

# Analysis of Current Limiting and Recovery Characteristics of Superconducting Fault Current Limiting Transformer (SFCLT) with YBCO Coated Conductors

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**Abstract**—Superconducting Fault Current Limiting Transformer (SFCLT) is expected to function as superconducting transformer in steady state and superconducting fault current limiter in fault condition. We have designed, fabricated and tested SFCLT with YBCO coated conductors to be operated in liquid nitrogen (LN<sub>2</sub>) at 77K and verified its technological feasibility. In this paper, we developed a simulation model to analyze electrical and thermal behaviors of SFCLT by solving the circuit equation and the heat conduction equation. By the use of this simulation model, we could evaluate the transition of resistance and temperature of the YBCO coated conductors during the fault current limitation as well as after the fault clearance, and verified the recovery criteria of SFCLT.

**Index Terms**—YBCO coated conductor, superconducting fault current limiter, superconducting transformer.

## I. INTRODUCTION

SUPERCONDUCTING power applications are expected to bring about low loss and high efficiency transmission as well as to improve the transmission capacity and power system stability. Recently, superconducting power apparatus such as fault current limiters, transformers, cables, SMES have been investigated and demonstrated [1]-[4].

From the viewpoints of system coordination and functional diversification of superconducting power apparatus, we have proposed and have been developing a Superconducting Fault Current Limiting Transformer (SFCLT) with functions of both superconducting transformer and superconducting fault current limiter from Step-1 to Step-5 [5]-[14]. As the Step-5 of our SFCLT project, we have designed, fabricated and tested SFCLT with the ratings of 3-phase, 2 MVA, 22 kV/6.6 kV using YBCO coated conductors, and verified fundamental and

excellent performance of both transformer and fault current limiter [12], [13]. In addition, ideal recovery characteristics into superconducting state after the current limitation and fault clearance were also examined.

In this paper, for the functional optimization of SFCLT with current limiting and recovery characteristics, we developed a simulation model to analyze the electrical and thermal behaviors of the 2 MVA class SFCLT. The validity of this simulation model was verified by comparison between simulation results and experimental results. By using this simulation model, we evaluated the transition of resistance and temperature of the YBCO coated conductors during the fault current limitation and after the fault clearance. Furthermore, the recovery criteria of SFCLT were suggested.

## II. SPECIFICATIONS OF 2 MVA CLASS SFCLT

The specifications and structure of 2 MVA class SFCLT with YBCO coated conductors are shown in Table I and Fig. 1 and 2. The details of SFCLT concept and specifications are to be referred to [12], [13]. We designed 3-phase SFCLT with the ratings of 2 MVA, 22 kV/6.6 kV. We fabricated a single phase demonstrator of the Y-Y connection SFCLT. HTS coils were arranged in both core legs (A-leg, B-leg) and immersed in LN<sub>2</sub> at 77 K together with the iron core. Low-voltage coils (A1~A6, B1~B6; total 12 coils connected in series) consist of two types of YBCO tapes, and high-voltage coils (A7~A10, B7~B10; total 8 coils connected in series) were made of Bi2223 tapes.

Low-voltage coils of SFCLT are divided into 2 parts: YBCO coils with current limitation function (Tr/FCL coil in Fig.2) and YBCO/Cu coils without current limitation function (Tr coil in Fig.2). Such a hybrid structure of HTS coils brings about the higher design flexibility for both transformer and current limiter with different ratios between Tr/FCL coils and Tr coils.

We carried out the current limitation and recovery tests of SFCLT at 50 Hz [14]. The test procedure is as follows: First, SFCLT is operated as a superconducting transformer with a steady load current. Secondly, a fault making switch connected in parallel with the load was closed for 5 cycles, in order to generate a large short-circuit current, where SFCLT works as a fault current limiter. Thirdly, after the fault period of 5 cycles, the switch was opened to clear the fault, and then SFCLT operates again as a superconducting transformer. The load

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TABLE 1 SPECIFICATIONS OF 2 MVA CLASS SFCLT.

| Phase                         | 3              |           |                     |
|-------------------------------|----------------|-----------|---------------------|
| Rated capacity                | 2 MVA          |           |                     |
| Rated voltage                 | 22 kV / 6.6 kV |           |                     |
| Rated current                 | 52.5 A / 175 A |           |                     |
| Turn ratio                    | 1334 / 396     |           |                     |
| Maximum magnetic flux density | 1.7 T          |           |                     |
| Leakage impedance             | 6.1% (@60 Hz)  |           |                     |
|                               | 5.3% (@50 Hz)  |           |                     |
| Material and $I_c$ @77K       | LV(I)          | YBCO      | 215 A <sup>1)</sup> |
|                               | LV(II)         | YBCO / Cu | 240 A <sup>2)</sup> |
|                               | HV             | Bi2223    | 73 A <sup>2)</sup>  |

※ 1)0.3 μV/cm 2)1.0 μV/cm



Fig. 1. Total structure of 2MVA class SFCLT.

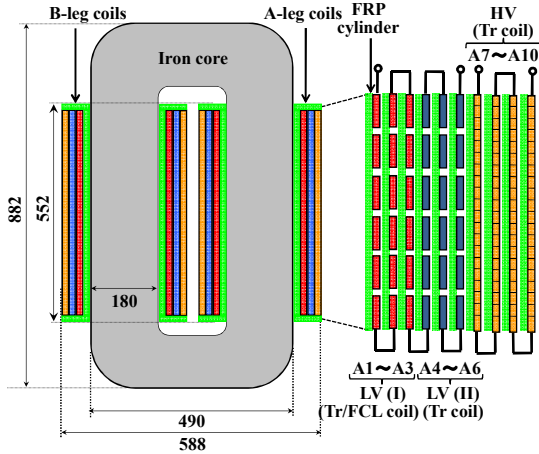


Fig. 2. Cross-section and coil arrangement.

current  $I_{LV}$  and prospective short-circuit current  $I_{PRO}$ , both in peak values, were taken as variable parameters in the current limitation and recovery tests.

### III. SIMULATION MODEL

We developed a simulation model to analyze electrical and thermal behaviors of SFCLT by solving the circuit equation and the heat conduction equation. Figure 3 shows the equivalent

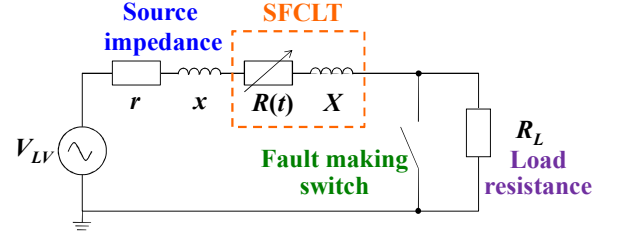


Fig. 3. Equivalent circuit for current limitation and recovery test of SFCLT.

circuit for the current limitation and recovery tests of SFCLT. The electrical circuit equation is shown as follows:

$$V_{LV} = (x + X) \frac{dI}{dt} + I(r + R(t) + R_L) \quad (1)$$

where  $r$  and  $x$  are the source impedance,  $R(t)$  and  $X$  are the resistance and leakage inductance of SFCLT, and  $R_L$  is the load resistance. Assuming that the YBCO tapes have uniform temperature distribution without hot spots, the heat conduction equation is shown as follows:

$$c(T) \frac{dT}{dt} = R(t)I^2 - \alpha(T)\Delta T \quad (2)$$

where  $c(T)$  is the specific heat,  $R(t)I^2$  is the Joule heat,  $\Delta T$  is the temperature rise of YBCO tapes, and  $\alpha(T)$  is the heat transfer coefficient of LN<sub>2</sub> [15].

In order to obtain the electrical and thermal behavior of the SFCLT, the time dependence of the electric field should be calculated. By using voltage ( $V$ ) and current ( $I$ ) waveforms of SFCLT acquired from the experimental data, the electric field ( $E$ ) and temperature ( $T$ ) of YBCO tapes were calculated successively by the following equations:

$$E = V / L \quad (3)$$

$$T = \int (VI - \alpha(T)\Delta T) / c dt \quad (4)$$

where  $L$  is the length of YBCO tapes. The temporal change of  $E$  and  $T$  in every half cycle was calculated and plotted in Fig. 4 as  $E$ - $\Delta T$  trajectories under various experimental conditions ( $I_{LV} = (0.2 \sim 0.4) * I_c$ ,  $I_{PRO} = (2 \sim 4) * I_c$ ).  $E$ - $\Delta T$  trajectories in Fig. 4 suggest that  $E$  depends on  $I$  and  $\Delta T$  during fault and during recovery, i.e.  $E$ - $I$ - $\Delta T$  characteristics need to be found out to understand current limitation and recovery process. By dividing  $E$  during fault and during recovery by the instantaneous values of  $I^2$  and  $I * I_{PRO}$ , respectively, we could obtain the electrical and thermal behavior of the SFCLT to be independent of experimental conditions (values of  $I_{LV}$  and  $I_{PRO}$ ), i.e. the normalized  $E$ - $I$ - $\Delta T$  characteristics as shown in Fig. 5 and 6. We used the normalized  $E$ - $I$ - $\Delta T$  characteristics in Fig. 5 and 6 as specific characteristics of the SFCLT based on its experimental data.

By using the simulation model with the  $E$ - $I$ - $\Delta T$  characteristics in Fig. 5 and 6, we simulated current, temperature and resistance of SFCLT under the experimental condition of  $I_{LV} = 64$  A and  $I_{PRO} = 876$  A. Comparison between simulation and experiment results are shown in Fig. 7. The simulation results agree well with the experiment results. The simulation results in other cases could also reproduce the experiment results. Thus, the validity of the simulation model was verified.

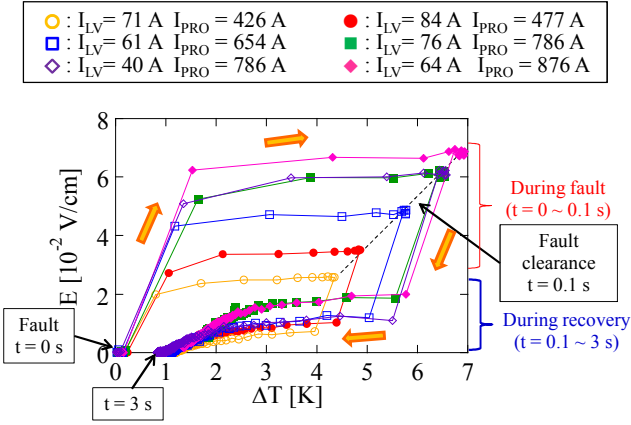


Fig. 4.  $E$ - $\Delta T$  trajectories in every half cycle during fault and recovery obtained by experiment.

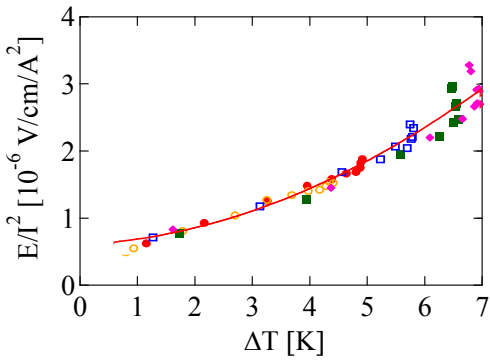


Fig. 5. Normalized  $E$ - $I$ - $\Delta T$  characteristics of SFCLT during fault obtained by experiment.

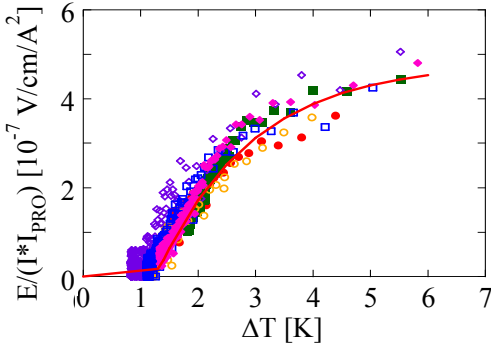
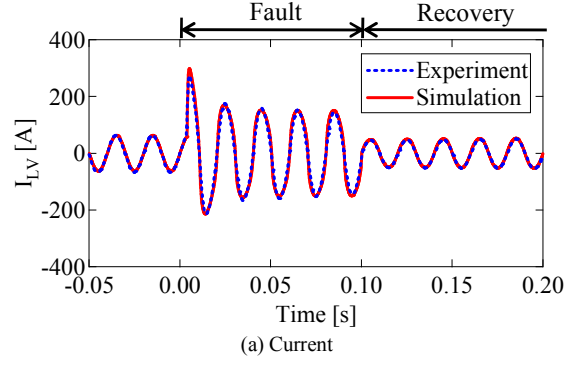


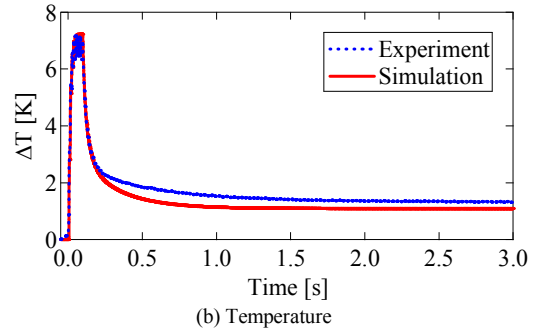
Fig. 6. Normalized  $E$ - $I$ - $\Delta T$  characteristics of SFCLT during recovery obtained by experiment.

#### IV. RECOVERY CRITERIA OF SFCLT

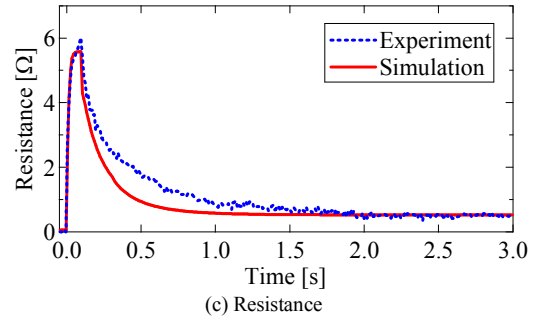
We discussed the current limitation and recovery process in term of the transition of  $E$ - $\Delta T$  characteristics. Figure 8 shows  $E$ - $\Delta T$  trajectories under (a)  $I_{LV} = 29.4$  A,  $I_{PRO} = 500$  A and (b)  $I_{LV} = 109$  A,  $I_{PRO} = 500$  A. These figures show  $E$ - $\Delta T$  trajectories from the steady state ( $E = 0$  V/cm,  $\Delta T = 0$  K,  $t < 0$  s) through the fault period ( $t = 0 \sim 0.1$  s) to the recovery period ( $t = 0.1 \sim 5$  s). The  $E$ - $\Delta T$  trajectory is like a cycloid, because  $E$  changes cyclically with the current and  $\Delta T$  rises rapidly by the heat generation during fault, where the operating point on  $E$ - $\Delta T$  plane is shifted from the origin toward the right



(a) Current



(b) Temperature



(c) Resistance

Fig. 7. Comparison between simulation and experiment results for current limitation and recovery tests ( $I_{LV} = 64$  A,  $I_{PRO} = 876$  A, Non-recovery case).

hand. In Figs. 8 (a) and (b), the trajectories during fault are equal under the same  $I_{PRO}$  condition. On the other hand, during recovery after the fault clearance,  $E$  drops rapidly and  $\Delta T$  decreases gradually due to cooling by LN<sub>2</sub>, then the operating point is shifted toward the origin. The operating point comes back to the origin in Fig. 8 (a), but  $\Delta T$  is balanced at 2.4 K in Fig. 8 (b). This is because the heat generation during recovery depends on the load current  $I_{LV}$  after the fault clearance. In Fig. 8 (b), the SFCLT could not recover into the superconducting state because a new temperature equilibrium was established due to the balance between the liquid nitrogen cooling and the heat generation under load after the fault clearance.

We carried out simulation under various  $I_{LV}$  and  $I_{PRO}$  conditions, and verified the recovery characteristics of SFCLT. Figure 9 shows the recovery characteristics. In this figure, the vertical axis and horizontal axis are normalized by  $I_c$  of YBCO tape for LV (I) coil in Table I. The symbols "O" and "X" show recovery case and non-recovery case, respectively, obtained by experiment results [14], and the red curve shows the recovery

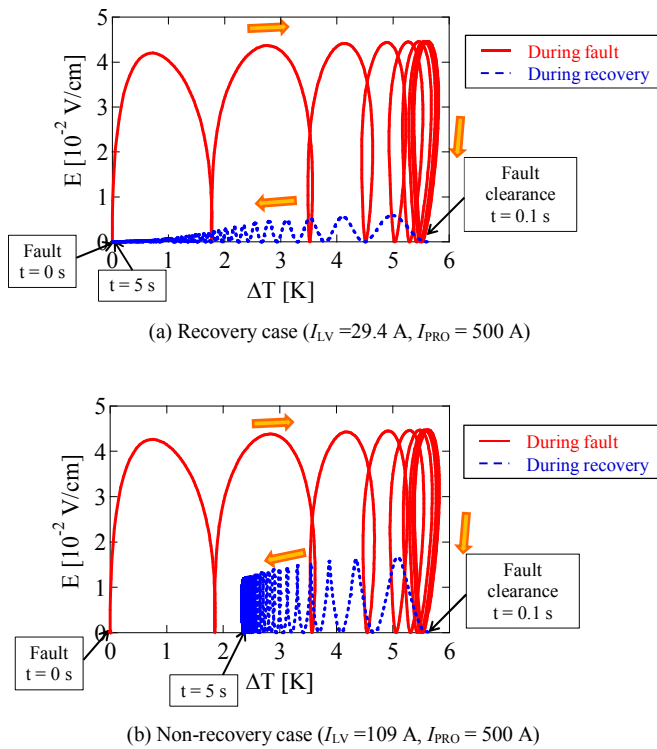


Fig. 8.  $E$ - $\Delta T$  trajectories during fault and recovery obtained by simulation.

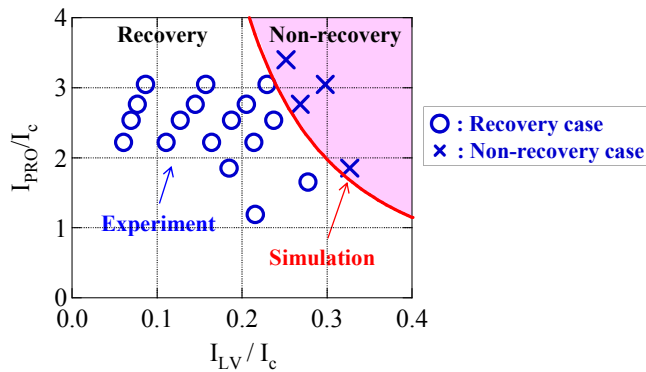


Fig. 9. Recovery criteria of SFCLT.

criteria obtained by simulation. The criteria were defined as  $\Delta T < 1$  K at 60 s after the fault clearance, which corresponds to the elbow point on cooling characteristics of LN<sub>2</sub> [15]. The experimental boundary between recovery case and non-recovery case was verified by the simulated criteria for different conditions of SFCLT.

## V. CONCLUSIONS

We developed a simulation model based on experimental data to analyze the electrical and thermal behaviors of SFCLT. The simulation results of current limitation and recovery characteristics were compared with the experimental data, and the validity of the model was confirmed.

By using this simulation model, we evaluated the transition of electric field and temperature rise during the fault current limitation as well as after the fault clearance. In the recovery

case, SFCLT could recover into superconducting state because the cooling by LN<sub>2</sub> was larger than the heat generation of YBCO coated conductors after the fault clearance. On the other hand, in the non-recovery case, SFCLT could not recover into superconducting state and a new temperature equilibrium was established under load after the fault clearance.

Furthermore, we verified the recovery process of SFCLT by using this simulation model. As the result, we could figure out the recovery criteria of SFCLT for different load current and prospective fault current conditions.

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