Modelling and simulation of resistive type superconducting fault current limiter using OpenModelica.

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***Abstract*—In order to introduce high-temperature superconducting fault current limiters (SFCL) into electrical networks, a model is needed to predict the various phenomena that appear within the limiter. This paper presents a model of a resistive type superconducting fault current limiter developed in OpenModelica software. The finite difference method is used to solve the heat equation. The model considers the electrical and thermal phenomena in the thickness and the length of the HTS tape, which allows to study the presence of hot spots phenomenon. An interfacial resistance is included in the proposed model.**

Keywords— ***Superconducting fault current limiter, hot spot, finite difference, OpenModelica, electro-thermal model.***

I. INTRODUCTION

The growing demand for electrical energy leads to increasing of current levels, which can exceed the maximum permissible values of the electrical equipment. As a consequence, the high thermal and mechanical stresses caused by fault currents can damage electrical devices. The new generation of SFCL, called the second generation 2G HTS is one of the most common ways to limit high-fault currents.

In fact, the FCL is essentially a variable impedance that is connected In series with a circuit breaker. During a fault, the impedance value increases until the fault current is reduced to a lower level that the circuit breaker will be able to handle. In addition to short-circuit protection, the application of FCL in electrical power systems can improve the stability of the system in the case of disturbances .

Since the discovery of high-temperature superconductors (HTS) in 1986, the superconducting fault current limiter has been considered as the most promising and innovative application in power systems. The main aspect to develop SFCL systems is the understanding the behavior of superconducting materials in quenching transition. At present, different rSFCL models have been developed. However, the majority of them are limited to a purely electrical model or a 1D electrothermal model that takes into account a homogeneous temperature distribution over the thickness or length. This paper proposes a modeling and simulation of high temperature resistive SFCLs using OpenModelica software considering the electrical and thermal behavior along the length and thickness (2D). The heat equation is discretized by the finite difference method, considering the heat propagation according to the length and thickness of the HTS. This equation combined with the eclectic algebraic equations represents a system of differential/algebraic equations (DAE). The solving method : differential/algebraic system solver (DASSL) integrated in OpenModelica represents a main advantage to use a such software. OpenModelica offers also the advantage that it is compatible with standard Functional Mock-up Interface (FMI) for co-simulation. FMI is a tool-independent standard for model exchange and co-simulation.

II. MODELING 2D OF HIGH TEMPERATURE SUPERCONDUCTORS TAPE

A. *Description of the HTS tape*

The model of HTS tape contains a stack of layers: buffers (oxides) and a superconducting layer e.g. (RE)BCO which is deposited on a metal substrate (stainless steel and Hastelloy). The entire tape is coated with a silver layer. However, in order to ensure a two-dimensional (2D) aspect, no silver layer has been added to the lateral side of the tape. Fig. 1 presents the discretization used for the HTS tape considering the interfacial resistance (R_{inter}) between the superconducting and silver layers. The length and thickness of each element depends on the number of discretization selected in the thickness and in the length.

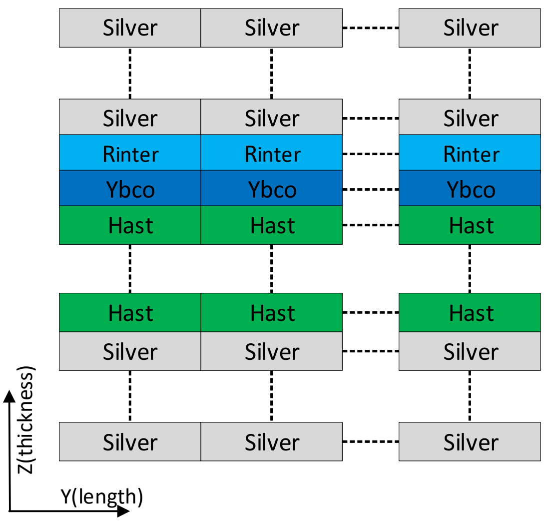

Fig. 1. HTS tape discretization.

B. Electrical Model

The resistance of each discretization element of HTS tape can be modeled as a non-linear resistance (1) depending on the current I and/or the temperature T.

$$R_{el}(J,T) = \rho(J,T)\,\frac{L}{S} \tag{1}$$

Where $\rho(J,T)$, L and S are respectively, the resistivity, the length and the longitudinal cross-section of the considered element. The resistivity of the superconducting layer has been evaluated by the non-linear E-J characteristic called the power law [1]. The electrical algebraic equations are obtained by applying Kirchhoff's circuit laws.

TABLE I. PARAMETERS OF THE (RE)BCO SUPERCONDUCTOR [1]

Parameters	*Value*	*Description*
E_c	1 µV cm^{-1}	Critical electrical field criterion
J_{c0}	2.5 MA cm^{-2}	Self-field critical current density
n	15	Power law exponent
ρTc	30 µΩ cm	Normal state resistance at T_c
α	0.47 µΩ cm^{-1}	Temperature coefficient
Tc	90 K	Critical temperature
T_0	77 K	Temperature of the LN2 bath
T_{Max}	250 K	Maximum admissible temperature

C. Thermal Model

The diffusion of heat both in thickness and length is important, especially when the fault current is close to the critical current Ic or in the case of hot spot phenomena [1]. The model proposed in this paper takes into account the two-dimensional (2D) behavior of heat conduction in the thickness and length (2D) of the HTS strip. The partial derivatives of the heat equation (2) have been transformed to a finite difference discretized form.

$$\rho_m\, C_p(T)\,\frac{\partial T}{\partial t} = \nabla.(k(T)\nabla T) + Q_j(T,I) \tag{2}$$

where Qj represents the total Joule losses inside the considered element, κ is the heat conductivity of the element, ρm is the mass density and Cp is the specific heat capacity.

III. Simulation Results

The presence of critical current density J_c inhomogeneities in superconductors causes the most critical defect (hot spot). To validate the proposed model, the power grid and the parameters studied in [1] have been used. A tape of 5 mm in length having a hot spot ($J_{cf} = 0.55J_c$) of 1 mm in length (Fig. 2) supplied by a DC source equal to 100A is used.

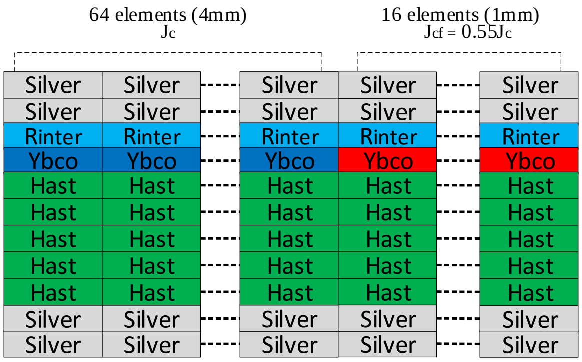

Fig. 2. HTS discretization used to simulate a hot spot in the length.

The solver (DASSL) integrated in OpenModelica has been used to solve the non-linear coupled equations with a large number of variables.

Fig. 3 et Fig. 4 presents the current evolution in the hottest element of each layer and the temperature measured on the upper surface of the tape in each 250 µm.

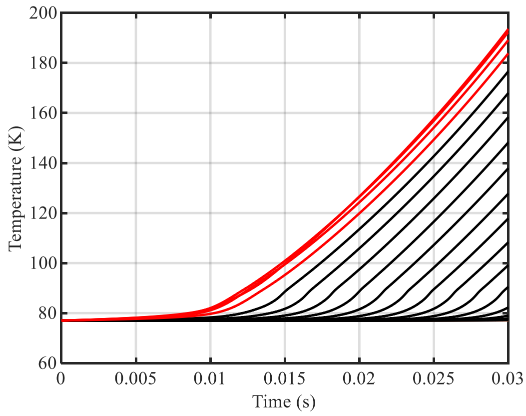

Fig. 3. Evolution of the temperature of the surface of the tape.

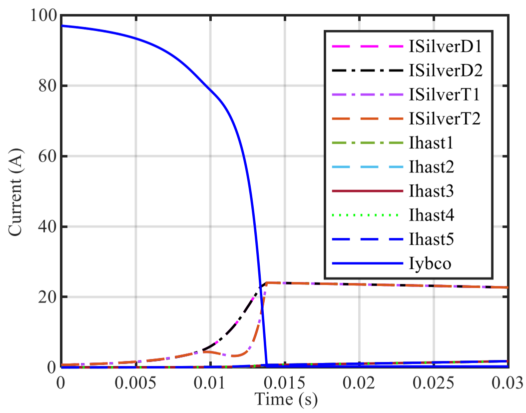

Fig. 4. Evolution of the current in each layer.

References

[1] C. H. Bonnard, F. Sirois, C. Lacroix, G. Didier, "Multi-scale model of resistive superconducting fault current limiters based on 2G HTS coated conductor" Supercond. Sci. Technol., vol. 30, 2016.