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ORIGINAL PAPER

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

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Abstract A superconducting fault current limiter (SCFL) consisted of a transformer with low reactance connected to the power line and with the secondary winding short-circuited by a modular superconducting limiter device with 16 elements connected in series was constructed and tested. The designed coupling transformer has low dispersion reactance in order to limit the voltage drop in the power line within the range of 5 % to 10 %. The experimental results showed that an insertion of a 0.125 Ω resistance limited the peak current to a factor of 2.5 times of the unlimited current. The power dissipation reached 39 kW during 100 ms, with an energy density of 380 J/cm^3. Based on these results, the SCFL will be further tested in a 3 MVA (15 kV/380 V) generator for currents up to 10 kA.

Keywords Superconducting fault current limiter · YBCO coated conductor · YBCO recovery characteristics · Current limiting ratio

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1 Introduction

Resistive fault current limiters using a modular device of YBCO coated conductor are devices with electrical behavior to switch off fault very quickly or limiting the fault current by the insertion of fast transition impedance (reflected resistance on the secondary side) in the grid. Due to this property, the resistive superconducting fault current limiters (SFCL) is at present the most proper solution with technical and economical feasibility to reduce the fault current levels in electric power transmission line. In order to couple the superconducting modular device with the high voltage grid low impedance (low reactance), a power transformer was designed and constructed. The insertion of a SFCL can solve the existing problem of fault current overload associated with the power demand growth, the increasing of the decentralized power generation and the interconnection of the power grid. The SFCL can prevent damage to the circuit components within 50 ms being this time interval necessary for circuit breaker actuation.

The development of the SFCL with the potential to reduce the fault current levels by a factor of 3 to 10 times makes these devices an essential component of the future smart electric grid. The reduced impedance (without great change in the load-flow during the fault current limitation) turns it to be one of the most promising superconducting devices for application in power systems.

The YBCO-coated conductor (CC) tapes for SFCL applications using high resistivity matrix must provide good mechanical properties essential for winding large coils or for assembling a parallel arrangement [1] using several straight tapes per element. During the fault, the prospective current can achieve up to 20 times the critical current, I_c generating strong electromagnetic forces on the tapes, thus requiring the use of HTS tapes with stainless steel reinforcement.

Table 1 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
Iron core		
Cross-section area (cm^2)	52	105
Inner height/diameter (cm)	33	11
Inner width/thickness (cm)	11	7
Weight (kg)	48	42

Considering the architecture of the YBCO CC tape and the stabilizer thickness selected for each SFCL design, the limiting period has to be restricted to a time as short as possible enabling the device to quickly recover the superconducting state in order to avoid irreversible degradation. Thus, for reducing the recovery time an efficient cooling scheme should be carried out to expose the broad tape surface to the liquid nitrogen coolant. The advantage of using several parallel-arranged tapes elements with a large number of parallel tapes with both surfaces exposed to coolant in comparison with bifilar coils, in which the inner surface is in contact with a G10 former, is evident [2].

In this work, we report the results from the evaluation several types and sizes of coupling transformer operating with secondary side short-circuited by a modular superconducting device. The performance of modular SFCL using eight plates of G10 with four YBCO tapes each with 0.4 m-length electrically connected in parallel with a shunt protection per element, totaling 16 elements was previously reported [3]. This configuration provides a homogeneous quench behavior of the HTS tapes and acts as a stabilizer for the system [3–6]. The SFCL tests were done under AC currents varying from 1 to 5 cycles for prospective current values from 1 kA up to 7.4 kA with effective limitation by the SFCL to 700 A.

2 Coupling Transformer Parameters and Design

A transformer constructed with copper windings with a primary winding connected in series with the power line and a secondary winding short-circuited by a modular superconducting device was designed with low impedance. During normal operation, the transformer with the short-circuited secondary presents a low voltage drop. In the fault current conditions, the current increases in the secondary and the superconducting devices quenches when its critical value is reached. The larger resistance insert in the secondary windings reflected to the power line side (no-load impedance condition) limiting the fault current.

The basic idea was to use a series transformer and a toroidal transformer to couple the Modular Superconducting Device (low self-inductance) with the high voltage power line for acting as a hybrid fault current limiter. The short-circuited secondary 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 4 up to 10. All the designs were carried out using thermal characteristics of the current transformer in which the fault current can achieve 100 times the nominal current, I_n during 100 ms.

The coupling transformers are designed with reduced effective power (no-load conditions), wherein the power in the transformer (short-circuited secondary) reaches 5 % (1:20 ratio) for the main power transformer to protect against the fault current. To reduce the dispersion reactance, the transformer was constructed with two half-coils for the secondary winding, and one coil for the primary winding inserted in between for each iron core legs.

These winding configurations were used for a single-phase series transformer and toroidal transformer, with the main characteristics summarized in Table 1. The insulation was improved to support 15 kV as the same insulation class of the main transformer of 100 kVA connected to the load.

3 Modular Superconducting Device

The Modular superconducting device was designed using the *American Superconductor* YBCO CC 344S type with 4.4 mm-width, 0.15 mm thickness, and critical current of $I_c = 72 \pm 2$ A (equivalent to 163 A/cm-width). The substrate of this tape is Ni-5 %at.W and the linear resistance per length of the tape is 0.354 Ω/m. The electric field developed within the superconductor tape under safe condi-

Fig. 1 Modular SFCL constituted by 16 elements containing four YBCO

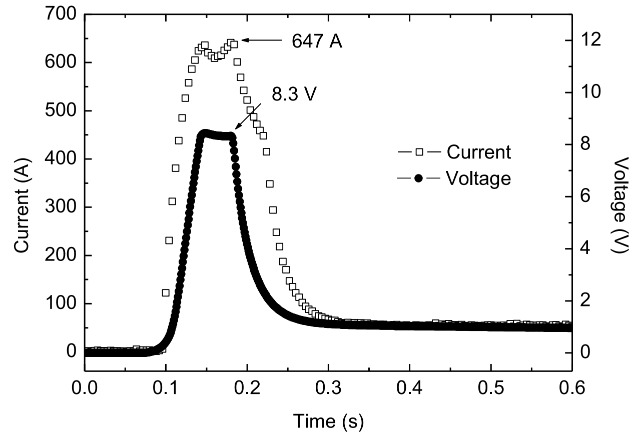

Fig. 2 Pulsed current test curve for a nominal 650 A peak

tions can reach 0.5 V/cm [5] with the shunt resistance of $R_{sh} = 180$ mΩ per element.

In the SFCL, design for a power grid is necessary to take into account the short transient time when the steady current above critical current could not induce quench. The current peak value under nonfault conditions must be evaluated to carry currents above I_c without quenching for a certain time. In our case, we use an external shunt resistor with a suitable resistance value for protecting the superconductor tape, and additionally as we can consider the stainless steel reinforcement performing the same function, this tolerance against transient results in conductor length reduction [6].

The modular SFCL (Fig. 1) for 220 V/300 A under steady condition is made of 16 elements each containing four 344S tapes 0.4 m-long in parallel association soldered at their ends on a copper bus bar with Sn–In alloy. The transition to the normal state occurs 2 ms after the start of fault current (phase angle, $\phi = 0°$) when the current peak was limited to 8 times I_c (2 kA).

During the operation, 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 of element, l and w are the conductor length and width, respectively, giving the nominal power of 55 kVA for this unit, corresponding to 48.8 V_{rms} A_{rms}/cm^2 for fault varying from 50 to 100 ms [4].

The dissipated energy is an important issue of coated conductor specifications for their use in SFCL, especially when it is considered in the design the limiting factor 10 for a prospective current of 7 kA. The equivalent resistance for the module can achieve $R = 473.3$ mΩ at 300 K and the power dissipation corresponds to 154 kW (SFCL voltage 220 V and limited current 700 A) during 100 ms; the energy density of about 922 J/cm^3 (77 %) is lower than the critical value of 1,200 J/cm^3, which corresponds to an energy density sufficient for reaching the melting temperature of solder [5].

4 Electrical Performance

4.1 Modular Superconducting Device Characterization

For evaluating the resistance growth and the recovery time, a test was done using a pulsed current of amplitude of one up to 2.5 times I_c with 0.1 s duration, followed right after by applying a lower current value equivalent to a 20 % I_c. The test results are presented in Fig. 2.

In the pulse current curve shown in Fig. 2, the voltage reached 8.3 V for 650 A, corresponding to a resistance value of $R = 12.8$ mΩ and a recovery time lower than 2 s, while the steady current was maintained at 60 A.

The fault current test for modular device was carried out using 3 MVA—15 kV/380 V transformers where the SFCL was connected between phase to ground (220 V—60 Hz line). The test results are summarized in Table 2.

Figure 3 shows the calibration current waveform for the fault current of 7.4 kA_{rms} without SFCL. With this device, the current limiting process starts with a small ratio before 2 ms and the transition to the normal state grows up until a limiting value reaches a factor of 10.6 in 5 cycles.

4.2 SFCL Characterization

As a preliminary step of field test, the SFCL constructed with a coupling transformer and the modular superconducting device was connected in series between phase to ground of 96 kVA motor-generator terminal to supply energy for resistive load (Y-connection) with a steady *rms* current of 70 A. The load was short-circuited (one phase) using a static switch with adjustable time to operate from 1 to 5 cycles.

Table 2 Summary of applied fault current tests

Prospective fault current (kA_{rms})	Limited current (A_{rms})	SFCL voltage (V_{rms})	Voltage per element (V_{rms})
0.8	506	87	74.9
1.0	552	113	5.9
2.0	618	153	8.0
3.4	634	176	9.9
4.2	673	187	10.5
5.7	673	194	11.0
6.2	692	201	11.3
7.0	696	203	11.5
7.4	695	202	11.4

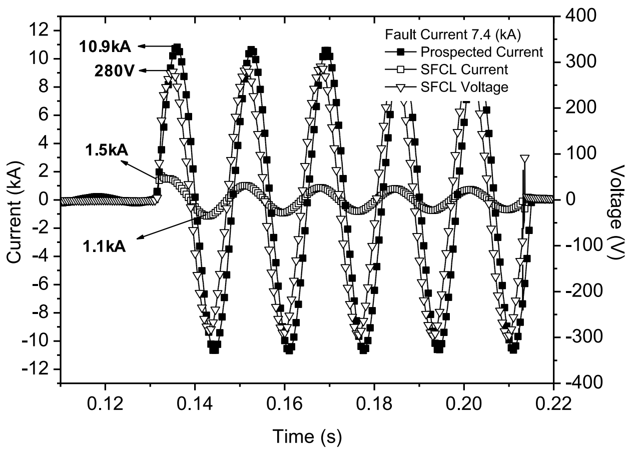

Fig. 3 Modular SFCL waveforms during fault current test: 7.4 kA—5 cycles

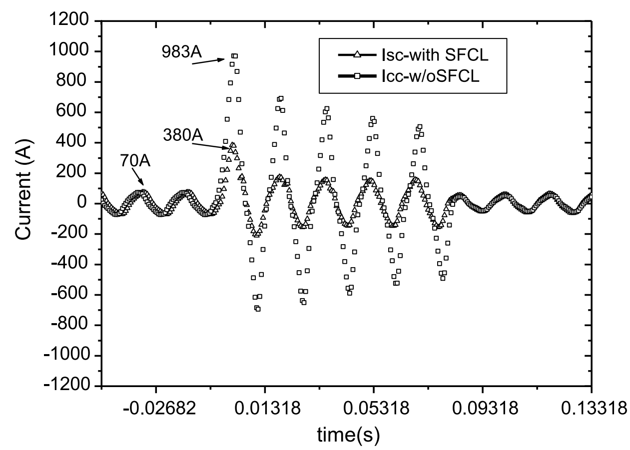

Fig. 4 Fault current test for 5 cycles without and with SFCL

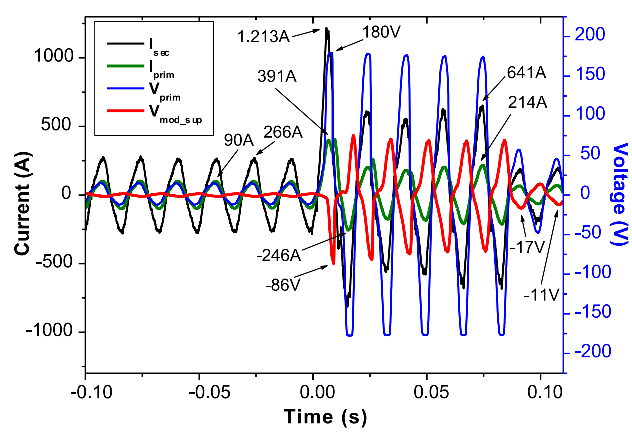

Fig. 5 Current and voltages waveforms during 5 cycles fault current test

Figure 4 shows the waveforms for the fault current without and with SFCL using as coupling series transformer of 2.5 kVA. The transition and the recovery process were completed before 4 ms under steady continuous current of 63 A_{rms}. The prospective fault current of 983 A after few milliseconds was limited to 380 A corresponding to limiting factor of 2.6.

The voltages and current waveforms during the fault current in the line (primary winding) and in the modular superconducting device (secondary winding) are presented in Fig. 5. In the line with steady current of 70 A, the fault current was limited to 391 A in the first peak and 214 A after 4 cycles. The voltage in the superconducting device reached 86 V and just after the fault was extinguished one can observe the recovery process under load the voltage is reduced to 17 V.

Figure 6 shows the current and voltages waveform for the fault current test using the toroidal coupling transformer of 5 kVA with SFCL. For steady current of 50 A, the prospective fault current reached 983 A (without SFCL) and with this device the current was limited to 396 A, corresponding to a limiting factor of 2.5. The maximum voltage in the modular superconducting device achieved 98 V when the primary winding voltage value reached 329 V.

The resulting resistance inserted within the circuit during the transition to the normal state for the SFCL showed that

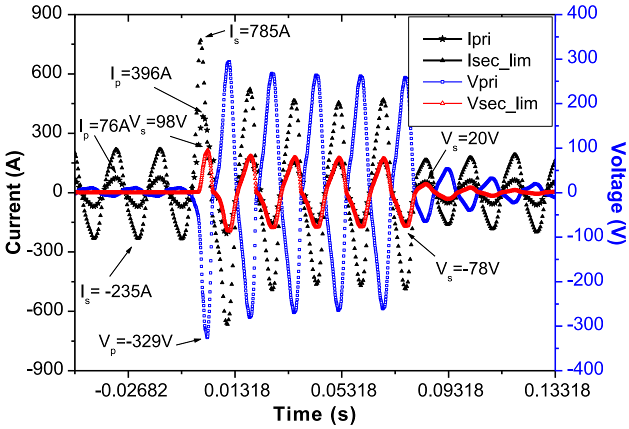

Fig. 6 SFCL tests using toroidal coupling transformer: current and voltages waveforms during 5 cycles fault current test

the limit value was achieved for a prospective current higher than 1 kA, reaching 0.125 Ω, which is equivalent to 26 % of the designed value with large margin to increase the limiting factor for higher fault current value. This resistance was reflected to primary side multiplied by 9 (turn ratio square) corresponding to 1.125 Ω.

5 Conclusion

The performance of a resistive SFCL using a modular superconducting device consisting of 16 elements were confirmed to act without degradation in a 220 V line for a prospective fault current of 1 kA, limiting the current to symmetric equivalent value of 396 A, which corresponds to a factor of 2.5 times.

The resulting resistance inserted in the circuit during the SFCL transition to normal state shows that the limit value was not achieved for prospective current of 1 kA reaching 0.125 Ω which is equivalent to 26 % of designed value (473.3 mΩ at 300 K). The power dissipation by Joule effect corresponds to 39 kW (SFCL voltage 98 V and limited current value 785 A) during 100 ms, with the energy density of about 380 J/cm^3 (32 %) lower than the critical value of 1200 J/cm^3.

The performance of the hybrid SFCL the modular superconducting device during the preliminary fault current test showed lower limiting factor as a function of low prospective fault current available in our facilities. Complementary field tests will be carried out using a 3 MVA—15 kV/380 V transformers in order to evaluate the critical designed parameters and determining the allowed value for the fault current without any degradation of superconducting device.

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