Modelling Interactions Between HTS Tapes and Permanent Magnets

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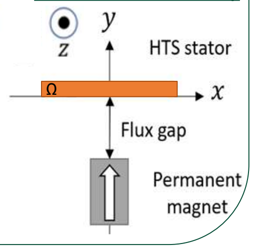
Background

- Permanent magnets (PMs) create highly inhomogeneous magnetic fields and are present in devices such as the high-temperature superconducting (HTS) dynamo.
- Widely available HTS coated-conductor tapes exhibit typical n-values of 20 - 60 and an angular magnetic field dependence on the critical current, $I_c(B,\theta)$.
- The Brandt analytical model poorly describes such devices, assuming a homogeneous magnetic field, operation within the Bean limit (n → ∞) and a constant critical current.

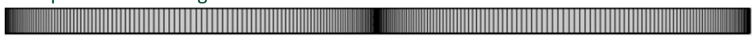
In this work, a finite-element model is constructed to describe the interaction between a coated-conductor HTS tape and a permanent magnet, which is the basis of an HTS dynamo, using COMSOL Multiphysics and measured data from commercial tapes.

Problem Geometry

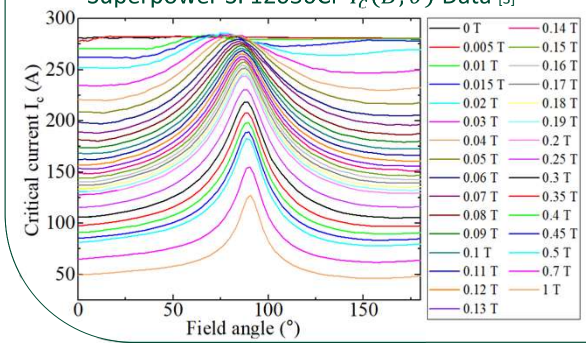


Modelling Methodology

- 2D segregated **H**-formulation model in x-y plane as in [1, 2], comprising a magnetostatic PM model and a time-dependent **H**-formulation model of the HTS tape. PM movement, to vary the flux gap, is mimicked via a translation operator and appropriate boundary conditions.
- The models are coupled via a Dirichlet condition by applying a magnetic field $\boldsymbol{H}_0 = \boldsymbol{H}_{ext} + \boldsymbol{H}_{self}$ on the boundary of the HTS model, where:
  - $\boldsymbol{H}_{ext}$ is the field from the PM model at the tape position.
  - $\boldsymbol{H}_{self} = \frac{1}{2\pi}\iint_\Omega J_z \frac{-(y_0-y)\,\hat{x}+(x_0-x)\,\hat{y}}{(x_0-x)^2+(y_0-y)^2}\,dx\,dy$, where Ω is the tape sub-domain.
- The HTS tape sub-domain uses two logarithmic meshes for greater clarity at the tape centre and edges:



Superpower SF12050CF $I_c(B,\theta)$ Data [3]



Governing equations:

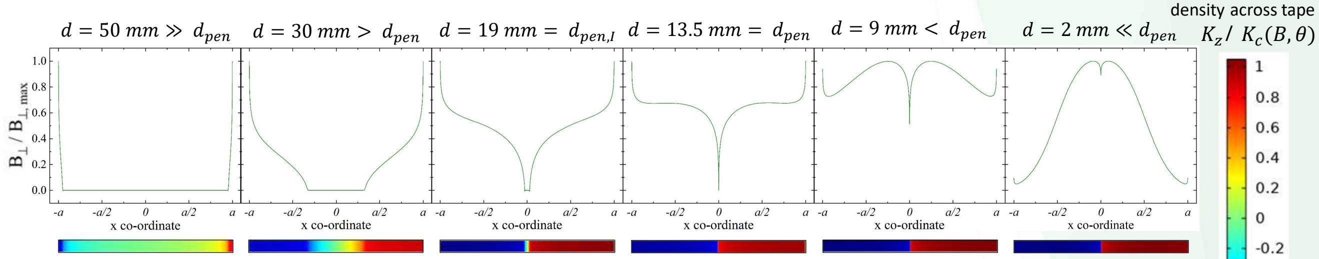
$$\boldsymbol{E} = \frac{E_0}{J_c(\boldsymbol{B})}\left|\frac{J}{J_c(\boldsymbol{B})}\right|^{n-1}\boldsymbol{J}$$

$$\nabla\times\boldsymbol{E} = -\frac{\partial\boldsymbol{B}}{\partial t}$$

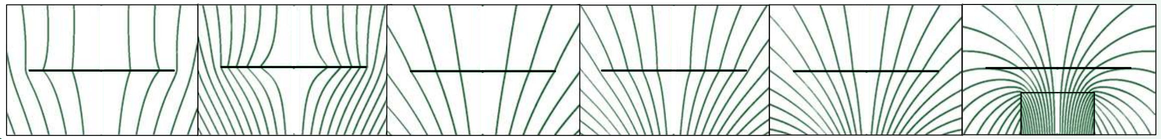
$$\nabla\times\boldsymbol{H} = \boldsymbol{J}$$

Flux Evolution with Permanent Magnet Approach

- When a PM is positioned perpendicularly to an HTS tape of width $2a$, flux penetrates the tape starting from the sides. A shielding current flows around the edges, and the central region remains flux free due to shielding effects.
- As the flux gap, d, is decreased, flux penetrates further into the tape until $d = d_{pen}$, the threshold value at which the flux fully penetrates the tape. At d_{pen}, the tape saturates to the critical current density, with a small current reversal region in the centre.
- For $d < d_{pen}$ the tape remains saturated, however $I_c(B,\theta)$ is suppressed as the field strength at the tape increases.



Flux contours (indicating direction only, not intensity) of the air subdomain surrounding the HTS tape:



Defining Full Field Penetration of Tape

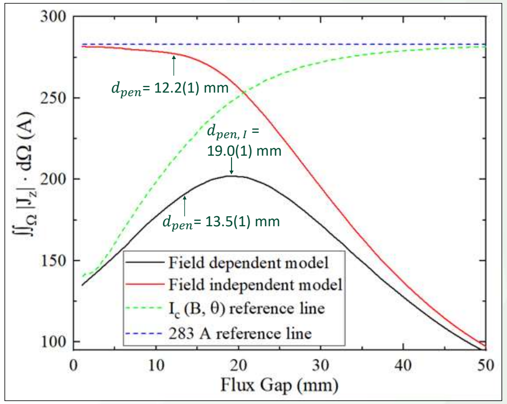
In addition to d_{pen}, the largest flux gap at which there is no region within the tape with $\boldsymbol{B} = 0$, an estimate of the field penetration can be made by examining the current flowing within the HTS stator.

Let $I_z' = \iint_\Omega |J_z| \cdot d\Omega$ and consider a tape with a field dependent $I_c(B,\theta)$. As the magnet approaches the stator, I_z' increases as the current flows in more of the tape until it reaches a maximum. At lower flux gaps, $I_c(B,\theta)$ is suppressed and I_z' is reduced. Thus we can define

$$d_{pen,\,I} = argmax_d \iint_\Omega |J_z| \cdot d\Omega.$$

For a tape with a constant I_c the physics is different. As the magnet approaches the tape, the current reversal zone becomes increasingly narrower and I_z' is asymptotic to I_c instead of exhibiting a maximum.

For the $I_c(B,\theta)$ model with the parameters in the figure caption, d_{pen}= 13.5(1) mm and $d_{pen,\,I}$ = 19.0(1) mm. These numbers don't align as there is a trade-off between the increase in I_z' from the current reversal zone narrowing and the decrease from $I_c(B,\theta)$ being suppressed across the whole tape.



Surface integrals of absolute current across the HTS tape as a function of flux gap using a 12 mm x 10 µm HTS stator and a 6 mm x 12 mm N52 grade PM, with the flux gap reduced from 50 mm to 0.5 mm at a rate of 0.5 mm/s. The model was run using field dependent $I_c(B,\theta)$ data with n = 20, as well as using a constant I_c of 283 A with n = 150.

References:
1) L. Quéval *et al.*, "Superconducting magnetic bearings simulation using an *H*-formulation finite element model" *Superconductor Science and Technology*, vol. 31, no. 8, p. 084001 2018
2) M. Ainslie *et al.*, "A new benchmark problem for electromagnetic modelling of superconductors: the high-T_c superconducting dynamo" *Superconductor Science and Technology*, vol. 33, no. 10, p. 105009 2020
3) R. Mataira *et al.*, "Origin of the DC output voltage from a high- Tc superconducting dynamo" *Applied Physics Letters*, vol. 114, no . 114, p. 162601 2019