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Fast FEM Modelling of First Generation High Temperature Superconducting Power Cables via Homogenization

1LPo2E-09

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Introduction

The goal of the presented research is to demonstrate that the electromagnetic and thermal physics inside a simple low voltage first generation superconducting cable may be modelled quickly and accurately via FEM when the cable is experiencing overcurrent, using a homogenization technique for the filamentary region of each tape. This technique has been used regarding tapes in [1][2] and redefined in [3].

A homogenized model is built via an **H**-*formulation* in COMSOL. In order to validate it, its calculations of losses, heat transfer and temperature are compared to the established technique of analytic equivalent circuit calculation coupled with finite difference heat transfer, built in MATLAB.

Homogenization Technique

$$J_{c0} = \frac{I_c}{S_{eq}}$$

S_{eq} – area of the homogenized domain used in the model;

J_{c0} – the local critical current density in self-field and 77 K;

I_c – the critical current for the given tape.

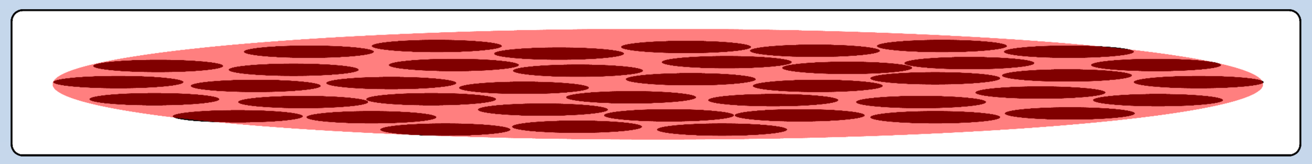

Figure 1: A sketch of the homogenization model in a typical BSCCO tape. Black ellipses represent filaments, while the red ellipse is the homogenized "equivalent domain".

Modelling in COMSOL…

H-*formulation* via the COMSOL *General PDE* module [4] using standard notation:

$$\nabla \times (\rho \nabla \times H) + \mu_0 \mu_r \frac{\partial H}{\partial t} = 0$$

Neumann boundary condition and initial condition equal to zero were used. Transport current via a pointwise constraint (left) and total losses for the doubled second half-cycle (right):

$$I_t = \int_S J_n dS \qquad Q = 2\int_{1/f}^{1.5/f} \int_S JE dt$$

For comparison between the multifilamentary and homogenized FEM models, the adapted Kim-Anderson approximation was used for magnetic field dependence of the critical current density [2]:

$$J_c(B,T) = J_{c0}(T) \times \frac{B_0}{B_0 + \sqrt{\gamma^2 B_\parallel^2 + B_\perp^2}}$$

The *Heat Transfer* module is used, where [5]:

$$\rho C \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + Q_{generated} + Q_{net\_flow}$$

$$J_{c0}(T) = \frac{J_{c0}(77K)}{(1 - 77K/T_c)^{3/2}} \times \left(1 - \frac{T}{T_c}\right)^{3/2} \quad T < T_c$$

…and MATLAB

For loss estimation, the equivalent circuit model [6] is used where the HTS and Ag are resistances in parallel:

$$R = \frac{1}{\left(\frac{1}{R_{HTS}} + \frac{1}{R_{Ag}}\right)}$$

$$R_{HTS} = \frac{10^{-4}}{I_c} \times \left|\frac{I}{I_c}\right|^{n-1}$$

For comparison between the equivalent circuit and the homogenized FEM model, constant critical current and current density is assumed.

Integrating the discrete product $I \times V$ for every timestep gives the power loss for 1 cycle.

Heat transfer is examined via 1D finite differences [7] and the following [5]:

$$\rho C \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + Q_{generated} + Q_{net\_flow}$$

$$I_{c0}(T) = \frac{I_{c0}(77K)}{(1 - 77K/T_c)^{3/2}} \times \left(1 - \frac{T}{T_c}\right)^{3/2} \quad T < T_c$$

At $T \geq T_c$, $R_{HTS} \gg \infty$, but as this is impossible [8]:

$$\rho = \frac{\rho_{HTS}\rho_{normal\_state}}{\rho_{HTS} + \rho_{normal\_state}} \qquad R = \frac{R_{HTS}R_{normal\_state}}{R_{HTS} + R_{normal\_state}}$$

And the equation on the right is used in COMSOL.

Configuration & Simulation Results

The tape used is characterized in [9]. A single conductor layer plus single shield layer cable is designed based on that tape. The model benefits from rotational symmetry (Figure 2) in order to minimize simulation time. The homogenization model for losses below critical current was verified in [3].

This theoretical cable does not have a protection or stabilization layer.

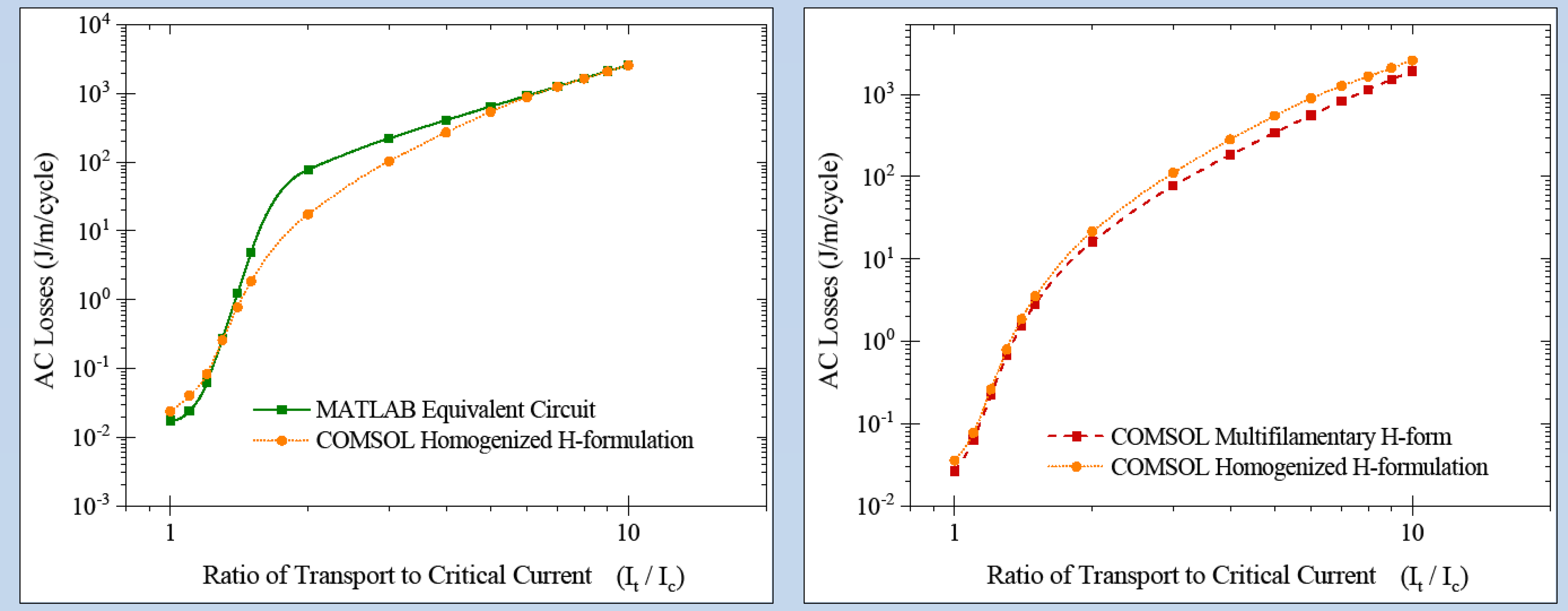

Figure 3: Comparison between losses in the equivalent circuit and homogenized model at field-independent critical current (LEFT) and between the multifilamentary and homogenized model with field dependence (RIGHT).

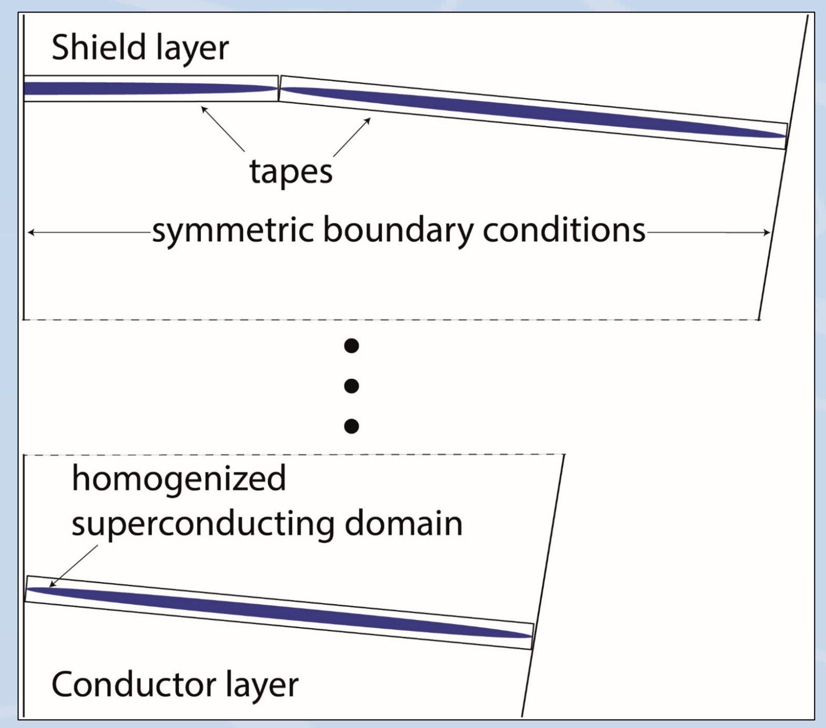

Figure 2: The configuration of the cable in COMSOL, using rotational symmetry.

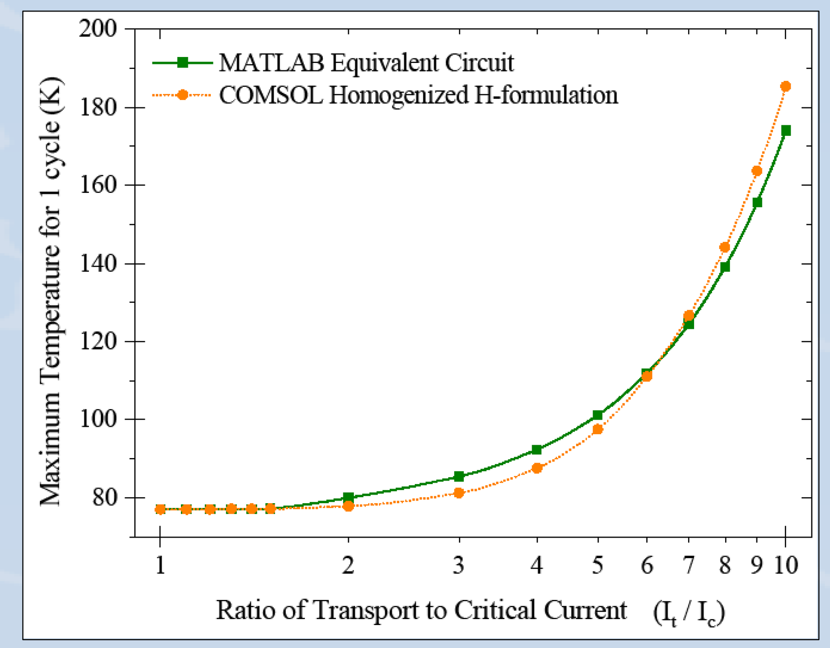

Figure 4: Maximum temperature calculated inside the cable models in MATLAB and COMSOL.

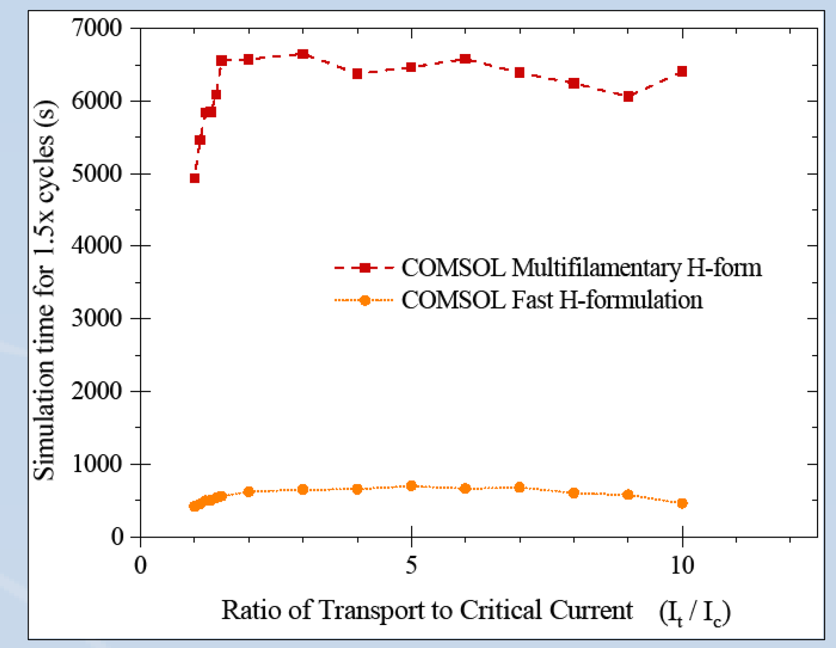

Figure 5: Time taken to simulate 1.5 cycles in a multifilamentary and in a homogenized model. Lines are a guide only.

Conclusions

This research demonstrated that a homogenization technique for first generation (BSCCO) tapes can be used to approximate the transport current power losses of a simple one-layer power cable above the critical current. This becomes visible from Figures 3 and 4 where the good match between simulations is shown.

Future work will include designing a cable with more than one layer, also including stabilisation and protection. The cable model will be simulated together with a fault current fault based on a realistic power grid.

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