Development of 2 MVA Class Superconducting Fault Current Limiting Transformer (SFCLT) with YBCO Coated Conductors

M Kotari[1], H Kojima[2], N Hayakawa[2], F Endo[2], H Okubo[1]

[1] Department of Electrical Engineering and Computer Science, Nagoya University, Nagoya 464-8603, Japan
[2] EcoTopia Science Institute, Nagoya University, Nagoya 464-8603, Japan

E-mail: koutari@okubo.nuee.nagoya-u.ac.jp

Abstract. We have been developing Superconducting Fault Current Limiting Transformer (SFCLT) with the functions of both superconducting transformer in normal operating condition and superconducting fault current limiter in fault condition. As the Step-5 of SFCLT project, in this paper, we designed and fabricated 2 MVA class HTS-SFCLT using YBCO coated conductors with the ratings of 3-phase and 22 kV/6.6 kV. The developed HTS-SFCLT is characterized by a hybrid structure of HTS coils using YBCO, YBCO/Cu and Bi2223 tapes for the design flexibility as both of the superconducting transformer and the superconducting fault current limiter. Fundamental tests of the HTS-SFCLT were carried out, and the design parameters as a superconducting transformer were verified.

1. Introduction

High temperature superconducting (HTS) power apparatus, e.g. transmission cables, fault current limiters, transformers, SMES, motors and generators, have been investigated and demonstrated [1]-[5]. The HTS power apparatus should be coordinated with a power system in order to improve the total efficiency and stability in a future power system.

From the 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 [6]-[14]. As the Step-4 of SFCLT project, we have designed, fabricated and tested 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. As the Step-5 of SFCLT project, in this paper, we designed and fabricated 2 MVA class HTS-SFCLT with YBCO coated conductors, whose ratings are 3-phase and 22 kV/6.6 kV. The HTS-SFCLT is characterized by the combination of different kinds of YBCO coated conductors in order to make the current limiting characteristics flexible and controllable. No-load, short-circuit and partial-load tests were carried out to confirm the design parameters and fundamental performance of the HTS-SFCLT as a superconducting transformer.

2. Concept of SFCLT

SFCLT proposed is characterized by the following concepts:

(1) SFCLT works as a HTS transformer in the normal condition, and also as a HTS fault current limiter in the fault condition.
(2) Quench-induced impedance of SFCLT is positively utilized as a fault current limiter in the fault condition.
(3) Fault current limiting function of SFCLT improves the transient stability of power system in the fault condition.
(4) Limiting impedance of SFCLT is activated in the fault condition, and leakage impedance of a transformer can be reduced, compared with that of conventional transformers.
(5) Reduced leakage impedance of SFCLT enhances the transmission capacity and static stability of power system in the normal condition.
(6) After fault current limitation, SFCLT recovers into superconducting state after the fault clearance.

The concepts (1)~(3) are fundamental functions of SFCLT, and (4)~(6) can be regarded as novel functions to be expected for SFCLT in a power system. Especially, as for the recovery characteristics in (6), we have verified that SFCLT could recover into superconducting state by itself immediately after the fault clearance, i.e. self-recovery performance [9]-[11], [13]. Figure 1 shows an example of the current limitation and recovery characteristics in Step-4 using 2G materials [13]. Against the prospective current I_{pro}=980A_{peak}, the fault current was limited to 516 A_{peak} (52.6% of I_{pro}) at first peak and 330 A_{peak} (33.7% of I_{pro}) at the 5th cycle, respectively, after the fault. In this case, the load current I_{LV2} after the fault clearance was equal to I_{LV1} before the fault, which means that SFCLT exhibited the self-recovery performance. Figure 2 shows the self-recovery characteristics of SFCLT in Step-4 as parameters of I_{LV1} and I_{pro} normalized by the critical current I_C of HTS tapes. A criterion of the self-recovery was quantified by a dotted curve for different load and fault conditions, which can be reflected to the design and operation of SFCLT.

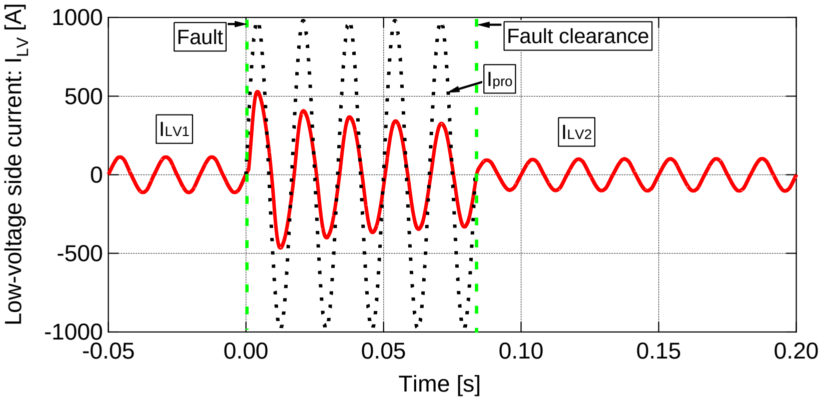


Figure 1. Current waveform of recovery test of HTS-SFCLT (Step-4)

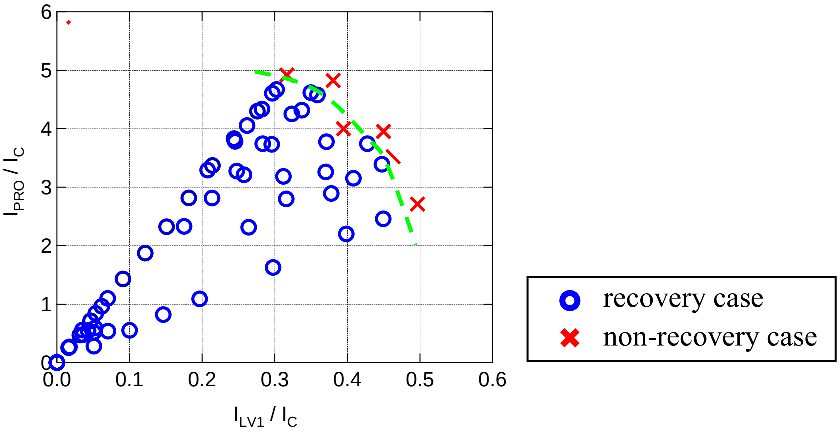


Figure 2. Recovery characteristics of HTS-SFCLT (Step-4)

3. Design and fabrication of HTS-SFCLT (Step-5)

3.1. Transformer design

The specifications and construction of HTS-SFCLT in the Step-5 are shown in Table 1 and Figure 3. We designed 3-phase HTS-SFCLT with the rating of 2 MVA, 22 kV/6.6 kV. As a single phase of the HTS-SFCLT, we fabricated 0.67 MVA, 12.7 kV/3.81 kV (Y-Y). HTS coils were arranged in both core legs (A-leg, B-leg) and immersed in liquid nitrogen at 77 K together with the iron core. Low-voltage coils (A1~A6, B1~B6; total 12 coils connected in series) were composed of two types of YBCO tapes, and high-voltage coils (A7~A10, B7~B10; total 8 coils connected in series) were composed of Bi2223 tapes. The specifications of each HTS tape are summarized in Table 2.

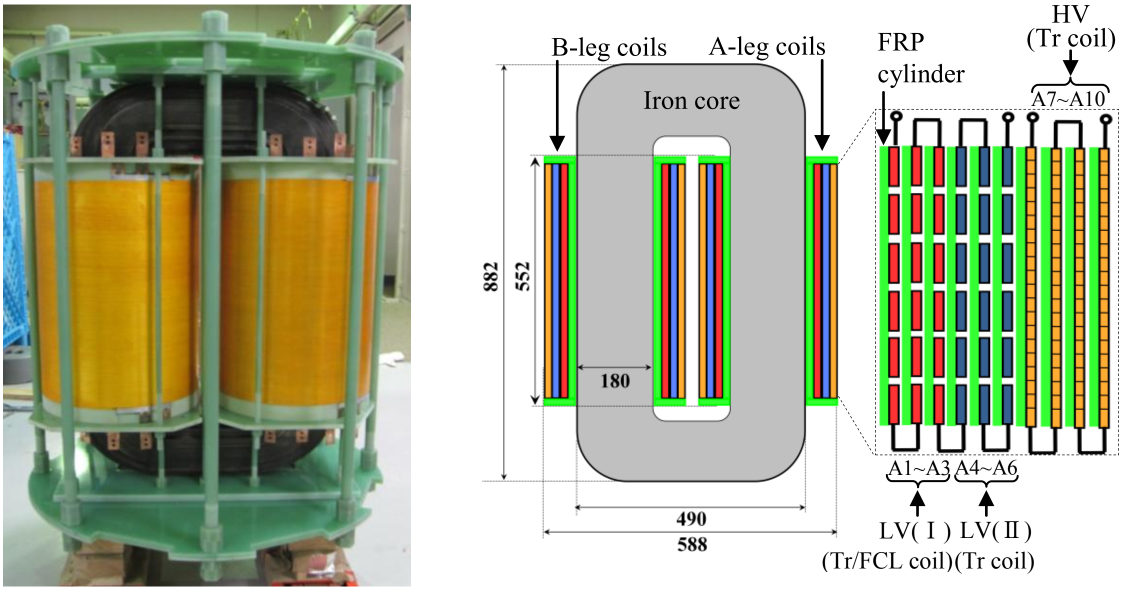
Table 1. Specifications of HTS-SFCLT (Step-5)

Phase	3
Frequency	60Hz
Capacity	2MVA
Rated voltage	22kV/6.6kV
Rated current	52.5A/175A
Turn ratio	1334/396
Leakage impedance	6.1%
Magnetic flux density	1.7T

Table 2. Specifications of 2G HTS tape (Step-5)

	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] @77K	$215^{1)}$	$240^{2)}$	$73^{2)}$
Length [m]	124	147	1154

1)0.3μV/cm 2)1.0μV/cm

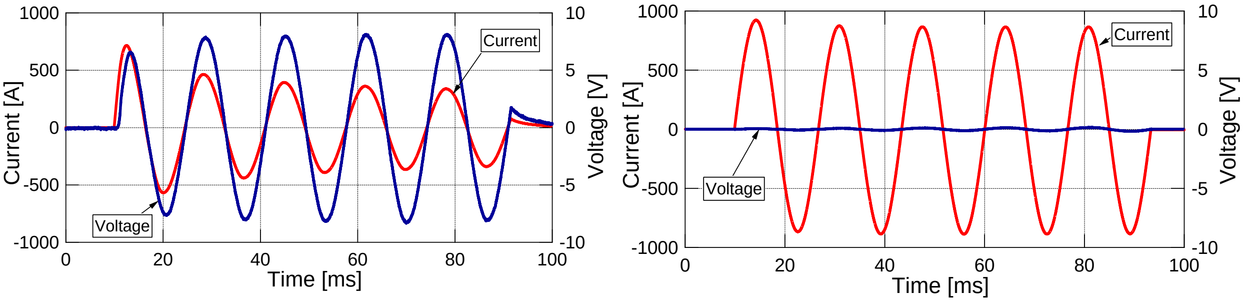


(a) Total structure (b) Cross-section and coil arrangement

Figure 3. Construction of HTS-SFCLT (Step-5)

3.2. Fault current limiter design

Low-voltage coils of the HTS-SFCLT (Step-5) were divided into limiting coil (Tr/FCL coil) and non-limiting coil (Tr coil), as was the case with the Step-4 [12], [13]. In the Step-5, A1~A3 and B1~B3 are Tr/FCL coils using LV(I) YBCO tape in Table 2, and A4~A6 and B4~B6 are Tr coils using LV(II) YBCO/Cu tape in Table 2. Such a hybrid structure of HTS coils brings about the higher flexibility for both transformer and current limiter design by the variation of the ratio between Tr/FCL coil and Tr coil.



(a) YBCO, LV(I) (I_{pro}=1164A_{peak})

(b) YBCO/Cu, LV(II) (I_{pro}=920A_{peak})

Figure 4. Current and voltage waveforms for different short tapes of YBCO for low-voltage coils

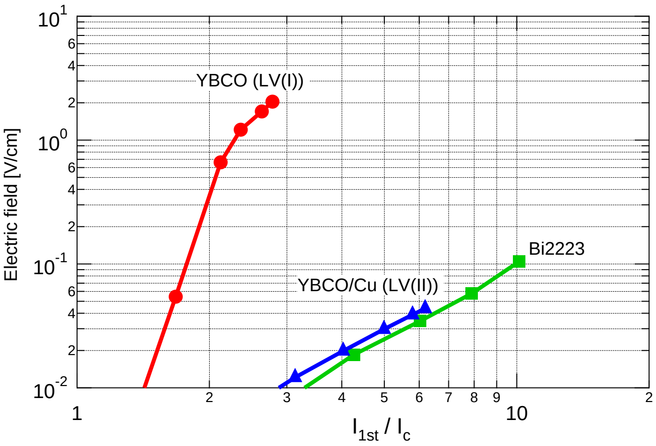


Figure 5. Electric field at first peak for YBCO, YBCO/Cu and Bi2223 tapes (short sample tape: 90 mm)

(a) YBCO tape

Figure 4 shows the current and voltage waveforms for YBCO and YBCO/Cu tapes with the effective length of 90 mm. In Figure 4 (a), against the prospective current I_{pro}=1164 A_{peak} (4.5×I_C), the current was limited to 715 A_{peak} (61% of I_{pro}) at the first peak and 340 A_{peak} (29% of I_{pro}) at the 5th cycle. On the other hand, in Figure 4 (b), YBCO/Cu tape exhibited no current limiting characteristics against I_{pro}=920 A_{peak} (4.0×I_C), because of the stabilizing copper.

Figure 5 shows the electric field at the first peak as a function of current normalized by I_C for each short sample of YBCO, YBCO/Cu and Bi2223 tapes. The YBCO tape has two orders higher electric field than the YBCO/Cu tape, which is suitable to realize the flexible current limiting characteristics at low-voltage coil by controlling the length and its ratio between YBCO and YBCO/Cu tapes.

(b) Low-voltage coil

Figure 6 shows the current and terminal voltage waveforms of YBCO coil A1 for I_{pro}=336 A_{peak}. In Figure 6, the current was limited to 309 A_{peak} (92% of I_{pro}) at the first peak and 241 A_{peak} (72% of I_{pro}) at the 5th cycle. Due to the reactance of the YBCO coil, the terminal voltage gradually increased with decreasing its phase difference against the current waveform during the current limitation.

Figure 7 shows the current limiting characteristics at the 5th cycle as a function of I_{pro} for low-voltage coils (A1~A3, B1~B3) using YBCO tapes. The current limitation can be seen for the current level I_{pro}>250 A_{peak}, and remarkable for I_{pro}>300 A_{peak}. The difference in the saturated levels of 250-300 A_{peak} for the limited current would be attributed to the difference in the generated resistance of each coil, which might be related to the length, coil diameter and inherent scatterings of YBCO coils.

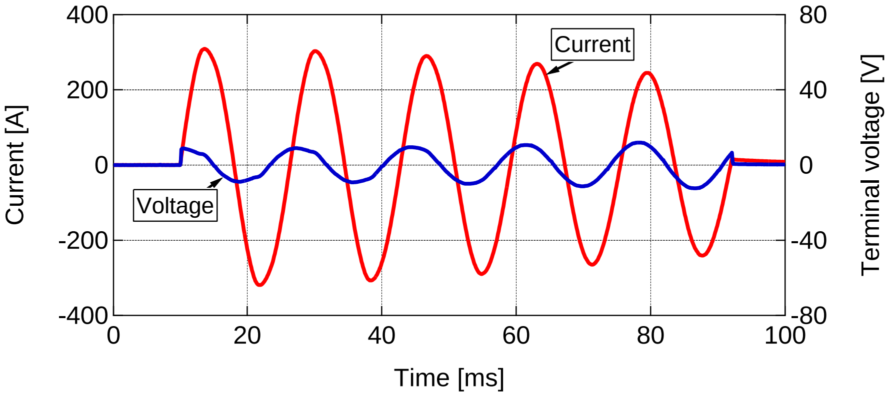


Figure 6. Current and terminal voltage waveforms at current limitation (Coil A1, I_{pro}=336A_{peak})

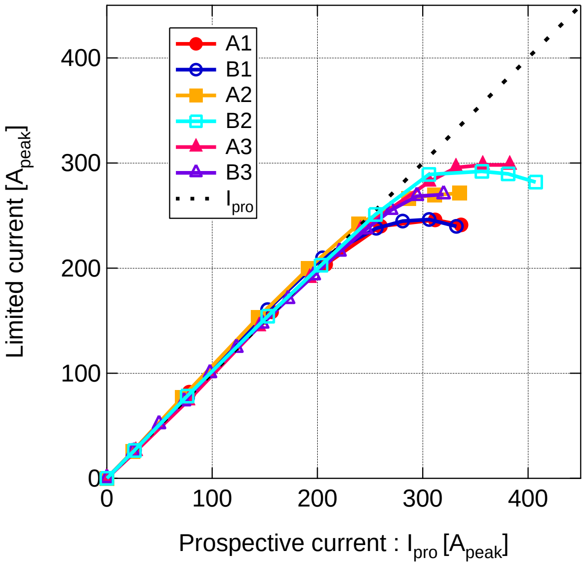
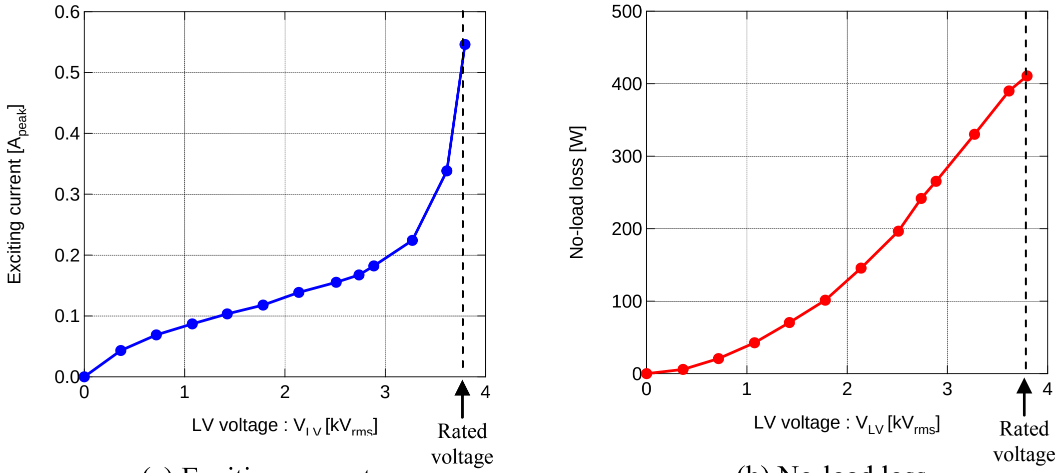


Figure 7. Current limiting characteristics at 5th cycle for low-voltage coils (A1~A3, B1~B3)

4. No-load, short-circuit and partial-load tests of HTS-SFCLT (Step-5)

The assembled HTS-SFCLT (Step-5) 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 the HTS-SFCLT as a superconducting transformer. In both tests, the turn ratio between high-voltage and low – voltage coils was confirmed to agree well with the design value. The results of no-load test are shown in Figure 8; (a) exciting current and (b) no-load loss. At the rated voltage of 3.81 kV_{rms}, the exciting current was 0.55 A_{peak}, whereas the no-load loss was 411 W. The leakage impedance obtained in the short-circuit test was 6.0%, which is also in good arrangement with the design value of 6.1%.

The partial-load test was carried out by connecting a resistive load of 1 Ω between the low-voltage terminals. Figure 9 shows the current and voltage waveforms at the partial-load test, where the current in the low-voltage coil was 92 A_{peak}, i.e. 37% of the rated current. The relationship in current and voltage waveforms between high-voltage and low-voltage coils was verified to be appropriate as a superconducting transformer.



(a) Exciting current (b) No-load loss

Figure 8. No-load test results of HTS-SFCLT (Step-5)

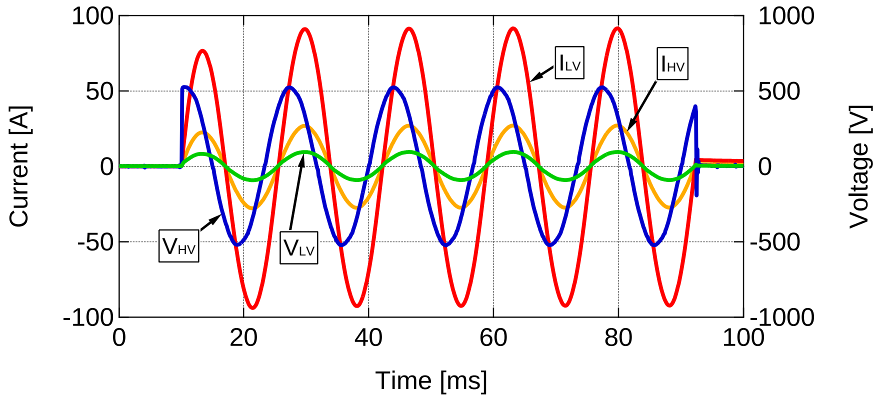


Figure 9. Current and voltage waveforms at partial-load test (I_{LV} = 92 A_{peak})

5. Key technologies for SFCLT development

From the viewpoints of transformer, fault current limiter, material and power system, key technologies for SFCLT development can be listed as follows:

- As for the transformer function, electrical insulation techniques and test procedure should be established. AC loss reduction of HTS tapes and the optimization of leakage impedance of SFCLT are expected.
- As for the fault current limiter function, electrical insulation techniques and test procedure are also inevitable, especially under quench-induced thermal/electrical combined stress. The flexibility and controllability of current limitation and self-recovery performance should be enhanced.
- From the material viewpoint, the performance of HTS tapes should be balanced in large current capacity, low ac loss, high electric field in overcurrent condition, etc, under the operating and cooling environment at the optimum temperature and pressure.
- From the power system viewpoint, the static and transient stability should be coordinated and optimized.

6. Conclusions

As the Step-5 of SFCLT project, we developed 2 MVA class HTS-SFCLT with YBCO coated conductors, and carried out the no-load test, short-circuit test and partial-load test as a superconducting transformer. The main results are summarized as follows:

- The design ratings of the HTS-SFCLT (Step-5) are 3-phase, 2 MVA, 22 kV/6.6 kV. A single phase of HTS-SFCLT was fabricated.
- Low-voltage coils were composed of YBCO tape for limiting coil (Tr/FCL coil) and YBCO/Cu tape for non-limiting coil (Tr coil). High-voltage coils were composed of Bi2223 tape. Electric field and current limiting characteristics of each tape and coil were verified.
- No-load, short-circuit and partial-load test results verified that the HTS-SFCLT would exhibit the fundamental performance with the design parameters as a superconducting transformer.

The developed HTS-SFCLT (Step-5) will be tested by current limiting test and recovery test after the current limitation.

Acknowledgement

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