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Current Limiting Characteristics of Parallel-Connected Coated Conductors for High-Tc Superconducting Fault Current Limiting Transformer (HTc-SFCLT)

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***Abstract*—We have been developing Superconducting Fault Current Limiting Transformer (SFCLT) as a superconducting transformer with current limiting function. As the Step-5 of the SFCLT project for the up-graded ratings of current and voltage, in this paper, we focused on the up-grading of current by parallel-connected YBCO coated conductors. Based on the asymmetric configuration of coated conductors, different parallel connections were tested and evaluated in terms of critical current level and current limiting characteristics under large ac current at 77 K in liquid nitrogen.**

***Index Terms*—YBCO coated conductor, superconducting fault current limiter, superconducting transformer.**

I. INTRODUCTION

High temperature superconducting (HTS) power application has been expected to reduce the transmission cost as well as improve the transmission capacity and stability of power system. In recent years, the development of HTS power apparatus such as fault current limiters, transformers, cable, SMES has remarkable progress by the improvement of HTS tapes [1]-[4]. Especially, the keenest interest in HTS tape production can be found in 2G coated conductors.

We have proposed and have been developing a "Superconducting Fault Current Limiting Transformer", abbreviated to "SFCLT", with the functions of both HTS transformer in normal operating condition and HTS fault current limiter in fault condition from Step-1 to Step-4 [5]-[9]. As the Step-4 of the SFCLT project, we designed, fabricated and tested HTc-SFCLT with YBCO coated conductors, and verified the fundamental functions of transformer and FCL. In addition, ideal self-recovery characteristics into superconducting state after the current limitation and fault clearance were also examined [10].

With the successful development of the Step-4 with the ratings of 100 kVA, 6600 V / 210 V, we now focus on the up-graded ratings of HTc-SFCLT with the larger capacity and higher voltage, as the Step-5 of the SFCLT project. In this paper, we focused on the up-grading of current by parallel-connected YBCO coated conductors. There are some researches on the parallel connection of YBCO coated conductors for the larger capacity of FCL and SMES [11], [12]. However, they have not discussed the pattern of parallel connection, taking account of the asymmetric configuration of coated conductors. Therefore, in this paper, for different patterns of parallel-connected YBCO coated conductors, fundamental critical current test and current limiting test were carried out and evaluated.

II. SPECIFICATIONS OF HTC-SFCLT (STEP-4)

The specifications and structure of HTc-SFCLT (Step-4) with 2G coated conductors are shown in Table I and Fig. 1. We designed 3-phase HTc-SFCLT with the ratings of 100 kVA, 6600 V / 210 V, 8.7 A / 275 A. As single phase of the HTc-SFCLT, we fabricated 33.3 kVA, 3810 V / 210 V, 8.7 A / 159 A (Y-Δ) HTc-SFCLT. Low-voltage coil consists of the 2G tapes, and high-voltage coil is composed of copper wire, both of which are immersed in liquid nitrogen at 77 K together with the iron core.

The transformer coil of the low-voltage HTS coil is divided into 2 parts; limiting coil with current limitation function (Tr / FCL coil in Fig.1) and non-limiting coil without current limitation function (Tr coil in Fig.1). Such a hybrid structure of HTS coils has a merit that HTc-SFCLT can obtain higher flexibility for the transformer and fault current limiter designs. In other words, 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.

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TABLE I
Specifications of HTc-SFCLT (Step-4)

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%
Material	LV(I)	YBCO
	LV(II)	YBCO / Cu stabilized
	HV	Copper

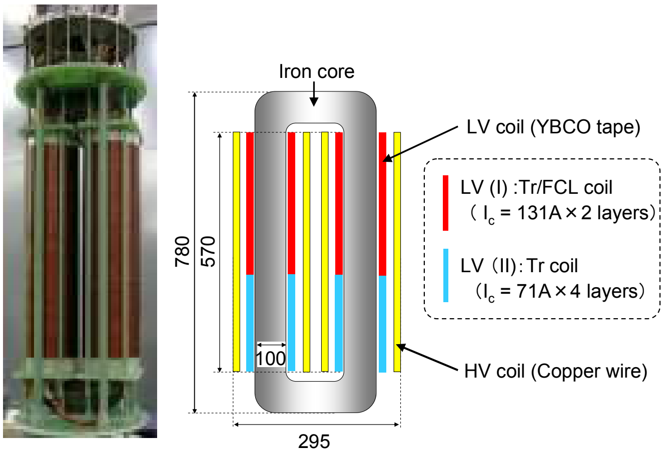

Fig. 1. Structure of HTc-SFCLT (Step-4).

We have carried out the no-load test, short-circuit test, current limiting test and recovery test, and verified that the HTc-SFCLT (Step-4) exhibited a fundamental performance as a superconducting transformer and an excellent current limiting function as a superconducting fault current limiter. Furthermore, the self-recovery characteristics after the current limitation and fault clearance have been discussed, and the self-recovery criterion was quantified for different load and fault conditions.

III. TEST SAMPLE AND EXPERIMENTAL METHOD

The specifications of YBCO coated conductor to be used as Tr / FCL coil in the Step-5 of the SFCLT project are shown in Table II. YBCO coated conductor is characterized by the asymmetric multi-layer configuration; e.g. substrate layer, buffer layer, HTS layer and stabilizer. Thus, in the case of parallel connection of 2 YBCO tapes, 3 patterns of test samples in Fig. 2 were prepared, i.e. Face-to-Back (F-B), Face-to-Face (F-F) and Back-to-Back (B-B), where the "face" is the stabilizer-side and the "back" is substrate-side. At the both terminals of test samples with the effective length of 90 mm, each tape was connected in parallel by current lead of copper.

TABLE II
Specifications of YBCO coated conductor

Substrate layer	Hastelloy (100μm)
Buffer layer	IBAD MgO (~70nm)
HTS layer	MOCVD YBCO (1μm)
Stabilizer	Ag (2μm)
Width	12 mm
Length	90 mm

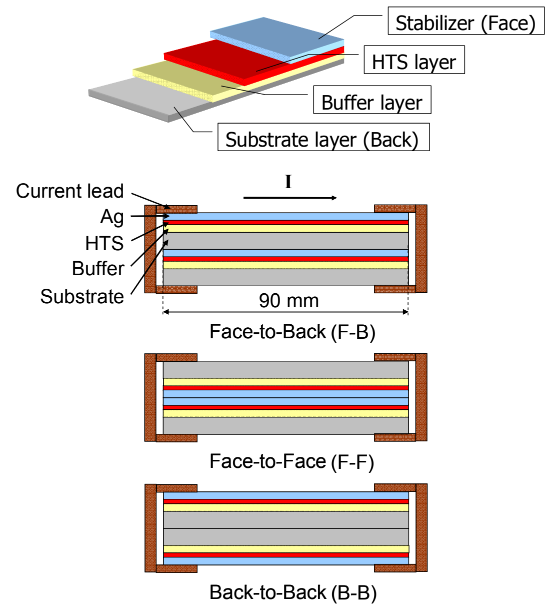

Fig. 2. Test sample.

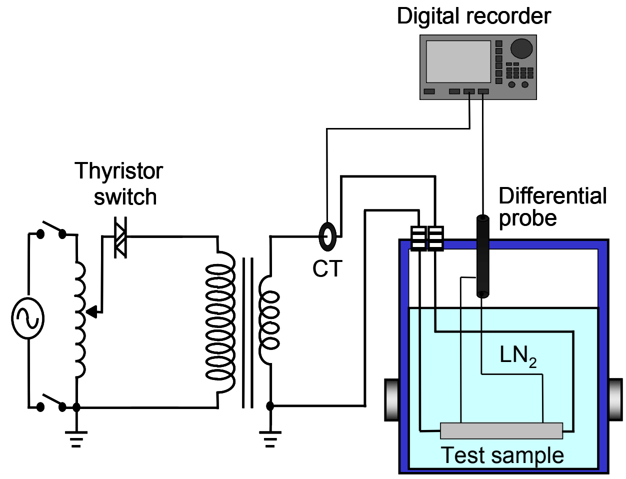

Fig. 3. Experimental setup.

The test sample was immersed in liquid nitrogen at 77 K, The critical current I_c was measured at 1μV/cm criterion. In the current limiting test of parallel-connected test samples, ac current with the peak value larger than their critical current was supplied for 5cycles (60Hz) by the operation of thyristor switch, as shown in Fig. 3. The transient current and terminal voltage waveforms were recorded and analyzed.

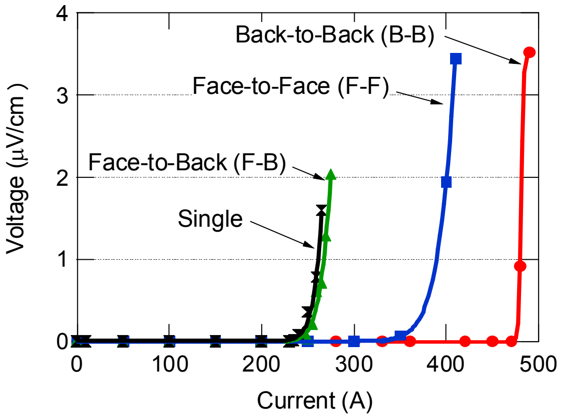

Fig. 4. Voltage-current characteristics of parallel-connected YBCO coated conductors.

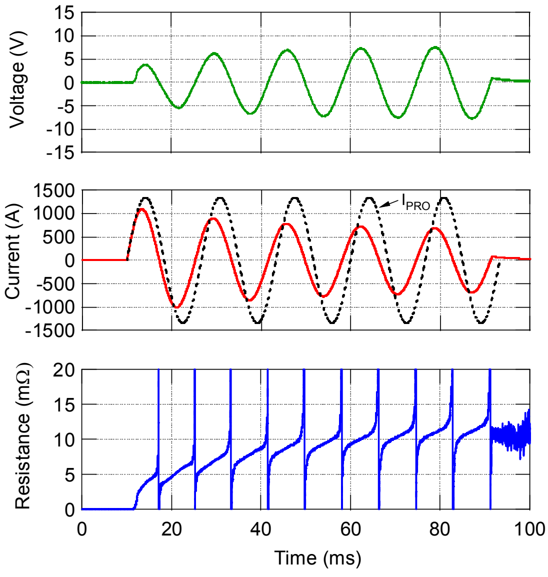

Fig. 5. Current, voltage and resistance (B-B, I_{PRO} = 1344 A_{peak}). at current limiting test

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Critical Current Characteristics

Figure 4 shows the voltage-current characteristics of each pattern (F-B, F-F, B-B) of parallel-connected YBCO coated conductors. The data of single tape is also shown in Fig. 4. I_c was 260 A for the single tape, 263 A for F-B, 395 A for F-F and 480 A for B-B. B-B has 1.8 times of I_c for the single tape, which was superior to the other parallel connections, whereas F-B exhibited almost the same I_c for the single tape. These experimental results verify that the current balance in each tape of parallel-connected sample depended on the symmetries of mechanical structure and electric distance between the HTS layer and the current lead.

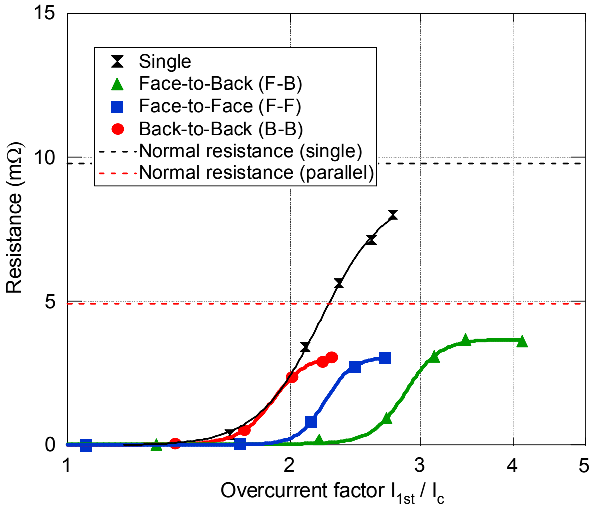

Fig. 6. Resistance as a function of overcurrent factor I_{1st}/I_c.

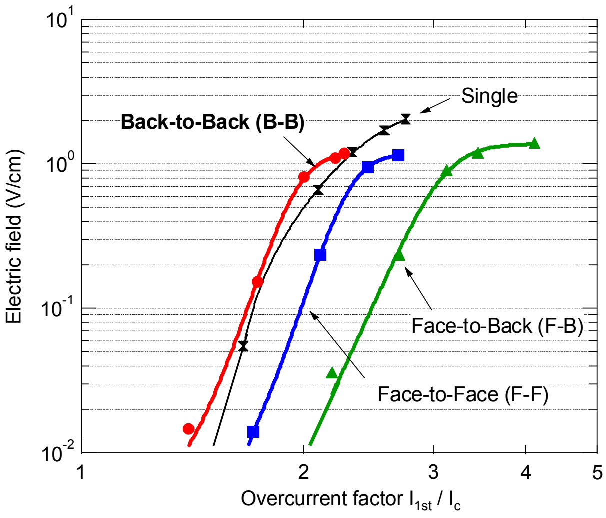

Fig. 7. Electric field as a function of overcurrent factor I_{1st}/I_c.

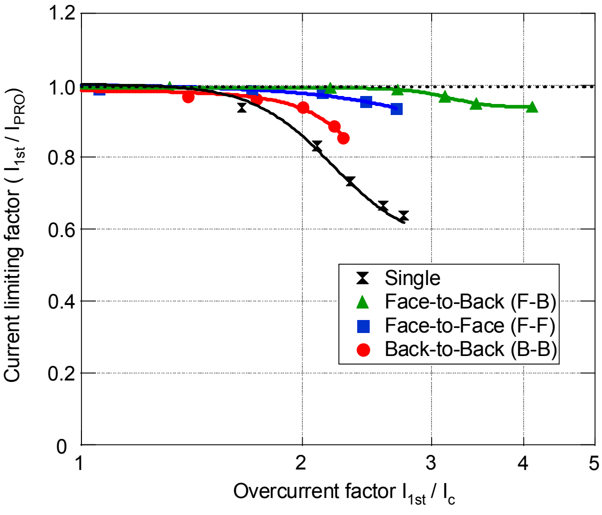

Fig. 8. Current limiting factor I_{1st}/I_{PRO} as a function of overcurrent factor I_{1st}/I_c.

B. *Current Limiting Characteristics*

Figure 5 shows an example of current, voltage and resistance waveforms of B-B sample for the prospective current I_{PRO} of 1344 A_{peak} (= $2.8\times I_c$). The current was effectively limited to 1142 A_{peak} (85% of I_{PRO}) at the first cycle and 692 A_{peak} (51% of I_{PRO}) at the 5th cycle. The resistance increased gradually up to about 4 times of that at the first peak during 5 cycles.

Figure 6 shows the generated resistance of each test sample with different parallel connections, together with the normal resistance at room temperature. The horizontal axis denotes the overcurrent factor, defined by the peak current I_{1st} at the first cycle normalized by the corresponding I_c. The maximum resistance at the first cycle for each test sample is similar at 62～73% of the normal resistance. The generated resistance in Fig. 5 exceeded 5 mΩ, which is higher than the normal resistance of parallel tapes in Fig. 6, resulting in the overheat of test sample. It should also be noted in Fig. 6 that the resistance for B-B is generated at the lowest overcurrent factor I_{1st}/I_c.

Figure 7 shows the electric field as a function of the overcurrent factor I_{1st}/I_c. The electric field at the first cycle reached as high as 1.2 V/cm and its inclination is almost the same in each parallel connection. However, the electric field for B-B is highest at a given overcurrent factor.

Figure 8 shows the current limiting factor defined by I_{1st}/I_{PRO} as a function of the overcurrent factor I_{1st}/I_c. Owing to the generated resistance in Fig. 6 and electric field in Fig. 7, the current limiting factor for B-B is found to be lower than the other parallel connections.

The parallel connection to be applied to the lager current capacity for SFCLT is discussed, based on the experimental results in the previous subsections. As for a transformer function of SFCLT, the larger I_c is requested for the up-graded ratings of current. On the other hand, as for a fault current limiter function of SFCLT, the higher resistance or electric field and the lower current limiting factor are expected. From the above viewpoints, the experimental data in Fig. 4 for I_c and Figs. 6-8 for FCL function may suggest that the parallel connection of B-B can be evaluated to be superior to the other connections.

V. CONCLUSIONS

Toward the Step-5 of SFCLT project for the up-graded ratings of current and voltage, we focused on the up-grading of current by parallel-connected YBCO coated conductors. For different patterns (F-B:Face-to-Back, F-F:Face-to-Face, B-B:Back-to-Back) of parallel-connected YBCO coated conductors, critical current and current limiting characteristics were examined.

Experimental results revealed that B-B had 1.8 times of I_c for the single tape. The electric field at the first cycle for B-B reached as high as 1.2 V/cm at the lowest overcurrent factor I_{1st}/I_c, which brought about the lowest current limiting factor I_{1st}/I_{PRO} at a given I_{1st}/I_c. From both viewpoints of transformer and fault current limiter of SFCLT, B-B could be evaluated to be superior to the other parallel connections.

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