Recovery Characteristics After Current Limitation of High Temperature Superconducting Fault Current Limiting Transformer (HTc-SFCLT)

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***Abstract*—Superconducting Fault Current Limiting Transformer (SFCLT) is one of the promising superconducting power apparatus, since it has both functions of superconducting transformer in normal condition and superconducting fault current limiter in fault condition. In this paper, current limiting and the recovery tests of high temperature SFCLT (HTc-SFCLT) with MCP-BSCCO2212 bulk coils were performed at liquid nitrogen temperature. Experimental results revealed that the HTc-SFCLT could successfully recover into the superconducting state by itself immediately after the fault clearance. Moreover, the recovery criterion of HTc-SFCLT as a function of load current was clarified.**

***Index Terms*—MCP-BSCCO2212, recovery, superconducting fault current limiter, superconducting transformer.**

I. Introduction

POWER utilities have devoted to reducing the costs of transmission and improving the stability and capacity of their power system. Superconducting technology is an attractive candidate for these purposes, since its innovation can provide both high efficiency and high reliability in the electrical network. Hence, during the last several years, research and development on superconducting power apparatus and its potential applications to the utilities have been carried out and demonstrated with industrial prototypes [1]–[4].

As one of the prospective solutions, we have proposed and have been developing a "Superconducting Fault Current Limiting Transformer", abbreviated to "SFCLT", with the functions of both transformer and fault current limiter [5]–[7]. According to its concept, significant benefit of SFCLT is the reduction of leakage impedance of superconducting transformer, improving the system stability and capacity in normal operating condition. On the other hand, in the fault condition, the limiting impedance induced by the quench of SFCLT winding will reduce the fault current and bring about the improved dynamic stability of the power system.

TABLE I
Specifications of HTc-SFCLT

Phase	1	
Frequency	60Hz	
Rated voltage	159V/61V	
Rated capacity	2.08kVA	
Leakage impedance	4.98%	
Limiting impedance	145% (2.55 Ω)	
Cross sectional area of iron core	8.88cm^2	
	LV	HV
Material	MCP-BSCCO2212/CuNi	Copper
Size	2x3mm^2/2x1.5mm^2	ϕ2.3mm
Number of turns	2x70	2x183
I_C (77K,self field,1μV/cm)	57A (coil A), 63A (coil B)	

We have already fabricated the HTc-SFCLT with MCP-BSCCO2212 bulk coils at liquid nitrogen temperature, and verified fundamental characteristics as a transformer and a fault current limiter [7]. One of the important concerns for the development of HTc-SFCLT is the recovery characteristics after the successful current limiting operation. Thus, in this paper, current limiting and the recovery characteristics of HTc-SFCLT have been investigated and evaluated. Especially, the recovery criterion of HTc-SFCLT as a function of load current was clarified.

II. Specifications of HTc-SFCLT

The specifications and construction of HTc-SFCLT [7] are shown in Table I and Fig. 1(a), respectively. We fabricated 159/61 V HTc-SFCLT with series connected MCP-BSCCO2212 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 liquid nitrogen at 77 K together with the iron core.

The MCP-BSCCO2212 monofilar coil is shown in Fig. 1(b). CuNi-alloy was soldered around BSCCO2212 bulk coil in order to avoid the development of hot spots in BSCCO2212 bulk coil during the current limiting operation. BSCCO2212/CuNi

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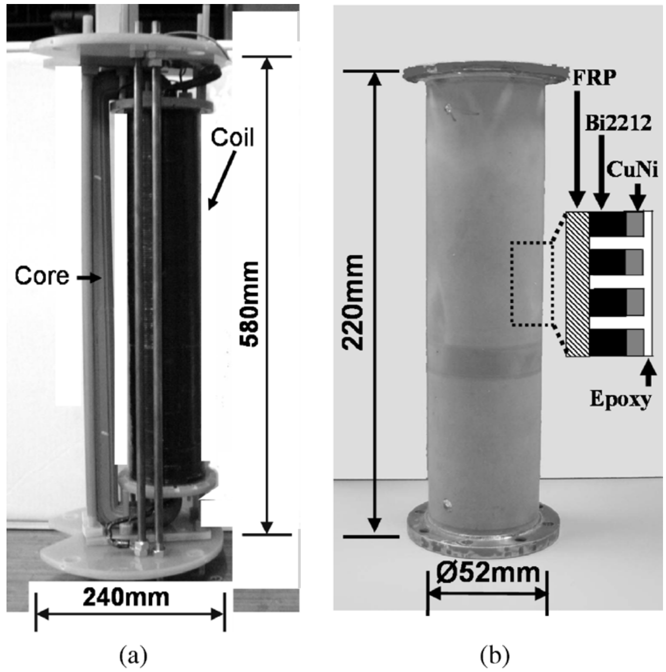

Fig. 1. Constructions of HTc-SFCLT and BSCCO2212 coil. (a) HTc-SFCLT. (b) BSCC02212 coil.

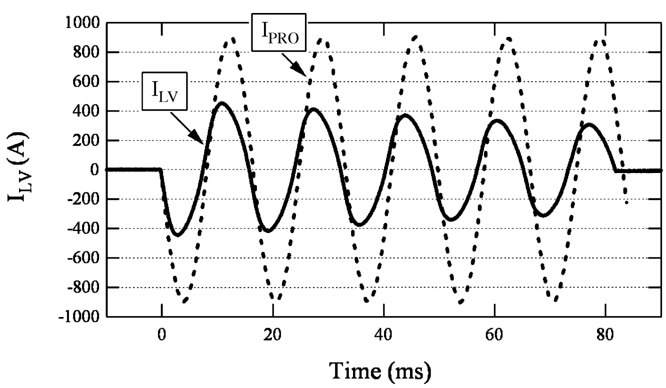

Fig. 2. Current limiting test result at $I_{PRO} = 908\ A_{peak}$.

composite was cut into the monofilar coil, and impregnated with epoxy resin for both electrical insulation and mechanical stability.

III. Current Limiting Test of HTc-SFCLT

The short-circuit test of HTc-SFCLT was performed under the large current level in order to confirm the function as a superconducting fault current limiter. Different prospective short-circuit currents I_{PRO} ranging up to 908 A_{peak} were applied for 5 cycles.

Fig. 2 shows the current limiting test result at $I_{PRO} = 908\ A_{peak}$. The limited current $I_{Limited}$ flowing in the BSCCO2212 bulk coil was 445 A_{peak} at 1st cycle, which suggested that the short-circuit current was limited to 49% of I_{PRO}. Furthermore, $I_{Limited}$ was 306 A_{peak} at 5th cycle, i.e. 34% of I_{PRO}. The current limiting function of HTc-SFCLT was evaluated as "current limiting ratio" ($I_{Limited}/I_{0PRO}$) versus I_{PRO} and shown in Fig. 3. The current limitation was

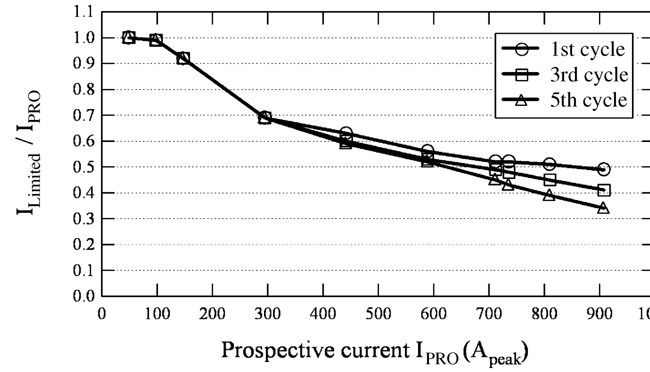

Fig. 3. Current limiting characteristics of HTc-SFCLT.

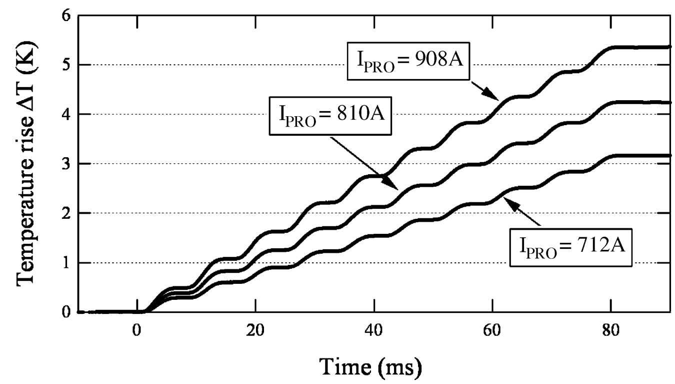

Fig. 4. Temperature rise during fault current limitation.

first observed at the current level $I_{PRO} > 100\ A_{peak}$, and $I_{Limited}/I_{PRO}$ reduced into 0.7 at $I_{PRO} = 300\ A_{peak}$ corresponding to about 5 times of I_c. At $I_{PRO} > 300\ A_{peak}$, $I_{Limited}/I_{PRO}$ depended on the current cycle, which may be attributed to the difference in the temperature rise of HTc-SFCLT.

The temperature rise of BSCCO2212 bulk coil during the current limiting process was calculated for different I_{PRO} and shown in Fig. 4, by assuming an adiabatic heating. In general, the higher temperature rise at the larger I_{PRO} would induce the larger resistance of superconductors, and reduce the short-circuit current. The temperature rise of BSCCO2212 bulk coil after 5 cycles at $I_{PRO} = 908\ A_{peak}$ was 5.4 K. The effective current limitation such as $I_{Limited}/I_{PRO} = 0.34$ in Fig. 3 could be brought about even at such a relatively small temperature rise, which may be attributed to the current limitation by flux-flow resistance of the coil. These results suggest that the developed HTc-SFCLT can exhibit excellent current limiting function as a superconducting fault current limiter.

IV. Recovery Test of HTc-SFCLT

The experimental circuit for the recovery test of HTc-SFCLT is shown in Fig. 5. The resistive load and thyristor switch were connected in parallel to the LV side of HTc-SFCLT. The test procedure is described as follows. First, when thyristor switch is open, HTc-SFCLT is operated as a transformer under a steady load current I_{L1}. Next, the thyristor switch is closed for 5 cycles to simulate a fault, leading to the large short-circuit current, HTc-SFCLT works as a fault current limiter. At 5 cycles after the

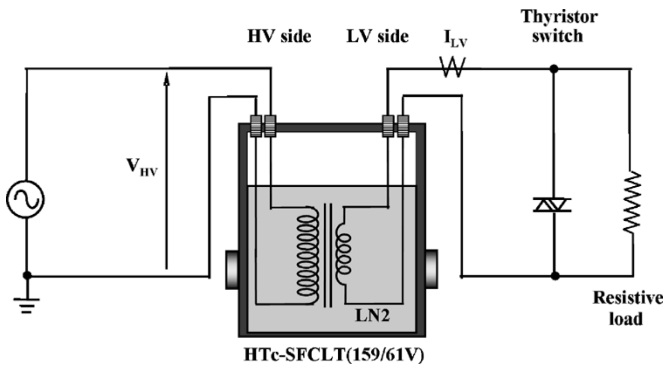

Fig. 5. Experimental setup for recovery test of HTc-SFCLT.

fault, thyristor switch is simply opened to clear the fault. The experiment was performed, taking I_{L1} of HTc-SFCLT and I_{pro} as variable parameters.

One of the experimental results is shown in Fig. 6(a) and (b). The figures show the waveforms of LV side current I_{LV} and HV side voltage V_{HV} of HTc-SFCLT at $I_{L1} = 53\ A_{peak}$ (93% of I_c) and $I_{PRO} = 712\ A_{peak}$ (1249% of I_c). The fault current was limited to 366 A_{peak} (51% of I_{PRO}) at 1st cycle and 313 A_{peak} (44% of I_{PRO}) at 5th cycle, respectively. Here, the load current I_{L2} after the fault clearance was 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, i.e. HTc-SFCLT required no recovery time in this case. In addition, as shown in Fig. 6(b), V_{HV} during the fault limitation dropped by less than 10% from its initial value, and V_{HV} after the fault clearance returned to the initial value without any transients.

Fig. 7 shows the ratio of I_{L2}/I_{L1} against I_{L1} for different I_{PRO}. The ratio I_{L2}/I_{L1} decreased with the increase in both I_{L1} and I_{PRO}. The recovery of HTc-SFCLT can be defined as the condition where HTc-SFCLT after the current limitation can carry the load current again without quenching or thermal runaway. Hence, in this paper, we regarded the recovery of HTc-SFCLT as the case of I_{L2}/I_{L1} greater than 0.99. The recovery characteristics of HTc-SFCLT is shown in Fig. 8, as the relation between I_{PRO}/I_{L1} and I_{L1}. This figure shows that, e.g. at $I_{L1} = 58\ A_{peak}$ nearly equal to I_c, HTc-SFCLT could recover up to a criterion of $I_{PRO}/I_{L1} = 14$, i.e. $I_{PRO} = 810\ A_{peak}$. In the same way, Fig. 8 can be divided by the solid line into two areas; "Recovery success region" and "Recovery failure region". The criterion I_{PRO}/I_{L1} decreased with the increase in I_{L1}, because of the temperature rise of HTc-SFCLT during the fault current limitation, as was shown in Fig. 4. In the nonrecovered case ($I_{L2}/I_{L1} < 0.99$), I_{L2} did not change with time after the fault clearance, as shown in the recovered case of Fig. 6(a). This may be because the coil after the fault clearance reaches a different thermal equilibrium from that before the fault. In other words, the heat generation by I_{L2} in the coil with the small resistance could be balanced with the cooling by LN_2.

Consequently, HTc-SFCLT was verified to recover by itself immediately after the fault clearance, and the recovery criterion was clarified as a function of load current.

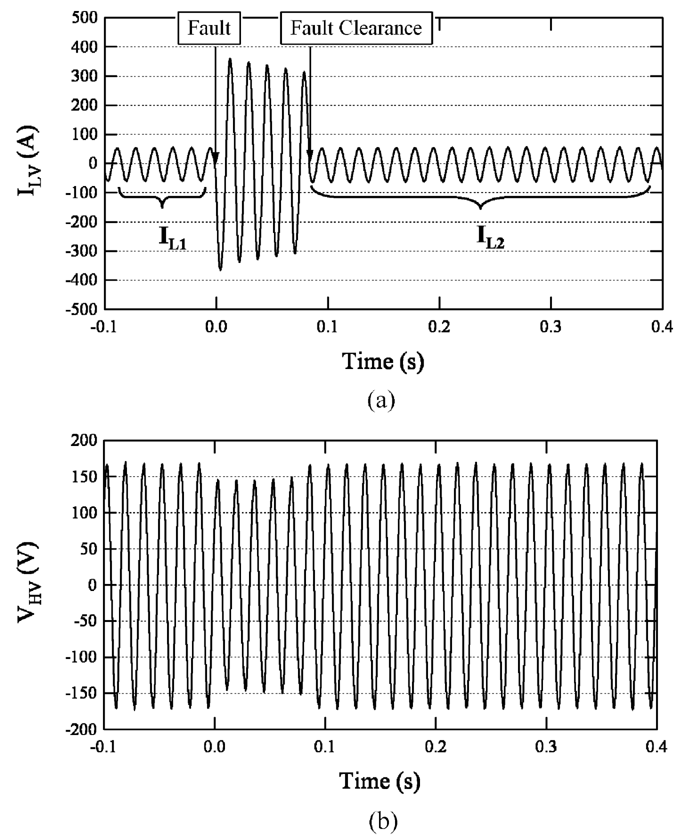

Fig. 6. Current and voltage waveforms from recovery test ($I_{PRO} = 712\ A_{peak}$). (a) LV current I_{LV} waveform for $I_{PRO} = 712\ A_{peak}$. (b) HV voltage V_{HV} waveform for $I_{PRO} = 712\ A_{peak}$.

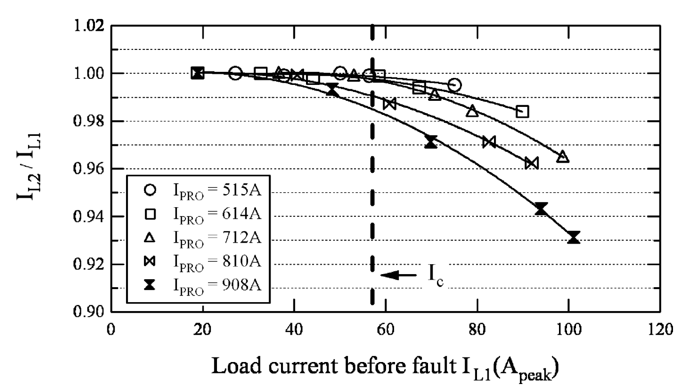

Fig. 7. Relation between I_{L2}/I_{L1} and I_{L1}.

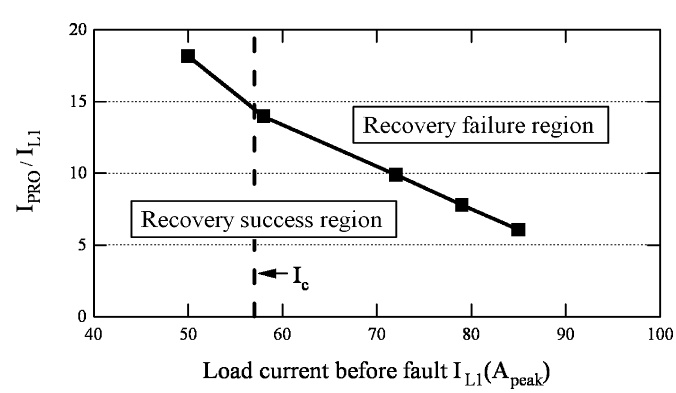

Fig. 8. Recovery characteristics of HTc-SFCLT.

V. Conclusion

We have developed HTc-SFCLT (High Temperature Superconducting Fault Current Limiting Transformer) with functions of both superconducting transformer and superconducting fault current limiter. In this paper, we focused on the current limiting and the recovery characteristics of HTc-SFCLT. The main results are summarized as follows:

(1) The current limiting tests revealed that HTc-SFCLT exhibited an excellent current limiting function as a superconducting fault current limiter. The prospective short-circuit current $\mathrm{I_{PRO}} = 908\ \mathrm{A_{peak}}$ was reduced to 49% at 1st cycle and 34% at 5th cycle, respectively.

(2) After the effective current limitation, HTc-SFCLT could successfully recover into the superconductivity state by itself immediately after the fault clearance.

(3) Recovery criterion $\mathrm{I_{PRO}/I_{L1}}$ was clarified as a function of load current $\mathrm{I_{L1}}$. For example, at $\mathrm{I_{L1}}$ nearly equal to the critical current, HTc-SFCLT could recover up to $\mathrm{I_{PRO}/I_{L1}} = 14$.

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