High-Tc Superconducting Fault Current Limiting Transformer (HTc-SFCLT) With 2G Coated Conductors

H. Okubo, C. Kurupakorn, S. Ito, H. Kojima, N. Hayakawa, F. Endo, and M. Noe

***Abstract*—We developed a 3-phase, 100 kVA, 6600 V/210 V high temperature Superconducting Fault Current Limiting Transformer (HTc-SFCLT) with functions of both superconducting transformer and fault current limiter. The HTc-SFCLT is characterized by the application of 2G coated conductors with the higher current limiting performance and flexibility than that of the HTc-SFCLT with 1G Bi2212/CuNi composite bulk material. Fundamental tests of the HTc-SFCLT were carried out, and the design parameters as a superconducting transformer and as a superconducting fault current limiter were verified.**

***Index Terms*—Superconducting fault current limiter, superconducting transformer, 2G coated conductor.**

I. Introduction

BECAUSE of keen interest in the application of superconductivity to power systems, extensive research has been carried out on superconducting power apparatuses such as fault current limiters, transformers, cables and SMES [1]–[4]. From the viewpoint of system coordination and functional diversification of superconducting power apparatus, we have been developing a "Superconducting Fault Current Limiting Transformer", abbreviated to "SFCLT", with the functions of both transformer and fault current limiter [5], [6]. In the fault condition, the quench of SFCLT winding will reduce the fault current and bring about the improved dynamic stability of the power system. Whereas, in the normal operating condition, the reduction of leakage impedance of superconducting transformer will enhance the static stability and transmission capacity.

As Phase-III of our SFCLT project, we developed the HTc-SFCLT with Bi2212/CuNi bulk coils operated at 77K [7]. The ratings of the Phase-III HTc-SFCLT are 3-phase, 6.25 kVA, 275 V/105 V. Performance tests revealed that the HTc-SFCLT exhibited (1) fundamental function as a transformer, (2) excellent current limiting function as a fault current limiter, and (3) self-recovery characteristics into superconducting state immediately after the fault clearance.

With the successful development of the Phase-III HTc-SFCLT, we are now focusing on an up-graded HTc-SFCLT with larger capacity and higher voltage, as the Phase-IV of SFCLT project. In this paper, we designed the HTc-SFCLT with the ratings of 3-phase, 100 kVA, 6600 V/210 V. The Phase-IV HTc-SFCLT is characterized by the application of 2G coated conductors with higher current limiting performance and flexibility than that of the Phase-III HTc-SFCLT, which is referred to as 2G HTc-SFCLT, hereinafter. No-load and short-circuit tests were carried out in order to confirm the function of the 2G HTc-SFCLT as a superconducting transformer. For the verification of its function as a superconducting fault current limiter, a current limiting test was also carried out.

II. Evaluation of Coated Conductors for 2G HTc-SFCLT

Extensive efforts have been made toward the development of 2G coated conductors with high superconducting performance and low cost [8]–[10]. The progress in recent years has been remarkable and some 2G coated conductors have been successfully demonstrated for various applications. Hence, 2G coated conductors are now expected to be used in electric power applications.

Under those technical backgrounds, we decided to apply the coated conductors to the 2G HTc-SFCLT because of its high critical current density and current limiting performance. We selected 3 kinds of 2G coated conductor samples, A, B and C, the specifications of which are listed in Table I, and fundamental characteristics, i.e. critical current (I_c) and n-value, and the current limiting characteristics were obtained. Each sample has I_c of 75 A, 71 A and 131 A at 77 K, and n-value of 23, 27 and 47, respectively.

Fig. 1 shows current and voltage waveforms of short sample C $(\mathrm{effective\ length} = 90\ \mathrm{mm}, \mathrm{voltage\ tap\ length} = 56\ \mathrm{mm})$ for the prospective current (I_{PRO}) of 1222 $\mathrm{A_{peak}} (= 9.3 \times I_c)$. The current was effectively limited to 738 $\mathrm{A_{peak}}$ (60% of I_{PRO}) at the first peak and 339 $\mathrm{A_{peak}}$ (28% of I_{PRO}) at the 10th peak. During the current limitation, the uniformity of voltage distribution was confirmed.

Fig. 2 presents the electric field at the first peak as a function of current normalized by I_c for each 2G coated conductor. The

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TABLE I
SPECIFICATIONS OF 2G HTS TAPES

Sample	A	B	C
HTS layer	DyBCO	YBCO	YBCO
Buffer layer	MgO	Y_2O_3/YSZ/ CeO_2	Alumina/YSZ/ MgO/STO
Substrate	Hastelloy	Hastelloy	Hastelloy
Stabilizer	Ag	Cu	Ag
Width (mm)	10.0	4.4	12.4
Thickness (mm)	0.100	0.200	0.105
I_c (A)@77K, 1μV/cm	75	71	131
n-value	23	27	47

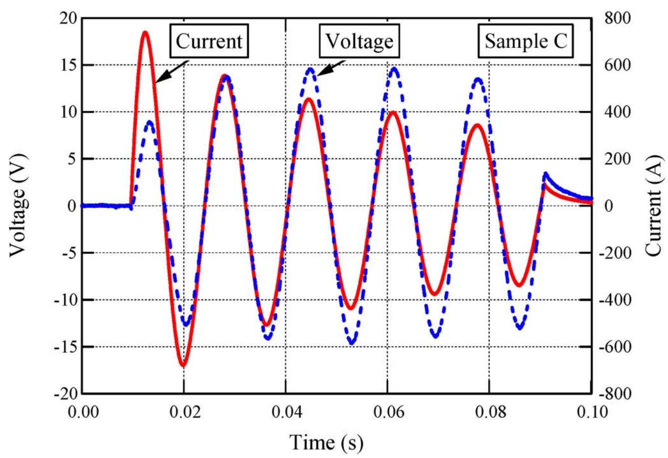


Fig. 1. Current and voltage waveforms of sample C ($I_{\rm PRO} = 1222\ \rm A_{peak}$).

result of Bi2212/CuNi bulk material used in the Phase-III HTc-SFCLT is also shown in the same figure. Maximum electric field of 1.95 V/cm and 1.4 V/cm were obtained for sample A and sample C, respectively. These values were approximately 100 times higher than that of Bi2212/CuNi bulk, and expected as the material for 2G HTc-SFCLT.

Maximum electric fields of sample A and C are high enough for the current limitation. However, in comparison with sample A, sample C has the higher I_c and n-value in Table I, as well as the higher electric field in the wide range of I_{1st}/I_c in Fig. 2. Hence, we decided to adopt sample C as the conductor for 2G HTc-SFCLT. Furthermore, sample B has less current limiting effect. However, it has an excellent stability due to thick copper stabilizer. Then, a combination of sample B and sample C will be a good choice to develop 2G HTc-SFCLT with flexibility in the design of both superconducting transformer and superconducting fault current limiter. More details are explained in the following section.

III. DESIGN AND FABRICATION OF 2G HTc-SFCLT

The specifications of 2G (Phase-IV) HTc-SFCLT and 1G (Phase-III) HTc-SFCLT are shown in Table II. We designed 3-phase 2G HTc-SFCLT with the ratings of 100 kVA, 6600 V/210 V, 8.7 A/275 A. As a single phase of 2G HTc-SFCLT, we fabricated 33.3 kVA, 3810 V/210 V, 8.7 A/159 A $(\rm Y - \Delta)$ HTc-SFCLT. Low voltage coil consists of the 2G tapes, and

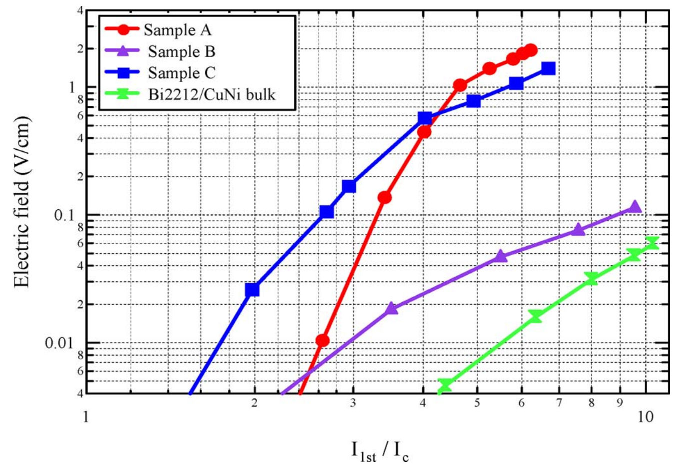


Fig. 2. Comparison of current limiting characteristics for different HTS materials.

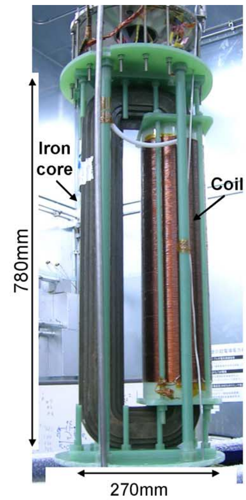
TABLE II
SPECIFICATIONS OF 1G HTc-SFCLT AND 2G HTc-SFCLT

		1G HTc-SFCLT	2G HTc-SFCLT
Phase		3	3
Frequency		60Hz	60Hz
Capacity		6.25kVA	100kVA
Rated voltage		275V/105V	6600V/210V
Rated current		13.1A/34.4A	8.7A/275A
Turn ratio		366/140	1344/74
Leakage impedance		5%	4.6%
Magnetic flux density		1.84T	1.7T
Material	LV	Bi2212/CuNi	YBCO
	HV	Copper	Copper

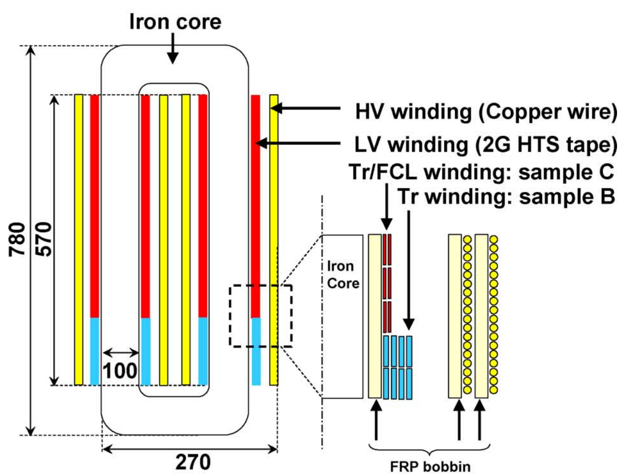
high voltage coil is composed of copper wire with 1.4 mm diameter, both of which are immersed in liquid nitrogen at 77K together with the iron core.

In the case of 1G HTc-SFCLT, 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 2G HTc-SFCLT, the transformer coil of the low voltage HTS coil is divided into 2 parts; limiting coil with current limitation function (Tr/FCL winding in Fig. 3) and non-limiting coil without current limitation function (Tr winding as shown in Fig. 3). Such a hybrid construction of HTS coils has the merit that 2G 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, 2G HTc-SFCLT can perform the desirable current limiting characteristics as well as transformer functions.

From the foregoing experimental result in Fig. 2, sample C was utilized as the limiting coil, and sample B was used as the non-limiting coil. Considering the rated current of low voltage coil of 159 $\rm A_{rms}$ (224 $\rm A_{peak}$), 2 tapes of sample C ($I_c = 131$ A) and 4 tapes of sample B ($I_c = 71$ A) were wound in parallel,

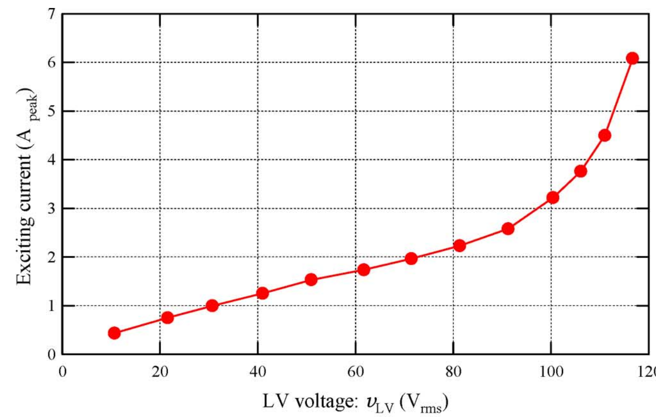


(a)

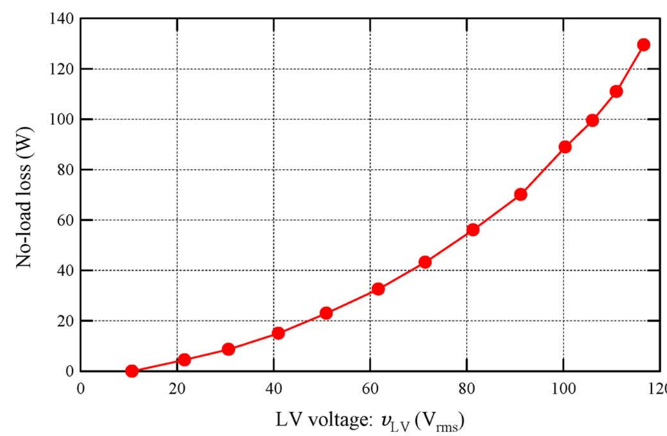


(b)

Fig. 3. Construction of 2G HTc-SFCLT. (a) Outer view; (b) cross-sectional view.



(a)



(b)

Fig. 4. No-load test result of 2G HTc-SFCLT. (a) Exciting current as a function of LV voltage; (b) no-load loss as a function of LV voltage.

respectively. From the above design concept, 2G HTc-SFCLT as shown in Fig. 3 was fabricated, where only one-leg coils are installed in the picture. As described above, the turns of limiting coil and non-limiting coil are flexible. The fabricated 2G HTc-SFCLT has 21 turns of limiting coil and 16 turns (43%) of non-limiting coil in each core leg for better current limiting function.

IV. Test Results of 2G HTc-SFCLT

A. No-Load and Short-Circuit Tests

The assembled 2G HTc-SFCLT of one-leg coils in Fig. 3(a) 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 2G 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 1344/74 in Table II. The result of no-load test is shown in Fig. 4; (a) exciting current and (b) no-load loss. At the rated voltage ($v_{\rm LV} = 105\ {\rm V_{rms}}$ for one-leg), the exciting current was $3.78\ {\rm A_{peak}}$, whereas the no-load loss was 99.6 W.

The leakage impedance obtained from the short-circuit test was 5.15%, which is approximately in good agreement with the design value of 4.6%. These results mean that the developed 2G HTc-SFCLT exhibits the fundamental performance as a superconducting transformer.

B. Current Limiting Test

Using the short-circuit test arrangement, a current limiting test of 2G HTc-SFCLT was carried out under current levels larger than those in the previous section. Prospective short-circuit current $I_{\rm PRO}$ for 5 cycles was taken as parameter.

Fig. 5 shows the current limiting test result at $I_{\rm PRO} = 862\ {\rm A_{peak}}\ (= 3.8 \times \text{rated current})$. The short-circuit current $i_{\rm LV}$ was limited to $413\ {\rm A_{peak}}$ (48% of $I_{\rm PRO}$) at first peak and $321\ {\rm A_{peak}}$ (37 % of $I_{\rm PRO}$) at the 10th peak, respectively. The current limiting characteristics $(i_{\rm LV} - I_{\rm PRO})$ of 2G HTc-SFCLT are summarized in Fig. 6. The current limitation can be seen at $I_{\rm PRO} > 300\ {\rm A_{peak}}$, i.e. 1.3 times of the rated current. $i_{\rm LV}$ at the first peak slightly increased with the increase in $I_{\rm PRO}$, whereas $i_{\rm LV}$ at the 10th peak was saturated at $320\ {\rm A_{peak}}$, irrespective of $I_{\rm PRO}$. These results suggest that the developed 2G HTc-SFCLT has an effective current limiting function as a superconducting fault current limiter.

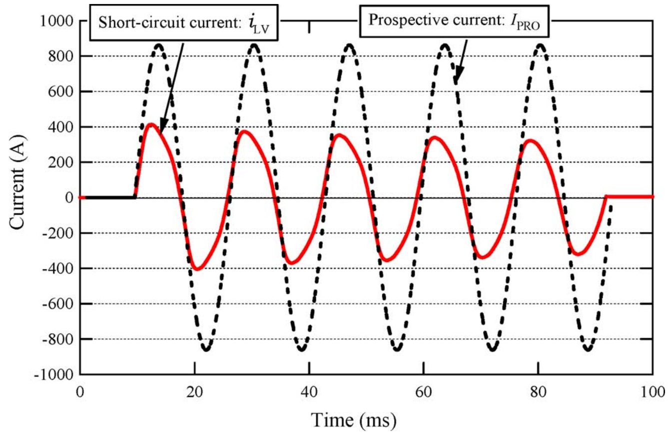


Fig. 5. Current limiting test result at $I_{\rm PRO} = 862\ {\rm A_{peak}}$.

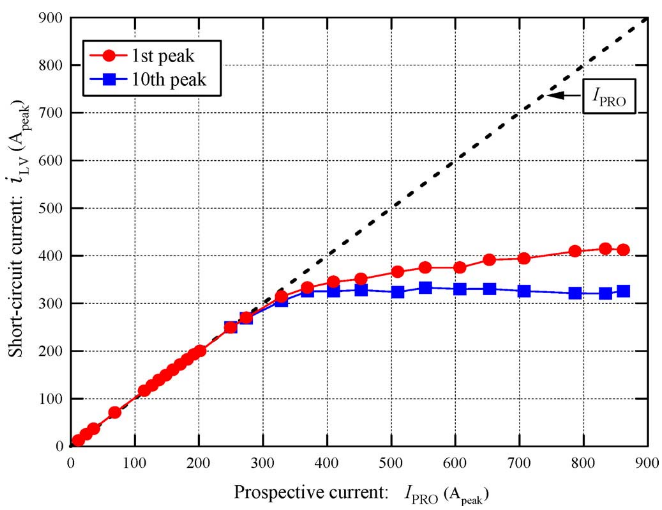


Fig. 6. Current limiting characteristics of 2G HTc-SFCLT.

V. Conclusion

As the Phase-IV of SFCLT project, we developed the 2G HTc-SFCLT with coated conductors. The main results are summarized as follows:

1) 2G coated conductor samples were examined and selected in terms of fundamental characteristics (I_c, n-value) and the current limiting characteristics. Maximum electric field of the selected 2G coated conductor sample was 100 times higher than that of Bi2212/CuNi bulk.
2) The design ratings of 2G HTc-SFCLT are 3-phase, 100 kVA, 6600 V/210 V, 8.7 A/275 A. A single phase of 2G HTc-SFCLT was fabricated.
3) HTS coils of 2G HTc-SFCLT were divided into limiting coil and non-limiting coil to obtain higher flexibility for the transformer and fault current limiter designs.
4) No-load and short-circuit test results confirmed that 2G HTc-SFCLT had a fundamental performance as a superconducting transformer.
5) The current limiting test revealed that 2G HTc-SFCLT exhibited the excellent current limiting function as a superconducting fault current limiter. The prospective short-circuit current $I_{\rm PRO} = 862\ {\rm A_{peak}}$ was reduced to 48% at the first peak and 37% at the 10th peak, respectively.

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