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# Self-recovery Characteristics of High-Tc Superconducting Fault Current Limiting Transformer (HTc-SFCLT) with 2G Coated Conductors

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**Abstract.** We have been developing Superconducting Fault Current Limiting Transformer (SFCLT) with both functions of superconducting transformer and superconducting fault current limiter. As the Step-IV of the SFCLT project, in this paper, we designed, fabricated and tested HTc-SFCLT with 2G YBCO coated conductors to be operated in liquid nitrogen at 77 K. The ratings of the HTc-SFCLT with 2G coated conductors are 3-phase, 100 kVA, 6600 V / 210 V. Especially, the possibility of self-recovery into superconducting state after the fault current limitation was investigated by the simple clearance of the fault, which is very important as a superconducting transformer and for power system operation. The criteria of self-recovery were quantified for different combination of load current before the fault and prospective fault current during the fault.

## 1. Introduction

In recent years, a development of high temperature superconducting power apparatus such as fault current limiters, transformers, cables and so on has remarkable progress by improvement of high temperature superconducting tapes [1]-[3]. From the viewpoint of coordination of superconducting power apparatus with the background power system in order to improve the total efficiency, controllability and stability in a future electric power network, we have proposed and have been developing a Superconducting Fault Current Limiting Transformer (SFCLT) with a function of both superconducting transformer in normal operating condition and superconducting fault current limiter in fault condition [4]-[6].

The SFCLT is expected to be operated as a superconducting transformer immediately after fault current limitation. That is to say, a self-recovery into superconducting state after a fault clearance is very important and essential for SFCLT. As the Step-III of the SFCLT project, we developed the HTc-SFCLT with 1G Bi2212 / CuNi bulk coils, whose ratings are 3-phase, 6.25 kVA, 275V / 105 V [5]. The performance tests of the HTc-SFCLT with 1G Bi2212 / CuNi bulk coils suggested the possibility of self-recovery in liquid nitrogen at 77 K. Afterwards, as the Step-IV of the SFCLT project, we designed, fabricated and tested HTc-SFCLT with 2G YBCO coated conductors [6]. The ratings of the HTc-SFCLT with 2G coated conductors are 3-phase, 100 kVA, 6600 V / 210 V. This HTc-SFCLT is characterized by the combination of different kinds of YBCO coated conductors, in order to make the

current limiting characteristics flexible and controllable to meet the desired performances. The aspect ratio of YBCO coated conductor is much larger than that of Bi2212 / CuNi bulk material, and the cooling of YBCO coil by liquid nitrogen is more effective than that of Bi2212 / CuNi bulk coil. Therefore, the HTc-SFCLT with 2G YBCO coated conductors is expected to be self-recovered more easily.

In this paper, no-load and short-circuit tests of the HTc-SFCLT with 2G coated conductors have been carried out and verified the design parameters as a superconducting transformer. The current limiting tests have also been conducted and confirmed the effective current limitation as a superconducting fault current limiter. Moreover, the self-recovery characteristics after the current limitation are quantitatively discussed for different load and fault conditions.

## 2. Design and fabrication of HTc-SFCLT with 2G YBCO coated conductors

The specifications and construction of HTc-SFCLT with 2G coated conductors are shown in table 1 and figure 1. We designed 3-phase HTc-SFCLT with the ratings of 100 kVA, 6600 V / 210 V, 8.7 A / 275 A. As a single phase of the HTc-SFCLT, we fabricated 33.3 kVA, 3810 V / 210 V, 8.7 A / 159 A (Y- $\Delta$ ) HTc-SFCLT. Low voltage coil consists of the 2G HTS tapes, whose characteristics are shown in table 2, and high voltage coil is composed of copper wire with 1.4 mm diameter, both of which are immersed in liquid nitrogen at 77 K together with the iron core.

**Table 1.** Specifications of HTc-SFCLT with 2G coated conductors.

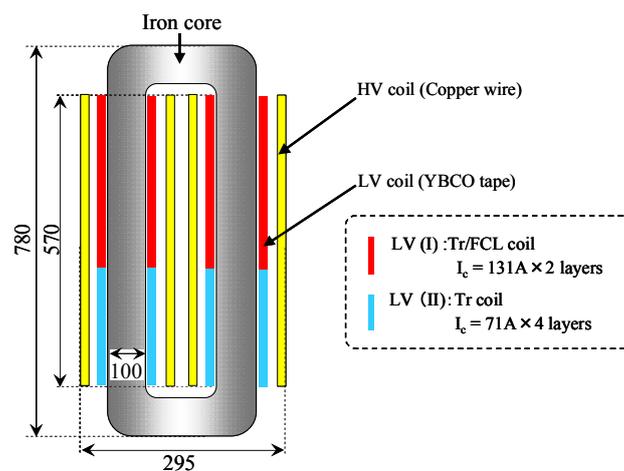
Phase	3
Frequency	60 Hz
Capacity	100 kVA
Rated voltage	6600 V / 210 V
Rated current	8.7 A / 275 A
Turn ratio	1344 / 74
Magnetic flux density	1.7 T
Leakage impedance	7%

**Table 2.** Specifications of 2G coated conductors.

	LV(I)	LV(II)
HTS layer	YBCO	YBCO
Substrate	Hastelloy	Hastelloy
Stabilizer	Ag	Cu
Width (mm)	12.4	4.3
Thickness ( $\mu\text{m}$ )	105	210
$I_c$ (A)@77 K, 1 $\mu\text{V}/\text{cm}$	131	71
n-value	50	20



(a) Total structure.



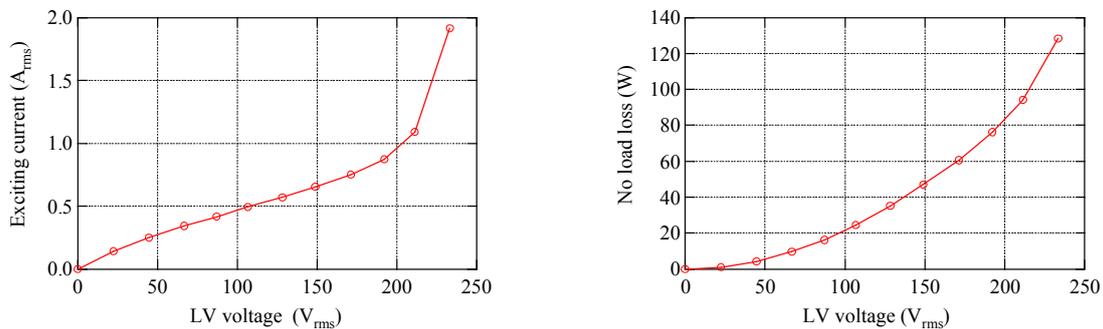
(b) Section structure and winding arrangement.

**Figure 1.** Construction of HTc-SFCLT with double-leg 2G YBCO coils.

In the case of HTc-SFCLT in Step-III [5], Bi2212 / CuNi bulk coil of the low voltage HTS coil was used as both the transformer coil and the fault current limiter coil. Therefore, the limiting resistance as the fault current limiter was restricted by the transformer design, i.e. the size and stiffness of Bi2212 / CuNi bulk coil. Here, in the case of HTc-SFCLT with 2G coated conductors [6], the transformer coil of the low voltage HTS coil is divided into 2 parts; limiting coil with current limitation function (Tr / FCL coil in figure 1,  $I_c = 131 \text{ A} \times 2 \text{ layers}$ ,  $n \approx 50$ ) and non-limiting coil without current limitation function (Tr coil in figure 1,  $I_c = 71 \text{ A} \times 4 \text{ layers}$ ,  $n \approx 20$ ). Such a hybrid structure of HTS coils has an advantage that HTc-SFCLT can be relieved from the above design constraint and obtain higher flexibility for the transformer and fault current limiter designs. With the variation of the ratio between the limiting Tr / FCL coil and the non-limiting Tr coil, HTc-SFCLT with 2G YBCO coated conductors can perform the desirable current limiting characteristics as well as transformer functions.

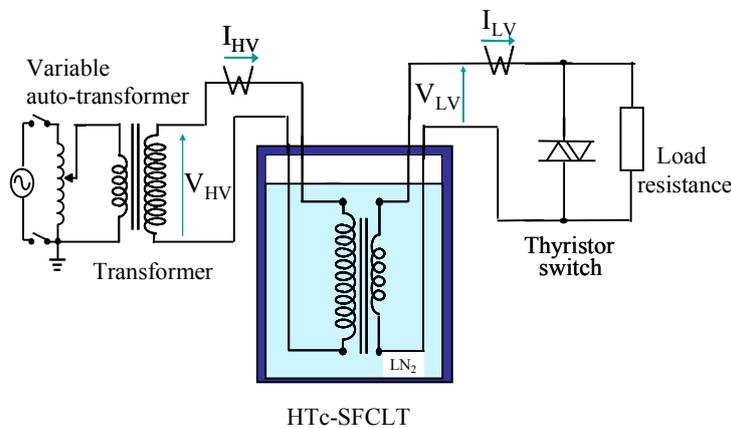
### 3. No-load and short-circuit tests

The assembled HTc-SFCLT of double-leg YBCO coils in figure 1 was immersed in liquid nitrogen at atmospheric pressure. No-load and short-circuit tests were carried out in order to confirm the design parameters of HTc-SFCLT as a superconducting transformer. In both tests, the turn ratio of high voltage and low voltage coils was 18.1, which is consistent with 3810 V / 210 V in table 1. The result of no-load test is shown in figure 2; (a) exciting current and (b) no-load loss. At the rated voltage, the exciting current was 1.09 A<sub>rms</sub>, whereas the no-load loss was 94.2 W. The leakage impedance obtained from the short-circuit test was 7.2%. These results mean that the developed HTc-SFCLT with 2G YBCO coated conductors well exhibits the fundamental performances as a superconducting transformer.



(a) Exciting current as a function of LV voltage. (b) No-load loss as a function of LV voltage.

**Figure 2.** No-load test result of HTc-SFCLT with double-leg 2G YBCO coils.

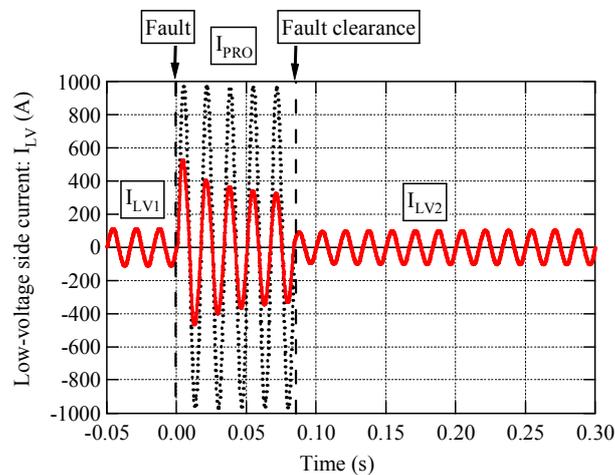


**Figure 3.** Experimental circuit for recovery test.

#### 4. Current limitation and recovery tests

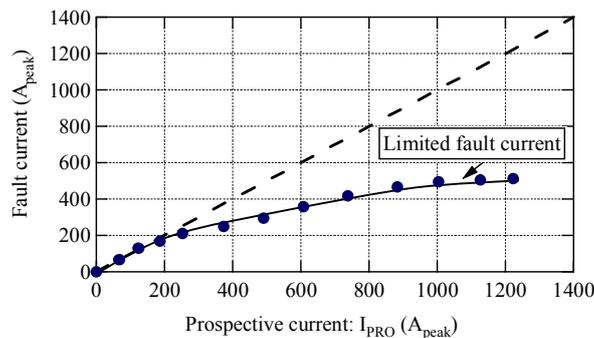
The experimental circuit for the recovery test of the HTc-SFCLT is shown in figure 3. The load resistance and thyristor switch were connected in parallel to the low-voltage side of HTc-SFCLT. The test procedure is as follows: Firstly, when thyristor switch is open, HTc-SFCLT is operated as a superconducting transformer under a steady load current  $I_{HV}$  and  $I_{LV}$ . Secondly, the thyristor switch is closed to simulate a fault, leading to the large short-circuit current  $I_{PRO}$ , then the HTc-SFCLT works as a fault current limiter. Thirdly, at 5 cycles after the fault, thyristor switch is simply opened to clear the fault. Such a series of procedure for current limitation and recovery tests was repeated, taking  $I_{LV}$  and  $I_{PRO}$  as variable parameters.

Figure 4 presents an example of the current limitation and recovery tests, where the peak value of prospective current ( $I_{PRO}$ ) designated by the broken curve was  $980 A_{peak}$ , load current ( $I_{LV1}$ ) before fault was  $112 A_{peak}$ . The fault current was limited to  $516 A_{peak}$  (52.6% of  $I_{PRO}$ ) at the first peak and  $330 A_{peak}$  (33.7% of  $I_{PRO}$ ) at the 10th peak, respectively, after the fault. In this case, the load current after the fault clearance ( $I_{LV2}$ ) was equal to  $I_{LV1}$ , which means that the HTS coil at the low-voltage side recovered into superconducting state by itself immediately after the fault clearance.



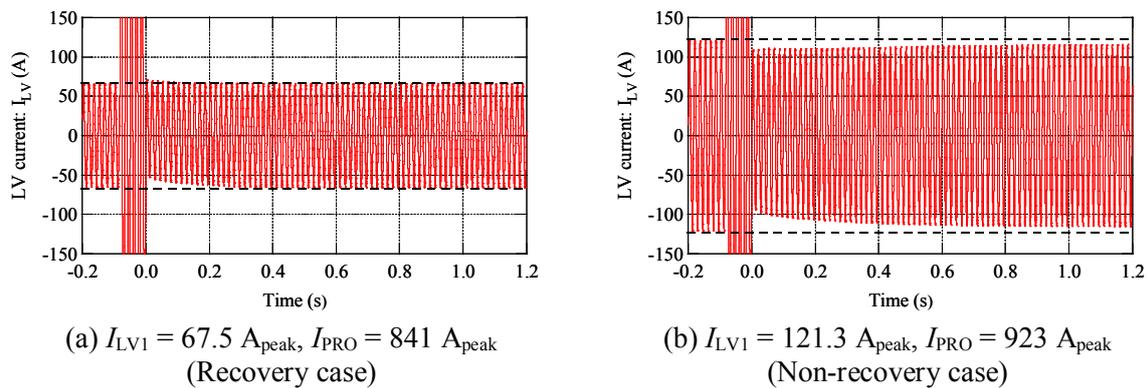
**Figure 4.** Current waveform of current limitation and recovery test.  
 ( $I_{PRO} = 980 A_{peak}$ ,  $I_{LV1} = 112 A_{peak}$ )

Figure 5 shows the fault current limitation characteristics of the HTc-SFCLT, where the broken line presents  $I_{PRO}$ , and the solid curve displays the limited fault current at the first peak after the fault. The fault current limitation appears at  $I_{PRO} > 300 A_{peak}$ , and  $I_{LV}$  is limited to 58% of  $I_{PRO}$  at  $I_{PRO} = 610 A_{peak}$  and 42% at  $I_{PRO} = 1220 A_{peak}$ . These results verify that the HTc-SFCLT with 2G coated conductors exhibits more excellent current limiting function as a superconducting fault current limiter than the HTc-SFCLT with 1G Bi2212 / CuNi bulk coil.

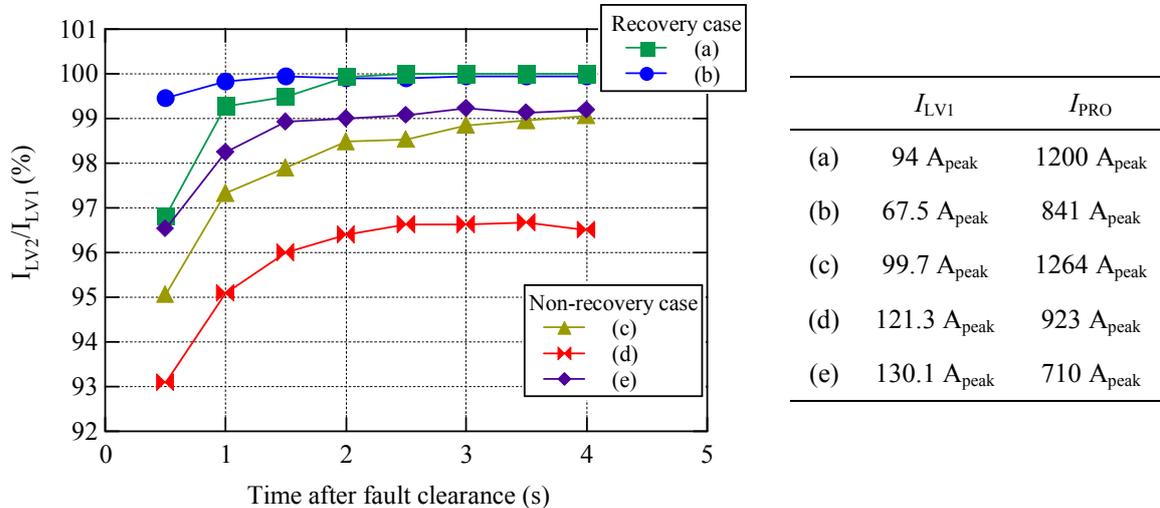


**Figure 5.** Fault current limitation characteristics of HTc-SFCLT with 2G coated conductors.

Figure 6 shows  $I_{LV}$  waveforms until 1 s after the fault clearance. For relatively low  $I_{LV1}$  and  $I_{PRO}$ ,  $I_{LV2}$  became equal to  $I_{LV1}$  as shown in figure 6(a). However, as shown in figure 6(b), in the case of large  $I_{LV1}$  and  $I_{PRO}$ ,  $I_{LV2}$  could not recover to  $I_{LV1}$  after the fault clearance. Figure 7 shows the recovery process of  $I_{LV}$  after the fault clearance for different combinations of  $I_{LV1}$  and  $I_{PRO}$ . In the cases of (a) and (b),  $I_{LV2} / I_{LV1}$  became larger than 99% at 1 s after the fault clearance, and recovered to almost 100% at 2 s. On the other hand, in the cases of (c), (d) and (e),  $I_{LV2} / I_{LV1}$  was smaller than 99% at 1 s after the fault clearance, and did not recover to 100% even at 4 s, which can be regarded as non-recovery cases. From experimental results in various conditions of  $I_{LV1}$  and  $I_{PRO}$ , we defined a requirement of self-recovery as  $I_{LV2} / I_{LV1} > 99\%$  at 1 s after the fault clearance.

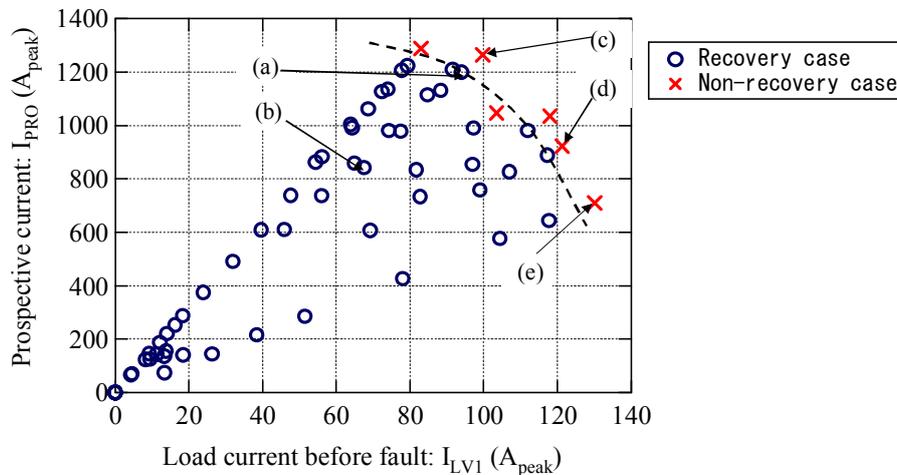


**Figure 6.** Current waveforms before and after fault clearance.



**Figure 7.** Recovery process after fault clearance.

Figure 8 shows the self-recovery characteristics of HTc-SFCLT with 2G coated conductors as parameters of  $I_{LV1}$  and  $I_{PRO}$ . The symbols “o” and “x” in figure 8 denote the recovery case and non-recovery case, respectively. A broken curve can be found between the recovery and non-recovery cases, which can be regarded as the criterion or the limit of self-recovery for the HTc-SFCLT. In other words, when the load current ( $I_{LV1}$ ) and the prospective fault current ( $I_{PRO}$ ) were lower than those on the critical curve in figure 8, the HTc-SFCLT would recover into superconducting state by itself immediately after the fault clearance.



**Figure 8.** Self-recovery characteristics of HTc-SFCLT with 2G coated conductors.

## 5. Conclusions

We developed the HTc-SFCLT with 2G YBCO coated conductors, and carried out the no-load test, the short-circuit test, the current limitation test and the recovery test. The main results are summarized as follows:

- The design ratings of the HTc-SFCLT are 3-phase, 100 kVA, 6600 V / 210 V, 8.7 A / 275 A. A single phase of the HTc-SFCLT was fabricated. YBCO coils of the HTc-SFCLT were divided into limiting coil and non-limiting coil to obtain higher flexibility for the transformer and fault current limiter designs.
- No-load and short-circuit test results verified that HTc-SFCLT with 2G coated conductors had a fundamental performance as a superconducting transformer.
- Current limiting characteristics of HTc-SFCLT with 2G coated conductors exhibited the excellent current limiting function as a superconducting fault current limiter.
- Self-recovery characteristics after the current limitation were discussed, and a criterion of the self-recovery was quantified for different load and fault conditions.

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