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Development and test of resistive superconducting fault current limiter; acting time and its recovery conditions.

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Abstract. Resistive-type of superconducting fault current limiters (RSFCL) have been developed for medium voltage class aiming to operate at 1 MVA power capacity and short time recovery (< 2 s). A RSFCL in form of superconducting modular device was designed and constructed using 50 m-length of YBCO coated conductor tapes for operation under 1 kV / 1 kA and acting time of 0.1 s. In order to increase the acting time the RSFCL was combined with an air-core reactor in parallel to increase the fault limiting time up to 1 s. The tests determined the electrical and thermal characteristics of the combined resistive/inductive protection unit. The combined fault current limiter reached a limiting current of 583 A, corresponding to a limiting factor of 3.3 times within an acting time of up to 1 s.

1. Introduction

Superconducting fault current limiters (SFCLs) are current limiting devices which present advantages of very low losses in steady state operation, high limiting impedance under fault conditions, reliable operation, very short reaction times to fault currents and an automatic response feature without the requirement of an external trigger mechanism. The resistive SFCLs present the electrical behavior near the ideal such as low impedance under steady operation and fast actuation. Nevertheless under the fault condition the maximum allowed electrical field, E = 50 V/m must be obeyed in order to withstand the critical current degradation [1-3]. The RSCFL actuation is attained with the insertion of a fast transition resistance of 0.354 Ω/m during 5 cycles, thus limiting the fault current value up to 100 ms.

In order to increase the acting time during a fault current event, a resistive SFCL was combined with a magnetic circuit using a short-circuited transformer with saturated core to analyze the coupling effect with the grid line [4]. More recently, a resistive SFCL was tested using an air-core reactor connected in parallel, but with the superconducting device acting only during the first 100 ms, being them disconnected by a circuit breaker, leaving only the air-core reactor limiting the current up to a total elapsed time of 1 s [5].

In the design of superconducting devices several restrictions must be taken into account for the thermal and electrical protection, such as the maximum allowable electrical field and the energy loss per volume, respectively E = 50 V/m and 1,200 J/cm^3 for the YBCO CC tape [5]. For the medium voltage class applications using the maximum electrical field, continuous long lengths of YBCO CC tapes are needed (e.g., for 15 kV it will need 300 m/phase). Also in the SFCL design several modular units should be considered in a series and/or parallel electric connection arrangements. The modular units permit to adjust the maximum current and voltage during limiting time, usually less than 100 ms, to a recovery under load using an external shunt protection. Fast and safe operation of the SFCL can prevent damage to the circuit components after 50 ms before circuit breaker actuation without air-core reactor and 1 s with it connected in parallel. The combined SFCL has the potential to reduce the fault current level by a factor of 3 to 10 times turning them into an potential candidate of the future smart electric grid.

The architecture of the commercial YBCO CC tapes, such as stabilizer thickness, high resistivity substrate and use of stainless steel tape as reinforcement, with a linear electric resistance of 0.354Ω /m, requires the pulsed current-voltage (I-V) measurements using short samples for determining the peak current limiting period, the maximum allowable temperature of 350 K and the recovery time from full normal state transition without any irreversible tape degradation. An efficient cooling scheme should also be considered to expose the broad tape surface to the liquid nitrogen coolant; in this condition the maximum allowed power dissipation per surface area is 32 W/cm^2 [6].

In this work, a modular SFCL was built using 2 x 25 m length of YBCO CC tapes in parallel, with a shunt protection with equivalent resistance R_{sh} = 0.078 Ω per sector, or R_{eq} = 1.86 Ω for the whole modular device with 24 sectors, without electrical joints (Fig. 1). This configuration provides a homogeneous quench behavior of the HTS tapes, with a copper contact in each 20 cm-length of YBCO CC tapes, working as a thermal sink (barrier) thus contributing for limit ing the maximum temperature within the tape (reducing the length to recovery) and acting as stabilizer in the device for decreasing the recovery time.

2. FCL design

The SFCL was constructed using the 344S type American Superconductor's YBCO CC tape (stainless steel tape reinforcement) with 4.4 mm-width, 0.15 mm thickness, and critical current, I_c = 72±2 A (equivalent to 163 A/cm-width). A short sample test was carried out for the I-V curve characterization applying the peak current value under non-fault condition to carry currents above I_c without quenching during 0.1 s; the current peak was limited to 2.5 times I_c.

The geometry of the modular superconducting device (Fig. 1) aims to expose all the surface of YBCO CC tape to the coolant with a pair of straight and parallel tapes wound on G10 tube and soldered at their ends to the 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.

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]. The power dissipation can achieve 73.3 kW (SFCL voltage 256 V and limited current 573 A) during 100 ms; the energy density of about 488 J/cm^3 is lower than the critical value of 1,200 J/cm^3 for YBCO tapes [6].

3. Electrical performance

3.1. Pulsed Current Characterization

A controlled DC power supply (10V/1000A) was used to characterize the stack with 2 x 344SS (I_c=72A each) in parallel tapes (0.1 m-length) soldered with Sn-In alloy, and protected by a shunt resistance R_{sh}= 0,17Ω/m. The test was carried out applying pulsed current during 100 ms up to a maximum value of 350 A, and a maximum electric field, E = 1 V/cm. During the transition and the recovery process for current I = 310 A, the elapsed time to recovery the superconducting properties is lower than 1 s, under load steady current of 144A. From the *E-t* curve (Fig. 2) the power loss can be determined at the maximum value for I = 310 A (I_{peak} =500 A) when reaches 700 W or 109 W/cm^2, corresponding to the energy density 1,548 J/cm^3 (774 J/cm^3 per tape).

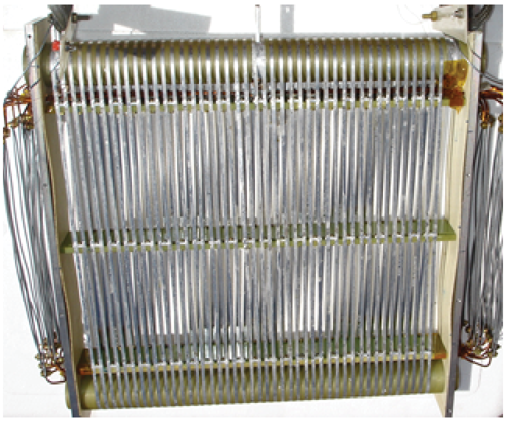

Fig. 1. Modular superconducting device constituted by 24 turns of a pair of YBCO CC tapes in parallel.

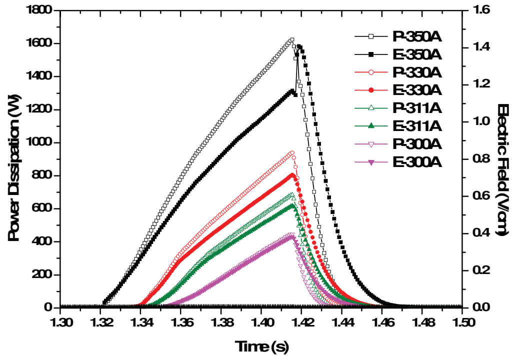

Fig. 2. Power loss and electric field as function of time and applied current peak.

3.2 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. The fault is induced when a resistive load (Y-connection) is short-circuited (single phase) using a fast static switch. The electrical circuit for testing was presented elsewhere [7].

The prospective fault current with this configuration can reach 1.9 kA with adjustable time to operate from 1 to 5 cycles. Fig. 3 shows the prospective fault current reaching 1.9 kA, after 2 ms the SFCL acts for limiting the current to 573 A, corresponding to a limiting factor of 3.3 for the first peak and 6.9 for the fifth peak. The measured voltage in the SFCL was low, V_{lim} = 256 V, when compared with the design value of 761 V, indicating that transition happens only in part of superconducting tape length. Fig. 4 shows the equivalent resistance increasing in RSFCL after transition (partial length) for the normal conductor reaching 0.9 Ω compared with the designed value of 1.86 Ω.

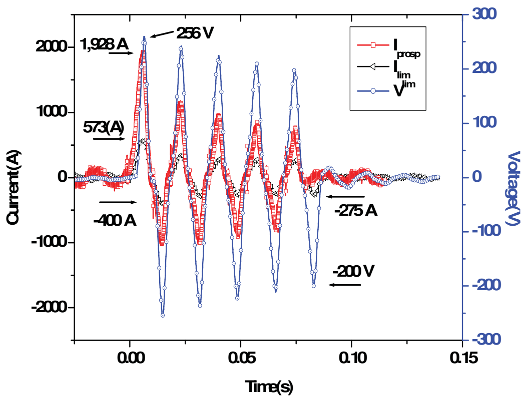

Fig. 3. Prospective fault current of 1.9 kA limited to 573 A with maximum voltage of 256 V

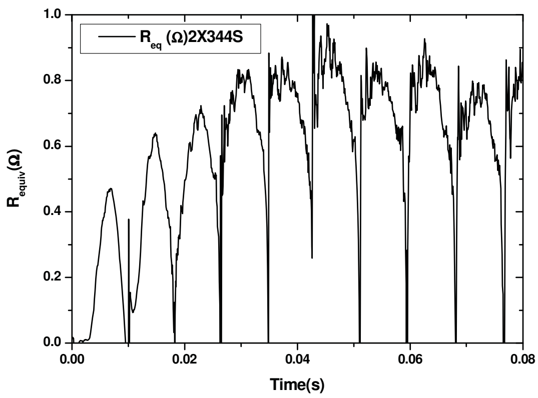

Fig. 4. Equivalent resistance of SFCL

3.3 Fault Current Test using Superconducting Device in parallel with an Air Core Reactor.

The basic concept for combining a magnetic circuit with the modular superconducting device is to get some benefits such as increasing the acting time to 1 s. Compared with the operation of conventional air-core reactors the advantages are the reduction of the Joule losses during steady current operation, because the current flows through superconducting device, and the reduction of the recovery time of the air-core reactor from several hours to several minutes.

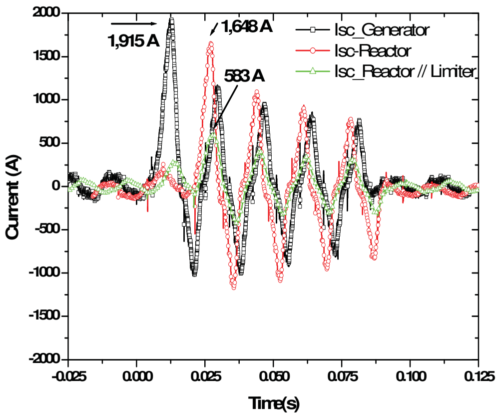

Fig. 5. Fault current values with and without the SFCL in parallel to the air-core reactor

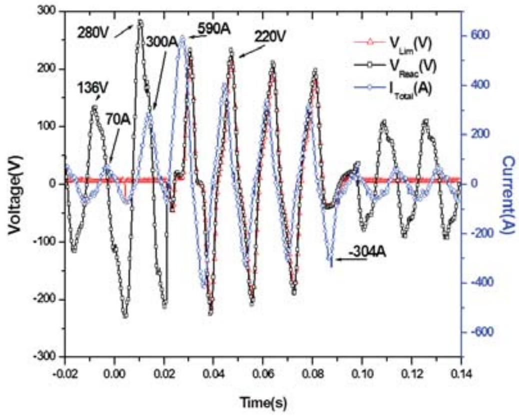

Fig. 6. Voltage and current waveforms for the SFCL in parallel to the air-core reactor

The current waveforms showed in Fig. 5 are the prospective fault current, the limited current by the air-core reactor and combined effect of SFCL with the air-core reactor connected in parallel. Together they can limit the prospective fault current value from 1.9 kA to 583 A. The waveforms showed in Fig. 6 present the voltages within the reactor and in the superconducting module acting together to limit the fault current value by a factor of 3.3. During next fault current test the limited current values reaches 590 A in the first peak and 304 A in the fifth peak, with very low voltage developed within the RSFCL, V_{lim} = 230V when compared with the design value of 761 V.

After measuring the voltage in each sector the results showed that the transition occurred in all of the 24 sectors, what suggests that all of them have the same characteristics and similar critical current values. The total electrical field per element is 0.12 V/cm.

4. Conclusions

The performance of resistive model of SFCL built with 344S YBCO tapes confirmed the limiting of the prospective fault current peak from 1.9 kA down to 583 A, acting just after 2 ms. The limiting factor was of 3.3 (first peak) and 6.9 (fifth peak). The maximum voltage measured in the SFCL reached 256 V (E= 10.2V/m) being a low value compared to the design value of 761 V, indicating partial transition of the YBCO tape length. The combined device with SFCL in parallel with the air-core reactor, to enhance the acting time from 0.1 s to 1 s, were tested and the result showed the limiting factor measured during the fault current test was 3.3 times, using an air core reactor with X/R= 33.46 (L=4.58 mH, X = 1.73 Ω). The equivalent impedance during 5 cycles when became fully resistive, reached |Z| = 0.87 Ω. The test results of the combined SFCL with the air-core reactor presented increased acting time concomitant with the reduction of the fault current level.

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