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Calculation of AC losses in large HTS stacks and coils

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***Abstract*— In this work, we present a homogenization method to model a stack of HTS tapes under AC applied transport current or magnetic field. The idea is to find an anisotropic bulk equivalent for the stack of tapes, where the internal alternating structures of insulating, metallic, superconducting and substrate layers are reduced while keeping the overall electromagnetic behavior. Our work extends the anisotropic bulk model originally presented by Clem et al. and later refined by Prigozhin and Sokolovsky. We disregard assumptions upon the shape of the critical region and use a power law E-J relationship allowing for overcritical current densities to be considered. The method presented here allowed for a computational speedup factor of up to 2 orders of magnitude when compared to full 2-D simulations taking into account the actual structure of the stacks without compromising accuracy.**

***Key Words*—Finite-element modeling, AC losses, coils, homogenization.**

I. INTRODUCTION

SEVERAL works have already modeled a stack of tapes as an anisotropic homogenous bulk. In a first work, Clem et al. [1] adhered to the following assumptions: 1) The critical current density J_c of the superconducting layer is constant. 2) The magnetic field is parallel to the tapes surfaces inside the subcritical region of the equivalent bulk. 3) The boundary between the critical and subcritical zones can be approximated with a straight line perpendicular to the tapes surfaces. In a further work by Yuan et al. [2] the first assumption is discarded by allowing a Kim like model for the critical current density $J_c(\boldsymbol{B})$ dependence. Although the second assumption is kept, the third is improved by using parabolas to fit the boundary between the critical and subcritical zones. More recently, a further improved model was presented by Prigozhin and Sokolovsky [3]. Their model for the anisotropic bulk limit, based on a quasi-variational inequality formulation, does not rely on any assumptions for the shape of boundaries separating the critical and subcritical zones in the stack. However, this formulation is based upon the critical state model using a Kim-like $J_c(\boldsymbol{B})$ dependence. Hence, it assumes a zero electric field E for all subcritical regions and does not allow for considering overcritical local currents. In what follows, a further generalization for the anisotropic bulk model is described where none of the aforementioned assumptions is considered. The treatment is based upon the widely used $\boldsymbol{H}$-formulation using edge elements [4,5] using a power law to describe the $\boldsymbol{E}-\boldsymbol{J}$ relationship. A scaled Kim-like model is used to characterize the $J_c(\boldsymbol{B})$ dependence. The model for the homogenized stack is compared to a fully featured stack of tapes to evaluate its accuracy. All calculations were performed using the Finite Element Method (FEM) software package COMSOL.

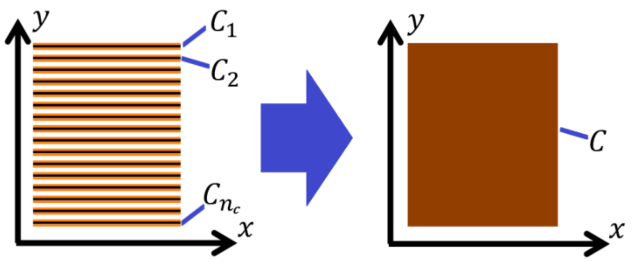

Fig. 1. Original and homogenized models for a stack of tapes. The labels $C_1, C_2, \dots, C_{n_c}$ and C denote each of the tapes in the actual stack (*left*), and the homogeneous-medium equivalent (*right*), respectively.

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II. MODELING STRATEGY

A. H-formulation

The model is based on the $\boldsymbol{H}$-formulation, widely used for simulating the electromagnetic behavior of superconductors in the low frequency regime [4,5]. Given an appropriate set of boundary and initial conditions, the model reduces to solving the following diffusion equation:

$$\nabla \times (\rho \nabla \times \boldsymbol{H}) = -\mu \frac{\partial \boldsymbol{H}}{\partial t}$$

Here, superconducting materials are modeled with a nonlinear resistivity described by a power law $\boldsymbol{E}-\boldsymbol{J}$ relationship.

B. Conventional modeling of a stack of tapes

To model a stack of n_c conductors (left side of Figure 1), each carrying a prescribed current $I_k(t)\ \forall k \in \{1,2,\dots,n_c\}$, one constraint ($C_k$) per conductor ensures such requirement is met:

$$I_k(t) = \int_{C_k} J(x,y,t)dxdy$$

Therefore, all tapes have to be geometrically represented and discretized. In turn, this creates a numerical problem with a large number of degrees of freedom. Although, use of mapped meshes for the high aspect ratio domains helps reducing this burden[6], real applications involving many conductors would require impractically large computing times.

C. Homogenized model for a stack of tapes

The use of an anisotropic bulk model (right side of Figure 1) does not require the geometrical detail of the actual stack. Therefore, the numerical problem is simplified as the discretization yields less degrees of freedom. However, a new constraint is required to assure the intended transport current. In the limiting case of a tightly packed stack composed by infinitely thin conductors, this condition can be expressed as:

$$K(y,t) = \int_C J(x,y,t)dx$$

here, $K(\tilde{y},t)$ is the current density per height transported by an infinitesimally thin conductor at $y=\tilde{y}$ in the stack's bulk equivalent C. Assuming all tapes transport the same current $I(t)$, $K(y,t)$ can easily be expressed as $K(y,t) = I(t)/D$, where D is the distance between the tapes in the original stack.

III. RESULTS

The proposed homogenization strategy was tested by simulating stacks of 16, 32 and 64 tapes, for both transport current and applied magnetic field test cases. Results were compared to simulations of the original stack where all layers:

superconducting, substrate, stabilizer and insulation, were considered (up to the μm scale). For the transport current case, AC currents at 50 Hz were imposed to each of the tapes in the stacks. Amplitudes of the applied currents were 70 A, 60 A and 50 A for the stacks of 16, 32 and 64 tapes, respectively. In all cases, a self-field I_c value of 99.227 A was assumed for a single tape. For the magnetization case, AC magnetic fields at 50 Hz were applied to each stack perpendicularly to the tapes surface. Amplitudes of the applied magnetic fields were 90 mT, 100 mT and 110 mT for the stacks of 16, 32 and 64 tapes, respectively. Values for the AC loss (in W/m) are shown in Tables 1 and 2 for transport current and applied field cases respectively. Overall, the homogenized model shows good agreement with the original stack with decreasing errors for the bigger stacks. In the same manner, computing times for both test cases are shown in Tables 3 and 4. Overall, the performance is better for the homogenized model than for the original stack. The speedup increases with the number of conductors considered. In particular, about two orders of magnitude speedup was achieved for the 64 tapes stack. This is clearly explained by the fact that while more mesh elements – and consequently, degrees of freedom – were required to simulate the original stack, no mesh increase was needed in the homogenized model. Figures 2 and 3 show respectively, the magnetic flux density magnitude $\boldsymbol{B}$ and the normalized critical current density J/J_c for the transport current case. In general, the magnetic field and current profiles in the original stack are reproduced by the anisotropic bulk model. Also, since a power law was used for the $\boldsymbol{E}-\boldsymbol{J}$ relation, local overcritical current values are reached as seen in Figure 3. A similar agreement was observed for the case of applied magnetic field (not shown).

TABLE 1 AC LOSSES, TRANSPORT CURRENT CASE

# of tapes	AC loss (W/m) in original stack	AC loss (W/m) in homogenized stack	Error (%)
16	6.74	6.86	1.72
32	11.33	11.40	0.61
64	15.44	15.47	0.20

TABLE 2 AC LOSSES, APPLIED MAGNETIC FIELD CASE

# of tapes	AC loss (W/m) in original stack	AC loss (W/m) in homogenized stack	Error (%)
16	10.30	10.05	2.45
32	19.86	19.49	1.88
64	41.28	40.61	1.61

TABLE 3 COMPUTING TIME, TRANSPORT CURRENT CASE

# of tapes	Computing time (s) in original stack	Computing time (s) in homogenized stack	Speedup factor
16	3251	639	5.09
32	8583	472	18.18
64	31206	426	73.25

TABLE 4 COMPUTING TIME, APPLIED MAGNETIC FIELD CASE

# of tapes	Computing time (s) in original stack	Computing time (s) in homogenized stack	Speedup factor
16	3702	539	6.87
32	12207	647	18.87
64	76734	676	113.51

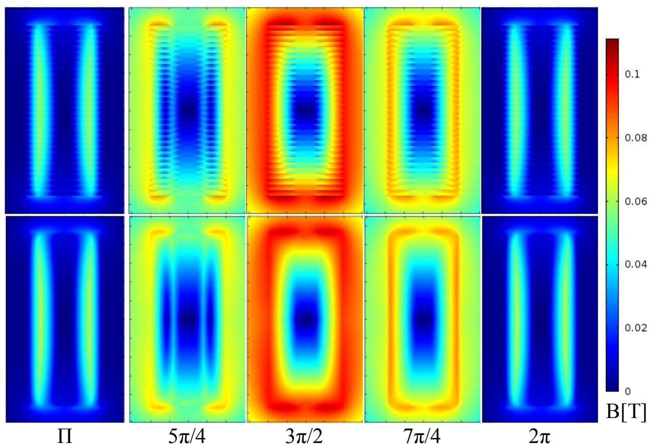

Fig. 2. Magnetic flux density magnitude B [T] for half AC cycle in a stack of 32 tapes in the transport current case. Top: Actual stack. For visualization purposes, domain edges are not plotted. Bottom: Anisotropic bulk model. The actual width of the superconducting layers is 4 mm while the height of the stack is 9.376 mm. The separation between ticks in the plot frames is 1 mm.

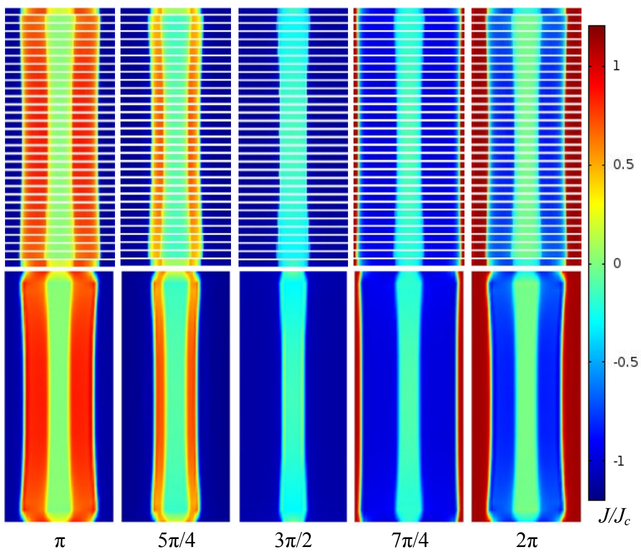

Fig. 3. Normalized current density J/J_c for half an AC cycle in a stack of 32 tapes (transport current case). Top: Actual stack of tapes. For visualization purposes, the superconducting layers' actual thickness is artificially expanded in the vertical direction. Bottom: Anisotropic bulk model.

IV. CONCLUSSION

The anisotropic bulk model for a stack of tapes was extended by the use of a continuous $\boldsymbol{E}-\boldsymbol{J}$ relationship, so that local overcritical current densities were considered. Furthermore, the model presented did not make any assumptions upon the shape of the boundaries between the critical and subcritical regions. The proposed strategy showed good agreement when compared to fully featured 2D simulations. Both current transport and magnetization cases in stacks of 16, 32 and 64 tapes were considered. In particular, calculation of AC losses yielded errors under 2.5%. In general, the anisotropic bulk model outperformed the full 2D simulations in terms of computational speed. A speedup factor of about two orders of magnitude was achieved for the larger coil. Given appropriate initial and boundary conditions, the homogenization method presented here can be used for simulating stacks, ROEBEL cables, and pancake and racetrack coils

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