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Development and Test of a Small Resistive Fault Current Limiting Device Based on Hg, Re-1223 and Sm-123 Ceramics

Carlos Augusto Cardoso Passos[a*], *Valdi Antonio Rodrigues*[a], *Juliana Nunes Oliveira Pinto*[a]

Vinícius Toneto Abilio[a], *Gabriel Mouzela Silva*[a], *Luiz Carlos Machado*[b], *Ian Pompermayer Machado*[b],

Antonio Augusto Lopes Marins[b], *Leonnam Gotardo Merízio*[b],

Paulo Cesar Martins da Cruz[a], *Emanuel José Bassani Muri*[b]

[a]*Department of Physics, University Federal of Espírito Santo - UFES, CEP 29060-900,*
Vitória, ES, Brazil
[b]*Department of Chemistry, University Federal of Espírito Santo - UFES, CEP 29060-900,*
Vitória, ES, Brazil

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Several reports describing Superconducting Fault Current Limiter (SFCL) containing members of the bismuth or yttrium ceramics were already described. However, none of these included the mercury and samarium cuprates. Consequently, we have conducted a study of a resistive-type superconductor fault current limiter based on $Hg_{0.82}Re_{0.18}Ba_2Ca_2Cu_3O_{8+d}$ samples and $SmBa_2Cu_3O_{7-d}$ ceramics. All polycrystalline samples were prepared by solid-state reaction method using commercial oxide and carbonate powders. The superconducting ceramic with 2.4 × 2.6 × 6.0 mm^3 dimensions was set up such that the electrical current flew through the area of 2.6 × 6.0 mm^2. All measurements were done at 77K and without applied magnetic field ($H_{app} = 0$). In the case mercury sample, the fault current of 16.1 A_{peak} was reduced to 8.1 A_{peak} by the superconducting element and sustained for 100 ms. The prospective/limited of current ratio observed in this experiment was ~ 2.0, as considered a 2.4 mm pellet thickness. When the test was realized with the samarium sample, the prospective/limited current ratio observed was approximately 1.2, for same ceramic thickness. The tests confirmed the capability of the resistive type SFCL to limit the fault current. These results open the possibility of future investigations into SFCL devices based on those superconducting ceramics in low power electronics and electrical motor.

Keywords: *High-Tc, Hg,Re-1223, Sm-123, protective device, fault current limiter*

1. Introduction

In modern electrical system, the unwelcome electrical failures are day-to-day increasing due to electrical discharge, pulse electromagnetic, complexity of power transmission and distributed generation systems[1]. Such as electrical failures can result in transient or permanent damage to electrical apparatus (electronic devices, electrical motor, transformers…), which would require a change in hardware[1-3]. For example, induction motors are often driven in situations that exceed the nominal operating conditions[4]. This overstress requires a higher electrical current due to the overload on the induction motor. This failure leads to an induction motor malfunction and causes thermal damage, power loss, breakdown of rotor bar and insulation degradation in stator winding[4]. As a result, the induction motor would need repairs sooner than expected.

It is essential to develop protection devices that can suppress the electrodynamics and thermal stresses of electrical equipment during an over-current state, including circuit breakers and fuses (conventional protective devices)[2,3]. In low voltage, the circuit breakers and fuses are common solutions. The circuit break has the reclosing operation time in ranges from few milliseconds to second for isolating the faulty section[5]. The fuse has lower cost but it could not be used repeatedly[6]. Moreover, the conventional fault current limiters affect transmission grids, electronic devices and electrical motor under normal condition. Therefore, a device with small impedance and delay time at nominal operation has become a necessity to meet future electrical equipment and system requirements[7,8].

From this point of view, Superconducting Fault Current Limiters (SFCL) has become one of the most attractive solutions to such an increase in fault event[8]. In simpler terms, this device uses the difference between the on-state (superconductor - zero electrical resistance and high critical current density) and the off-state (normal) with electrical resistivity for current limitation[7-9]. There are basically two principles of SFCL namely resistive and inductive types[8]. However novel devices have been considered to two basic concepts[9].

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*e-mail: carlosaugustocp@gmail.com

1. **Resistive type SFCL** with impedance in parallel – it can introduce a pure electrical resistance or resistive with magnetic field assisted quench;
2. **Bridge type SFCL** – this type of limiter uses superconducting inductance, diodes or thyristors arranged as a full bridge rectifier a limiting coil and a voltage source.;
3. **DC biased iron core type SFCL** – in this case superconducting element is one of the coils;
4. **Shielded iron core type SFCL** – it consists of a conventional primary winding around an iron core with kind of fork and superconducting cylinder in between. Sometimes this type is called inductive;
5. **Fault current controller type SFCL** – this type uses thyristors arranged with superconducting inductances.

Among these types of SFCLs, the resistive type appears to be most attractive from the size and cost point of view, if we consider the advances in the synthesis procedures of polycrystalline High-Tc materials[10].

Considerable attention has been given to superconducting fault current limiter prototypes based on $YBa_2Cu_3O_{7-d}$ (Y-123)[11-14] and $Bi_2Sr_2Ca_2Cu_3O8+d$[14,15]. However, other high-Tc compounds are possible. In this respect, our initial investigation of a small resistive SFCL based on an $Hg_{0.82}Re_{0.18}Ba_2Ca_2Cu_3O_{8+d}$ (Hg, Re)-1223 superconductor has confirmed the capability of limiting the fault current[16,17]. Hg,Re-1223 ceramic has the highest critical transition temperature, *i.e.*, $T_c = 135$ K at atmospheric pressure. In our opinion, this compound is a candidate for the technological applications at liquid nitrogen temperature, considering that the expected operational temperature of the envisaged applications should be $T_{use} \sim T_c/2$, whereas for most electronic-type applications the temperature of operation should be ~ 2/3 T_c[16,17].

Another promising compound is the $SmBa_2Cu_3O_{7-d}$ (Sm-123) superconductor ceramic. Due to advances in synthesis procedures of that compound, many researchers have produced align grains to improve both T_c and critical current density (J_c)[18-22]. The results indicated an upgrade of development and quality control of Sm-123 ceramic. Moreover, this material exhibits high J_c under magnetic fields (peak effect)[18,20,23] which is important parameter for type inductive SFCL, motors and maglev transportation[21]. Because of the improvement on the properties of Sm-123, the replacement of $YBa_2Cu_3O_{7-d}$ (Y-123) by Sm-123 might drastically improve the performance in practical applications[18-21].

In this work, we proposed to use Hg,Re-1223 e Sm-123 ceramics and to investigate their current limiting characteristics based on the experimental results.

2. Experimental

2.1. *Synthesis procedure*

The procedure to synthesize the superconductor samples began with the preparation of ceramic precursor[24,25]. Firstly, $Ba_2Ca_2Cu_3O_x$ (99.0% PRAXAIR) and ReO_2 (99.0% Aldrich) in powder form were mixed at the molar relationship 1:0.18, respectively[26]. The powder mixture was homogenized in an agate mortar and it was pelletized with an uniaxial pressure of 0.5 GPa. Secondly, the pellet was annealed at 850°C in a flow of oxygen for 15 h. The precursor was crushed, homogenized and compacted again before being annealed a second time at 930°C for 12 h under O_2 gas flow[26]. The later procedure is repeated seven more times.

Finally, the prepared precursor was blended with HgO (99.0% Aldrich) at the molar relationship 1:0.82, respectively. They were homogenized in an agate mortar and pelletized with an uniaxial pressure of 1 GPa. The pellet with a typical dimensions $5 \times 5 \times 20$ mm^3 was wrapped in a gold foil (99.999%) and introduced in an 8 mm inner diameter quartz tube. A quartz rod (7 mm diameter and 40 mm length) was also introduced together with the pellet received an extra quantity of Hg (l) which turned immediately into amalgam form with gold. The ratio between the mercury mass and the gold mass was 0.045[27,28]. Based on the study of quartz tube filling factor (ff)[26], we used ff $\cong$ 1.0 g/cm^3 and $ff_{Hg} \cong 0.010$ g/cm^3[26]. The quartz tubes were sealed in a high vacuum of 3×10^{-6} Torr. The average density of the pellet samples was $\rho = 4.2(2)$ g/cm^3[28,29]. All procedures have taken place inside a glove box filled with argon gas. In order to improve the grain growth, the annealing time was changed to 72 h at 865°C, as compared to Sin et al.[27]. All details of the synthesis processes and sample characterization were reported elsewhere[28-30].

Samples of $SmBa_2Cu_3O_{7-d}$ were prepared by a solid-state reaction method using commercial oxide powders of Sm_2O_3 (99.99%), CuO (99.99%), and $BaCO_3$ (99.99%). Prior to weighing and mixing, the oxides and carbonate powder were pre-annealed at 110°C for more than 24 h in air to release moisture. Then, the powders were weighed in a glove box, homogenized in an agate mortar for one hour, and put placed into alumina crucibles and calcined at 930°C for 40 hours in air[24,27-31]. The obtained precursors were again homogenized, pressed into pellets (with the a diameter of 16 mm), sintered in a horizontal tube furnace in flowing oxygen (10 ml/min) at about approximately 1060°C for 72 h, then cooled to 520°C and, held at this temperature for 24 h, subsequently cooled in the furnace to room temperature[31].

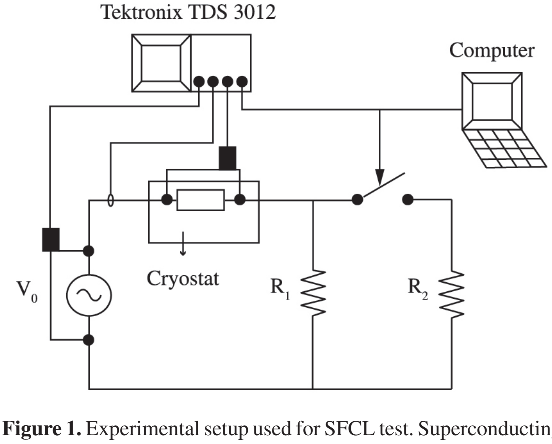

Figure 1. Experimental setup used for SFCL test. Superconducting pellet is placed into cryostat in series with load resistance.

2.2. *Resistive type of SFCL setup*

The experimental setup of the superconducting element in series with the electrical circuit is illustrated in Figure 1[16,17]. This ac electrical circuit consists of a source voltage, a load resistance R_1 and a fault resistance R_2. The source voltage of 23.0 V_{ac} was connected in series to a gold wire with 2mm diameter to replace the superconducting ceramic and a load resistance ($R_1 = 20.0 – 40.0\ \Omega$). The fault resistance ($R_2 = 0 – 20.0\ \Omega$) was connected in parallel with the load resistance by an electronic switch to simulate the impedance reduction. In order not to exceed the maximum temperature of the superconductor, the duration of the short circuits was limited to 100 ms. The superconducting ceramic, with dimensions of $2.4 \times 2.6 \times 6.0\ mm^3$, was set up such that the electrical current flowed through an area of $2.6 \times 6.0\ mm^2$. The temperature was measured by a copper-constantan thermocouple attached to the sample hold and linked to the HP 34401A multimeter. The voltage and current values were measured using a TEKTRONIX TDS3014 oscilloscope and a TEKTRONIX TDSA6302 probe system. The frequency of the power source was 60 Hz[16,17].

3. Results and Discussion

3.1. *Test for Hg,Re-1223 ceramic*

For the first ac test (without Hg,Re-1223 ceramic) it was used a gold wire with 2mm diameter to replace the Hg,Re-1223 ceramic, a voltage of 23.0 V_{peak} was applied to the $R_1 = 20.0\ \Omega$ (switch open) resistor, which resulted in an electrical current of 1.2 A_{peak}. Then, the switch was turned on simulating the short-circuit fault. It was chosen $R_2 = 4.0\ \Omega$ such that the current prospective was of 6.3 A_{peak}.

Hg,Re-1223 pellet was inserted electrical circuit. A voltage of 23.0 V_{peak} was applied to the $R_1 = 20.0\ \Omega$ (switch open) resistor, which also resulted in an electrical current of 1.2 A_{peak} through the transverse area where the superconducting ceramic was connected. When the switch was turned on, a slight decrease of the applied voltage ($V_0 = 21.0\ V_{peak}$) was observed under fault condition operation[32].

Figure 2a displays the result of the test where the solid curve indicates the voltage on the superconductor element. The voltage on the superconductor was zero before the fault. When the fault occurred, voltage increased immediately. It means that the superconductor pellet had zero impedance before the fault. During the fault, the current increased and the superconducting element changed its state, *i.e.*, the ceramic introduced an electrical resistance while the over-current state continued. In this experiment, the current was limited down to 4.0 A_{peak} (see Figure 2b).

The prospective/limited of current ratio observed in this experiment was ~1.6 for 2.4 mm pellet thickness. The ac test was done with the superconducting element immersed in liquid nitrogen in order to keep the temperature unaltered.

An addition ac test was performed with a resistor $R_2 = 1.5\ \Omega$ simulating a different fault current scenario. As before, the applied voltage value has decreased (Figure 3a). Moreover, the fault current expected was of 16.1 A_{peak} and

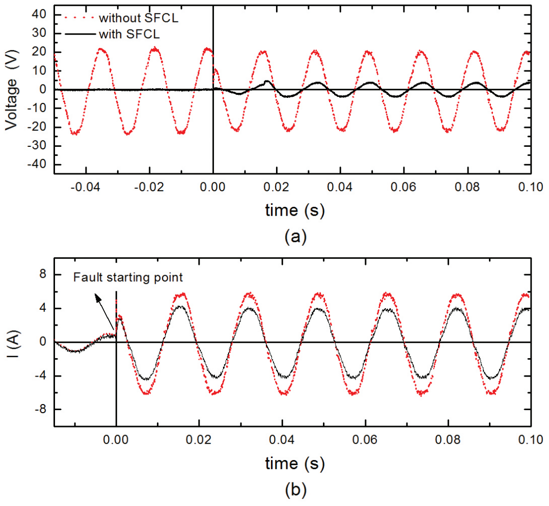

Figure 2. First ac test of the device for a fault duration time of five cycles. Here was used Hg,Re-1223 sample. The resistances were $R_1 = 20.0\ \Omega$ and $R_2 = 4.0\ \Omega$.

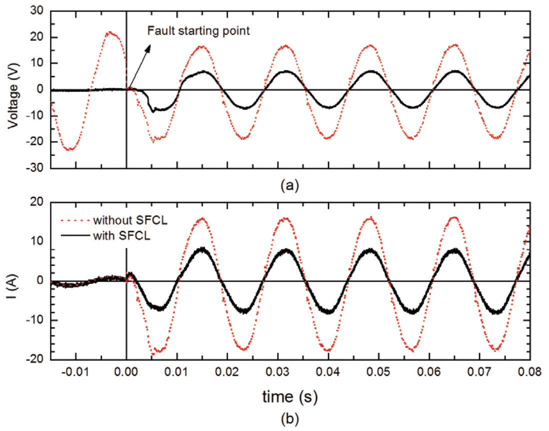

Figure 3. Second ac test of the device for fault duration time of five cycles. This test was done with Hg,Re-1223 sample. The resistances were $R_1 = 20.0\ \Omega$ and $R_2 = 1.0\ \Omega$.

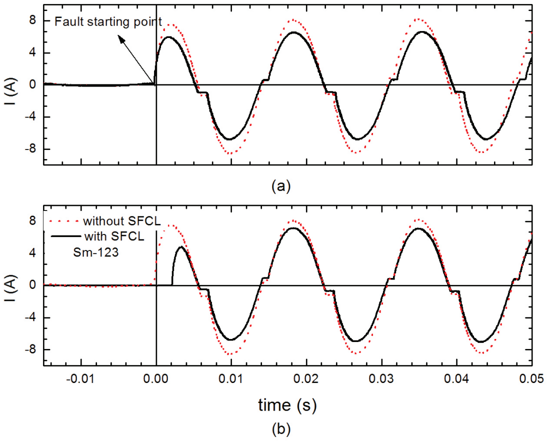

Figure 4. Current of short-circuit of Sm-123 ceramic at 77K. (a) Current limiting characteristics for two superconducting element in series; (b) Only one element in line with the load resistance R_1.

reduced to 8.1 A_{peak} by the superconducting element, as shown in Figure 3b. In this case the prospective/limited of current ratio observed in this experiment was of 2.0, as considered a 2.4 mm ceramic thickness (see Figure 3b).

3.2. *Test for Sm-123 ceramic*

The procedure of measurement was similar for Sm-123 ceramic. However, it was used two pellets such that the total thickness was 2.4mm. Current characteristics of resistive SFCL also were measured at 77 K and shown in Figure 4.

To make this test, the load resistance was $R_1 = 20\ \Omega$ and the fault resistance $R_2 = 3{,}3\ \Omega$. When the switch was turned on simulating the fault current event (impedance reduction), the prospective current was 8.2 A_{peak} (see Figure 4a). After that, another new configuration was used with two superconducting elements in series. In this situation, the electrical current was limited at 6.6 A_{peak}. Then the prospective/limited current ratio observed in this experiment was approximately 1.2, as considered a 2.4 mm Sm-123 ceramic thickness.

An additional test was performed under identical initial conditions to verify whether any damage to the Sm-123 intergrain connectivity had occurred. In this case, only one superconducting element was removed. The result indicated that the superconducting ceramic might not have undergone degradation because it was able to limit the current, as shown in Figure 4b.

4. Conclusions

Preliminary experimental studies of a resistive SFCL based on (Hg,Re)-1223 and Sm-123 superconductors for a protected electrical circuit were performed. The devices have been tested at low voltage and current levels to investigate their behavior. The tests confirmed the capability of the resistive type SFCL to limit the fault current at 100ms. As the current increase, the superconducting element change its state, i.e., the ceramic presents resistance while persists the over-current. For first tests, the current was limited at 66% (0.66 I_{peak}) and, the second test, the fault current was limited at 50% (0.50 I_{peak}). The superconductor sample did not present any degradation and its critical temperature has not changed after the test. By ac magnetic susceptibility, it was verified that the Tc did not change, which shows to be this type of device viable to this application. These results will be applied to determine optimal condition in future superconducting fault current limiter (SCFL) devices based on (Hg,Re)-1223 and Sm-123 ceramics.

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