Fault Current Limiter Using Transformer and Modular Device of YBCO Coated Conductor

Carlos A. Baldan, Jérika S. Lamas, André A. Bernardes, Carlos Y. Shigue, and Ernesto Ruppert

***Abstract*—In this work, we report on the evaluation of a superconducting fault current limiter (SFCL). It is consisted of a modular superconducting device combined with a short-circuited transformer with a primary copper winding connected in series to the power line and the secondary side short-circuited by the superconducting device. The basic idea is adding a magnetic component to contribute to the current limitation by the impedance reflected to the line after transition of the superconducting device. The evaluation tests were performed with a prospective current up to 2 kA, with the short-circuited transformer of 2.5 kVA, 220 V/660 V connected to a test facility of 100 kVA power capacity. The resistive SFCL using a modular superconducting device was tested without degradation for a prospective fault current of 1.8 kA, achieving the limiting factor 2.78; the voltage achieved 282 V corresponding to an electric field of 11 V/m. The test performed with the combined SFCL (superconducting device + transformer) using series and toroidal transformers showed current limiting factor of 3.1 and 2 times, respectively. The test results of the combined SFCL with short-circuited transformer showed undesirable influence of the transformer impedance, resulting in reduction of the fault current level.**

***Index Terms*—Current limiting ratio, step up transformer, superconducting fault current limiter, YBCO coated conductor.**

I. Introduction

SUPERCONDUCTING fault current limiters (SFCLs) are devices with potential to protect the power distribution systems against faults that cause damage and blackouts. Resistive SFCLs present electrical behavior near the ideal, with insertion of a fast transition resistance due to changing from the superconducting state to the normal state with high resistivity during short time, normally until 5 cycles, thus limiting the fault current value. In order to evaluate the performance of resistive SFCLs combined with magnetic circuit a short-circuited transformer are used to provide the coupling effect with the grid line. To reduce the effect of the current limitation just due to insertion of the short-circuited transformer, low impedance units were designed and constructed with toroidal and series configurations for comparative analysis. Under normal operation the short-circuited transformer presents a low voltage drop in the range of 5% to 10% that is possible to compensate using a voltage regulator unit. They also generate low magnetic fields from 2% to 5% of the value for full load condition, resulting in very low losses.

The superconducting device was designed considering the maximum allowed electrical field, $E = 50$ V/m in the YBCO coated conductor (CC) tape [1]–[3]. For medium class voltage applications continuous long lengths of YBCO CC tapes are needed for building several modular units with series and parallel electrical connections. The modular units permit to adjust the maximum current and voltage during limitation time up to 100 ms. For safety operations SFCLs can prevent damage to the circuit components within 50 ms being this time interval necessary for circuit breaker actuation but for the electric utilities company side the desirable time must be increase to 500 ms. The increase in the limitation time can be achieved by combining the modular superconducting device with an iron-core magnetic circuit connected in series and/or in parallel with the grid line. The removal of the superconducting device will occur after 5 cycles for the sake of superconducting device recovery through the opening of a fast switch. These combined SFCLs have the potential to reduce the fault current levels by a factor of 3 to 10 times making them an essential component of the future smart electric grid.

Using commercial YBCO CC tapes with high resistivity matrix with a linear resistance of $0.354\ \Omega/\mathrm{m}$ it can insert a high resistance value limiting the fault current level to a maximum allowable temperature of 350 K. The YBCO CC tapes with stainless steel reinforcement 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 [1], mounted on glass fiber reinforced plastics (G10) plates with several elements according with the voltage level application. The strong electromagnetic forces generated by the high fault current level require a high tensile strength reinforcement.

Considering the architecture of the commercial YBCO CC tapes such as stabilizer thickness, substrate resistance and use of reinforcement, one requires prior pulsed current measurements using short samples for determining the peak current limiting period and the recovery time from full normal state transition in order to avoid any irreversible tape degradation. An efficient cooling scheme should also be considered to expose the broad tape surface to the liquid nitrogen coolant.

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Fig. 1. Picture of the modular superconducting device constituted by 24 series sectors containing a pair of YBCO CC tapes in parallel and connected with shunt resistors.

In this work, we designed a SFCL using 2×25 m length of YBCO tapes in parallel, with a shunt protection per element with equivalent resistance of 0.18 Ω/m, totalizing 24 sectors without tape splicing. This configuration provides a homogeneous quench behavior of the HTS tapes and acts as stabilizer for the device [3]–[5]. The tests were performed in AC single phase-ground line, an adjusted time length from 1 to 5 cycles with prospective fault current up to 2 kA.

II. SFCL Parameters and Design

The SFCL was constructed using the YBCO CC tape with stainless steel reinforcement 344S type with 4.4 mm-width, 0.15 mm thickness, and critical current, $I_c = 72 \pm 2$ A (equivalent to 163 A/cm-width) supplied by American Superconductor. This tape, manufactured with Ni-5%at.W substrate, has a linear resistance per length equivalent to 0.354 Ω/m at room temperature.

The electric field developed within the superconductor under safe condition can reach 50 V/m with the shunt resistance of $R_{sh} = 78$ mΩ per sector or 1.86 Ω equivalent for the whole modular device (with 24 series sectors) [6].

Using a short sample setup the electric characterization was carried out to evaluate the peak current value under non-fault condition to carry currents above I_c without quenching during 0.5 s. In our case considering the stainless steel reinforcement as an additional electric shunt protection results in conductor length reduction [7]. The transition to the normal state occurs from 2 ms up to 4 ms after the start of fault current when the current peak was limited to 8 times I_c.

The geometry of the modular superconducting device (Fig. 1) aims to expose all the surface of YBCO tape to the coolant with a pair of straight and parallel tapes wound on G10 tube and soldered at their ends to copper terminals. The modular unit constituted by 24 sectors in series was designed for operating at 761 V under a steady current of 150 A. In the same unit it is possible to associate 12 sectors in parallel with the other ones to operate at 380 V and steady current of 300 A.

The nominal power per area of the SFCL can be calculated multiplying U_{nom}/L by I_c/w, where U_{nom} is the nominal voltage, I_c the critical current, L and w are the conductor length and width, respectively, giving the nominal power of 96 kVA for this unit, corresponding to a rms power value 57 VA/cm^2 for fault duration varying from 50 up to 100 ms [3].

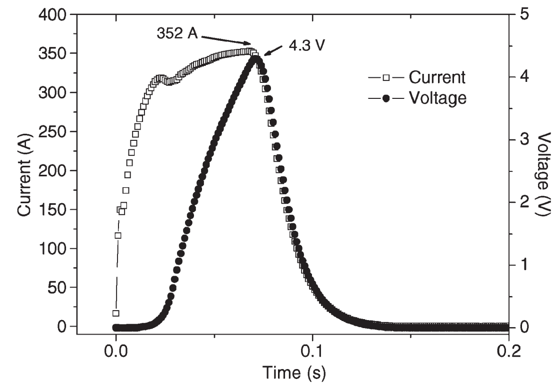

Fig. 2. Pulsed current test curve two tapes in parallel for nominal 350 A peak.

The power dissipation corresponds to 94.6 kW (SFCL voltage 262 V and limited current 352 A) after 100 ms; the energy density of about 303 J/cm^3 is lower than the critical value of 1,200 J/cm^3. The energy released in the YBCO CC tape could be enough to degrade the YBCO layer and it is also sufficient for reaching the melting temperature of solder used between the YBCO CC tape and the stainless steel reinforcement [6].

III. Electrical Performance

A. Pulsed Current Characterization

For evaluating the resistance growth and the recovery time, a short sample test using pulsed current of amplitude of one up to 2.5 times I_c with 0.1 s duration is done followed right after by a lower current value equivalent to 20% I_c. The test result is presented in Fig. 2 for two YBCO tapes in parallel with a shunt protection. In the pulsed current curve (Fig. 2) the voltage reached 4.3 V for 352 A, corresponding to a resistance value of $R = 12.2$ mΩ for 10 cm sample length or equivalent value of 0122 Ω/m and a recovering time after the current peak lower than 0.2 s, while the steady current was maintained at 60 A.

B. Short-Circuited Transformer Design

The basic concept is to combine a magnetic circuit with the modular superconducting device for getting some benefits such as the short-circuited transformer constructed with lower conductor volume for operation at high power energy system during the fault (high voltage and high current) and obtaining larger limiting time for improving the SFCL performance. In this work our aim was to design low impedance toroidal and series type short-circuited transformers for comparison. They were constructed with copper windings, with the primary winding connected in series with the power line and the secondary winding short-circuited by a modular superconducting device; the combined SFCL can present a promising current limiting ratio. After transition to the normal state a fast resistance grows up proportional to the superconducting tape length; that equivalent resistance value is reflected back to the power line side (no-load impedance condition) limiting the fault current.

TABLE I
MAIN CHARACTERISTICS OF COUPLING TRANSFORMERS

Transformer type	Series	Toroidal
Power (kVA)	2.5	5.0
Voltage (V)	220/73.3	220/73.3
Current (A)	11.3/34.1	22.7/68.1
Turn ratio	3:1	3:1
Impedance (%)	< 2	< 2

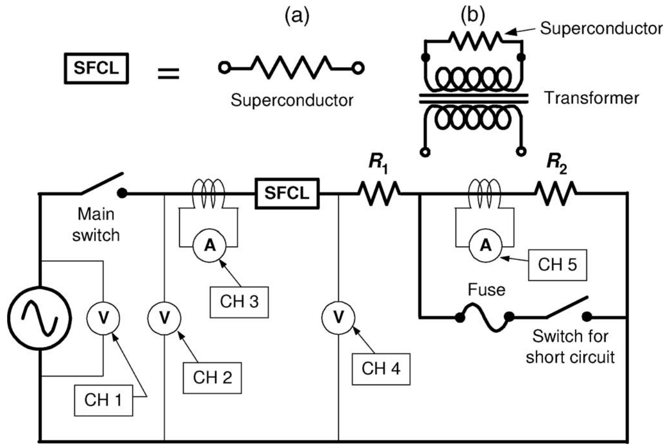

Fig. 3. AC fault current test electric circuit used for testing of (a) the modular superconducting device (MSD) and (b) combined with a transformer (MSD + transformer).

The short-circuited transformer presents a low voltage drop in the power line, low losses and low magnetic flux when a steady current is flowing in the windings. In the fault current condition the secondary side operates at low voltage and high current levels when the fault occurs and after 2 ms a full length of YBCO tapes quenches limiting the current with ratio of 3 up to 10 adjustable when the turns ratio was selected.

At the same time all voltage in the power line will be applied to the primary winding of short-circuited transformer resulting in saturation of the iron core decreasing the voltage at secondary and the current flowing in the superconducting module.

All the design was carried out using thermal characteristics of current transformer in which the fault current can achieve 100 times the steady current flowing during 100 ms. These winding configurations were used for construction of a single-phase series transformer and a toroidal type transformer, whose main characteristics are summarized in Table I.

C. Fault Current Test of Resistive Modular Device

The modular superconducting device unit (MSD) constituted by 24 sectors in series was designed for operation at 761 V and steady current of 150 A. During the fault current test carried out using a 96 kVA motor-generator the device was connected in series between phase to ground, with a steady rms current of 70 A, when resistive load (Y-connection) was short-circuited (single phase) using a fast static switch. The prospective fault current with this configuration can reach 1.8 kA with adjustable time to operate from 1 to 5 cycles.

The Fig. 3 shows the electrical circuit used for resistive SFCL test. The values for the resistive loads R_1 and R_2 were selected for each fault current level, reaching the steady state current before the fault and the peak value after short circuit.

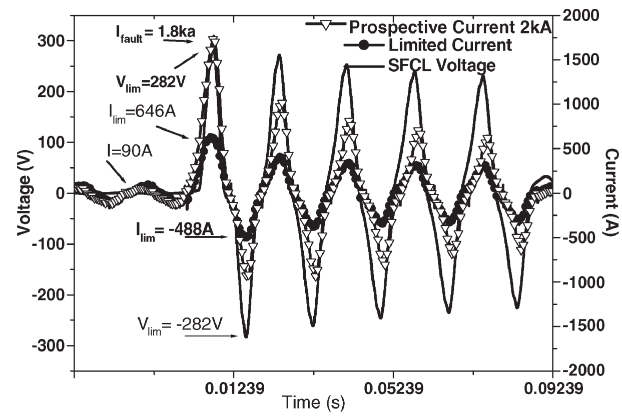

Fig. 4. Resistive SFCL waveforms during fault current test 2 kA–5 cycles.

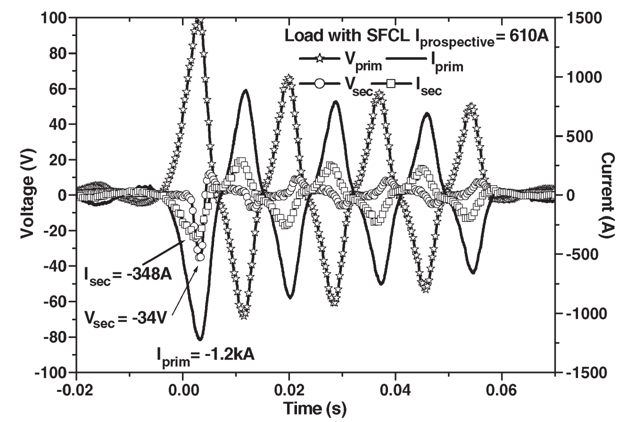

Fig. 5. Resistive SFCL waveforms during fault current test at 660V/0.6 kA load side.

The calibration current waveform, shown in Fig. 4, achieves the prospective fault current value of 1.8 kA_{peak} without any protection.

After the insertion of a resistive SFCL the fault current was limited by factor of 2.78 in 5 cycles, corresponding to a limited current value of 646 A_{peak}. The limitation process starts with a small ratio during 2 ms and the transition to the normal state grows up until the equivalent resistance reaches a design value of 1.86 Ω.

Using a step-up transformer the voltage value for the SFCL connected in series with the load was increased to 660 V. The corresponding waveforms were shown in Fig. 5. The prospective fault current reached 610 A, just after the SFCL insertion the current achieved 348 A, corresponding to a limiting factor of 1.75 with very low voltage developed within the SFCL, $V_{sec} = 34$ V when compared with the design value of 761 V.

D. Fault Current Test Using Short-Circuited Transformer With Superconducting Device

Using the electrical circuit shown in Fig. 3 with short-circuited transformer (2.5 kVA series type transformer) connected to a motor-generator line, the values of R_1 and R_2 were adjusted for steady current of 70 A and the prospective fault current of 1.2 kA without the superconducting device.

The Fig. 6 shows the combined SFCL waveforms with corresponding values indicated by the index "prim" related to the primary winding of the series transformer connected to the load. The voltage and the current in the superconducting device

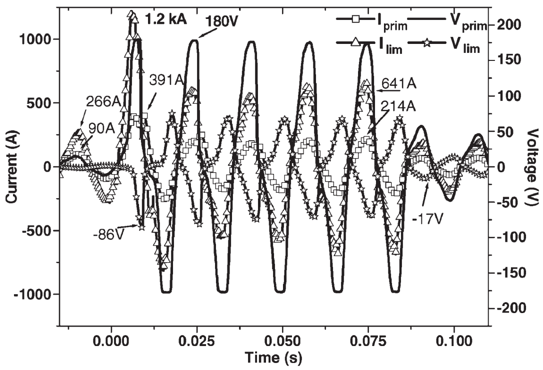

Fig. 6. Combined SFCL with series short-circuited transformer during the fault current test at 1.2 kA–5 cycles.

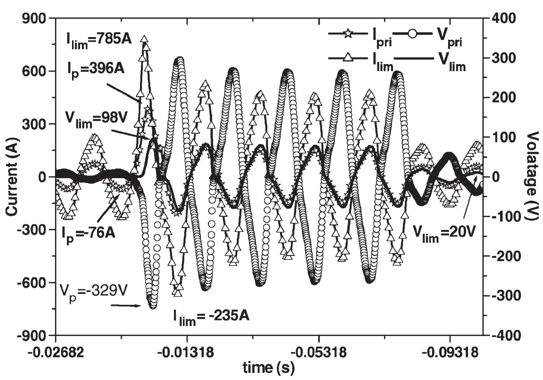

Fig. 7. Combined SFCL with toroidal coupling transformer during the fault current test at 0.8 kA–5 cycles.

are indicated by index "lim". The prospective fault current value (at primary side) reaches 1.2 kA and after 2 ms was limited to 391 A, corresponding to a limiting factor of 3.1 times. In the superconducting device the current was limited to 641 A by an equivalent resistance developed after transition corresponding to the voltage value of 86 V.

The combined SFCL $(\mathrm{MSD} + \text{transformer})$ with the short-circuited transformer constructed with a toroidal iron core coil was subjected to the fault current test. Fig. 7 shows the waveforms in the transformer primary side (load in series) with steady current 76 $\mathrm{A_{peak}}$ reached in the first peak after fault 785 $\mathrm{A_{peak}}$ and limited to 396 $\mathrm{A_{peak}}$ during the superconducting device quench, corresponding to a limiting factor of 2 times. The voltage is very low in the short-circuited transformer before the fault start. Right after the transition it reaches the maximum value 329 $\mathrm{V_{peak}}$ supplied by the motor-generator.

Considering the low winding volume in the short-circuited transformer the effect of subdivision of the secondary winding which covers the primary winding for reducing the reactance dispersion and consequently the transformer impedance was not observed. The measured current limitation ratio of 3 times is very low and the voltage level in the superconducting device achieved only 220 $\mathrm{V_{rms}}$ which is much lower than the designed value of 1 $\mathrm{kV_{rms}}$.

IV. Conclusion

The resistive SFCL performance using a modular superconducting device was tested without degradation in a 220 V line for a prospective fault current of 1.8 kA, achieving the limiting factor 2.78 for a limiting current of 646 A. To evaluate the resistive SFCL in a 660 V line a second test was carried out using a step up transformer and a prospective fault current of 610 A. The peak fault current was limited to 348 A, corresponding to a limiting factor of 1.75, with very low voltage developed within the superconducting device, $V_{\mathrm{sec}} = 34$ V as compared with the design value of 761 V. The current limitation effect by transition of superconductor to normal state was observed after 3 ms, when the voltage developed achieved 282 V, which corresponds to the electric field of 11 V/m. During the fault current limitation the power of 92 kW was released with the equivalent resistance reaching 0.43 Ω, which corresponds to 23% of the designed value of 1.86 Ω at 300 K. The SFCL voltage value was 282 V and the limited current value of 646 A was measured during 100 ms. The YBCO CC tapes used herein have a critical energy density with degradation observed when values reaches 1200 J/cm^3; the experimental value achieved 303 J/cm^3 during the test corresponding to less than 25% of the critical value.

The combined SFCL $(\mathrm{MSD} + \text{series transformer})$ tests were done under a prospective fault current value (at primary side) of 1.2 kA; after 2 ms was limited to 391 A, corresponding to a limiting factor of 3.1 times. In the superconducting device the current was limited to 641 A. The combined SFCL $(\mathrm{MSD} +$ toroidal transformer$)$ presented a prospective fault current value (at primary side) of 0.8 kA, limited to 396 A during the superconducting device quench, corresponding to a limiting factor of 2 times. Due to the low winding volume in the short-circuited transformer the effect of subdivision applied in the secondary winding to cover the primary winding for reducing the reactance dispersion and the total impedance were not observed in series or toroidal type transformers. The test results of the combined SFCL with short-circuited transformer showed undesirable influence of the transformer impedance, resulting in reduction of the fault current level.

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