Impact of strain-dependent J_c on SCIF in 2G HTS magnets

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***Abstract*—2G HTS tapes are strong candidates for the development of future high magnetic field magnets. However, for such applications, field stability and quality are an issue due to the presence of Screening Current-Induced Field (SCIF) and the large magnetic field drift (FD). We propose here to model the screening currents induced during the ramping of a magnet composed of thousands of turns of 2G HTS tapes. The problem includes the strong coupling between the electromagnetic and mechanical model of the magnet through the critical current density. Thus, the latter does not only depend on the magnetic flux density and its orientation but on the local mechanical deformation as well. It is shown that the hysteresis loop shown by the central magnetic field is strongly dependent on the degradation of the critical current arising from mechanical deformation.**

***Keywords*—2G HTS magnets, screening current, screening current-induced field.**

I. INTRODUCTION

2G HTS tapes have reached a matured state that is leading to applications requiring even greater energy density than currently available [1]. In large-scale 2G HTS magnets with tapes of tremendous aspect ratio, the presence of screening currents is known to degrade the quality and stability of the magnetic field [2]. An effect that is amplified by the hoop stress arising from the Lorentz force in large-scale magnets [3]. However, there is no comprehensible study strongly coupling the electromagnetic and the mechanical behaviors of such magnets, yet. In the following work, a functional approach was used to represent the dependence of the critical current density upon the magnetic flux density and the strain average over the tape cross-section. The electromagnetic model uses the new $T-A$ homogenous approach, which is based on the $T-A$ formulation of the Maxwell equations. The mechanical model takes into account the material properties of the different structural elements of the superconducting winding. In this preliminary version of the document, the mechanical model has not been fully implemented and only the dependence of the J_c on the strain is presented.

II. COUPLED ELECTROMAGNETIC AND MECHANICAL MODELS

A. Electromagnetic model: $T-A$ formulation

In the $T-A$ formulation, described in [4], the current vector potential $\mathbf{T}$ is computed in HTS layers simplified as 1D lines, and the magnetic vector potential $\mathbf{A}$ is computed over the entire system from the following equations,

$$\partial_z \left(\rho_{\mathrm{sc}} \partial_z T_{\mathrm{r}}\right) = \partial_t B_{\mathrm{r}} \tag{1}$$

$$\frac{1}{r}\partial_r \left(r \partial_r A_\phi\right) + \partial_z^2 A_\phi = \mu_0 J_\phi \tag{2}$$

A homogeneous Dirichlet condition is applied to A_ϕ at the boundaries of the ”universe”. The transport current for the series-connected tapes is impressed as a Dirichlet boundary condition on T_{r}, satisfying,

$$\frac{I}{\delta} = T_1 - T_2 \tag{3}$$

where I is the transport current and δ is the thickness of the superconductor. T_1 and T_2 are the values of T_{r} at the edges of the 1D HTS layers as shown in Fig. 1. The stack of 1D HTS layers are lumped into sets of homogeneous bulks. T_{r} is defined exclusively over the bulks.

B. Elastoplastic mechanical model (not yet fully implemented)

The non-impregnated 10 pancakes (inner - outer radii: 2 cm - 4 cm, height: 4.45 cm) making the magnet are wound with insulated commercial 4 mm wide REBCO tapes. No co-wound metallic tape is considered in the present study. The elastoplastic model, $\sigma = \tilde{E}\left(\epsilon\right)\epsilon$, relies on the stress-strain relation measured on short samples. The stress σ in the winding is solved via,

$$\nabla \cdot \sigma = \mathbf{j} \times \mathbf{B} \tag{4}$$

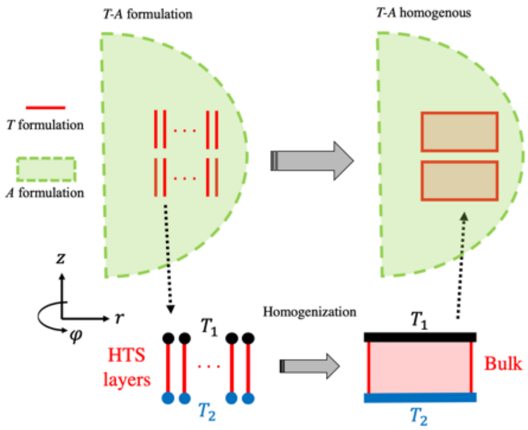

Fig. 1. 2D axisymmetric representation of the solenoidal magnet. The superconducting layers are reduced to 1D lines which are subsequently bunched into bulks.

$\tilde{E}$ is the tensor of Young's moduli depending on ϵ. The Poisson ratio ν is assumed constant for all the materials.

C. Definition of critical current J_c and n index

The electrical resistivity of the HTS material ρ_{sc} is given by the $E - J$ power law with a constant n index equal to 25 and a critical electric field $E_c = 10^{-4}$ V/m^{-1}. The critical current density is divided into a modified Kim relation [4] and a normalized expression depending only on the local strain ϵ so that $J_c(\mathbf{B}, \epsilon) = J_{c,B}(\mathbf{B}) \times J_{c,M}(\epsilon)$. The total critical current density as a function of strain is shown in Fig. 2. The blue-bullet curve is the J_c under traction (loading). For the different strains passed the irreversible strain ϵ_{irr} ($\sim$0.3%), the unloading leads to new curves (red bullets, gray dashed curve). The blue bullet curve and the red bullet, gray-dashed curves were obtained from measurements on tapes provided in [5]. The black oriented curve indicates a likely evolution of J_c after degradation has already occurred.

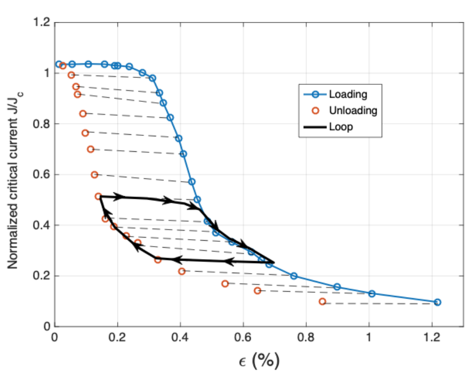

Fig. 2. Dependence of J_c on the strain ϵ [5]. The original curve is referred to as "loading". The J_c enters an irreversible region around 0.3% for which a different curve has to be considered as shown by the "unloading" portions. In red, a strain-dependent degraded J_c.

III. Preliminary Results

Preliminary results on the SCIF is given in Fig. 3 as a function of the nominal magnetic flux density at the center of the magnet computed from a uniform current density $\mathbf{B}_n$. The SCIF is equal to the difference $B_n - B_{scif}$, where B_{scif} is the magnetic flux density computed from the actual distribution of current density inside the HTS layers. Two cases are shown for which the J_c is strain-free and strain-dependent. The black SCIF loop shows a result for which J_c is strain-free (reference case). For the strain-dependent J_c, the SCIF loop flattened thereby indicating a larger amount of dissipation occurring inside the superconductor which arises from the degradation of J_c (red loop in Fig. 2) leading to an increasing in the resistance of the superconducting winding. If the HTS tapes in the magnet winding experience a strain larger than ϵ_{irr}, the strain-dependent case is likely to lead to further degradation rendering the magnet impractical for user operation.

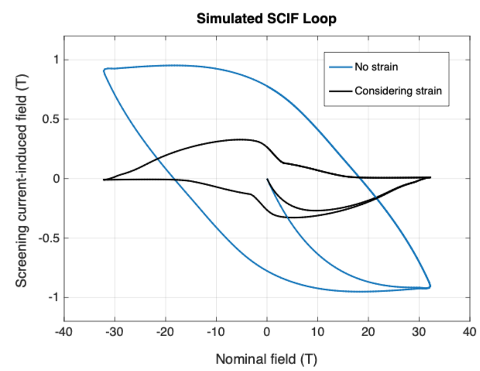

Fig. 3. SCIF loops for strain-free (blue) and strain-dependent (black) J_c.

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