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Thermal–electrical analogy for simulations of superconducting fault current limiters

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ABSTRACT

In spite of the recent advances achieved with superconducting fault current limiters (SCFCL's), modeling and simulation of such devices are still important issues. There are different approaches for modeling SCFCL's, whereas computational simulations provide a better understanding of the behavior of SCFCL devices. In addition, results of hard experimental access may be achieved by means of computational simulation. The aim of this paper is to present a simple computational model to predict both the electrical and thermal behaviors of SCFCL devices. The main contribution of the present work is the use of a thermal–electrical analogy to solve the heat transfer equations inside SCFCL sub-components, which enables one to handle with relative easy the strong and nonlinear coupling between thermal and electrical phenomena. The limitation and quenching behavior of a resistive SCFCL assembly was investigated for overcurrents up to 67 kA_{rms} (V_o = 1 kV_{rms}). Simulation results were compared to overcurrent experimental tests. A good agreement between simulations and tests has been found in the present work. Moreover, the results of the developed model were also compared with finite element results reported in the literature.

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1. Introduction

The development of superconducting fault current limiters (SCFCL) becomes necessary due to the increase of short-circuit levels in power systems. Such devices can protect a circuit against large short-circuit currents in the first half cycle of current [1]. In the last years many concepts of SCFCL have been presented [2–6]. Among then, the resistive concept (R-SCFCL) appears as the simplest one; it is connected in series to the circuit to be protected and, in case of a short circuit, a fast transition of the superconducting material to the normal state occurs. The transition to the normal state switches the current to a shunt resistor connected in parallel to the superconductor material. The use of a shunt resistor in a parallel connection is also recommended to avoid overheating and hot-spots in the superconductor material [7–9].

In spite of the recent advances achieved with R-SCFCL, the simulation and tests of such devices are still important issues. There are different approaches for modeling such devices, whereas testing procedures have been under discussion aiming at standardization. Computational simulations of these devices are necessary in order to understand the behavior of SCFCL devices inserted in power system before its installation and to estimate results of hard experimental access. Different methodologies have been proposed in order to predict the thermal and electrical behaviors of SCFCL devices as, for example, detailed and computationally-intensive 3-D finite element models [10,11] and less computationally-intensive but also quite accurate 1-D models with nonlinear resistance [12–15], to name just a few.

The aim of this paper is to present a simple computational model to predict both the electrical and thermal behaviors of SCFCL devices. The complicated helicoidal geometry of the SCFCL device investigated in the current work is approximated by a composite plane wall with four layers. For the heat transfer analysis, one assumes one-dimensional transient heat conduction across each layer's thickness. For the electric circuit analysis, the SCFCL device is modeled as variable nonlinear resistance, whose magnitude depends on the temperature inside the superconductor layer. The temperature of the superconductor layer is in turn obtained from the solution of the heat transfer equations subjected to internal heat generation and to appropriate boundary and initial conditions.

The main contribution and innovative aspect of the present work is related to the use of a thermal–electrical analogy to solve

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the heat transfer equations inside each layer of the SCFCL device. As will be demonstrated in this work, with the thermal–electrical analogy the strong coupling between thermal and electrical phenomena becomes easier to be handled because the heat transfer equations become mathematically equivalent to an RC electric circuit equations. The employment of the thermal–electrical analogy was used for some authors to predict the thermal behavior of some electric equipments and devices [16–19]. To our knowledge, there is a lack of published papers employing this method to simulating SCFCL devices, though some works employed the thermal–electrical analogy to investigate the thermal behavior of SCFCL devices [20–23]. The present investigation represents a progress of our previous works reported in [14,24] in two important directions. First, previous restrictive assumptions about heat transfer through the SCFCL device are relaxed and, second, not only the superconductor material and the shunt are taken into account but also the solder between them. The simulations reported here are restricted to R-SCFCL devices based on MCP-BSCCO-2212 superconducting materials [25]. However, the proposed computational model is quite general and may also be used to predict the electrical and thermal behaviors of SCFCL devices based on other materials like coated conductors (2G HTS tapes).

The manuscript is organized as follows. Section 2 briefly describes the experimental set-up designed to run the short-circuit tests. Section 3 describes the computational model proposed to predict both the thermal and electrical behaviors of R-SCFCL devices. In Section 4 our numerical results for temperature, electric current and voltage drop across the SCFCL device are compared with previous finite element results reported in the literature as well as with experimental data obtained in short-circuit tests. Finally, in Section 5, the main conclusions of the current work are set forth. In the end, an appendix describes the main mathematical aspects behind the thermal–electrical analogy. Further details on this method are properly referenced along the text.

2. Experimental set-up for short-circuit tests

In order to compare the simulations results with experimental data, short circuit tests were carried out in the High Current Laboratory of the Electric Power Research Center (CEPEL). Twelve R-SCFCL components were cooled in an open bath of liquid nitrogen (77 K), connected in series with the test circuit and subjected to nearly symmetric fault currents (60 Hz) of 5.0 kA_{rms} (TestA), 25 kA_{rms} (TestB), 67 kA_{rms} (TestC), under 1.0 kV_{rms} during 0.06 s. More details about the circuit tests can be found in [14,26,24].

Fig. 1 presents the tested assembly that consist in commercial R-SCFCL components manufactured by Nexans SuperConductors GmbH. Each R-SCFCL component consists of a shunted BSCCO-2212 monofilar coils with a total length of 270 cm and presents an average critical current density J_c equal 985 A/cm^2 at 77 K and critical temperature T_c of about 92 K. The average of critical current is equal to 526 A (standard deviation equals to 12 A) and the cross section equals to 0.534 cm^2. The nominal current of such components is 330 A.

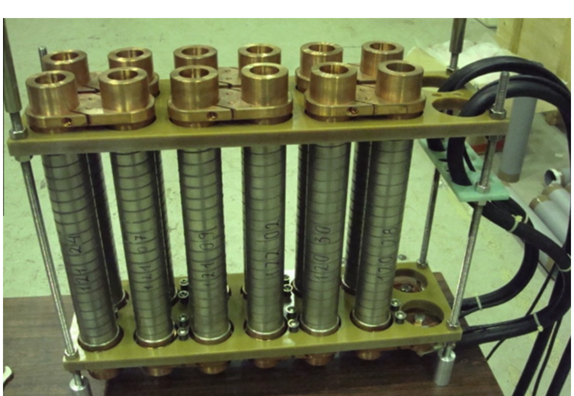

Fig. 1. Twelve tested R-SCFCL components connected in series.

3. Computational model for the electro-thermal behavior of SCFCL

The computational model proposed in the current work to predict the electrical behavior of a R-SCFCL device is schematically sketched in Fig. 2. The electric circuit shown in Fig. 2 reproduces quite well the short-circuit tests described in the previous section. Each R-SCFCL component was modeled as three resistors in parallel connection (see Fig. 2). These resistors represent the following sub-components: the shunt resistor, the solder between the superconductor material and shunt and the superconductor material. In order to promote mechanical stabilization, a thin tube of fiber reinforced plastics (FRP) is glued coaxially into the superconducting tube during the manufacture of these R-SFCL components. The R-SFCL components can thus withstand mechanical stress upon cooling into LN_2, as well as large axial forces along the coil in the short circuit case [9]. Actually, in a more realistic computational model the FRP sub-component should also be taken into account; nevertheless, in this work, one assumes that it has a very large resistance value and, therefore, it was not inserted in the circuit shown in Fig. 2.

The computational model for the electric circuit analysis makes use of the power law EJ curve characteristic of the superconductor material, that describes the behavior of the electrical field as a function of the current density. The R-SCFCL device to be simulated consists in the BSCCO-2212 superconductor. Such material presents a typical EJ curve as shown in Fig. 3. This curve can be mathematically described as a power law:

$$E = E_c\left[\frac{J}{J_c(T_{sp})}\right]^n \quad (1)$$

where E_c (1 μV/cm) is the criterion for the determination of J_c,$J_c(T)$ is the critical current density of the BSCCO-2212, which can be approximated to a linear dependence on the superconductor material temperature (T_{sp}) as described in [14] and n is the exponent, which varies for each stage of the transition. According to [27], the n value is equal to U_0/k_bT_{sp} in the first stage, called flux-creep. In the second stage, referred to the flux-flow, the n value was considered equal to 3, and in the last stage, referring to the normal state, $n = 1$ [28].

The values of R_c and L_c shown in Fig. 3 are adjusted according to the desired value of the fault current. The computational model for the electric circuit sketched in Fig. 3 comprises the following non-linear ordinary differential equation:

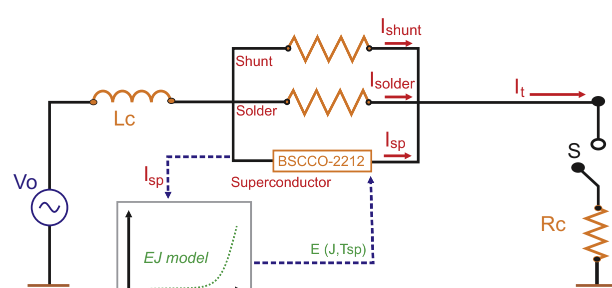

Fig. 2. Equivalent circuit to simulate the R-SCFCL devices with all its sub-components. The BSCCO-2212 is modeled as a controlled voltage source (see text).

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