Magneto-thermal finite element modeling of 2nd generation HTS for FCL design purposes

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Abstract. Coated conductors are very promising for the design of novel and efficient Fault Current Limiter (FCL). However, before considering using them in a power grid, their thermal and electromagnetic behaviors in the presence of over-critical currents need to be investigated in details. In this context, we performed finite element magneto-thermal modeling of coated conductors under over-critical current on several geometries. Accordingly, we have investigated the substrate electrical connectivity and thermal properties on the HTS-FCL behavior. All simulations were performed using in *COMSOL Multiphysics*®, a commercial finite element package, which has a built-in coupling between the thermal and electrical equations, allowing us to compute both quantities simultaneously during the solving process. Our simulations allowed us to formulate thresholds for the current density usable in coated HTS as well as limitation capability of a device made of these new conductors.

1. Introduction

Recent advances in thin film technology and epitaxial growth allowed the emergence of coated conductors (CC) as a second generation of high-temperature superconductors (HTS), which, by their expected low price and high critical current density, seems to be the favored candidate for resistive Fault Current Limiters (FCLs) [1–3]. In the recent past, several authors have proposed numerical magneto-thermal models to describe the behavior of CC-FCL [4–6]. Such simulations are of great interest to design efficient limiters since they allow a better understanding of these devices, which are hard to design in a way that thermal stability is ensured over all conditions of operation. Nonetheless, numerical models proposed in the literature are usually not suitable for quick and simple calculations. Indeed, implementing home developed code or using typical finite element method (FEM) software is often time consuming and requires considerable resources. In this paper, we present a magneto-thermal model that is very easy to implement.

By using a simple $\vec{\mathbf{H}}$ formulation in two dimensions, we developed a numerical approximation to model high aspect ratio geometries, which are always difficult to implement in FEM. Our simulations were developed using a widely used commercial software, hence providing us an easy way to share engineering with academics and industries.

2. Theoretical model

In this section, we briefly introduce our coupled model, which simulates the electrical and thermal behavior of a typical HTS-FCL, as well as an aspect ratio (AR) approximation that allows reducing drastically the time required to perform the simulations.

Our geometrical model is based on commercial coated conductors available from Theva [7]. The coated HTS tapes are made of four layers. A thick conductive substrate layer made of Hastelloy C276, which is usually electrically isolated from the HTS; a MgO buffer layer; a superconductive film made of DyBCO ($DyBa_2Cu_3O_7$) and a silver stabilizer in electrical contact with the superconductor. In order to simulate the CC-FCL behavior, we used a 2D geometry (a conductor of infinite length) 20 times thicker than the real one. As depicted in figure 1, we intentionally omitted the buffer layer, which does not influence importantly the electromagnetic and thermal behavior of the tape, to reduce the computation time. The magneto-thermal model was implemented in *COMSOL Multiphysics®* [8], a FEM open structure software that allows great freedom to deal with partial differential equations (PDE).

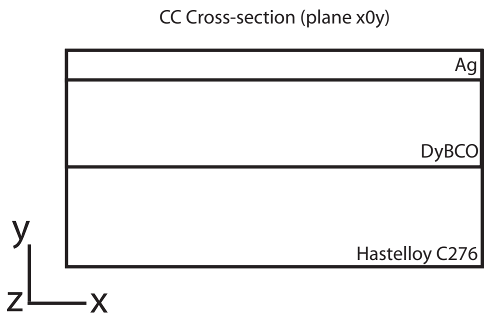

Figure 1. Cross section of the simulated CC (not drawn to scale). The tape is 10 mm wide and is composed of three layers: 1) Hastelloy substrate (1.8 mm), 2) DyBCO film (60 μm) and 3) an Ag stabilizer (60 μm). We intentionally omitted the MgO buffer layer to reduce the computation time.

The electromagnetic formulation, briefly summarized here, is based on a direct use of the magnetic field $\vec{\mathbf{H}}$ as a state variable [9].

From Faraday's law, the coupling of the magnetic and electric fields is described as

$$\nabla \times \vec{\mathbf{E}} = -\frac{\partial \vec{\mathbf{B}}}{\partial t} \tag{1}$$

where $\vec{\mathbf{E}} = E_z$, is the longitudinal electric field given by the non-linear relation

$$E_z = \rho(J_z)J_z \tag{2}$$

the current density is obtained by the Ampère's Law, which in quasi-static 2D approximation is expressed as

$$J_z = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \tag{3}$$

In order to simplify the notation, we will omit the z subscript for J_z and E_z in the remainder of the paper.

The input parameter, i.e. the transport current in our case, is imposed by the boundary conditions such that the integral of the magnetic field on the border of a circular domain, representing the liquid nitrogen (LN2), equals the source current at each time step:

$$I_{src}(t) = \oint \vec{\mathbf{H}} dl' \tag{4}$$

The use of edge elements guarantees the continuity of the tangential component of the magnetic field from one element to the adjacent one. In this way the equation $\nabla \cdot \vec{\mathbf{B}} = 0$ does not have to be added to the model, since it is automatically satisfied [10].

For the thermal part of our model, we used the following conduction equation:

$$Q = \rho_m C_p \frac{\partial T}{\partial t} - \nabla \cdot (-k \nabla T) = E \cdot J \tag{5}$$

Where Q is the power density dissipated in the tape, ρ_m is the subdomain mass density, C_p the heat capacity and k the thermal conductivity tensor.

The heat exchanged with the LN2 bath is expressed by mean of a boundary condition at tape-coolant interface.

$$\hat{\mathbf{n}} \cdot (k \nabla T) = h(T_s - T_0) \tag{6}$$

Where h is the convection heat transfer coefficient which depends on the tape surface temperature (T_s) as shown in the inset of figure 4 and T_0 is the LN2 boiling temperature (77 K).

The macroscopic behavior of the HTS is described by means of a non-linear resistivity, which depends, in our model, on the temperature and local current density. For the purpose of this paper, we used a combined exponent power law to illustrate our ability to introduce complex non-linear functions in the model. Also, we used n=20 for $J < J_c$ and n=10 for $J \geq J_c$.

$$\rho(J,T) = \begin{cases} \rho_{pl}(J,T) & , T < T_c \\ \rho_n & , T \geq T_c \mid \rho_{pl}(J,T) \geq \rho_n \end{cases} \tag{7}$$

$$\rho_{pl}(J,T) = \frac{E_0}{J_c(T)} \left(\frac{|J|}{J_c(T)} \right)^{n-1} \tag{8}$$

$$J_c(T) = J_{c_0} \left(\frac{T_c - T}{T_c - T_0} \right)^{\alpha} , T < T_c \tag{9}$$

T_c is the critical temperature (90 K), ρ_n is the normal resistivity (130E-8 Ωm), J_{c0} is the critical current density (1E10 A/m^2), α is an empirical factor (1.5 [11]) and E_0, the critical electrical field (1E-4 V/m).

The simulations were developed in 2D for lower aspect ratio than the real FCL tape. Four physical parameters have been scaled in the thicker geometry to approximate the real solution [12]. These parameters are C_p, J_{c0}, k and E. Using lower AR geometries allows reducing the number of elements required to keep the convergence and accuracy of our model, i.e. with a reduced number of nodes, the shape of the elements and, consequently, the quality of the interpolated results can be improved. In our case using an AR 20 times larger allows reducing the number of elements from 19346 to 2516, which corresponds to a reduction of the computation time by $\approx$45.

3. Numerical results

We investigated the influence of the imposed current on the HTS stability threshold. For this, we used a typical fault current waveform, i.e. an initial peak current of 3 times the amplitude of the nominal current corresponding to 89% of J_{c0} for less than 5 ms (see figure 3 for current waveforms). In addition, the effect of electrical connectivity between the tape layers as well as the substrate materials on the HTS-FCL behavior near the current threshold are computed.

3.1. Peak current threshold

Using coated superconductors allow to attain higher critical current density than massive conductors. Nevertheless, the small thickness of CCs makes them very sensitive to temperature excursions. As depicted in figure 2, a very small fluctuation of the imposed current (less than 5 mA) is responsible for a sudden warming of the device. Under these circumstances, a current threshold is established for which the thermal stability is lost. Comparable results have been observed by reducing slightly the thickness of the silver stabilizer. This reduction increases the overall current density within the tape in the normal state and favored instabilities by Joule heating.

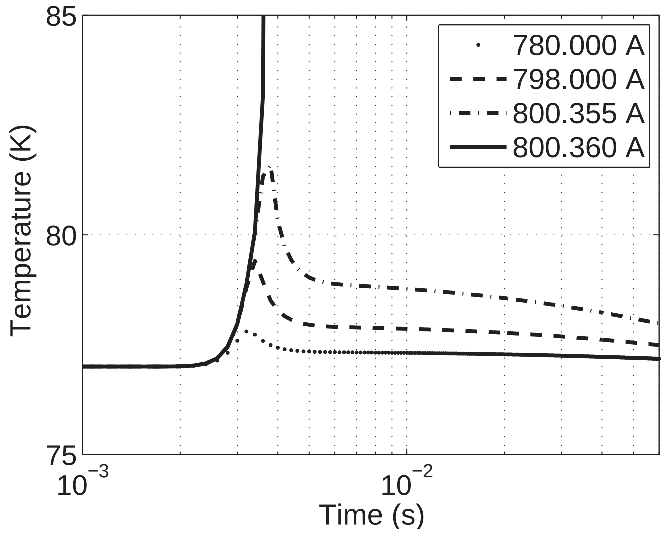

Figure 2. Effect of the current on the thermal stability. A threshold current around 800 A is observed for this model.

3.2. Effect of a shunted tape

The rapid recovery seems impossible once the HTS has switched to his normal state. This is particularly true if the tape does not have a shunt resistance (i.e. Ag and/or hastelloy) to absorb part of the dissipated energy. This can be observed in figure 3. The normal resistance of the HTS, which is higher than that of the substrate and the stabilizer (we did not yet introduce a temperature dependance for the resistivity of these layers), makes the power generated within the DyBCO practically negligible in comparison to that in the silver film. In this case, the superconducting state will be recovered only if the stabilizer film succeeds in trading the generated heat with the nitrogen bath before the next current peak is reached. Adding a parallel resistance lowers the global resistance of the tape, so that more current can flow into the tape without attenuation. This effectively leads to a decrease of losses in the HTS film and produce less Joule losses in the conductive parallel paths. Therefore, the shunted limiter requires more tape length to limit the same imposed current.

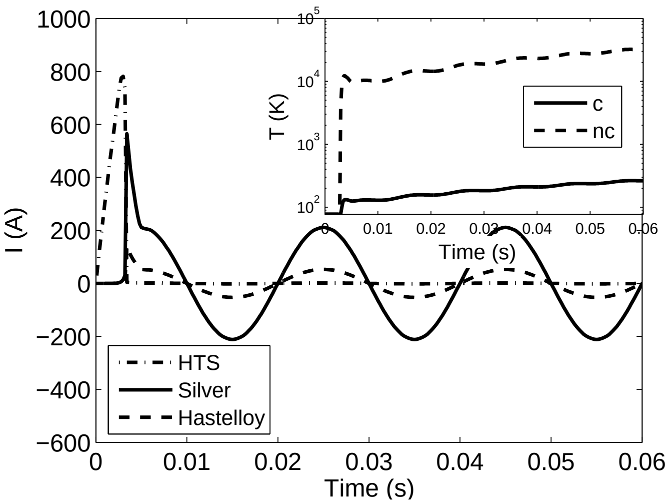

Figure 3. Distribution of the current (I_{peak}=810 A) in the tape materials for a shunted tape (substrate and stabilizer). The inset is the temperature of the tape for a shunted (c) and non-shunted (nc) device. For a non-shunted configuration, all the current goes in the HTS which has a high resistivity in the normal state. This has a direct effect on the temperature increase.

3.3. Effect of the substrate material

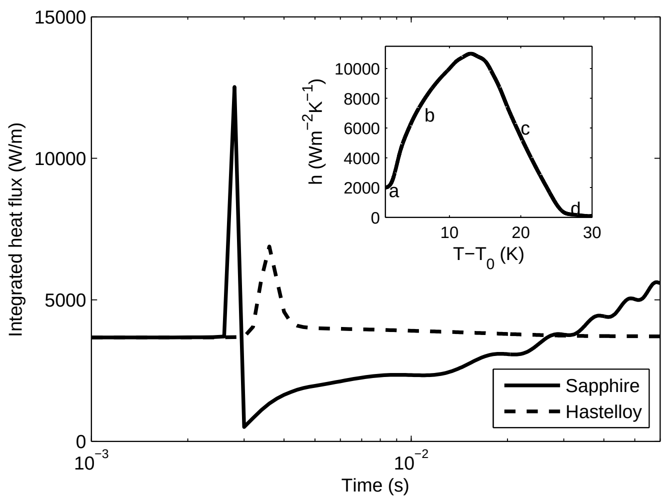

Figure 4. The integrated heat flux, which is defined as $\oint h(T_s - T_0)dl$, represent the heat exchange between the tape and the coolant. The inset is the convective heat transfer which presents four usual heat transfer regimes: (a) free convection, b) nucleate boiling c) transition boiling and d) film boiling. On the main figure, we observe that the surface temperature of the sapphire substrate increases rapidly and suddenly makes the convective coefficient reaches the film boiling region (the observed drop). At this stage, the tape is almost “isolated” from the coolant and it burns out quickly (I_{peak}=800.355 A).

The materials constituting the tape have an important influence on the thermal exchange between the coolant and the tape surface. As depicted in figure 4, by comparing two usual CC substrates, such as hastelloy and sapphire, we observe that a rapid increase of the surface temperature induce a huge drop on the thermal flux within the tape-coolant interface. The combination of a low heat capacity and a high thermal conductivity gives sapphire a thermal diffusivity (defined as $\alpha_d = k/\rho_m C_p$) that is more than 1000 times larger than hastelloy. However, the heat, which is not readily stored in the sapphire substrate (low C_p), can not be released due to the rapid increase of the surface temperature that led to the film boiling regime (figure 4, inset, region d). In this particular case, the heat transfer with the LN2 is at its minimum and leads to quasi-adiabatic conditions.

4. Conclusion

In this paper we have presented a new finite-element model for studying electromagnetic and thermal behavior of HTS, specifically for FCL applications. The model, which consist in coupling the electromagnetic and thermal equations in a single solving process, is simpler to implement and much faster than other models based on solving the two parts separately and exchanging the results at each time step. The model, having been implemented in a widely used commercial software package (*COMSOL Multiphysics*®), provides an easy way to share engineering knowledge between users. It is ready to be tested against experimental data and to be used to design FCL applications.

Acknowledgments

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