

Simulation of electrical and thermal behavior of high temperature superconducting fault current limiting transformer (HTc-SFCLT)

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Abstract. Superconducting Fault Current Limiting Transformer (SFCLT) is expected to perform functions both of transformer in the normal operating condition and of fault current limiter in the system fault condition. As the Phase-3 of the SFCLT project, we have been developing SFCLT based on Bi2212/CuNi bulk coils at LN₂ temperature and verified its technical feasibility. In this paper, we developed a numerical model for evaluation of the electrical and thermal behavior of HTc-SFCLT such as current limitation and recovery characteristics. This model took into account E-J characteristics of Bi2212/CuNi bulk coil and its electrical and thermal transient phenomena during the operation of HTc-SFCLT. The simulated current agreed well with the experimental data with the error of less than 5%. The excellent current limitation and self recovery characteristics obtained by the experiments could also be reproduced. With the numerical model, current and thermal behavior of HTc-SFCLT was simulated for different parameters of conductor configuration, which would be useful for the future design and optimization of HTc-SFCLT.

1. Introduction

Recently, extensive research and development on applied superconductivity to power transmission have been carried out around the world not only in laboratory test but also in field demonstration. From the viewpoints of system coordination and functional diversification of superconducting power apparatus and systems, we have proposed and have been developing a “Superconducting Fault Current Limiting Transformer”, abbreviated to “SFCLT”, with the functions of both superconducting transformer and superconducting fault current limiter [1]-[3]. In Phase-3 of the SFCLT project, we have fabricated the HTc-SFCLT with Bi2212/CuNi bulk coils at LN₂ temperature, and verified fundamental characteristics as a superconducting transformer and a superconducting fault current limiter [3]. In this paper, we developed a numerical model for evaluation of the electrical and thermal behavior of HTc-SFCLT. The simulation results were compared with the experimental results to prove the validity of the numerical model.

2. Specifications of HTc-SFCLT

Specifications of HTc-SFCLT are shown in table 1 [3]. We designed and fabricated a HTc-SFCLT with series-connected Bi2212/CuNi bulk coils (coil A and coil B) as the low-voltage coil (inner coil). The high-voltage coil (outer coil) was composed of copper wire. The HTc-SFCLT was immersed in LN₂ at 77K together with the iron core. The Bi2212/CuNi bulk coil is shown in figure 1. CuNi-alloy was soldered around Bi2212 bulk in order to avoid the development of hot spots in Bi2212 bulk during the current limiting operation. The Bi2212/CuNi composite was cut into the monofilar coil, and impregnated with epoxy resin for both electrical insulation and mechanical stability.

Table 1. Specifications of HTc-SFCLT.

Phase	1 (3)	
Frequency	60Hz	
Rated voltage	159V/61V (275V/105V)	
Rated capacity	2.08kVA (6.25kVA)	
Leakage impedance	4.98%	
	LV	HV
Material	Bi2212/CuNi	Copper
Size	2x3mm ² /2x1.5mm ²	φ2.3mm
Number of turns	2x70	2x183
I _C	57A (coil A), 63A (coil B)	-
(77K, self field, 1μV/cm)		

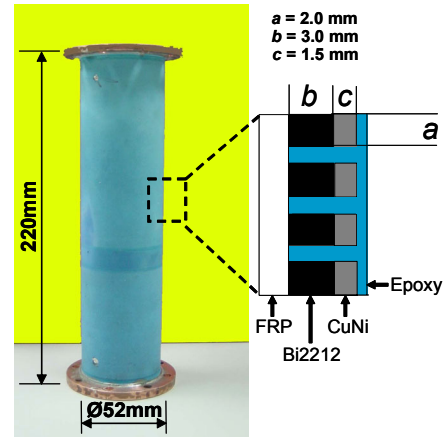


Figure 1. Bi2212/CuNi bulk coil.

3. Simulation model

For modelling the behavior of HTc-SFCLT, the electrical and thermal characteristics of Bi2212/CuNi coil were included in the numerical analysis code. The simulation model consists of 2 parts; the calculation for electrical circuit equation and the calculation for heat equation. The simplified equivalent electrical circuit, including HTc-SFCLT, is shown in figure 2. As shown in figure 2, Bi2212/CuNi coil is regarded as the parallel-connected resistance of Bi2212 (R_{Bi}) and CuNi-alloy (R_{CuNi}). R_{Bi} was derived from E-J characteristics of Bi2212. V_{LV} is the equivalent source voltage at the low voltage side of HTc-SFCLT, R is the equivalent circuit resistance, R_L is the load resistance and L is the leakage inductance of HTc-SFCLT. The geometry parameters of coil (a , b and c as shown in figure 1) are fixed as the fabricated ones ($a = 2.0$ mm, $b = 3.0$ mm, $c = 1.5$ mm). The electrical circuit equation is shown in equation (1).

$$V_{LV} = IR + L \frac{dI}{dt} + I(R_{Bi} // R_{CuNi}) + IR_L \quad (1)$$

For calculating the heat equation, we assumed that in case of a fault, the coil would heat up uniformly along its length, i.e. the coil was homogeneous along its whole length. With this assumption, we applied the heat equation as shown in the following equations (2), (3), (4) and (5) for both Bi2212 and CuNi.

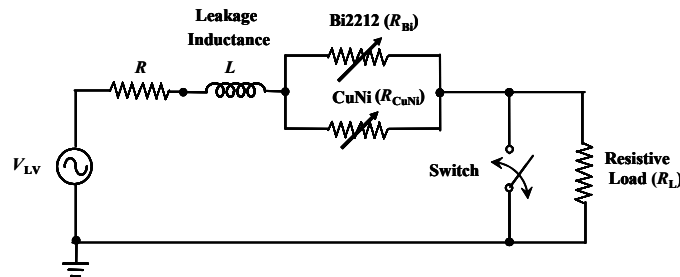


Figure 2. Equivalent electrical circuit for numerical simulation of HTc-SFCLT.

$$C \frac{dT}{dt} = Q - W \pm Q_{12} \quad (2)$$

$$Q = I^2 R_{\text{Bi}} \text{ or } Q = I^2 R_{\text{CuNi}} \quad (3)$$

$$W = \alpha A (\Delta T) \quad (4)$$

$$Q_{12} = \lambda S (\Delta T_{12}) \quad (5)$$

where C is the thermal capacity, T is the temperature, Q is the joule heat, W is the cooling power of LN_2 , Q_{12} is the heat transfer between Bi2212 and CuNi-alloy, α is the heat transfer coefficient to LN_2 , A is the surface area for heat transfer, λ is the heat transfer coefficient between Bi2212 and CuNi-alloy, S is the surface area between Bi2212 and CuNi-alloy, ΔT is the temperature difference between conductor (Bi2212 or CuNi-alloy) and LN_2 , and ΔT_{12} is the temperature difference between Bi2212 and CuNi-alloy. E-J characteristics of Bi2212 was modelled according to [4], where the relation of critical current density J_c and temperature T of Bi2212 [5] was taken into account.

The operation of HTc-SFCLT is as follows: firstly, when the switch in figure 2 is open, HTc-SFCLT acts as a transformer under a steady load current I_{L1} . Next, the switch is closed for 5 cycles to simulate a fault, leading to the large short-circuit current, and then HTc-SFCLT works as a fault current limiter. At 5 cycles after the fault, the switch is simply opened to clear the fault. The experiments were performed [3], taking I_{L1} and the prospective short-circuit current I_{PRO} as variable parameters.

4. Simulation results and discussions

One of the simulation and experimental results is shown in figures 3 and 4. The figures show the waveforms of low-voltage side current I_{LV} and the temperature rise during the fault current limitation of HTc-SFCLT at $I_{L1} = 48 \text{ A}_{\text{peak}}$ and $I_{\text{PRO}} = 908 \text{ A}_{\text{peak}}$. In the experiment, the fault current in figure 3 was limited to $392 \text{ A}_{\text{peak}}$ (43% of I_{PRO}) at the 1st cycle and $309 \text{ A}_{\text{peak}}$ (34% of I_{PRO}) at the 5th cycle, respectively. The load current I_{L2} after the fault clearance was nearly equal to the load current I_{L1} before the fault, which suggested that HTc-SFCLT recovered into superconducting state by itself immediately after the fault clearance. According to the thermal analysis under adiabatic condition based on current and voltage waveforms in the experiment, the temperature rise ΔT of Bi2212 bulk coil in figure 4 was 5.3 K after 5 cycles.

The simulation results were compared with the experimental results as shown in figures 3 and 4. The simulated current agreed well with the experimental data with the error of less than 5%. Though

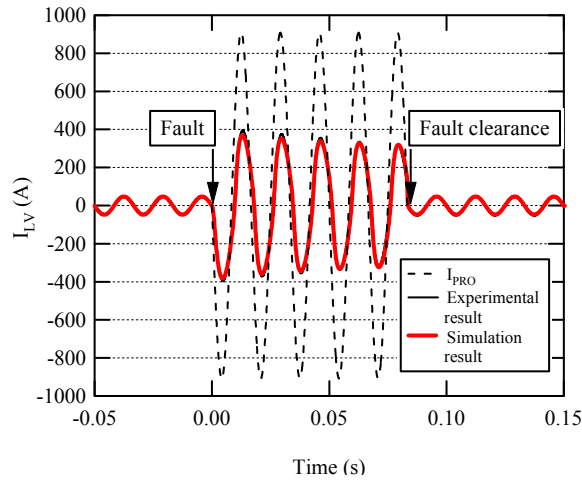


Figure 3. Comparison between simulation and experimental results (current limitation).

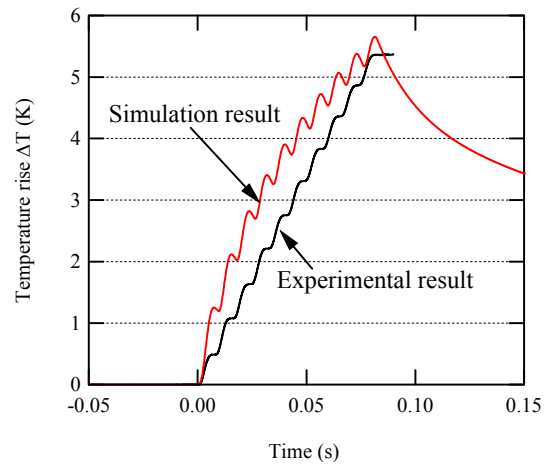
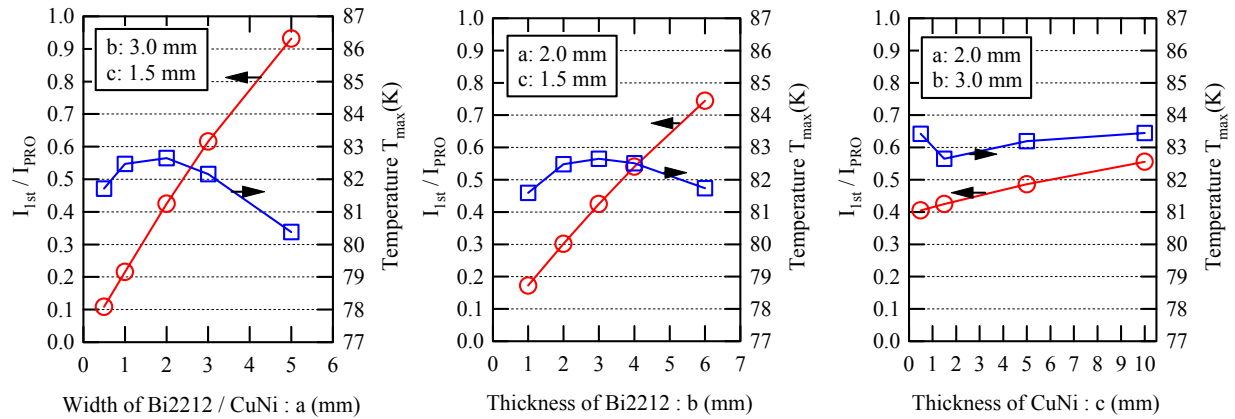


Figure 4. Comparison between simulation and experimental results (temperature rise).



(a) Dependence of width of Bi2212/CuNi. (b) Dependence of thickness of Bi2212. (c) Dependence of thickness of CuNi.

Figure 5. Current limitation factor I_{1st}/I_{PRO} and maximum temperature T_{max} for different geometry parameters.

the temporal change of temperature rise was higher than the experimental one, the maximum temperature at the 5th cycle was almost equal to the experimental value. With these comparison results, the validity of the numerical model was verified.

Numerical simulation of fault current limitation and temperature rise was further performed for different parameters of conductor configuration (a , b , c). Figure 5 shows the current limitation factor I_{1st}/I_{PRO} , where I_{1st} is the peak current at the 1st cycle after the fault, and maximum temperature T_{max} at the 5th cycle as a function of (a) width of Bi2212/CuNi, (b) thickness of Bi2212 and (c) thickness of CuNi for $J_c = 950$ A/cm² and $I_{PRO} = 908$ A_{peak}. Simulation results revealed that I_{1st}/I_{PRO} increased with the increase in parameters a and b , according to the increase in the critical current $I_c (=J_c \times a \times b)$. On the other hand, there existed the maximum value of T_{max} for parameters a and b , as the result of heat balance between heat generation and cooling during fault current limitation. I_{1st}/I_{PRO} and T_{max} were not so much sensitive to the parameter c , i.e. CuNi-alloy, which confirms that the current limitation and recovery characteristics of HTc-SFCLT in figures 3 and 4 were dominated by the flux-flow state of Bi2212.

Thus, the developed simulation model was verified to be useful to analyze the electrical and thermal behavior of HTc-SFCLT. The model is expected to be applied to the estimation of HTc-SFCLT performance with the higher ratings of capacity and voltage, and its optimization design.

5. Conclusion

We developed a numerical model to simulate the electrical and thermal behavior of HTc-SFCLT. The simulation results for current limitation and recovery characteristics were compared with the experimental data, and the validity of the model was confirmed. With this developed simulation code, the design and optimization of HTc-SFCLT in the next phase can be expected.

Acknowledgments

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