# Current Limiting and Recovery Characteristics of 2 MVA Class Superconducting Fault Current Limiting Transformer (SFCLT)

Hiroki Kojima, Masashi Kotari, Toyoaki Kito, Naoki Hayakawa *Member IEEE*, Masahiro Hanai *Member IEEE*, and Hitoshi Okubo *Member IEEE*

***Abstract*—We have been developing Superconducting Fault Current Limiting Transformer (SFCLT) with the function of both superconducting transformer in steady state and superconducting fault current limiter in fault condition. As the Step-5 of SFCLT project, 2 MVA class HTS-SFCLT using YBCO coated conductors with the ratings of 22 kV / 6.6 kV has been developed. One of the important concerns for the development of HTS-SFCLT is the current limiting and recovery characteristics as well as the transformer function. Thus, in this paper, current limitation and recovery tests of the HTS-SFCLT are carried out. The current limiting test have revealed that the HTS-SFCLT exhibits the excellent current limiting function as a superconducting fault current limiter, where the prospective short-circuit current $I_{PRO}$ = 784 $A_{peak}$ is reduced to 34% at the first peak and 18% at the 5th cycles. The HTS-SFCLT has been able to recover into superconducting state immediately after the fault clearance. According to the transition of generated resistance of the HTS-SFCLT, the criteria of recovery into superconducting state are quantified for different combinations of load current before the fault and prospective short-circuit current during the fault.**

***Index Terms*—Current limiting operation, fault current limiter, transformer, recovery characteristics, YBCO coated conductor.**

## I. Introduction

SUPERCONDUCTING power apparatuses should be coordinated with a power system in order to improve the total efficiency and stability in a future power system [1]. From a viewpoint of system coordination and functional diversification of superconducting power apparatus, we have proposed and have been developing Superconducting Fault Current Limiting Transformer, abbreviated to "SFCLT", with the functions of both superconducting transformer and superconducting fault current limiter from Step-1 to Step-4 [2]–[6].

One of the most important technical issues for a realization of practical and optimum SFCLT is a quantitative evaluation of the current limiting and recovery function. 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 well as the current limiting function. As the Step-4 of SFCLT project, we designed, fabricated and tested the pilot HTS-SFCLT with the ratings of 3-phase, 100 kVA, 6600 V / 210 V using YBCO coated conductors, and verified fundamental and excellent performance of both HTS transformer and fault current limiter [3].

As the Step-5 of SFCLT project, we have designed and fabricated 2 MVA class HTS-SFCLT with YBCO coated conductors, whose ratings are 3-phase and 22 kV / 6.6 kV, i.e. on a distribution voltage level [5]. In this paper, current limitation and recovery tests of the HTS-SFCLT are performed. Through the quantitative evaluation of recovery characteristics, we find the criteria of recovery into superconducting state.

## II. Design and Fabrication of 2 MVA Class HTS-SFCLT

The specifications and construction of 2 MVA class HTS-SFCLT in the Step-5 are shown in Table I and Fig. 1. We designed 3-phase HTS-SFCLT with the rating of 2 MVA, 22 kV / 6.6 kV. We fabricated a single phase model of the Y-Y connection HTS-SFCLT. The HTS-SFCLT has two core legs (A-leg, B-leg) and immersed in liquid nitrogen at 77 K with the iron core. Low-voltage coils (A1-A6, B1-B6; total 12 coils connected in series) are composed of two types of YBCO tapes, and high-voltage coils (A7-A10, B7-B10; total 8 coils connected in series) are composed of Bi2223 tapes. The specifications of HTS tapes are summarized in Table II. Each HTS tape is single conductor, supposing that the rated current is nearly equal to the critical current $I_c$.

Low-voltage coils of the HTS-SFCLT are divided into limiting coil (Tr / FCL coil) and non-limiting coil (Tr coil). A1-A3 and B1-B3 coils are Tr / FCL coils using LV (I) YBCO tape in Table II, and A4-A6 and B4-B6 coils are Tr coils using LV (II) YBCO / Cu tape in Table II. Such a hybrid structure of HTS coils allows the higher flexibility for both transformer and current limiter design by the variation of the ratio between Tr /

Manuscript received 3 August 2010. This work was supported by the Grant-in-Aid for Scientific Research (S) of the Ministry of Education, Culture, Science and Technology, Japan.

H. Kojima. N. Hayakawa, and M. Hanai are with the EcoTopia Science Institute, Nagoya University, Nagoya 464-8603, Japan (e-mail: h-kojima@esi.nagoya–u.ac.jp; nhayakaw@nuee.nagoya-u.ac.jp; mhanai@esi.nagoya-u.ac.jp).

M. Kotari was with the Department of Electrical Engineering and Computer Science, Nagoya University, Nagoya 464-8603, Japan. He is now with the Central Research Institute of Electric Power Industry, Yokosuka 240-0196, Japan.

T. Kito and H. Okubo are with the Department of Electrical Engineering and Computer Science, Nagoya University, Nagoya 464-8603, Japan (e-mail: kito@okubo.nuee.nagoya-u.ac.jp; okubo@nuee.nagoya-u.ac.jp).

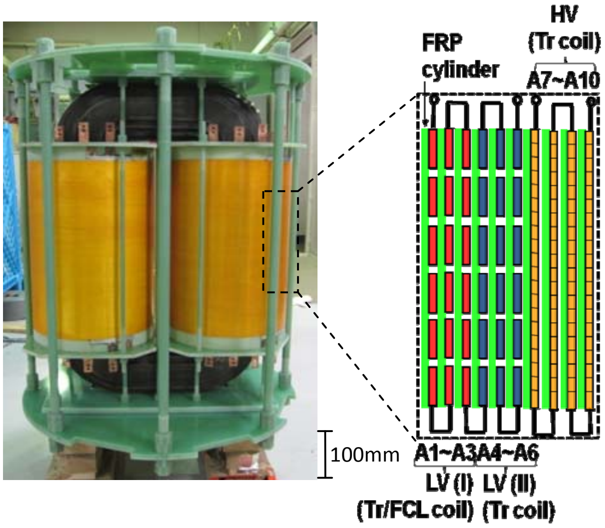



Fig. 1. Construction of HTS-SFCLT (Step-5).

TABLE I DESIGN SPECIFICATIONS OF HTS-SFCLT (STEP-5)

| | |
|---|---|
| Phase | 3 |
| Capacity | 2 MVA |
| Rated voltage | 22 kV / 6.6 kV |
| Rated current | 52.5 A / 175 A |
| Turn ratio | 1334 / 396 |
| Leakage impedance | 5.3% (@ 50 Hz) |

TABLE II SPECIFICATIONS OF 2G HTS TAPE

| | LV (I) | LV (II) | HV |
|---|---|---|---|
| HTS layer | YBCO | YBCO | Bi2223 |
| Substrate | Hastelloy | Hastelloy | — |
| Buffer layer | IBAD MgO | IBAD MgO | — |
| Stabilizer | Ag | Cu | Ag |
| Width [mm] | 12 | 12 | 2.6 |
| Thickness [mm] | 0.105 | 0.095 | 0.230 |
| $I_c$ [A] @ 77 K | 215 [a] | 240 [b] | 73 [b] |
| Length [m] | 124 | 147 | 1154 |

[a]0.3 μV/cm, [b]1.0 μV/cm

FCL coil and Tr coil.

The function of Step-5 HTS-SFCLT as superconducting transformer has already been verified in [5]. In this paper, we focus on the function of current limitation and recovery.

## III. CURRENT LIMITING CHARACTERISTICS

An experimental setup for current limiting test is shown in Fig. 2. In the current limiting test, the circuit breaker $CB_2$ was kept closed, and the circuit breaker $CB_1$ was closed during 5 cycles (0.1 s, 50 Hz). We observed the voltage $V_{HV}$ and the current $I_{HV}$ of high-voltage coils, and the current $I_{LV}$ of low-voltage coils.

In Fig. 3, the $I_{LV}$ waveform for the prospective current $I_{PRO}$ of 786 $A_{peak}$ (= $I_c$ × 3.0) is shown. The fault current was limited to 267 $A_{peak}$ (34% of $I_{PRO}$) at the first peak and 145 $A_{peak}$ (18% of $I_{PRO}$) at the 5th cycle, respectively, after the fault.

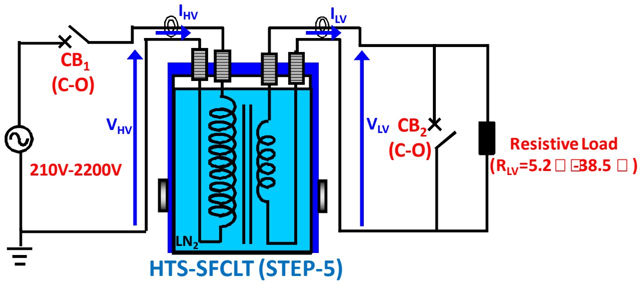



Fig. 2. Experimental setup for current limiting and recovery test.

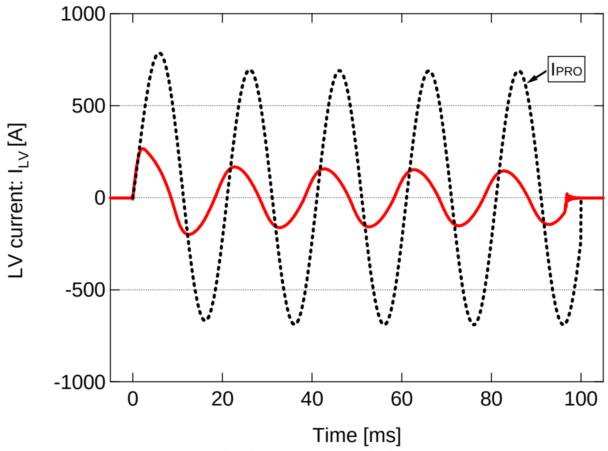



Fig. 3. Current limiting characteristics ($I_{PRO}$ = 786 $A_{peak}$).

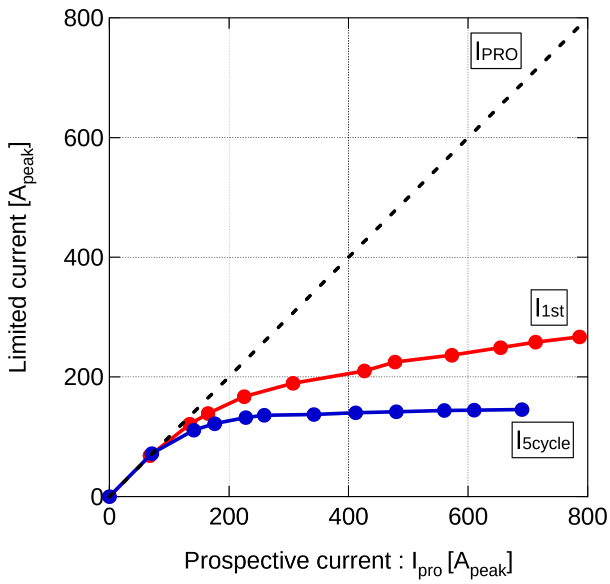
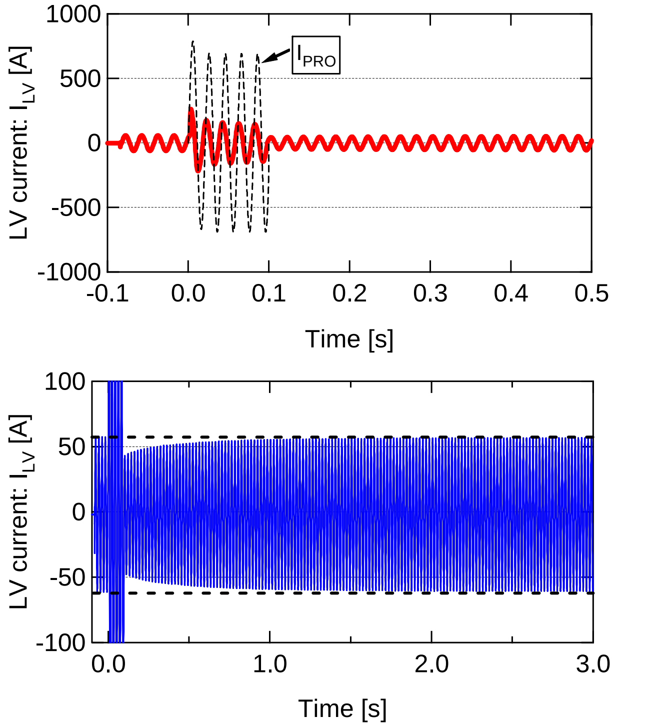
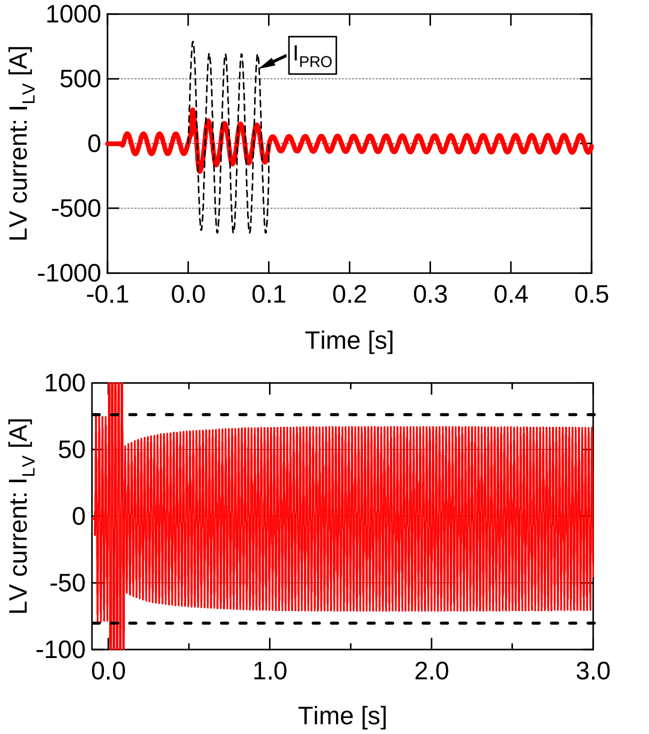



Fig. 4. Current limiting characteristics of HTS-SFCLT.

The fault current limiting characteristics of the HTS-SFCLT are shown in Fig. 4, where the broken line presents $I_{PRO}$. The limited fault current $I_{1st}$ of low-voltage coils at the first peak continues to increase with the increase in $I_{PRO}$. On the other hand, the limited fault current $I_{5cycle}$ at the 5th cycle remains at about 145 $A_{peak}$. The difference between $I_{1st}$ and $I_{5cycle}$ means a temporal rise of limiting resistance, and the increment of the



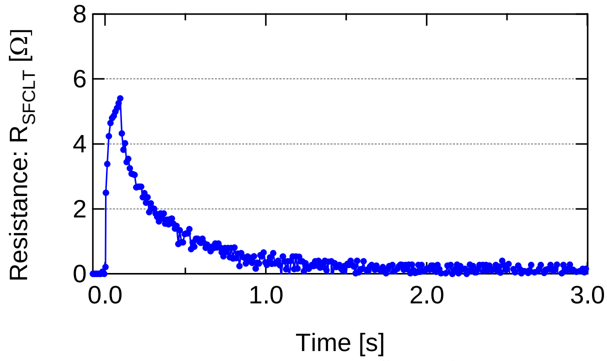

(a) $I_{LV}$ = 58.9 $A_{peak}$ (= $I_c$×0.23), $I_{PRO}$ = 786 $A_{peak}$ (= $I_c$×3.0) (Recovery case)



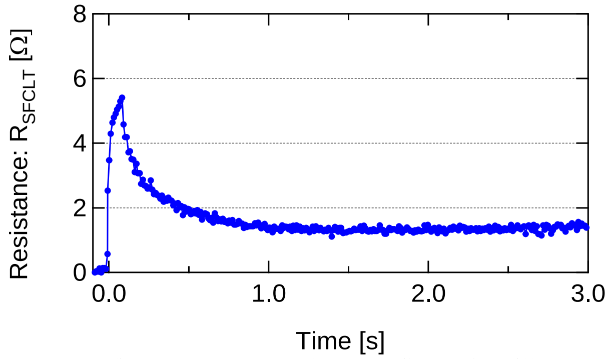

(b) $I_{LV}$ = 76.9 $A_{peak}$ (= $I_c$×0.30), $I_{PRO}$ = 790 $A_{peak}$ (= $I_c$×3.1) (Non-recovery case)

Fig. 5. Current waveform during fault and recovery process of HTS-SFCLT.

difference implies an enlargement of dissipated energy during fault in HTS-SFCLT.




(a) Recovery case (corresponding to Fig. 5(a)).




(b) Non-recovery case (corresponding to Fig. 5(b))

Fig. 6. Resistance in recovery test during fault and after fault clearance.

## IV. Recovery Characteristics

The experimental circuit for the recovery test of the HTS-SFCLT is shown in Fig. 2. The load resistance $R_{LV}$ (5.2-38.5 Ω) and circuit breaker $CB_2$ were connected in parallel to the low-voltage terminal of HTS-SFCLT. The test procedure is as follows: Firstly, $CB_1$ is closed when $CB_2$ is open, and HTS-SFCLT is operated as a superconducting transformer under a steady load current. Secondly, $CB_2$ is closed to simulate a fault, leading to the large short-circuit current, and then the HTS-SFCLT works as a fault current limiter. Thirdly, at 5 cycles after the fault, $CB_2$ is simply opened to clear the fault. Such a series of switching procedure for current limitation and recovery tests was repeated for various $I_{LV}$ and $R_{LV}$.

In Fig. 5, $I_{LV}$ waveforms until 3 s after the fault clearance are shown, in the cases of (a) $I_{LV}$ = 58.9 $A_{peak}$, $I_{PRO}$ = 786 $A_{peak}$ and (b) $I_{LV}$ = 76.9 $A_{peak}$, $I_{PRO}$ = 790 $A_{peak}$. A temporal development of a resistance $R_{SFCLT}$ of HTS-SFCLT is shown in Fig. 6 for the cases (a) and (b). The current limiting function in Fig. 5 agrees with the result of current limiting test in Fig. 4. In the case of Fig. 5(a), $I_{LV}$ is limited to 267 $A_{peak}$, i.e. 34% of $I_{PRO}$, at the 1st peak and to 145 $A_{peak}$, i.e. 18% of $I_{PRO}$, at the 5th cycle. For case (a), by clearing the fault, $I_{LV}$ recovered to the current before the fault as shown in Fig. 5(a), and $R_{SFCLT}$ recovered to the level of ordinary superconducting transformer operation by about 1 s after the fault clearance as shown in Fig. 6(a). This result reveals that the HTS-SFCLT works as a fault current limiter and recovers under a load by itself to superconducting

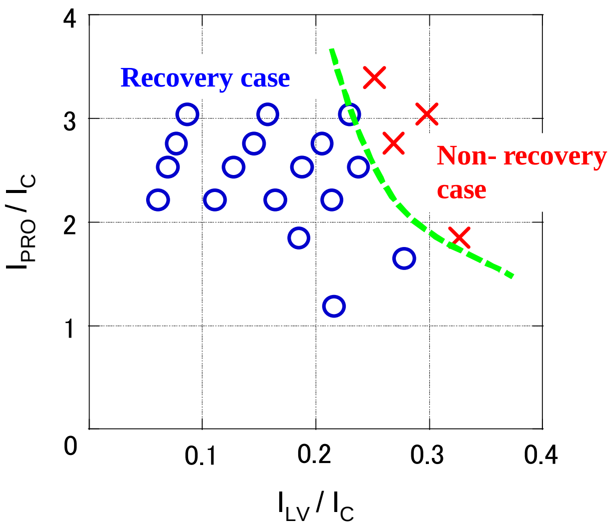



Fig. 7. Recovery limit of HTS-SFCLT.

transformer. However, for the case (b), $I_{LV}$ could not recover after the fault clearance as shown in Fig. 5(b), and $R_{SFCLT}$ remains a certain resistance as shown in Fig. 6(b), even though the difference in $I_{PRO}$ and limiting resistance during fault is small between the cases (a) and (b). This case can be considered as a non-recovery case.

The limitation of self-recovery would be dominated by the temperature rise during fault, the Joule heating due to the load current and the residual resistance after the fault clearance. This implies that the criterion of self-recovery will be expressed by $I_{PRO}$ and $I_{LV}$. In Fig. 7, the self-recovery characteristics of HTS-SFCLT are shown as parameters of $I_{LV}$ and $I_{PRO}$, which are normalized by $I_c$. The symbols "○" and "×" in Fig. 7 denote the recovery case and non-recovery case, respectively. A broken curve can be found between the recovery and the non-recovery cases, which can be regarded as the criterion or the limitation of self-recovery for the HTS-SFCLT. In other words, when the load current $I_{LV}$ and the prospective fault current $I_{PRO}$ are lower than those on the critical curve in Fig. 7, the HTS-SFCLT will recover under a load into superconducting state by itself after the fault clearance. The recoverable $I_{PRO}$ decreases with the increase in $I_{LV}$, because the Joule heating after the fault clearance is larger for the larger $I_{LV}$ and the higher temperature rise of superconductor associated with the larger $I_{PRO}$. From this result, we could find the recovery criteria of the developed HTS-SFCLT in terms of the operation current and the fault current for the critical current $I_c$.

## V. Conclusion

As the Step-5 of SFCLT project, we developed 2 MVA HTS-SFCLT with 2G YBCO coated conductors, and carried out the current limitation test and the recovery test.

We demonstrated that the fabricated HTS-SFCLT exhibited the excellent current limiting function as a superconducting fault current limiter. For the prospective fault current $I_{PRO}$ of 786 $A_{peak}$, HTS-SFCLT could limit the fault current up to 267 $A_{peak}$ (34% of $I_{PRO}$) at 1st peak and up to 145 $A_{peak}$ (18% of $I_{PRO}$) at the 5th cycle.

Self-recovery characteristics after the current limitation were discussed from the temporal development of the resistance after the fault clearance. Then, a criterion of the self-recovery was quantified for different fault conditions. These results will become the basis for the practical and optimum design of HTS-SFCLT.

## References


[1] *Status of Development and Field Test Experience with High-Temperature Superconducting Power Equipment*, CIGRE Technical Brochure, WG D1.15, 2010.

[2] N. Hayakawa, S. Chigusa, N. Kashima, S. Nagaya, and H. Okubo, "Feasibility study on superconducting fault current limiting transformer (SFCLT)," *Cryogenics*, vol. 40, no. 4–5, pp. 325–331, Apr.–May 2000.

[3] H. Kojima, S. Ito, N. Hayakawa, F. Endo, M. Noe, and H. Okubo, "Self-recovery characteristics of high-Tc superconducting fault current limiting transformer (HTc-SFCLT) with 2G coated conductors," *J. Phys.: Conf. Ser.*, vol. 97, 012154, Mar. 2008.

[4] K. Omura, H. Kojima, N. Hayakawa, F. Endo, M. Noe, and H. Okubo, "Current limiting characteristics of parallel-connected coated conductors for high-Tc superconducting fault current limiting transformer (HTc-SFCLT)," *IEEE Trans. Appl. Superconductivity*, vol. 19, no. 3, pp. 1880–1883, Jun. 2009.

[5] M. Kotari, H. Kojima, N. Hayakawa, F. Endo, and H. Okubo, "Development of 2 MVA class superconducting fault current limiting transformer (SFCLT) with YBCO coated conductors," *9th Eur. Conf. Appl. Superconductivity*, Dresden, 2009.

[6] N. Hayakawa, H. Kojima, F. Endo, and H. Okubo, "Progress in development of superconducting fault current limiting transformer (SFCLT)," *Appl. Superconductivity Conf.*, Washington, D.C., 2010, 3LZ-04.