Test results of fault current limiter using YBCO tapes with shunt protection

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Abstract. A Fault Current Limiter (FCL) based on high temperature superconducting elements with four tapes in parallel were designed and tested in 220 V line for a fault current peak between 1 kA to 4 kA. The elements employed second generation (2G) HTS tapes of YBCO coated conductor with stainless steel reinforcement. The tapes were electrically connected in parallel with effective length of 0.4 m per element (16 elements connected in series) constituting a single-phase unit. The FCL performance was evaluated through over-current tests and its recovery characteristics under load current were analyzed using optimized value of the shunt protection. The projected limiting ratio achieved a factor higher than 4 during fault of 5 cycles without degradation. Construction details and further test results will be shown in the paper.

1. Introduction

Resistive superconducting fault current limiter (SFCL) are devices with electrical behavior near the ideal when it changes its state from the superconducting to the normal state, limiting the fault current by the insertion of a fast transition resistance in the grid. Due to this property SFCL are at present the most proper solution to reduce the fault current levels in the electric power transmission. The insertion of SFCL can solve the existing problem of over duty fault current associated with the growth and increasing interconnection of the power grid and can prevent damage to the circuit components within 50 ms, being this time interval necessary for circuit breaker actuation.

The development of the SFCL has the potential to reduce the fault current levels by factors of 3 to 10 times. The compact size, reduced inductance (no power factor correction required) and the cost-effective when it is compared with the inductive limiters makes the resistive SFCL preferred for electrical applications.

The YBCO coated conductor (CC) consisting in an YBCO ceramic thin film deposition on oxide-buffered Ni-W alloy substrate has unique features such as high n-values, high resistivity substrate, superior electromechanical performance, large surface area available for cooling and, the availability in long-lengths provides advantages for SFCL applications [1]-[2]. The YBCO tape, especially one with stainless steel (SS) reinforcement on both sides, provides good mechanical properties such as tensile strength above 250 MPa at room temperature, essential for designing SFCL using bifilar coils.
or parallel arranged conductors, soldered and mounted on G10 plates with several elements connected in series [3]. After the fault the device should recover its superconductor state in short period of time in order to avoid any degradation of the HTS tapes. The contact surface of these tapes with the liquid nitrogen bath increases the efficiency cooling scheme thus reducing the recovery time.

In this work, we report the results from the evaluation of a fault current limiter using eight G10 plates with four YBCO tapes with 0.4 m in length in parallel with a shunt protection per element, in a total of 16 elements, to provide a homogeneous quench behavior of the HTS tapes and to act as stabilizer to the system [4]-[7]. The tests were done in DC and AC (60 Hz) over-current pulse, lasting 100 ms for DC measurements and varying from 1 to 5 cycles for AC tests. The pulse current reached an intensity of 2 kA corresponding an eight times $I_c$. After the fault a steady current is imposed to determine the recovery time under load.

2. FCL design and experimental setup

The SFCL prototype was designed using the American Superconductors YBCO CC 344S type with 4.4 mm width, 0.15 mm thickness, and critical current, $I_c = 72$ A (163 A/cm-width). The substrate of this tape is Ni-5%at.W and the linear resistance per meter of the tape is 3.54 mΩ/cm. The electrical field developed within the superconductor length under safe condition can reach 0.5 V/cm [4] with the shunt protection $R_{sh} = 180$ mΩ per element.

The SFCL for steady conditions 220 V/300 A constitute in 16 elements containing four 344S tapes of 0.4 m in parallel association soldered at their ends on a copper bus bar with a Sn-In alloy (Fig.1).

![Figure 1. Fault Current Limiter constituted by four YBCO tapes with 0.4 m length soldered in parallel and connected with shunt protection in each element.](image-url)

The DC characterization was performed using a DC power supply (10 V/1000 A) by applying a pulse current varying from $I_c$ up to 2.4$I_c$. The measure consist in the application of the pulse of current during 100 ms followed by a steady current of 100 A ($I < I_c^*$, $I_c^*$ = element critical current) in order to evaluate the behavior and the recovery time under those conditions. A voltage-current curve at liquid nitrogen temperature (77 K) was measured to obtain the critical current of the system. The voltage signals were measured using a digital multimeter Agilent 34410A and the pulses were created and applied by an arbitrary waveform generator Agilent 33220A.

For AC measurements pulses of current intensity of 8$I_c$ were applied in two elements and also in the whole SFCL prototype during 1 to 5 cycles (60 Hz) followed by a steady current of 200 Arms during the recovery time. The SFCL was connected in series with a motor-generator (96 kVA/380 V). The fault was controlled by a static switch by short-circuiting the load in series with the SFCL. The
current and voltage signals were measured by a four-channel digital storage oscilloscope Tektronix TDS 5054 for acquiring the waveforms, and saving their instant data in real time.

3. Tests results - Electrical performance

3.1. DC Characterization

The voltage-current curve at liquid nitrogen temperature for two elements with four parallel tapes each on the surface of the SFCL is compared in Fig. 2. The plot shows the result for the total critical current in both elements. In one of them, the critical current was $I_{c}^* = 270$ A. The index $n = 28$ was calculated from the potential law equation $E = E_c (I/I_c)$ to the I-V experimental data, where $E$ is the electric field, $E_c = 1 \mu V/cm$ the electric field criterion to determine the critical current, $I$ is the applied current, and $I_c$ is the critical current. In the second element, the critical current was not reached under this voltage limit of 0.4 mV what suggests that this element has a higher transition current since the critical currents can vary along the length of the HTS tape.

![Figure 2. I-V curves for the DC pulsed current measurements for two elements with four YBCO tapes at 77 K.](image)

For evaluating the resistance growth and the recovery time, a test using pulsed current of amplitude of 1 up to 2.5 times $I_c$ with duration of 0.1 s, followed right after by applying a lower current value equivalent to a 20% of $I_c$. The results for 1.5$I_c$ and 2.2$I_c$ are presented in Fig. 3 and 4.

For the pulsed current of 420 A (Fig. 3), the voltage reached 7.8 mV and 4.7 mV in each element, corresponding to a resistance value of 18.5 $\mu\Omega$ and 11.2 $\mu\Omega$, what suggests only the beginning of the transition to the normal state. In this case, the recovery occurred immediately after the extinction of the pulse current. Under 583 A (Fig. 4) the voltages were 3.8 V and 3.1 V and the resistance was 6.5 m$\Omega$ and 5.3 m$\Omega$, respectively. The recovery time for both elements was near 300 ms.
3.2. AC Fault current tests
The two elements of SFCL and the whole SFCL prototype were protected by a shunt resistor of 180 m\(\Omega\)/element. The two elements were tested under fault current during one cycle, reaching \(I_{\text{peak}} = 1.7\text{ kA}\), maximum voltage of 10 V. Fig 5 shows the current and voltage waveforms during the transition for two elements where the recovery process was completed within 80 ms after fault. The voltage peaks of 10 V (element 1) and 2.8 V (element 2) correspond to resistance values of 5.9 m\(\Omega\) and 1.65 m\(\Omega\), respectively. Figure 6 shows the current and voltage waveforms for fault periods of three cycles. It is observed the same behavior as for one cycle test but with longer recovery time.

![Figure 3](image3.png)

**Figure 3.** Pulsed current of 420 A lasting 100 ms in two elements of a SFCL.

![Figure 4](image4.png)

**Figure 4.** Pulsed current of 583 A lasting 100 ms in two elements of a SFCL.
According to the obtained results for two elements, it is expected that the voltage range per element is about from 3 V to 10 V, depending on the $I$ of each element. In the test result for the SFCL prototype shown in Fig. 7, the maximum voltage reached 150 V for 1.9 kA current during one cycle corresponding to the resistance value of 78.9 mΩ. After the current fault the voltage decreases to 24 V and after 100 ms it reaches 1.9 V indicating the recovery time after few seconds. During the three cycles test (Fig. 8) the voltage of 112.5 V and the resistance of 68.2 mΩ were achieved under 1.65 kA current peak. The recovery time also occurs within few seconds after fault being proved by the decrease of total voltage.
For five cycles of fault it was measured the signals for the whole SFCL assembly and for one element in order to compare the total voltage to the voltage reached by one element of the assembly. The current peak of 1.8 kA generated a voltage of 120 V (Fig. 9) on over the SFCL and a voltage of 6.5 V in one element. The resistances are 66.7 mΩ for the whole SFCL assembly and 3.6 mΩ for one element. The recovery time of the whole SFCL assembly occurs within few seconds while in this particular element the recovery time occurs 160 ms after the beginning of the current pulse. The transition in all of the 16 elements can be observed in the sequence of pictures (Fig. 10) as well as the recovering process under load condition.
Figure 9. Fault current in SFCL prototype and one element for five cycles period.

Figure 10. Pictures sequence during 1.8 kA fault current in the SFCL prototype for five cycles period.

The element voltage and total voltage shows that the transition in all of the 16 elements is occurring, which is confirmed by the sequence of pictures during SFCL test, so that it is reasonable to
assume all of them have contributed to limit the fault current. The recovery process can be observed with a short recovery time feature for the YBCO tapes. The total electrical field per element is around 0.2 V/cm, which is below the safe condition of 0.5 V/cm.

4. Conclusions
The electrical properties of a resistive SFCL constituted by two elements containing four parallel YBCO tapes reinforced with stainless steel were measured reaching a total critical current higher than 270 A. The DC test was carried out maintaining a steady current of 20% $I_c$ after fault current extinction in order to evaluate the recovery time. The results showed good response after fault and also after the extinction of the fault, reaching a recovery time of 300 ms for 2.2 $I_c$ per element. The recovery time in both elements occurred 80 ms after fault. The two elements are part of the SFCL prototype. Under current of 1.9 kA peak, the total voltage reached 150 V achieving 68.2 mΩ resistance value. One element was measured to compare its voltage with the total one. The results show that in this prototype the quench is non uniform and the transition to the normal state occurs similarly in all of them. The response of the SFCL was no longer than 3 ms and the recovery time occurred within few seconds.

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