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# Electrothermal modeling of HTS coils using homogenization and different formulations

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**Abstract**—HTS coils are used in various applications, however, it is complicated and time-consuming to model their multiphysics behavior. We have developed a simple homogenized method to accurately simulate HTS coils, in the context of electrothermal quench. Different numerical models are benchmarked for these computations, and they show very good agreement for different configurations of homogenized method.

**Keywords**— benchmark, coils, HTS, numerical modeling

## I. INTRODUCTION

High Temperature Superconducting (HTS) racetrack coils are used in rotating machines due to their high power density and light weight. However, modelling HTS coils is still a complicated and time-consuming process due to their inherent non-linear multiphysics behavior, when applied to the case of electrothermal quench. In electrothermal transients, there is a need for a fast and accurate numerical modeling software.

An alternative for considering detailed geometries (with all layers defined explicitly) is using anisotropic homogenized geometries, where all the layers of HTS tapes are considered as a single material with homogenized electromagnetic and thermal properties [1]. This reduces the computation times for the electrothermal calculations, while giving precise results when compared to the detailed model, as we show in the text. We also present a benchmark of several numerical models in order to assess their relative accuracy.

TABLE 1: Material properties

Material	Thickness [ $\mu\text{m}$ ]	$k$ [ $\text{Wm}^{-1}\text{K}^{-1}$ ]	$C_p$ [ $\text{J/kg}\cdot\text{K}$ ]	$\rho$ [ $\text{ohm}\cdot\text{m}$ ]	Density [ $\text{kg/m}^3$ ]
HTS	2	9	156.65	$3 \cdot 10^{-7}$	6390
Ag	4	400	235	$1 \cdot 10^{-8}$	10500
Hastelloy	100	7	425	$120 \cdot 10^{-8}$	8940
Stycast	50	0.8	138.6	$1 \cdot 10^{13}$	2290

## II. MODELING METHOD AND PROPERTIES

### A. Geometrical parameters and properties

The 2D models are applied to a racetrack coil of 5 tapes as shown in Fig.1 (a). The electrical and thermal properties of the layers for a turn are presented in Table 1. We have considered these properties to be constant for the purpose of simplicity in benchmarking, however, in reality the resistivity ( $\rho$ ), heat conductivity ( $k$ ), and heat capacity ( $C_p$ ) will depend on temperature. Only the critical current density ( $J_c$ ) of the superconductor is temperature dependent to allow for coupling between the electromagnetic and electrothermal properties [1]. The critical current of the considered superconductor is 150 A. These layer properties on a turn basis are homogenized in the same way as specified in [1]. A sinusoidal current wave is used as an input, with different peak amplitudes (170 A and 180 A) and 5 Hz frequency, to ensure a high temperature rise. The coil is cooled with liquid Nitrogen. A convection condition deduced from the boiling curve is used on all sides except the inner radius [1].

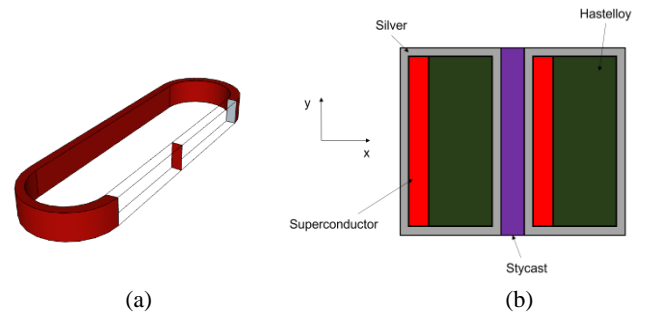


Fig. 1. (a) Racetrack coil and its cross section, and (b) layers of HTS turns with Stycast as an insulating layer.

### B. Modelling methods

A number of modelling methods and their combinations, in different software, are used to solve the above problem. These combinations are H-A formulation and FEM (Detailed & Homogenized) [2], H-phi with FEM (GetDP Detailed & Homogenized) [3], H-formulation with FEM, MEMEP with Finite Difference [4], MEMEP with METEP [1], and T-A

with Equivalent lumped electrical circuit model. All these methods use the same mesh and number of timesteps for the following computations.

### III. RESULTS AND DISCUSSION

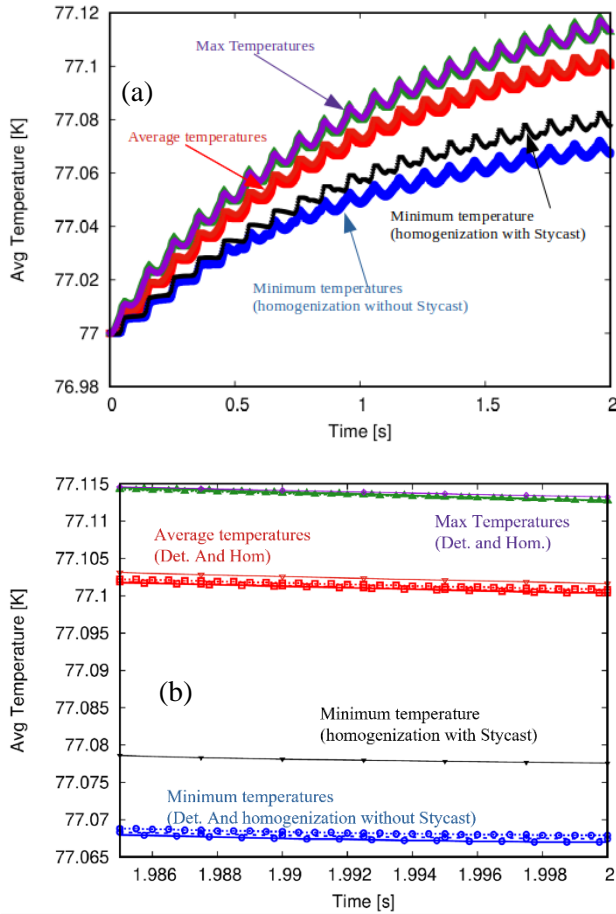


Fig. 2. (a) Detailed (H-A and H-phi) vs Homogenized models (H-A and H-phi). (b) is zoom of (a) and shows difference in minimum temperature, and good agreement otherwise. Thermal properties are solved using FEM in all these cases.

#### A. Detailed vs Homogenized model

Fig. 2 (a) and (b) compare the detailed (Det.) and homogenized (Hom.) methods for 170 A AC current input. GetDP homogenized models does not include the Stycast in the homogenization, due to its comparatively high resistivity, whereas H-A homogenized model does. Here it can be seen that there is very good agreement between these models for the average temperature (red curves) and maximum temperature (green and purple curves). The minimum temperature is comparatively higher in the case when Stycast is included in the homogenization (black curve vs blue curves). However, for quenches, maximum temperature is the most important quantity, and thus we show that keeping Stycast in the homogenization can be acceptable for these cases as it can make the models simpler and faster. The homogenized method takes 446 s, versus 2654 s of detailed method in GetDP for this case, which is almost 10 times faster than the latter.

#### B. Benchmark between different methods (homogenized)

Fig. 3 (a) and (b) shows comparison between different models for the homogenized case at 170 A current input. The results have very good agreement with each other. They also have good agreement with detailed models, and differences between the models are in the 3rd decimal point. Figure 3 (c) shows the case of 180 A input current, where we have thermal runaway (quench) at around 1.85 s. The models have very good agreement for this case as well. The curve where Stycast

is kept out of homogenization (H-phi with FEM: GetDP) also predicts the quench at the same time as other models where Stycast is included in homogenization. The computation times for these homogenized models range between few minutes to hours.

### IV. CONCLUSION

We have developed a simple homogenized method that is orders of magnitude faster than detailed method. The benchmark between detailed and homogenized methods, using different formulations, shows good agreement, even for quench scenarios, and can be used for accurate multiphysics modeling of HTS coils in rotating machines.

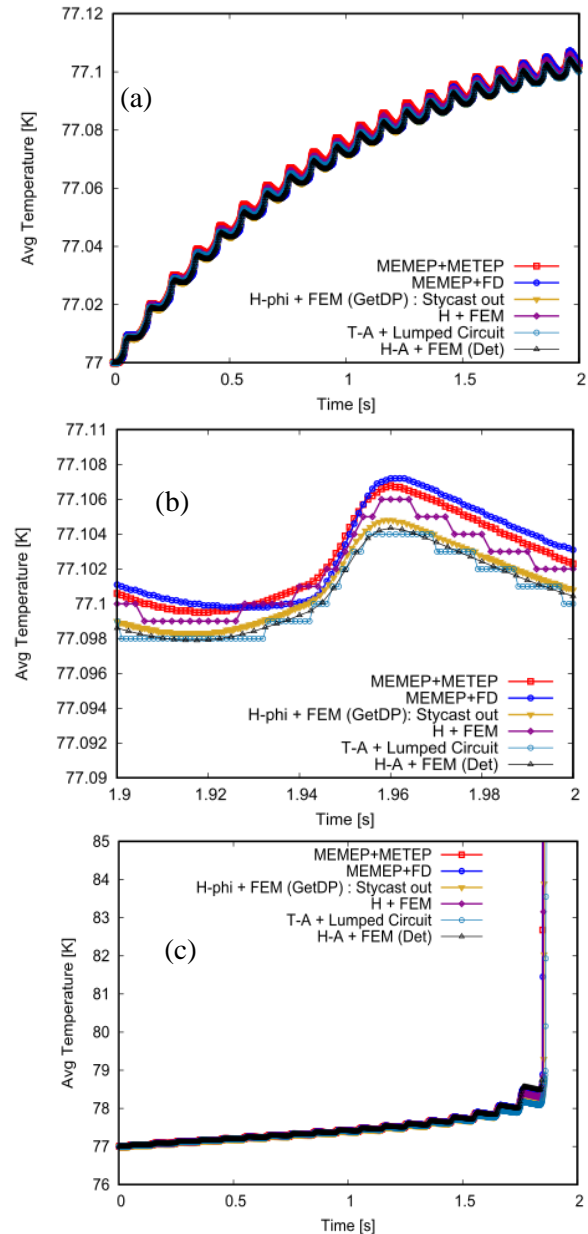


Fig. 3. (a) and (b) shows agreement between different formulations for the homogenization method for 170 A. (c) shows agreement in models for quench with an applied current of 180 A.

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