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Short-Circuit Tests and Simulations With a SCFCL Modular Assembly

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Abstract

Short-circuit tests and simulations carried out with a resistive SCFCL modular assembly are presented. Each SCFCL module consists of a BSCCO 2212 bulk coil with a critical current of about 520 A at 77 K. Series and parallel connection were tested. In series connection, prospective current as high as 67 kA_{rms} was limited to about 11 kA_{peak} in the first peak. In parallel connection, prospective current as high as 65 kA_{rms} was limited to about 20 kA_{peak} in the first peak. Low fault current tests were also carried out (current peaks of about $3I_c$) and in this case the SCFCL module takes more time to actuate, being considered satisfactory for "inrush" currents. Computational simulations were done considering the bulk coil E-J curve and heat transfers between SCFCL components and the LN_2 bath. The simulations can reasonably predict the performance of the SCFCL assembly and provide additional information such as the temperature rise of superconductor and shunt.

Keywords: Superconducting Fault Current Limiter \ Short-Circuit Tests \ BSCCO-2212

1. Introduction

Due to increase of levels of fault currents around the world because of growing consumption of electricity, interconnection of generation and transmission systems and insertion of power plants unforeseen under the original plan, the use of fault current limiters in electrical systems has become more frequent in recent years.

Among the fault current devices in study, superconducting fault current limiters (SCFCL) are one of the most promising due to their characteristics: does not need to be replaced after a short-circuit, presents low impedance under normal conditions and does not require any sensor or actuation system (self triggering). There are several types of SCFCLs. The resistive type is the most studied nowadays, due to its relative simplicity, low inductance and size.

In this paper we investigate the behavior of these devices when subjected to high and low fault currents. The term low faults describes peaks of fault currents that are only about three times the value I_c of the components used. How we will see, the time of transition from superconducting state to normal state of such devices depends on the level of the fault current. The low fault current test aimed to show how the SCFCL would react in the presence of an insrush current.

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The tests were performed with 12 modules manufactured by Nexans Superconductors GmbH (MCP-BSCCO-2212). These modules have a CuNi alloy soldered throughout their whole length, which acts as a shunt resistor, to avoid hot spots during the transition from superconducting to normal state (quenching) [1]. The total length of a single component is 270 cm and the transversal section area of the superconducting material is 0.534 cm^2. The components were tested in series and parallel connection.

A simple computational method was developed to simulate the behavior of these devices allowing the assessment of the temperature rise during a short-circuit. The temperature rise is a hard parameter to measure and the simulation of this parameter helps us to predict the final temperature of the components.

2. Procedures

2.1. Tests

The twelve SCFCL components were cooled in a liquid nitrogen bath (77 K) in the High Current Laboratory of ELETROBRAS CEPEL (Electric Power Research Center) and subjected to short-circuits tests. The test circuit is composed of impedances that controls the value of the prospective fault current (without the SCFCL) and transformers that controls the voltage of circuit. A better description of test circuit can be found in [2]. In table 1, we summarize the main characteristics of three tests performed (*T1*, *T2* and *T3*).

Table 1. Short-Circuit Test Parameters

Test	Fault Current (kA_{rms})	Voltage (kV_{rms})	Connection	Branches	Fault Duration (s)
T1	67	1.0	Series	1×12	0.08
T2	65	0.5	Parallel	2×6	0.08
T3	1.2	0.135	Single Component	1×1	2.0

The peak values of fault current does not correspond to *rms* value $\times \sqrt{2}$, since the prospective currents are not symmetric. *T3* corresponds to the low fault test, carried out to study the slow transition from superconducting to normal state of these devices when subjected to currents in order of $3I_c$ (I_c = 526 A).

2.2. Computational Simulations

The computational simulations were made considering the heat exchange of SCFCL with N_2 bath in order to approximate our simulations to a more realistic condition. We consider a uniformly heating of superconducting material and shunt resistance along their lenght [3]. The following equations (1, 2 and 3) describes the termal behavior of model.

$$\rho c\left(T_{sp}\right)\frac{dT_{sp}}{dt} = EJ - Q_2 - Q_1 \tag{1}$$

$$Q_1 = h_1 A_1 \left(T_{sh} - 77\right) \tag{2}$$

$$Q_2 = \frac{h_2 A_2}{C_2}\left(T_{sp} - T_{sh}\right) \tag{3}$$

In 1 - 3, T_{sp} is the temperature of superconducting material (K), T_{sh} is the temperature of shunt resistance (K), Q_1 is the rate of convective heat transfer between the shunt resistance and liquid nitrogen, Q_1 is the rate of conduction heat transfer between the superconducting material and the shunt resistance, A_1 is the surface area of shunt for convective heat transfer, h_1 is convective heat transfer coefficient (0.02 W/cm^2K), h_2 is the conduction heat transfer coefficient (5.0×10^{-4} W/cmK), A_2 is the surface area of solder between BSCCO 2212 and shunt, C_2 is the solder thickness between BSCCO 2212 and shunt (0.2 mm), ρ is the volumetric density (6.0 g/cm^3) and $c(T_{sp})$ is the specific heat (J/kgK) of the superconducting material.

The simulations are done considering the superconducting material as a variable resistor, according with E-J curve described in [4], connected in parallel with the shunt resistance. A linear dependence of critical current J_c density on temperature T_{sp} of BSCCO 2212 was also taken in account [5]. In normal state, the resistance of a single limiter module was modeled according with the linear behavior of BSCCO 2212 above its onset critical temperature T_c (104 K) [6] obtained from a experimental resistance × temperature curve. A homogeneous T_c distribution is assumed in our simulation model. All simulations were developed using the Alternative Transient Program (ATP) version of EMTP and ATPDraw for Windows via MODELS language.

3. Results and Discussion

In Fig. 1 we observe the results of short circuit tests performed in CEPEL's High Current Lab. For the test *T1* the first current peak without SCFCL of 98.8 kA_{peak} was limited to 11.0 kA_{peak} with the SCFCL assembly in series connection. The subsequent current peaks are about 3.15 kA_{peak}. In the test *T2* the first current peak without SCFCL of 109.9_{peak} kA was limited to 20.6_{peak} kA with the SCFCL assembly in parallel connection. The subsequent current peaks are about 6.6 kA_{peak}.

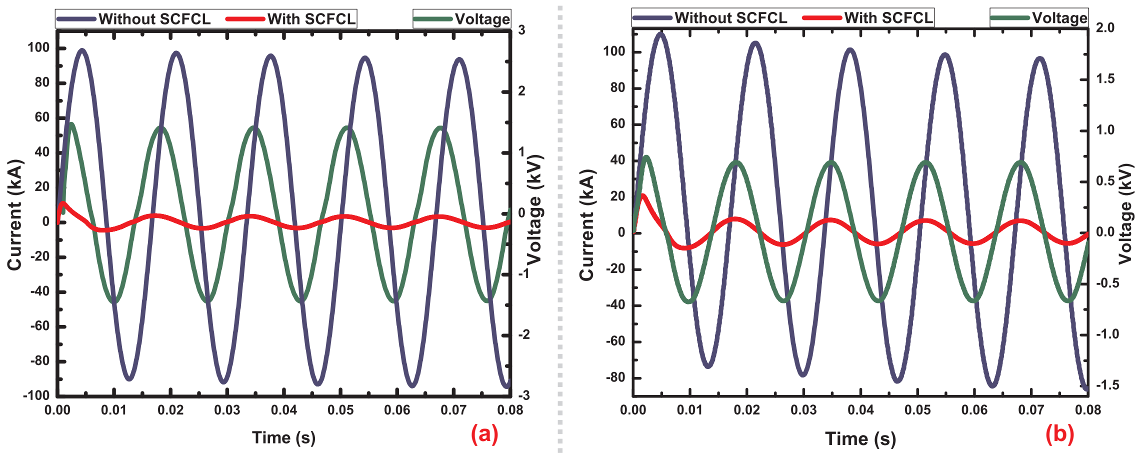

Figure 1. Tests results; comparison between prospective current and limited current for a) Series connection (*T1*) with prospective current = 67.0 kA_{rms} subjected to 1.0 kV_{rms} and b) Paralell connection (*T2*) with prospective current = 65.0 kA_{rms} subjected to 0.5 kV_{rms}.

These behaviors suggests that the transition from superconducting to normal state occurs in the first cycle of current once after that, the current remains in a quasi "steady-state" regime. This can be explained of following way: after transition of superconductor material, its resistance becomes much higher than resistance of CuNi metal (shunt). Because they are soldered one in another, the current flows almost completely in the shunt.

Figures 2 and 3 show experimental results of limited current and voltage compared with the respective simulated results for *T1* and *T2* respectively. In both simulations (*T1* and *T2*) we observe a sudden change in the second peak of simulated limited currents with a correspondent voltage spike occurring at the same instant. These differences between calculated and measured data probably came from the sharp superconducting-normal transition in the simulation which did not happen in the measurement, since magnetic fields were not taken into account in our model and the superconducting material was approximated to a single homogeneous material. In fact there are intrinsic heterogeneities that lead to changes in the value of T_c along the superconductor material. In addition, a homogeneous distribution of temperature upon quenching was also assumed, but the temperature may vary in function of the position in the bulk.

From these simulations we can also estimate the temperature rise of the BSCCO 2212 and CuNi shunt during the tests, as shown in figure 4. We note, a fast heating of BSCCO 2212 during the transition from superconducting to normal state in both curves. After the transition of BSCCO material, the temperature rises smoothly because the current flows almost entirely through the shunt. For this reason, the temperature of shunt is higher than temperature of superconductor material at the end of tests.

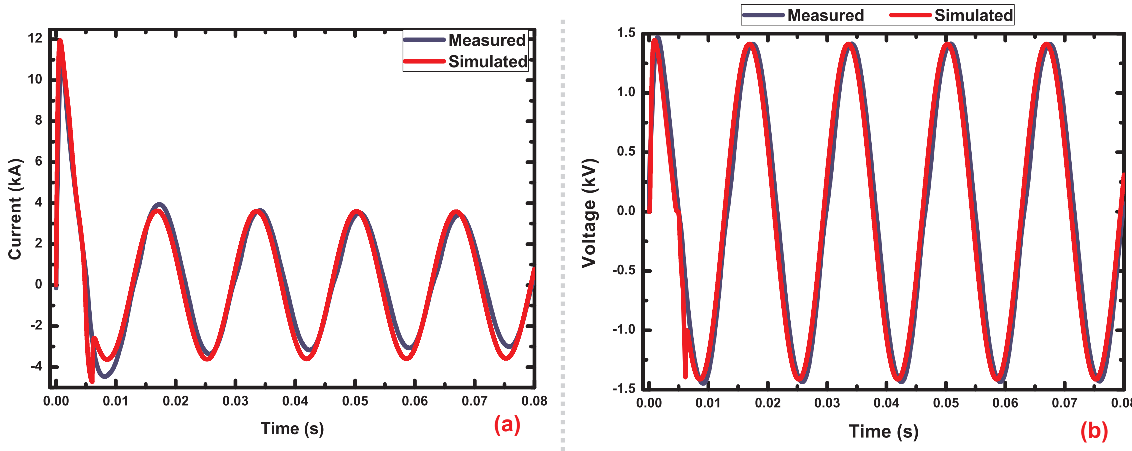

Figure 2. Comparison between measured and simulated results of limited current and voltage across SCFCL assembly. Fault current: 67.0 kA_{rms}, subjected to 1.0 kV_{rms} (*T1* - series connection)

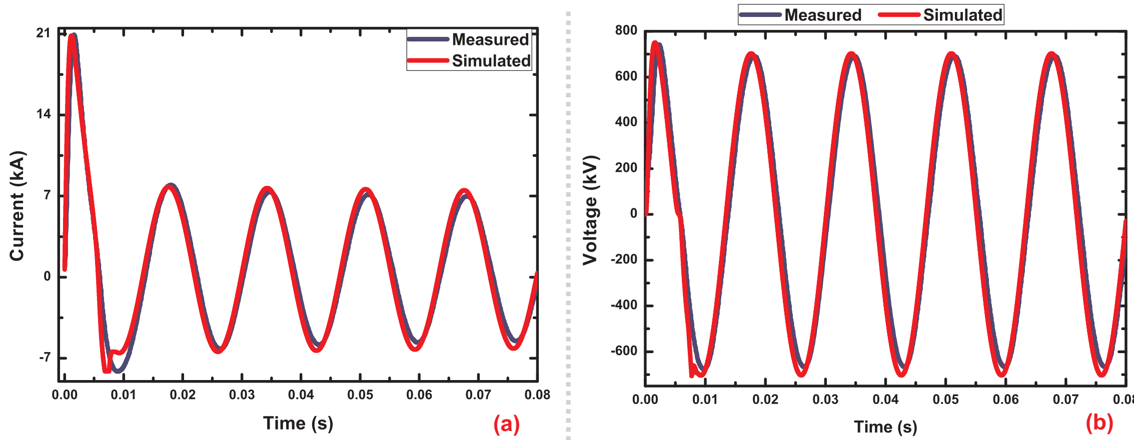

Figure 3. Comparison between measured and simulated results of limited current and voltage across SCFCL assembly. Fault current: 65.0 kA_{rms} subjected to 0.5 kV_{rms} (*T2* - parallel connection).

The temperatures of shunt and BSCCO reaches high values on test *T2* because of parallel connection, once in this kind of connection, higher currents flows in each limiter module than in series connection (*T1*), as we can observe in figures 2 (a) and 3 (a).

The results of low fault test *T3* can be observed in figures 5 and 6. In the figure 5 (a) we show the first 0.3 second of test and observe that the SCFCL does not actuate, once there is no much difference between currents of circuit with and without the SCFCL module. Figure 5 (b) shows the voltage across the SCFCL terminals and confirms the idea that the superconductor material still does not develop a considerable resistance because the voltage is lower than 2.5 V_{peak}. This voltage rises due the resistance contact of SCFCL module with the circuit.

However, the resistance of superconductor material starts to develop on the time once the current peak of circuit is about $3I_c$. In the figure 6 (a) we observe differences on current peaks of circuit with and without the SCFCL module in last 0.3 second of test (between 1.7s and 2.0s). Due the development of resistance of SCFCL module, the voltage across its terminals rise as showed in figure 6 (b). This voltage does not reach values higher than 20 V what indicates that BSCCO 2212 material is just initiating the transition to the normal state.

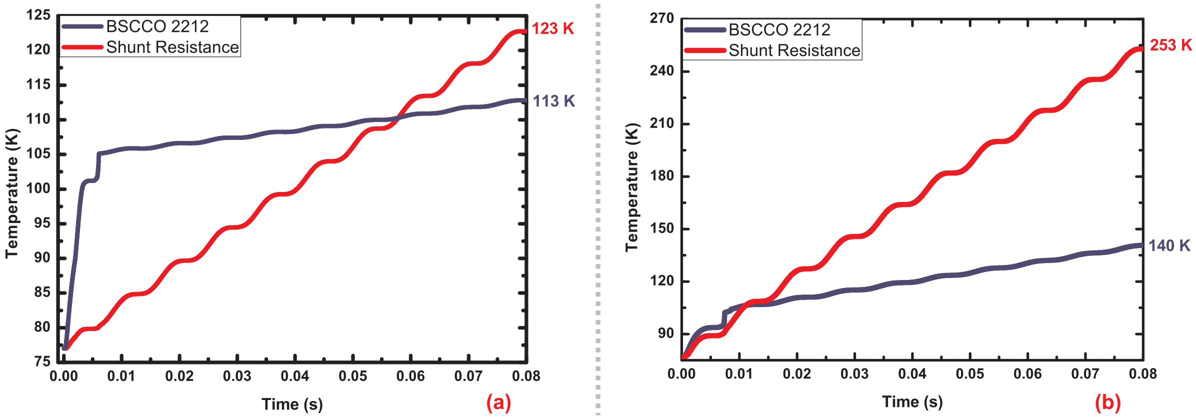

Figure 4. Temperature rise during short-circuit for a) Test *T1* - series connection and b) Test *T2* - parallel connection.

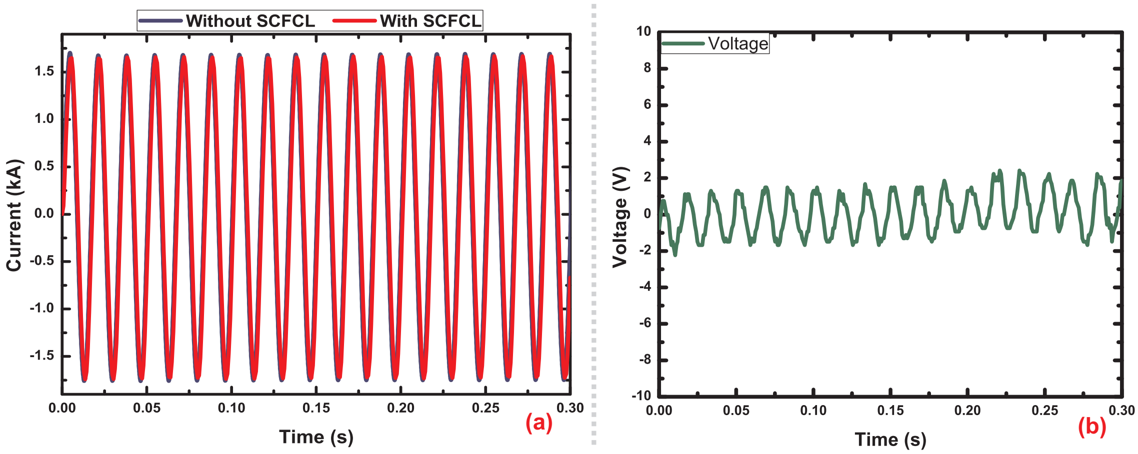

Figure 5. Result of *T3* in the first 0.3 seconds: a) The current of circuit with and without the SCFCL and b) Voltage across the SCFCL module.

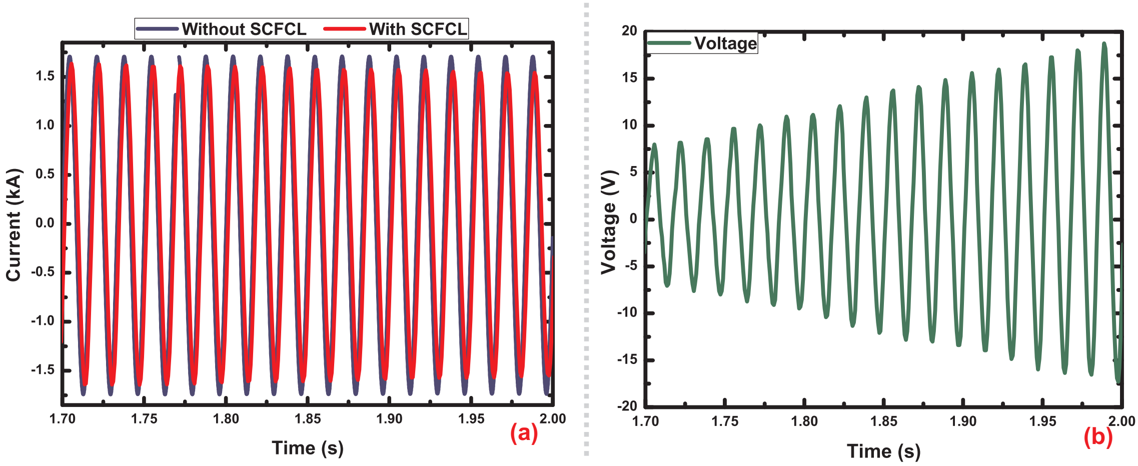

Figure 6. Result of *T3* in the last 0.3 seconds: a) Comparison current of circuit with and without the SCFCL and b) Voltage across the SCFCL module

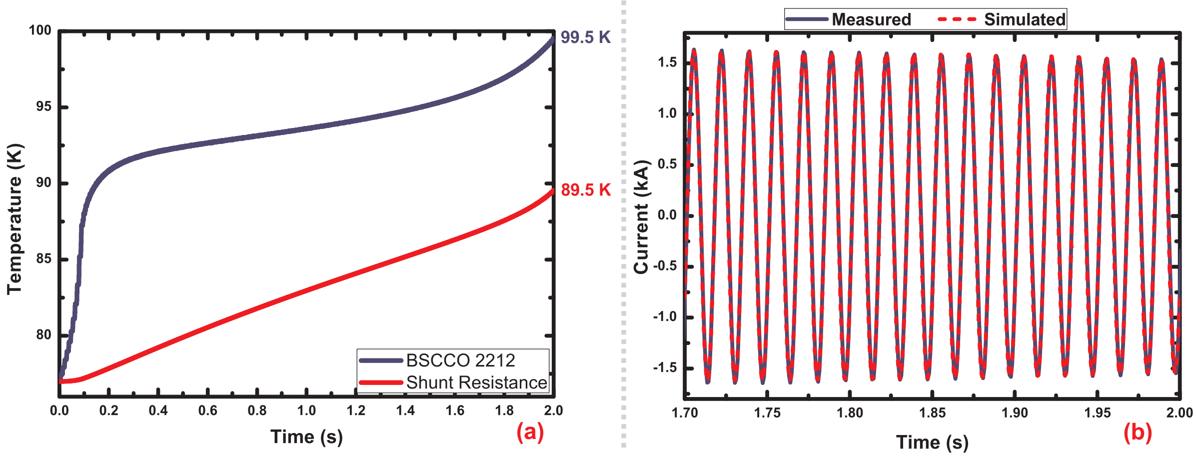

Figure 7. Results for Test *T3*, a)Temperature rise during low fault test and b) Comparison between measured and simulated currents.

The simulation model was used to estimate the temperature rise during test *T3*, as we can observe in figure 7 (a). This simulation result show us that the BSCCO 2212 does not really transited to normal state once the final temperature 99.5 K was lower than its onset critical temperature T_c (104 K). Figure 7 (b) show us the comparison between measured current and simulated current for the time between 1.7 s and 2.0 s on test *T3*. The simulation result agrees well with the measured current.

4. Conclusions

This work aimed to study the behavior of a resistive SCFCL, by simulating and testing SCFCL BSCCO 2212 components when subjected to high and low fault current levels. According to test and simulation results, we conclude that these devices can be considered effective for protecting circuits against problems caused by raising short circuit current levels, since they limited fault currents of about 65 kA_{rms} and 67 kA_{rms} to 11 kA_{peak} and 20 kA_{peak} at first peak. We also conclude from test *T3* that at low faults the superconductor material of these components takes more time to develop a considerable resistance value and might not move to normal state. This result can be considered satisfactory for ”inrush” currents, when the SCFCL should not actuate.

Although our simulations presented some differences in comparison to experimental results, we can consider the algorithm satisfactory for practical purposes. The simulation method developed in the present work can be further improved, by considering heterogeneous temperature and T_c distributions, as well as by including the effect of the magnetic field.

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