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## Current limitation and recovery function for superconducting fault current limiting transformer (SFCLT)

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### Abstract

Superconducting Fault Current Limiting Transformer (SFCLT) is expected to have both superconducting transformer function and superconducting fault current limiter function. We have so far developed the 2 MVA-class SFCLT based on YBCO coated conductors, and experimentally evaluated its current limitation and recovery characteristics. In this paper, we constructed a simulation model for current limitation and recovery characteristics of SFCLT for different HTS coil characteristics and design, and derived the optimized design for the effective current limitation and extended recovery criteria under the rated voltage of the 2 MVA-class SFCLT.

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Keyword: superconducting transformer, superconducting fault current limiter, current limitation, recovery, optimization

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### 1. Introduction

High temperature superconducting (HTS) power apparatus have been required to have high performance and power system coordination. From the viewpoint of these requirements, we have proposed Superconducting Fault Current Limiting Transformer (SFCLT) which has both superconducting transformer function and superconducting fault current limiter function [1]. SFCLT is expected to decrease the leakage impedance as a transformer and limit the fault current due to generate impedance during the fault, which can improve the static and transient stability in a power system. Recent years, SFCLT is being developed all over the world [2-4]. We have developed a 2 MVA, 22 kV/6.6 kV class SFCLT and verified the fundamental functions [5,6]. However, the SFCLT function has not yet been optimized, e.g. the balance between current limitation and recovery function. In this paper, for the optimization of SFCLT design and operation, we discussed current limitation and recovery functions for different HTS coil characteristics and design under the rated voltage of the 2 MVA-class SFCLT.

### 2. Structure of SFCLT

The fundamental specifications and structure of the 2 MVA-class SFCLT are shown in Table 1 and Fig.1. We designed 3-phase SFCLT with the rating of 2 MVA, 22 kV/6.6 kV, and fabricated the single phase of a 0.67 MVA, 12.7 kV/3.81 kV (Y-Y). High-voltage and low-voltage coils were arranged in both iron core legs (A-leg, B-leg) in series. Low-voltage coils were made of two different kinds of YBCO tapes which are YBCO (A1 ~ A3, B1 ~ B3; 6 coils) and YBCO/Cu (A4 ~ A6, B4 ~ B6; 6 coils), while high-voltage coils were made of Bi2223 tapes (A7 ~ A10, B7 ~ B10; 8 coils).

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%		
Material and $I_c$ @ 77K	LV(I)	YBCO	215 A (0.3 $\mu$ V/cm)
	LV(II)	YBCO/Cu	240 A (1 $\mu$ V/cm)
	HV	Bi2223	73 A (1 $\mu$ V/cm)

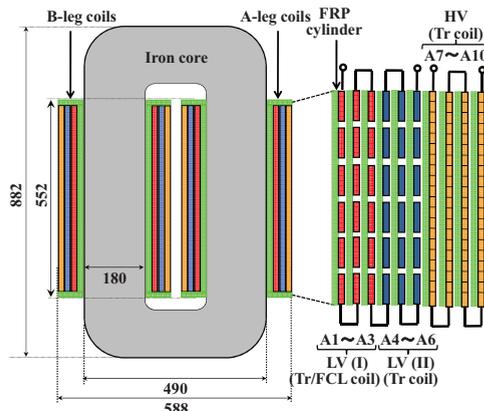


Fig.1. Structure of 2 MVA-class SFCLT

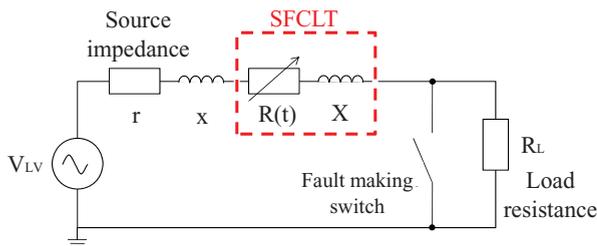


Fig.2. Equivalent circuit for current limitation and recovery of SFCLT

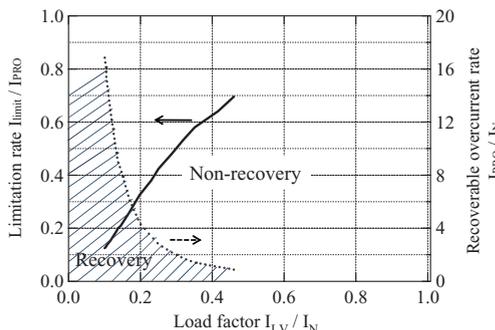


Fig.3. Current limitation and recovery criteria of SFCLT

### 3. Fault current limitation and recovery characteristics

We evaluated the current limitation and recovery characteristics of SFCLT by using a simulation model [6] which was constructed from the equivalent circuit in Fig.2. The load current  $I_{LV}$  before fault flows in the low-voltage coil of SFCLT with the rated current  $I_N$ . The prospective fault current  $I_{PRO}$  is expected to be limited to  $I_{limit}$  during fault. The fault current limitation and recovery criteria for different load and fault conditions are shown in Fig.3. The left vertical axis is the limitation rate  $I_{limit}/I_{PRO}$  at the 1st peak of recoverable fault current, and the right vertical axis is the recoverable overcurrent rate  $I_{PRO}/I_N$ , respectively, against load factor  $I_{LV}/I_N$ . The dotted curve in Fig.3 expresses the boundary between recovery and non-recovery cases, where the recovery case is defined as that the temperature rise of SFCLT is lower than 1 K after the fault clearance. The current limitation is effective with the low

limitation rate and the recoverable  $I_{PRO}/I_N$  increases remarkably with the decrease in the load factor  $I_{LV}/I_N$ . This is because the recovery process after the fault clearance strongly depends on the balance between the heat generation by the successive load current and the cooling effect by  $LN_2$ .

#### 4. Extension of current limitation and recovery criteria

It is expected to increase the recoverable  $I_{PRO}/I_N$  at the higher load factor  $I_{LV}/I_N$  for the efficient and rational design and operation of SFCLT. In this section, we discuss the extension of current limitation and recovery criteria from the viewpoint of HTS coil characteristics and design.

##### 4.1. HTS coil characteristics (critical current $I_c$ , n value)

According to the experiments of the 2 MVA-class SFCLT [5], the critical current  $I_c$  of YBCO coil was 95.6  $A_{peak}$  and the n value at flux flow state was 2. Taking these YBCO coil characteristics as parameters, we evaluated the current limitation and recovery criteria.

Current limitation and recovery criteria for  $I_c = 95.6 A_{peak}$  and 247  $A_{peak}$  ( $= I_N$ ) at  $n = 2$  is shown in Fig.4, while those for  $n = 2$  and 3 at  $I_c = 247 A_{peak}$  is shown in Fig.5. The plateau region in each figure corresponds to the transition region between nucleate boiling and film boiling of heat flux of  $LN_2$ . In Fig.4, the recovery region is extended for the larger  $I_c$ . This is due to the decrease in generated resistance for the larger  $I_c$  under the fixed  $I_{PRO}$  and  $I_{LV}$ , which means that the heat generation after fault becomes smaller, and the cooling effect becomes higher. In Fig.5, the recovery region is extended for the larger n value, due to the effective current limitation at the larger current region.

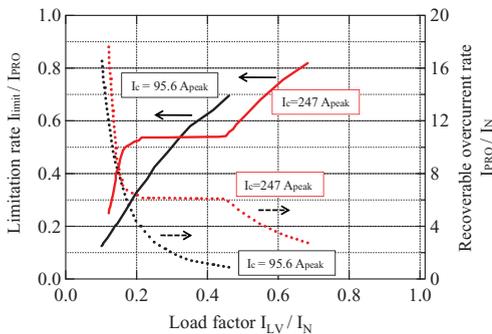


Fig.4. Current limitation and recovery criteria for different critical current ( $n = 2$ )

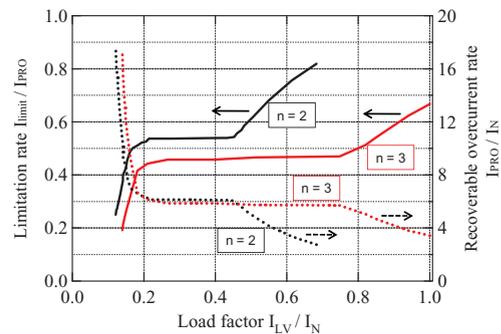


Fig.5. Current limitation and recovery criteria for different n value ( $I_c = 247 A_{peak}$ )

##### 4.2. HTS coil design (YBCO coil rate $\eta_{YBCO}$ , utilization factor $I_N/I_c$ )

We evaluated the current limitation and recovery criteria in terms of HTS coil design, i.e. YBCO coil rate  $\eta_{YBCO}$  and utilization factor  $I_N/I_c$ .  $\eta_{YBCO}$  is defined as the YBCO coil length divided by the total low-voltage coil length (275m), which was 46% for the 2 MVA-class SFCLT.

Figure 6 describes current limitation and recovery criteria for  $\eta_{YBCO} = 46\%$ , 75% and 100%. The recovery region is extended with the increase in  $\eta_{YBCO}$ . This is because the electric field per unit length of YBCO coil becomes smaller with the increase in  $\eta_{YBCO}$ , which means that the heat generation during and after fault becomes smaller. Figure 7 describes current limitation and recovery criteria for  $I_N/I_c = 1.0$ , 0.5 and 0.33, i.e. the parallel number of HTS tapes are 1, 2 and 3, respectively. The recovery region is extended with the decrease in  $I_N/I_c$ , because the current flow and heat generation in each HTS tape becomes smaller with the decrease in  $I_N/I_c$ .

Figure 8 shows the current limitation and recovery characteristics at the maximum and recoverable load current (point A, i.e.  $I_{LV}/I_N = 0.52$ ,  $I_{PRO}/I_N = 15.8$  in Fig.7) under the rated voltage. The limitation rates are  $I_{1st}/I_{PRO} = 0.53$  at the 1st peak and  $I_{10th}/I_{PRO} = 0.11$  at the 10th peak. The maximum temperature rise is 48 K during fault, and the recovery time is 8.8 seconds after the fault clearance.

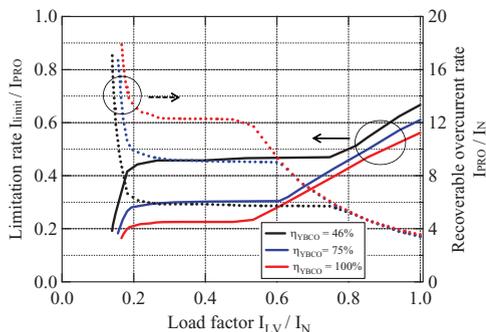


Fig.6. Current limitation and recovery criteria for different YBCO coil rate  $\eta_{YBCO}$  ( $I_c = 247 A_{peak}$ ,  $n = 3$ ,  $I_N/I_c = 1.0$ )

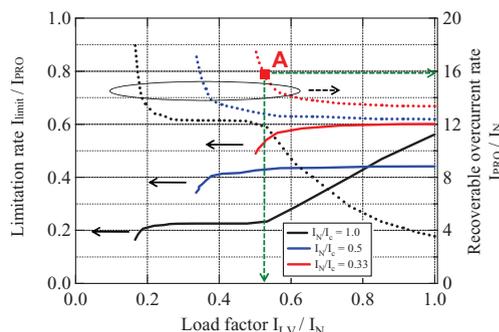


Fig.7. Current limitation and recovery criteria for different utilization factor  $I_N/I_c$  ( $I_c = 247 A_{peak}$ ,  $n = 3$ ,  $\eta_{YBCO} = 100\%$ )

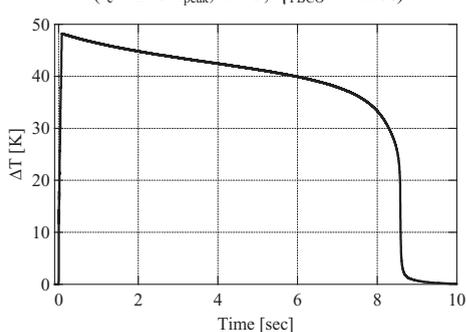
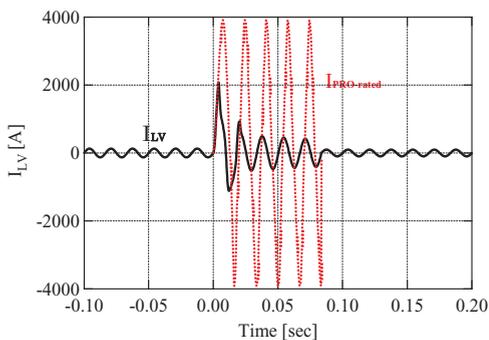


Fig.8. Current limitation characteristics (a) LV current (b) Temperature rise ( $I_c = 247 A_{peak}$ ,  $n = 3$ ,  $\eta_{YBCO} = 100\%$ ,  $I_N/I_c = 0.33$ )

### 5. Conclusions

We evaluated the current limitation and recovery characteristics for the YBCO coated conductor based the 2 MVA-class SFCLT for different conditions. Simulation results revealed that the current limitation and recovery criteria of SFCLT can be extended with the increase in critical current  $I_c$  and  $n$  value at flux flow state of YBCO tapes, as well as with the increase in YBCO coil rate  $\eta_{YBCO}$  and the decrease in utilization factor  $I_N/I_c$ . We also derived the optimized design for the 2 MVA-class SFCLT with the extension of current limitation and recovery characteristics under the rated voltage.

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