimum design of cryogenic system for cooling of a resistive SFCL element. A bifilar coil for resistive SFCL for 10 MVA system was incorporated as a model in this numerical study. From the numerical simulation result, it was found that the averaged temperature on the shunt and Bi-2212 element at 500 kW, 100 ms was 711.1 K and 198.4 K respectively. The temperature variation with the change of the hot-spot size and time is also obtained. The maximum temperature was continuously increased in all cases until the hot-spot stops at 100ms and it was going down after then. Such as, the details of temperature distribution on the SFCL element obtained from this numerical study and it should be very valuable information on the decision of the cooling capacity of cryogenic system.**

1. INTRODUCTION

With the continuous growing of the electrical power demand, the power transmission and distribution systems are increasing. Due to the increase of electric power and complexity of the control system, the equivalent impedance in a power line decreases and the size of fault current continuously increases. Therefore, the conventional mechanical type of fault current limit switch is recognized not enough to protect the power system under the fault state and the superconducting fault current limiter (SFCL) has been attracted in electrical power industry.

The most attractive physical characteristic of superconducting material is the immediate loss of superconductivity of the material as it reaches the critical temperature and it turns into normal conductivity. In the normal conducting situation, the resistance of the superconductor increases rapidly and limits the current passing through the material. It is called a quench state. In the high temperature resistive SFCL system, the system uses this characteristic of the superconductor and limits the excessive current not to pass the system.

Under the quench state in the SFCL system, the excessive current turns into the thermal heating energy called hot-spot and rapidly increases the temperature of the SFCL element. To restrict the over current in an electrical power line for a limited time, the SFCL should resist the fault current and shunt the current through other line, not through the superconducting path.

In this study, a quasi-3dimensional numerical simulation algorithm was developed to anticipate the temperature change in the resistive SFCL element with the change of the fault time and the size of fault current in the system. It is sure that the simulation result obtaining from the algorithm will be very important information to design an optimum resistive SFCL in its size and choosing material for the electrical power industry.

2. RSFCL AND ITS GEOMETRY

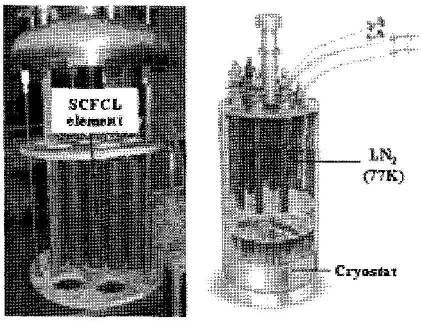
2.1. The RSFCL System incorporated to This Study

When fault current flows through the SFCL, the excessive current turn into the thermal energy source to heat the SFCL element for the fault time (ms). It is called that the SFCL system is under the quench state. In this situation, the SFCL plays a good role to limit the over current to pass the switching system.

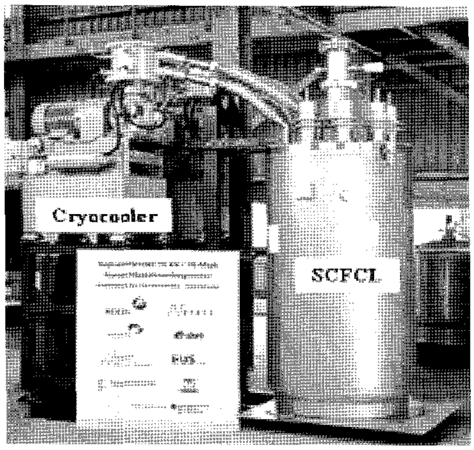
Fig. 1 shows the resistive SFCL system with 10 MVA of capacity that is incorporated to this numerical study. In Fig. 1 (a), it is shown that the resistive SFCL element bundles and cryostat, containing the liquid nitrogen (LN_2) of 77 K. The total system of the resistive SFCL designed for experimental study is shown in Fig.1 (b).

2.2. Structure of Model SFCL Element and Its Dimension

The SFCL element incorporated to this numerical study was designed by NEXANS, Germany for the resistive SFCL system with 10 MVA. Fig. 2 shows the schematic of the element with its dimension. Bi-2212 was applied to the superconducting material and the element consists of five layers of different materials and winded out to make a cylindrical shape.



(a) RSFCL element bundles and cryostat containing liquid nitrogen (LN_2)



(b) RSFCL and cryogenic system with coolant of liquid nitrogen (LN_2)

Fig. 1. The resistive SFCL system with 10 MVA of capacity.

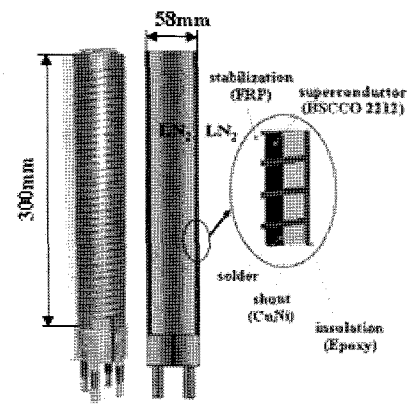


Fig. 2. Configuration of resistive SFCL element for a system of 10 MVA capacity.

Fig. 3 shows the schematic of the unit element for the numerical modeling. It shows the detail geometry and materials consisting of the element. For the numerical simulation, only a part of the element was taken to save the calculation time because the geometry is ax-symmetrical.

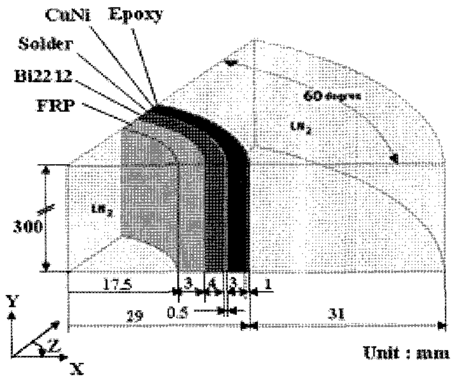


Fig. 3. Schematic and materials consisting of the resistive SFCL element.

3. NUMERICAL SCHEME AND BOUNDARY CONDITIONS

In this study, FVM (Finite Volume Method) was employed to simulate the conduction heat transfer on the SFCL with the change of time and the heat flux generated by the quench state in the SCFL element. In the numerical calculation, the hot spot is assumed to starts homogeneously at the shunt (Cu-Ni) with 500 kW of joule heat for 100ms under the quench state. Then the thermal energy is conducted up to the LN_2 (77 K) that surrounds the SFCL element through the other material layers.

For the numerical simulation of the heat transfer phenomena in the SFCL element, the control volume of the element can be reasonably defined as;

- Quasi-3D flow
- Laminar flow
- Incompressible flow
- Transient state

The general-purpose FVM CFD code, PHOENICS (ver.3.4) [1], has been used for a numerical study of the transient laminar incompressible flow field. 3-dimensional Navier-Stokes equations [2] were solved with the energy equation in the numerical calculation. The no-slip condition on the solid wall contact with LN_2 has been modeled by the logarithmic law. Time differencing has been fully implicit backward while advection terms are hybrid differenced. A conjugate gradient technique for pressure corrections in transport equations has been incorporated and 'SIMPLE' algorithm [4] has been employed for the velocity/pressure coupling in this application.

3.1. Governing Equations

The basic equations of fluid dynamics in the control volume are based on the Navier-Stokes equations that are comprised of equations for conservation of mass and momentum and energy equation given as,

Continuity equation

$$\frac{\partial U_i}{\partial x_i}+\frac{\partial U_j}{\partial y_i}+\frac{\partial U_k}{\partial z_i}=0 \quad (1)$$

Momentum equation

$$\frac{\partial U_i}{\partial t}+\frac{\partial}{\partial x_j}(U_iU_j)=-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)-\overline{u_iu_j}\right]-g_i \quad (2)$$

Energy equation

$$\frac{\partial}{\partial t}(\rho h)+\frac{\partial}{\partial x_i}(\rho u_i h)=\frac{\partial}{\partial x_i}[k(\frac{\partial T}{\partial x_i})]+S \quad (3)$$

3.2. Numerical Domain of Physical Model

BFC (Body Fitted Coordinates) grid generation method [3] in conjunction with non-orthogonal grids allowing irregular geometries has been used to generate the numerical grid in this study and the optimized grid size of the 3-D model was 65*20*25. Fig. 4 shows a prospective 3-dimensional numerical domain of blade-to-blade path of the rotor incorporated for this numerical study.

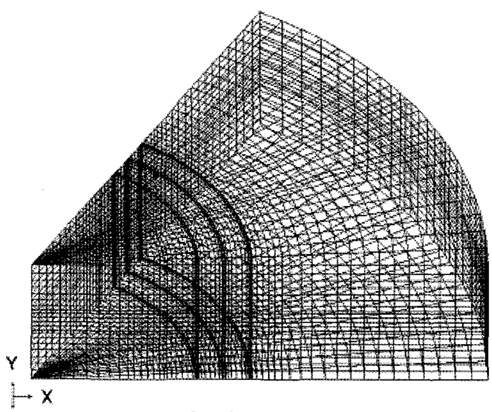


Fig. 4. A prospective view of 3-dimemsional numerical grid of the resistive SFCL (65x20x25).

3.3. Boundary and Initial Conditions

The SFCL element is assumed to be submerged into LN_2 (77 K) to cool down the joule heat. To simulate the physical condition of the heat transfer of the element, the initial and boundary conditions were defined as given below.

1) Initial Conditions:
- Shunt is homogeneous Cu-Ni alloy.
- Hot-spot starts instantaneously in the shunt and continues for 100 ms.
- No evaporation occurs in LN_2 during the quench period
- Total simulation time for the transient calculation is 0~150 ms.

2) Boundary Conditions:
- Potential flow is defined on the control surface.
- Properties of material of 5-component of the element is fixed and given in Table II.
- Total thermal energy is 500 kW and is generated continuously for the first 100 ms.

The thermal conductivity and specific heat are the function of temperature. However, those are assumed to be constant at this stage of the research.

3.4. Major Parameters and Their Ranges

The standard energy source that induces the quench state on the SFCL system is 500 (kW). However, the energy density was set up on five steps as shown in Table I; two higher steps and two lower steps than the standard amount to see its effect on the maximum temperature reached on the element. The thermal energy was supplied to the shunt (Cu-Ni) for the first 100 ms and discontinued after then, but the calculation was continued up to 150 ms to check the temperature variation after stopping the thermal energy.

TABLE I
CALCULATION RANGE OF ENERGY DENSITY (E/D) AND ITS TIME

No.	Energy Source	Energy Density (kW/m^3)	Calculation Time (ms)
1	250 kW (50%)	1.001E+07	
2	400 kW (80%)	1.602E+07	With E/S :
3	500 kW (100%)	2.002E+07	0~100 ms Without E/S :
4	850 kW (150%)	3.003E+07	101~150 ms
5	1000 kW (200%)	4.004E+07	

The density, specific heat and thermal conductivity of the materials consisting of the SFCL element is defined as constant variables for the calculation at the stage of the research. It is given in Table II given below.

TABLE II
MATERIAL PROPERTIES OF THE SFCL AT 77 K [6]

Material	Density (kg/m^3)	Specific heat (J/kg K)	Thermal conductivity (W/m K)
N_2(l)	807	2051	0.1396
N_2(g)	4.604	1084	0.00723
FRP	250	1000.0	0.035
Epoxy	1900	789.0	0.35
Bi-2212	6700	142.4	4.7
Solder	11340	109	40.7
Cu-Ni	8954	178.0	181.0

4. RESULT AND DISCUSSIONS

A transient numerical simulation was conducted to estimate the conductive heat transfer phenomena on the materials consisting of the model SFCL element under the quench state. The simulation results were analyzed by two ways;

- Variation of the maximum temperature of the SFCL element with the change of the thermal energy density occurred on the shunt.
- Variation of the temperature distribution on the SFCL element with the change of time.

4.1. Analysis Method of Simulation Results

The transient analysis of temperature distribution on the model SFCL element is the most important job in the analysis of the simulation result. For this, we took the temperature distribution values on O-O line in the middle x-y plane of z-direction as shown in Fig. 5.

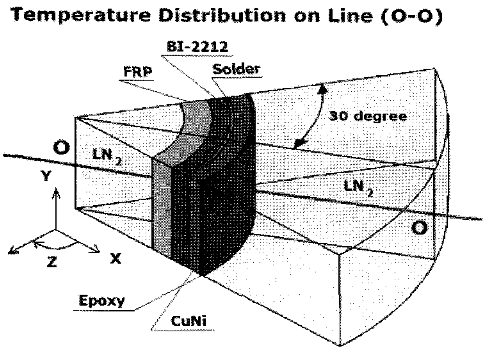


Fig. 5. Location of the temperature distribution on the SFCL element in the numerical domain.

4.2. Temperature Distribution on the SFCL Element with the Change of Energy Density

Fig. 6 shows variation of the average temperature of the SFCL element at 100 ms of fault time with the change of the energy source on the shunt. It is found that the temperature linearly increases with the energy source and it reaches up to 341.2 K at 100 ms.

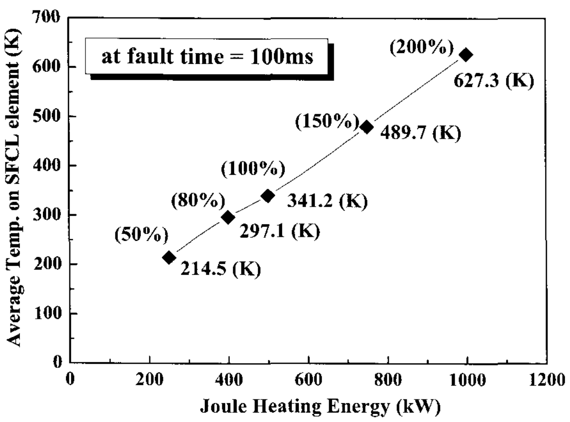


Fig. 6. Variation of average temperature of SFCL element with the change of Joule heating energy at fault time = 100 ms.

Fig. 7 shows variation of the hot-spot temperature of the SCFL element at 100ms of the fault time with the change of the energy source on the shunt. The maximum temperature occurs at the shunt material where the hot-spot starts and it reaches up to 743.1 K at 100 ms with 500 kW.

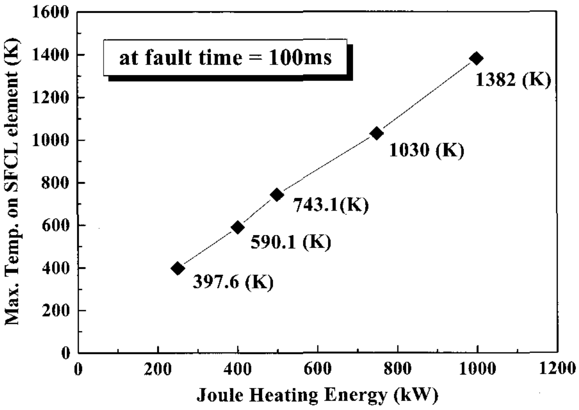


Fig. 7. Variation of maximum temperature of SFCL element with the change of Joule heating energy at fault time = 100 ms.

An averaged temperature of the shunt (Cu-Ni) is very important parameter to monitor because the shunt should sustain the over-current condition for a period of time without melting. As shown in Fig. 8, the averaged temperature of the shunt reaches up to 711.1 K at 100 ms of fault time with 500 kW of heat source.

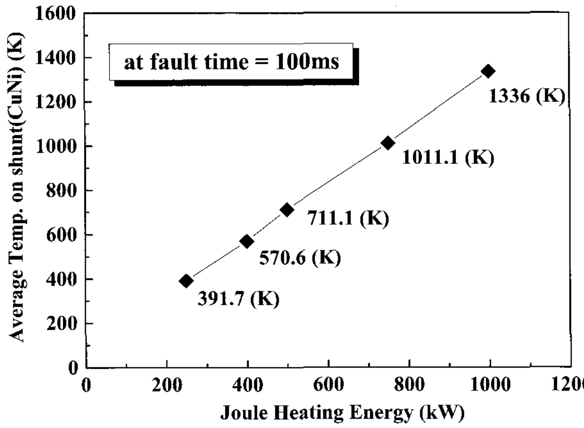


Fig. 8. Variation of average temperature on shunt (Cu-Ni) element with the change of Joule heating energy at fault time = 100 ms.

4.3. Variation of Temperature with the Change of Fault Time

It is also very important to trace the temperature change with the fault time for an optimum design of the SFCL element. Fig. 9 shows variation of average temperature of SFCL element with the fault time. The temperature is linearly increases and reaches up to 350 K at 100 ms of the fault time with 500 kW. After then, it still goes up with very low rate of increment even the heat source is stopped after 100 ms of fault time. It is due to the latent heat source transferred from the shunt to other materials in the element.

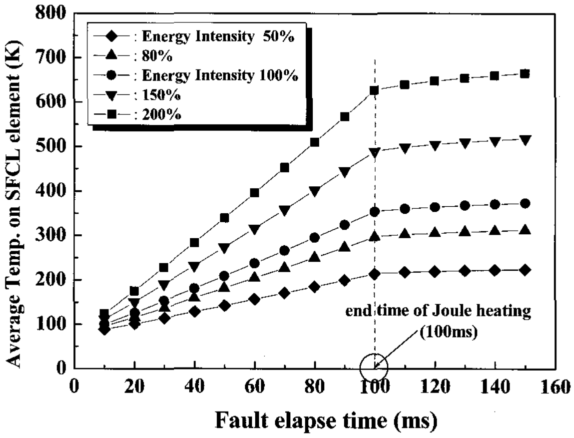


Fig. 9. Variation of average temperature of SFCL element with the change of fault elapsed time.

Fig. 10 shows variation of the maximum temperature of SFCL element with the fault time. The temperature is linearly increases and reaches over to 710 K at 100 ms of the fault time with 500 kW. The maximum happens on the shunt material where the hop spot starts. After 100 ms of fault time, it decreases because the energy source of hot spot is disappeared.

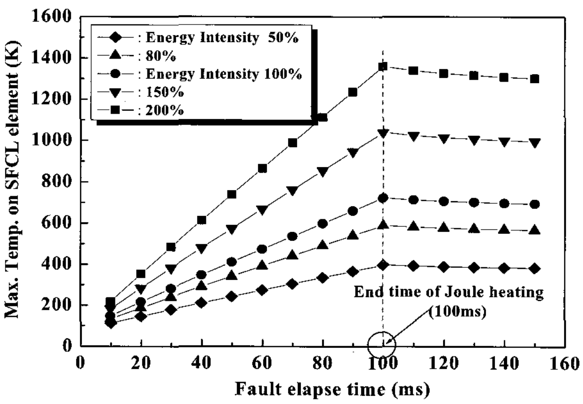


Fig. 10. Variation of hot-spot temperature of SFCL element with the change of fault elapse time.

4.4. Temperature Distribution on the SFCL Element

Fig. 11, Fig. 12 show the temperature distribution on the SFCL at 100 ms of fault time with 500 kW. From the transient calculation result, we could have visualization of temperature diffusion on the element with time.

From the figures, we understand that the heat flux generated on the shunt easily transfers to the epoxy side that faces to LN_2 than to the solder side. Because of this, the temperature distribution on the epoxy is lower than that of the solder as shown in Fig. 11. Fig. 12 shows the details of the temperature distribution on the shunt.

The temperature is higher on the epoxy side than on the solder side. It is due to the cooling effect of LN_2 on the epoxy side. Therefore, to protect the shunt from melting for the period of fault time, we should seriously consider the thermal conductivity of the material located between the shunt and LN_2.

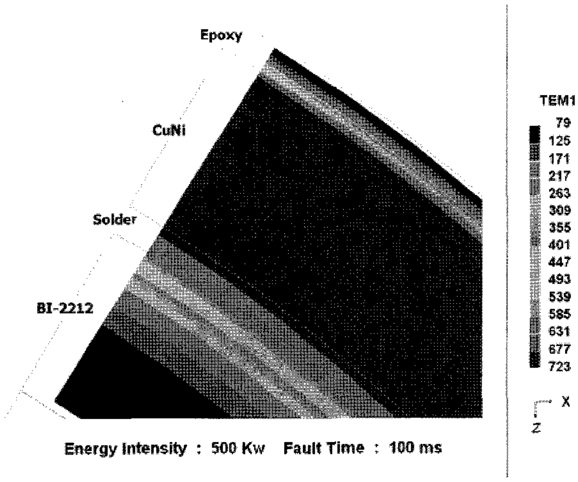


Fig. 11. Temperature distribution on the surface of SFCL element after 100ms of faulting elapse time at the energy intensity of 500 kW.

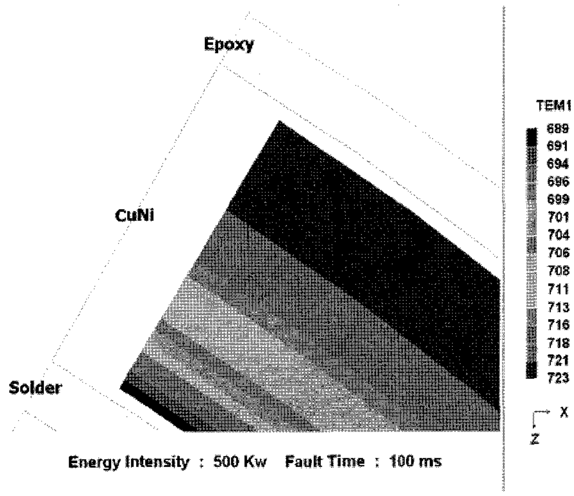


Fig. 12. Temperature distribution on the surface of the shunt (Cu-Ni) after 100 ms of faulting elapse time at the energy intensity of 500 kW.

5. CONCLUSION

The high temperature SCFL has been developed to protect the voltage transmission and distribution system by fault current in the electrical power generation industry. When the fault current occurs in the system, the limit switch experiences the quench state and the superconducting material loses its superconductivity because of the thermal energy generated by the fault current in the system. In order to have an optimum design of SFCL for practical application, it is very important to find out the temperature variation of SFCL element in the limited time.

In this study, a transient numerical simulation was carried out to have detailed information of the temperature variation in the SFCL element with the change of time and the size of the thermal energy source due to the fault current. This detailed information of the temperature distribution on the SFCL element obtained should be very valuable information for the decision of the cooling capacity of cryogenic system.

From the simulation results,

1) The average temperature of the shunt (Cu-Ni) and Bi-2212 is 711.1 K and 198.4 K respectively at 500 kW, 100 ms.
2) It takes longer time than expected to be transferred the joule heating energy from the shunt to Bi-2212 because of the conductivity characteristics of the solid material in SFCL.
3) The highest temperature in the shunt is about 720 K and more thermal energy is transferred to the solder side than the epoxy side which has lower thermal conductivity than solder.
4) The average temperature of SFCL continuously increases even though the hot-spot stopped at 100 ms. It is due to the latent heat transfer of the solid components in the SFCL element.
5) The average temperature of the shunt (Cu-Ni) decreases after 100 ms because the heat source is disappeared.

ACKNOWLEDGEMENT

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