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Investigation of 2G coil SCFCL - Modeling and Testing

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Abstract. A non-adiabatic model for SCFCL has been developed. The model is based on the superconductor E-J curve. Heat transfer is modeled by means of a thermal electrical analogy, making the simulations easier to be implemented, because the coupling between electrical and the heat transfer differential equations becomes a straightforward task. Simulation results agree well with experimental testing.

1. Introduction
In spite of the recent advances achieved with superconducting fault current limiters (SCFCL’s) [1, 2], simulation and tests of such devices are still important issues. There are different approaches for modeling these devices, whereas testing procedures have been under discussion aiming at standardization [3]. In the present work, a non-adiabatic model is used to simulate the thermal and electrical behavior of a commercial resistive SCFCL component (R-SCFCL) based on second generation superconducting tapes (2G tapes). The model takes into account the characteristic E-J curve of the HTS material as well as the strong coupling between electrical and thermal phenomena. A commercial SCFCL component was tested in the High Power Facilities of CEPEL (Electric Power Research Center). This component was manufactured by Nexans SuperConductors GmbH. Similar components were employed in the ENSYSTROB project, which demonstrated a 2G coil based R-SCFCL in a medium voltage grid [4].

2. Short-Circuit Tests
The R-SCFCL component consists of parallel 2G tapes arranged in two shunted coils which are mounted in an anti-parallel configuration, resulting in a negligible inductance [4]. This component can transport a nominal current of 600 A_{rms} and withstand a maximum voltage of 400 V_{rms} (≈ 0.5 V/cm). It was designed with a high I_c (1200 A, 77 K), in order to withstand large inrush currents, since the SCFCL should not actuate (quench) under inrush currents. The R-SCFCL component was cooled into LN2 bath (77 K) and tested in the High Current Laboratory of CEPEL. The test circuit is described in [5]. Prospective current was measured...
without the presence of SCFCL (an asymmetrical prospective current of 53 kA_{peak} \ (20 \ kA_{rms})). Fault current limiting test was carried out by connecting the SCFCL component to the test circuit. The fault current limiting test was repeated under the same conditions, showing high repeatability, with negligible variations in limited currents and voltage values.

3. Model

A 1D model was developed where each 2G tape layer is represented by a resistor. Buffer layers are not considered, since they are much thinner (submicrometric range) than the other layers. The HTS layer is modeled as a variable non-linear resistor connected in parallel to ohmic resistors (substrate, silver layer and external shunt). The HTS layer is based on the characteristic EJ curve of the 2G tapes employed in the component (non stabilized SuperPower tapes, according to the SCFCL manufacturer). This tape has an Ag cap layer (2 \mu m) and an additional Ag layer (1 \mu m) surrounding the tape [6]. For the present simulations we consider an Ag top layer (3 \mu m) above the HTS layer and a bottom Ag layer (1 \mu m) below the substrate. Each layer is considered as a homogeneous material with spatially uniform properties. A MATLAB Script-File (m-file) was used to build the model and solve the electrical and thermal differential equations.

![Thermal-electric circuit to solve the thermal behavior.](image)

The one dimensional time-dependent heat transfer across the layers is modeled by a thermal electrical analogy (figure 1). Deep details about thermal electrical analogy can be found in [7, 8]. In the equivalent RC circuit shown in figure 1, resistances correspond to heat conduction of each material, while capacitors correspond to respective thermal capacity. The convective heat transfer between 2G tapes and LN\_2 is modeled as a convective resistance. Internal heat generation at each layer is represented by current sources. A DC voltage source (77 V) simulates the LN\_2 bath (77 K). The temperature rise of each layer is calculated as a voltage drop between \text{\textit{T}_{material}} and \text{\textit{g}} (figure 1). The use of a thermal-electrical analogy makes the simulations easier to be implemented, because the coupling between the electrical circuit and the heat conduction differential equations becomes a straightforward task. Such analogy is possible, once the temperature is assumed to be spatially uniform within each layer during the transient. This assumption is reasonable since the thicknesses of the layers are very small and the Biot number is lower than 0.1 [9].

4. Results and Discussion

Testing results are shown in figure 2. An asymmetrical prospective current of 53 kA_{peak} \ (20 \ kA_{rms}) was limited to 4.6 kA_{peak} \ (first peak) and the follow current decayed from 4 kA_{peak} to 3 kA_{peak}.

Simulation and testing results agree well (figure 3). Slight differences between simulation and test curves may be attributed to model assumptions, specially the assumption of a HTS
homogeneous layer, with no local variations of $I_c$ along 2G tapes. In fact, $I_c$ may vary locally along the tapes due to inhomogeneity in the HTS material [10].

Figure 2. Test result: prospective and limited current.

Figure 3. Experimental and simulated results: (a) limited current, (b) voltage; prospective current = 53 kA$_{peak}$ (20 kA$_{rms}$).

Figure 4a shows the simulated current passing through each layer and external shunt. The current in HTS layer attains a maximum of about 1740 A in 1.5 ms and goes to almost zero in about 4 ms. This actuation time with a relatively low quench current agrees well with the expected behavior of 2G tapes. The HTS layer attains a relatively high resistance value and the current is diverted to the external shunt and silver layers. Since the thickness of Ag top layer is higher than the thickness of Ag bottom layer, the current flowing in the top layer is higher than that of the bottom layer. Just a small current flows in the Hastelloy substrate due to its high resistivity.

The "slow" decay of follow current presented in figure 3a can be understood by looking at the behavior of follow currents in shunt and silver layers (figure 4a). The resistance of these layers rises considerably with temperature, lowering the follow current, mainly in the case of silver layers. Figure 4b depicts the calculated temperature rise in each layer as well as in the external shunt. Quenching of HTS layer ($T_c \approx 92$ K) takes place in about 2 ms; after quenching, the temperature of HTS layer exhibits a quasi monotonic increase. The other layers present a similar behavior, excepting the fast initial transient of the HTS layer (see the insert in figure 4b). Tape layers attain practically the same temperature due to their low thickness and consequent
Figure 4. Simulated current in each SCFCL tape layer and shunt (a); temperature rise in tape layers and shunt (b).

fast interlayer heat transfer. Since the metallic shunt is not in contact with 2G tape, it presents a different temperature.

5. Conclusions
In conclusion, the 2G coil R-SCFCL presented an optimal current limiting performance, in good agreement with manufacturer specifications. Simulation and test results agree very well. In addition, simulations provided results of hard experimental access such as the currents flowing in each subcomponent as well as the thermal evolution of each subcomponent. The use of a thermal-electrical analogy showed to be an effective and straightforward way to deal with the strong coupling between electrical and heat conduction phenomena. Further improvements may be achieved by considering the presence of possible inhomogeneities in the HTS layer, since these inhomogeneities may affect material properties, especially local $J_c$ values.

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