2nd Generation High-Temperature Superconducting Wires for Fault Current Limiter Applications

Y.Y. Xie, K. Tekletsadik, D. Hazelton and V. Selvamanickam

Abstract — **In this paper, we report the results from evaluation on the use of 2nd generation high-temperature superconducting wires, or 2G HTS conductors, as elements for superconducting fault current limiter (SFCL). The unique features of 2G HTS conductors such as high N-values, superior electromechanical performance, large surface area available for cooling, and their availability in long-lengths that could be produced by high-throughput and low-cost manufacturing, may provide advantages for SFCL applications. We tested SuperPower's standard ion-beam-assisted-deposition based 2G HTS conductors under various conditions. First, individual conductors 10-20 cm long with dc critical current (Ic) ranging from 180 amps to 277 amps were tested at prospective fault current up to 3 kA (peak). 2G HTS conductors demonstrated good fault current limiting performance, including first peak limitation. Quench current was in the range of 1.8 to 3 times Ic, and the response time was within 1 ms. Secondly, 3-5 conductors in parallel connections demonstrated uniform current sharing and fast recovery under no-load condition. Finally, an assembly consisted of 12 elements in series connection was tested at high-power condition at KEMA PowerTest. Each element had four 40 cm long conductors with Ic ~ 120 A in parallel connection. With 1080 V supply voltage and 90 kA prospective fault peak current, the fault current was limited to 32 kA at the 1st peak with 3.2 kA in the HTS elements. The response time was less than 1 ms. All these testing results indicate that our 2G HTS conductors are promising for practical SFCL applications.**

Index Terms — **Fault current limiters (FCL), superconducting fault current limiter (SFCL), high-temperature superconductors, 2nd generation high-temperature superconducting wires (2G HTS conductors), quench time, quench current.**

I. INTRODUCTION

WITH the dramatically increased demand on electric power, the new power generation is being added and the power delivery networks are being upgraded. The levels of faults from events such as lightning striking a power line, or downed trees or utility poles shorting the power lines to ground, can increase beyond the capabilities of the existing equipment, leaving circuit breakers in an "over-duty" condition. Fault-current limiters (FCL) using high temperature superconductors offers a solution to control fault-current levels on utility distribution and transmission networks, and are one of the most exciting applications of superconductors in electrical engineering [1-5]. SuperPower, Inc. and its research partners have been working on a three-phase program since 2002 to develop practical Superconducting FCL or SFCL to meet the needs from the electric power industries including American Electric Power (AEP). In July of 2004, a preprototype SFCL using 36 melt-cast-processed (MCP) BSCCO elements from Nexans SuperConductors GmbH was constructed [6-7]. The MCP-BSCCO elements were each ~ 20 cm long and with dc critical current of ~ 1590 A. This device termed the Matrix Fault Current Limiter (MFCL) employed technology that offers modular features that enable the scale-up to transmission voltage levels of 138kV. With this preprototype MFCL, we demonstrated current limiting performance at phase-to-ground voltage up to 8660 VAC and prospective fault current up to 25.5 kA (peak) in a cryostat at 74 K. At 8660 VAC, the fault current was limited to 84% at the first peak and 56% at the 3rd cycle compared to the prospective fault current 25.5 kA (peak). Although this test result was encouraging, it was soon realized that a number of improvements on the performance of the HTS elements were needed to make it possible to develop Alpha prototype for single-phase 138 kV applications [8]. Those desired improvements post difficult challenges due to the following features of MCP BSSCO elements:

(1) Low n-value (8-12) – the quench current is much higher than the critical current as a result of which it requires higher current to quench, in the order of >10*Ic. This increases the total material volume needed in SFCL;

(2) Large number of elements needed. Number of elements determines device size (along with high voltage), steady state losses (connections) and rating of device cryogenic system – It is desirable to maintain the number per phase to a manageable level. It is challenging to develop longer elements with high individual energy level to minimize total number of parts;

(3) Questionable reliability. Very high reliability is required since loss of elements has negative impact on heat load and introduces debris that could compromise high voltage;

(4) Slow return to superconducting state after fault. Fast return to superconducting state while carrying load current - recovery under load (RUL), is needed to deal with repetitive faults, but bulk material has limited cooling surface area.

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In contrast, 2G HTS conductors may provide solutions to those challenging issues because of their following unique features:

(1) High n-value (20-40) – the 2G conductor quenches at around 2 – 3 times Ic, and so it limits fault current faster and to a lower level;

(2) 2G HTS conductors in 300+ m length and good uniformity are already available [9]

(3) Superior electro-mechanical properties have been shown in SuperPower's 2G HTS conductor – reduces the chance for mechanical failure and increase the flexibility of element configuration/design [9];

(4) 2G HTS conductors have larger cooling surface area vs. bulk volume ratio, which is beneficial to faster recovery;

(5) Several structural features of 2G HTS conductors can be tuned to optimize SFCL element performance.

These potential advantages for FCL applications motivated us to experimentally evaluate the fault current limiting performance of SuperPower's ion-beam-assisted-deposition (IBAD) based 2G HTS conductors. A significant advantage of using IBAD-based 2G is the ability to use various types of substrates. The substrate that is currently used in SuperPower's 2G conductor is Hastelloy which has a high resistivity which is preferable for FCL applications. The conductor used in this study did not include any additional resistive stabilizer. This paper reports our preliminary investigative work on 2G SFCL and test results.

II. LOW-POWER TEST SETUP AND PROCEDURE

We constructed a laboratory-scale test circuit to test the concept of 2G SFCL. The schematic diagram of the test circuit is shown in Fig.1. The system voltage is provided by an isolated transformer that has primary 208 VAC and variable secondary 5/10/20/40 VAC. The short circuit current can vary up to 7000 A. Shunt impedance is variable from either pure resistive to resistive/inductive impedances. Only the HTS and the current leads are immersed in liquid nitrogen (LN_2) during the test. Line frequency was 60 Hz. The short circuit faults were generated and controlled by a bipolar thyristor switch. The voltage and current waveforms were recorded by a LeCroy *WaveRunner* 6050A Oscilloscope through LeCroy AP031 Differential Probes and PEM CWT30B Rogowski Current Waveform Transducers, respectively. The duration of the faults varies from 5 to 12 cycles. We can also apply faults repetitively and the gap between each two faults can be as short as 3 seconds.

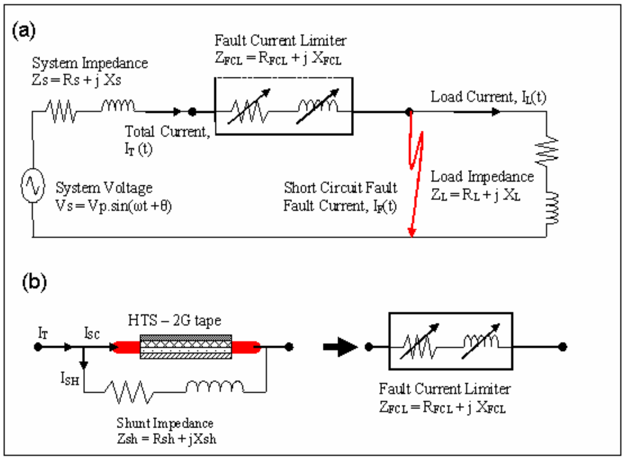


Fig. 1, Illustration of the lab-scale test setup: (a) Schematic diagram of single-phase power system representation, (b) Equivalent circuit of FCL.

A. Tests on individual conductors

During the test, a single IBAD-based 2G HTS conductor typically 10 cm long and 12.4 mm wide was in parallel connection with a shunt coil. The supplied voltage was 20 VAC and the prospective fault current was 3000 A.

B. Conductors in parallel connection – current sharing during fault and recovery under no load condition

In order to meet the requirement for 1 kA class applications in power transmission lines, it is necessary to use more than one 2G HTS conductors in parallel since the typical dc Ic available in long length or large production volume is around 200-250 A per cm width which is equivalent to 250 - 310 A in SuperPower's 12.4 mm wide conductors (our newer conductors are 12 mm wide). Whether all conductors in parallel connection uniformly share the current during faults is a key subject we want to investigate through the test. To evaluate the performance, we fabricated a simple fixture to hold 3-5 conductors together in parallel connection as a module to replace the single conductors in the test circuit. The waveforms of the total current flowing through the module and the current flowing through one of the three conductors were monitored and recorded. The fixture is adjustable to host conductors in different lengths, but the typical length of the 2G HTS conductors used in this type of tests was 20 cm. We used two groups of samples in the tests:

(1) Three 2G HTS conductors each 20 cm long, 12.4 mm wide and with 2.4 µm metal layer. Ic was 277 A for all three samples. We applied faults with prospective fault current of 442 A, 705A, 1140A, 1360A, 1650A, 2320A, and 3800A at 20 VAC with No shunt. At 3800 A, the fault duration was increased gradually from 5 cycles to 12 cycles until the conductors failed. 2G HTS conductors were allowed to completely cool down before being applied with the next fault.

(2) A different set of three 2-G conductors each 20 cm long, 12.4 mm wide and with 2.2 µm thick silver overlayer. Ic was 180 A for all three samples. Similarly to the last set of conductors, we applied multiple faults at prospective fault

current 3800 A with during from 5 cycles to 12 cycles. All three conductors survived with the 12-cycle fault. Then recovery tests were carried out with this set of conductors. For each recovery test, we applied 6 repetitive 12-cycle faults with interval about 3 seconds. We did 5 recovery tests until one of the conductors failed.

III. RESULTS FROM LOW-POWER TESTS

Fig. 2 plots the waveforms of currents and voltages when an individual 2G HTS conductor (M3-119-FCL-2B) which has Ic of 252 A and 1.2 µm thick silver overlayer was subject to an 8-cycle fault with prospective fault current of 3000 A. The waveform in purple is the current flowing through the 2G conductor. It is shown that 2G conductor quenched at ~ 500 A which is about two times of the conductor's Ic and the response time was within 1 ms. The current in the shunt is shown in the red waveform. The total current was limited to ~ 1500 A at the 1st peak of fault which is half of the prospective fault current. The voltage over the 2G conductor reaches above 15 V (peak) during the fault, meaning the 1.5 V/cm voltage level is sustainable by 2G HTS.

Multiple samples were tested under similar conditions and all demonstrated current limiting performance, including 1st peak limitation. Quench current was in the range of 1.8 to 3 times critical current. Response time is within 1 ms.

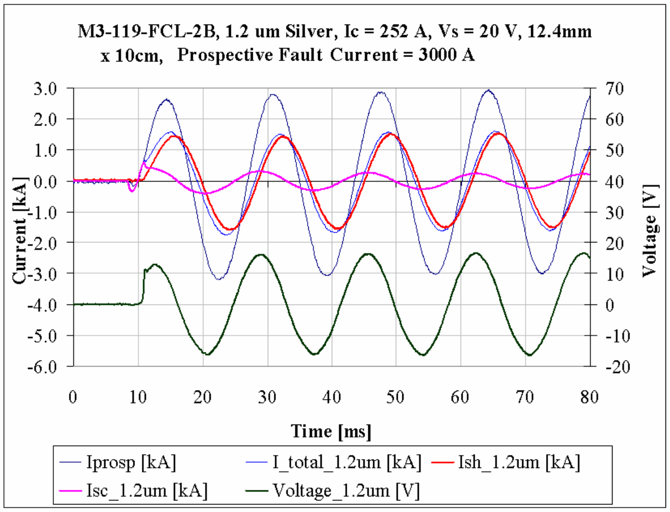


Fig. 2, The waveforms of currents and voltages taken at different locations of the test circuit when a 2G HTS conductor in parallel connection with a shunt coil was subject to a 8-cycle fault (only 4.5 cycles are shown). I_{prosp}, I_total, I_{sh}, I_{SC} are the waveforms of the prospective fault current, total current in the 2G conductor and the shunt, the current in the shunt only and the current in the 2G conductor only, respectively. "Voltage" is the waveform of the voltage across the 2G HTS conductor.

The results of test on the three 2G conductors in parallel connection are shown in Fig. 3 and Fig. 4. In Fig.4, three conductors each with Ic of 277 A were supplied with 5-cycle fault. It is shown that the current flowing though one of the conductors (in light blue) is comparable to the average current or to 1/3 of the total current in this 3-conductor module implying a uniform current sharing among the three conductors during the short circuit faults. This module was later subjected to faults with duration from 6 to 12 cycles. Two conductors failed at the 11th cycle with accumulative energy at the same level as the individual conductors. The 3rd one failed at the next 12-cycle test. Failure of parallel conductors close to each other means small variation in conductor quality and good predictability of life expectancy.

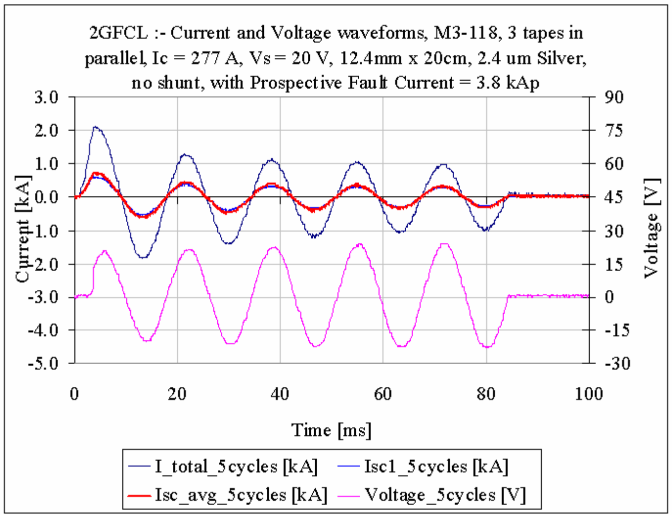


Fig. 3, Waveforms of the current in three 2G conductors in parallel connection during a 5-cycle fault. I_total and Isc are the current flowing through the 3-conductor module and in one of the three conductors, respectively. Isc_avg is I_total divided by a factor of 3. The decreasing current and increasing voltage during the fault indicate the heating on the 2G HTS.

In the test shown in Fig. 4, the second set of three 2G conductors each of which had Ic of 150-180 A were subject to 6 repetitive 12-cycle short circuit faults at about 3 s intervals after they survived a single 12-cycle fault. The accumulative heating effect can be seen from the decreasing amplitude of the current waveform and the increasing amplitude in the voltage waveform during each fault. Calculating from the three faults shown in Fig. 5, the accumulative energy is 100 J/cm/wire. The average for each fault is about 33 J/cm/wire – similar to single fault situation. We repeated the recovery test a few times. This set of conductors failed after the 5th recovery test. The large surface area of 2G conductors is beneficial to recovery. RUL performance needs to be tested under different breaker switching sequence scenarios.

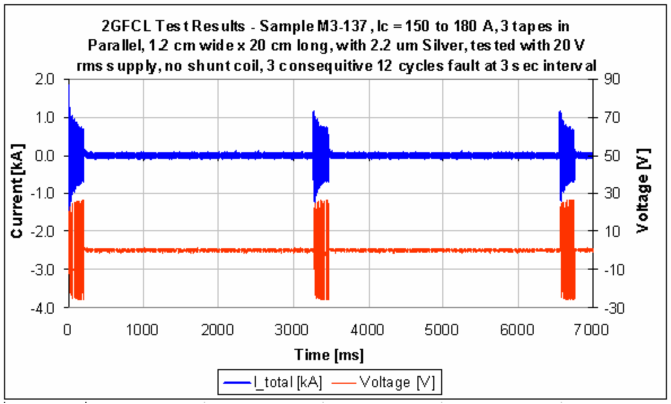


Fig. 4, Waveforms of the current (in blue) and voltage (in red) in the 3-conductor module during a 6 repetitive 12-cycle fault recovery test (only 3 repetitive faults are shown). The prospective fault current for each fault was 3800 A. The interval between two 12-cycle faults was about 3 seconds. Accumulative heating effect on the 2G conductors during the faults can also be seen from the change in the amplitude of the waveforms of current and voltage.

IV. HIGH-POWER TEST ON AN ASSEMBLY WITH 12 ELEMENTS

To demonstrate the suitability of 2G HTS conductors for current limiting application at higher currents and voltages comparable to utility requirements provided for alpha MFCL, we designed and fabricated a mock-up assembly as described in the following:

(1) The assembly consists of 12 elements each 40 cm long with four 2G HTS conductors 12.4 mm wide in parallel connection. Ic of the 2G HTS conductors is in the range of 120-130 A.

(2) 2 sets of 6 shunt coils were fabricated.

The photograph of the 12-element assembly immersed in the open LN_2 test bath is shown in Fig. 5.

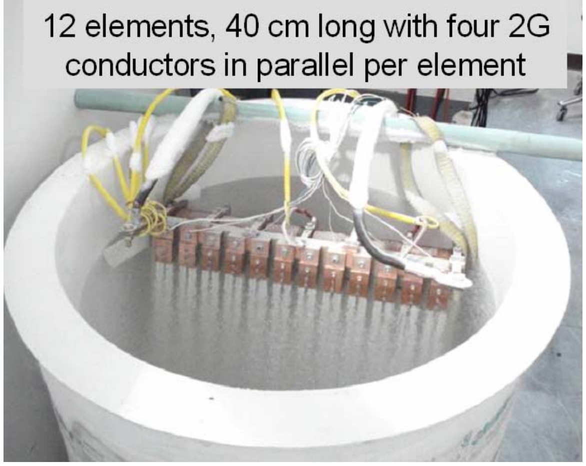
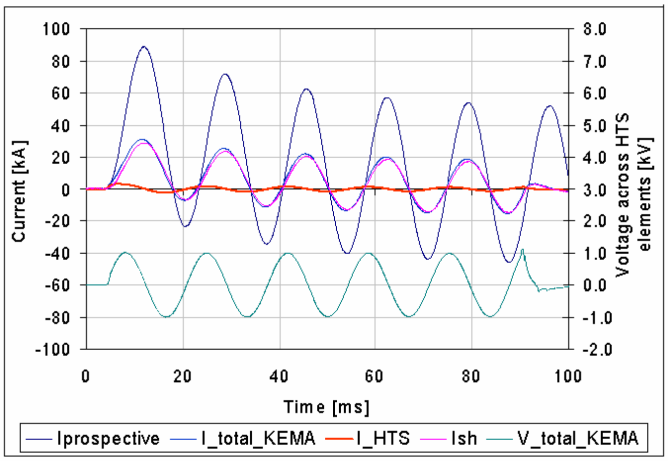


Fig. 5 Photograph of the assembly consisted of 12 elements in the open LN_2 test bath.

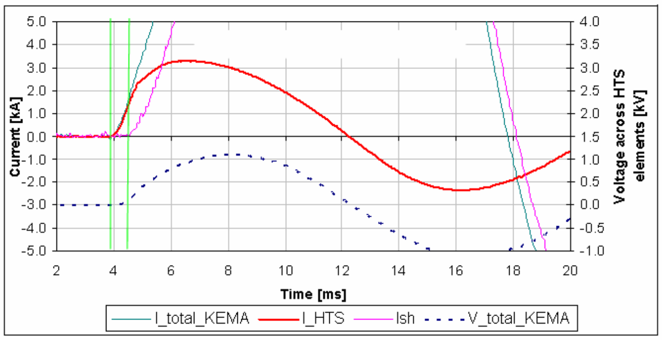
The actual test was carried out KEMA PowerTest. KEMA provide test voltage ranging from 120 V rms to 1200 V rms and fault current ranging from 3 kA peak to 100 kA peak. The short circuit tests started with the lowest fault current setting (5kA rms at 480 V rms) and lowest supply voltage setting, 120 V rms, and gradually stepped the voltage up to a maximum of 1200 V rms. A total of 51 tests were carried out.

V. HIGH-POWER TEST RESULTS AND DISCUSSION

A typical test result on the 12-element mock-up assembly – one of the tests after replacing the damaged 2G HTS elements with new ones and the internal shunt coils with the external shunt inductor, is shown in Fig. 6. The supply voltage was 1080 V with prospective fault current of 33.75 kA rms (90 kA peak) at 5 cycles. Current was limited to 31.81 kA peak at the 1st peak ~ 35 % of the prospective fault current, implying that AEP's requirement of 26 kA rms (70 kA peak) fault condition is satisfied with this performance and Alpha prototype can be designed using 2G SFCL. The current in the 2G HTS elements was limited to to 3.16 kA peak and shunt current was 29.10 kA peak. The HTS elements sustained voltage level at 2.1 V/cm peak (1.5 V/cm rms) as shown in the figure. Fig. 6(b) is a closer look at the 1st cycle of the fault. The 2G HTS currents quenched at 2350 A that is about 4 times of their total dc I_c. The ratio 4 is slightly highly than what we observed in low-power tests. The response/quench was still rapid in 0.5-1 ms.



(a)



(b)

Fig. 6, Test result at 1080 V supplied voltage with prospective fault current of 33.75 kA rms (90 kA peak). I_prospective is the prospective fault current. I_total, I_HTS and I_{sh} are the current flowing through the assembly, 2G HTS elements and shunt coils, respectively. V_total is the voltage across all the 2G HTS elements connected in series.

To summarize the test results on the 2G HTS mock-up assembly, the main parameters obtained from tests at the highest power level without damaging the elements are listed in Table I and compared with the MCP-BSCCO based preprototype MFCL described in Section I. It is shown in the table that superior performance was obtained in all aspects using 2G SFCL.

Table I High-power current limiting performance:
2G HTS mock-up SFCL vs. MCP-BSSCO based preprototype MFCL

High-power SFCL test	2G HTS conductor	MCP-BSCCO
Prospective current	90 kA	80 kA
Limited current	32 kA	40 kA
Current through element	3 kA	25 kA
Response time	< 1 ms	4 – 5 ms
Element quality range	Narrow	Broad

VI. CONCLUSION

Superior current limiting performance, including 1st peak limiting, quench current only 2-4 times of Ic, fast response time and fast recovery, has been observed in IBAD-based 2G HTS conductors though low-power and high power tests on single conductors, three conductors in parallel connection and an assembly with 12 elements in series each with four parallel connected conductors. The performance at high-power test conditions satisfies AEP's requirements of 26 kA rms (70 kA peak) fault conditions. Thus Alpha prototype for 138 KV applications can be designed using 2G SFCL.

Further optimization on the 2G HTS conductor structure such as stabilizer and substrate, and assembly structure may yield better performance of single conductors.

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