Modelling of hysteresis losses in HTS Cable-in-Conduit Conductors for large scale applications

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***Abstract*—Several conductor designs featuring HTS stacked tapes for high field, high current applications are being proposed. These conductors are planned to operate in time varying magnetic field and current; thus, the estimation of AC losses is fundamental for the conductor design. In this work, a numerical model based on the finite element method (FEM) and the H-formulation is described, benchmarked against available analytical formulae and applied to real case operational scenario. The impact of the losses – computed with the FEM model – on the operational margin of the coil is assessed with a thermal-hydraulic model.**

Keywords—HTS conductor, hysteresis losses, large scale, FEM modelling

I. Introduction

The quest for high current, high field conductors based on High Temperature Superconductors (HTS) is ongoing [1]. Most of the designs relies on the stacked-tape concepts [2] as well as on the Cable-In-Conduit Conductor (CICC) layout, developed for Low Temperature Conductors (LTS).

Such conductors are required to operate in time-varying magnetic field and current, such as coils for nuclear fusion applications [3], thus they generate AC losses. The losses need to be estimated and eventually reduced during the conductor design and they need to be removed by suitable cooling of the coil. It is thus of paramount importance to be able to quantify the losses to optimize the conductor design and reduce the cooling needs of the coil. So far, the design and analysis of these conductors are relying on the estimation of the coupling losses, which have been measured for few conductors [4]. However, it has been shown that the contribution of the hysteresis and fully coupled losses is not negligible and in several conditions during coil operation, they overcome the coupling losses [5]. This is a peculiar feature of HTS conductors which are composed of wide (few mm) tapes. Instead, in LTS conductors composed of fine filaments (tens of micron) and coils employed in similar contexts the opposite is typically true, i.e., coupling losses typically larger than hysteresis ones [6].

In this work, a numerical model based on the finite element method (FEM) and on the H-formulation is used to estimate the hysteresis losses in large scale conductors, focusing on those proposed by ENEA [7] and SPC [3], see Fig. 1. The model is first benchmarked against available analytical models, then it is applied to a relevant operational scenario foreseen for the coil under investigation. The losses computed with the FEM model are then used as input in a thermal-hydraulic model to assess the impact of the hysteresis losses on the temperature margin to quench of the coil during operation.

II. Numerical Model

A. Description

The FEM model adopted in this work is a 2D model based on the H-formulation [8] and it has been implemented in COMSOL [9]. The choice is based on the flexibility granted by the H-formulation and on the available literature on the topic. Furthermore, in order to optimize the computational time, the homogenization technique proposed in [10] has been adopted: the entire stack is homogenized, thus neglecting the details of each tape, while taking into account the interaction between them. The J_C of the stack is scaled with the cross-section fraction of the superconductor, i.e. $J_{C,stack} = J_{C,tape} \times A_{tape}/A_{stack}$. The model then computes only the hysteretic contribution to the losses of each stack. The dependence of the critical current density on the magnetic field and its orientation is taken into account.

B. Benchmark

The model of one square stack has been benchmarked against analytical formulae available in literature: Fig. 2 shows that the FEM model agrees well with a formulae that gives the losses (in terms of energy per cycle) in a square conductor [11], while, above the penetration field (B_p), the computed results are in agreement with an analytical model developed for the losses (in terms of power per unit length) in a slab [12].

From this result, the need for a numerical model is evident in order to produce more accurate results than analytical models to account, e.g., for the stack aspect ratio.

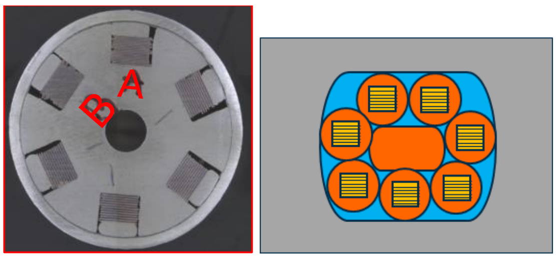

Fig. 1 Cross-section of HTS conductor concepts proposed by ENEA and SPC.

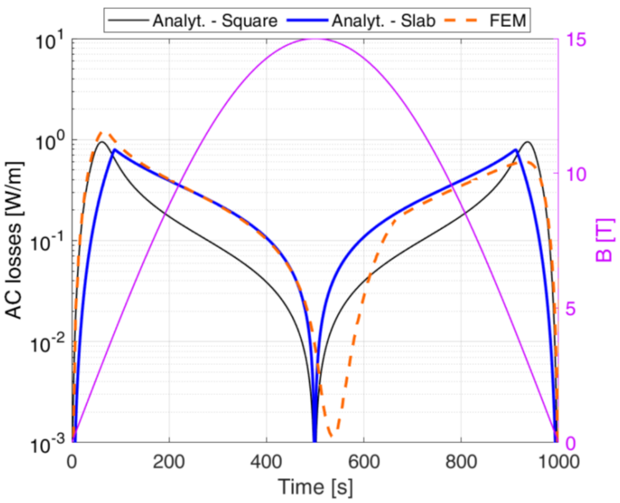

Fig. 2 Evolution of the losses computed with analytical and FEM models. The evolution of the magnetic field is reported in magenta.

Furthermore, the presence of more than one stack, at fields below B_p, prevents the possibility of computing the losses of *N* stacks as *N* times the losses of one stack. For example, the losses of stacks A and B in the ENEA conductor, see Fig. 1, were computed with the FEM model both with the 2 stacks together and as the sum of the losses in A and B. It has been found that the sum of the losses underestimates the actual losses, especially at field below B_p, e.g., at 3 T, the error is around 50%.

III. Results

The hysteresis losses in an operational scenario foreseen for the coil under investigation were computed with FEM model for a CICC made of 7 3 mm x 3 mm stacks, each composed by 30 tapes, as that proposed by SPC. The losses have been used as input to the thermal-hydraulic model of the coil [13], in order to compute the temperature margin, i.e., the margin to the quench of the conductor during the coil operation.

It can be observed from Fig. 3 that, during the magnet charge, up to t = 500 s, and steep discharge –which used to ignite the plasma–, the impact on the temperature margin when hysteresis losses are included in the calculation is not negligible and this result calls for more optimized conductor designs in order to fulfill the design requirements of at least a 1.5 K temperature margin during operation.

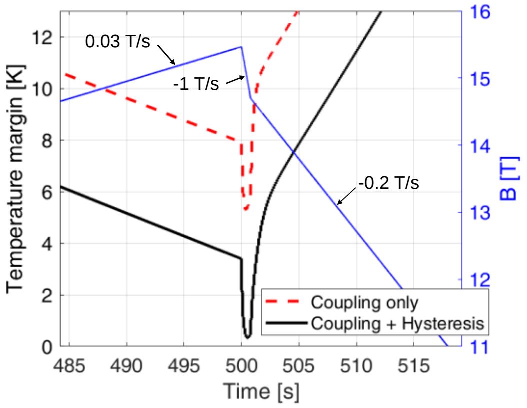

Fig. 3 Evolution of the temperature margin when coupling losses only or when coupling and hysteresis losses are considered. The magnetic field and its ramp rates are also reported

IV. Conclusions

A finite element model for the computation of hysteresis losses in large scale HTS conductors has been developed, benchmarked and applied. The relevance of hysteresis losses in such conductors has been shown, with a thermal-hydraulic model, in terms of reduction of the temperature margin during operation.

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