Modelling Interactions Between HTS Tapes and Permanent Magnet Fields in an HTS Dynamo

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***Abstract*—The interactions between a permanent magnet (PM) and a coated conductor tape lies at the heart of several types of high-temperature superconducting (HTS) devices, including the HTS dynamo. The applied magnetic field from a PM is typically highly spatially inhomogeneous with large field gradients occurring near the edges of the PM. This situation differs substantially from the well known Brandt analytical model, which describes flux penetration and current behaviour of type-II superconducting strips in a spatially-homogeneous applied magnetic field. The Brandt model also assumes the superconductor exhibits a constant critical current (J_c) throughout, and hence does not take into account the more complex behaviour of practical HTS tapes which exhibit an angular magnetic field-dependence of the critical current, $J_c(B, \theta)$. In this work, a finite-element model is developed to include such considerations and describe the interaction between a permanent magnet and an HTS coated-conductor wire at small flux gap distances similar to those used in the HTS dynamo. The effect of varying key parameters is studied including: (1) changing the critical current, (2) including an anisotropic magnetic field dependence to the critical current density, (3) changing the relative width of the PM to the coated conductor tape, and (4) changing the flux gap between the magnet and the HTS tape. The effects on the flux penetration and current behaviour of the HTS tape are calculated and compared to the Brandt model. Of particular interest are the key differences in the flux penetration profile which are observed when the magnet width is much smaller than the width of the coated conductor tape.**

***Keywords*—HTS modelling, HTS dynamo, flux pump, coated conductor, numerical modelling, finite-element modelling**

I. Introduction

The Brandt model [1], [2] is a useful tool to describe the behaviour of superconducting tapes in the presence of magnetic fields. However key underlying assumptions (of the Bean limit ($n \rightarrow \infty$) and a homogeneous, externally applied magnetic field) are not always valid experimentally. For example - highly inhomogeneous magnetic fields are often present in applications such as the high-temperature superconducting (HTS) dynamo, where a rotating permanent magnet (PM) passes by an HTS stator tape [5], and magnetic levitation, where strong magnetic field gradients occur perpendicular to the thrust direction [6].

In addition, many practical HTS devices operate at liquid nitrogen temperatures (77 K) to avoid the need for expensive liquid helium cooling. At this temperature, widely available HTS coated conductor tapes exhibit typical *n*-values between 20 and 40 [3] and hence are not well-described by the Bean limit. Even at 4.2 K, the *n*-values of many commercial tapes only increase to between 40 and 60 [4]. The analytical model also assumes a constant critical current density, J_c, but in real HTS tapes, J_c has a magnetic field-angular dependence, $J_c(B, \theta)$ [3].

Consequently, modelling the magnetic field and current behaviour of real coated conductor tapes in inhomogeneous, perpendicular applied fields is of interest. In this work, such a model is constructed using the commercial finite-element modelling software COMSOL Multiphysics [7], and *n*-values and $J_c(B, \theta)$ measured from real tapes.

II. Modelling Method

The geometry of the inhomogeneous PM model is shown in Fig. 1. This assumes the 2D case for simplicity. A PM of width *a*, height *b* and remanent flux density B_r, is centred stationary at a distance *c* beneath an HTS coated-conductor wire of width *e* and thickness *d*, such that the axis of the PM is perpendicular to the tape. The remanent flux density of the magnet is increased from 0 T to a maximum value B_{max} at a variable rate of *r* mTs^{-1}. The parameterisation of all variables allows the model to be easily adapted for different contexts.

The model implements the coupled H-A formulation as described and applied in [8], [9], using the H-formulation within the superconducting subdomain and the A-formulation to model the permanent magnet and the surrounding subdomain.

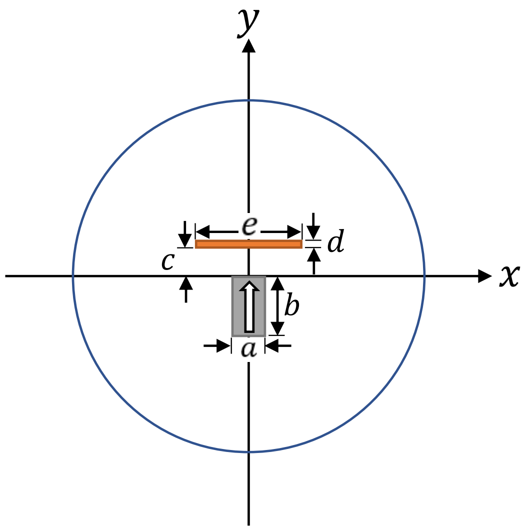

Fig. 1. Geometry of the inhomogeneous applied field model. A permanent magnet is stationary, centred under an HTS tape, and the remanent flux density of the magnet is increased.

III. Initial Results

To initially validate the HTS model, the shielding behaviour of an ideal HTS tape under an externally applied homogeneous magnetic field is examined by approximating to the Bean limit using $n = 120$. The computed results are compared to the Brandt analytical model in Fig. 2 for a range of critical currents. For each I_c, the value of J_c is taken to be constant as $J_c = \frac{I_c}{d \cdot e}$. The value at which flux penetrates the center of the tape such that it is no longer fully shielded, B_p, is calculated for different values of I_c. Table I gives the parameters used for this homogeneous model. Results for the simulation agree closely with the Brandt analytical model.

The inhomogeneous PM case is then considered and also presented in Fig. 2. Parameters used for this example inhomogeneous model are shown in Table I. In this case, a more realistic n-value of $n = 20$ is chosen to better describe practical HTS tape. Similarly a flux gap of 3.7 mm is chosen, as this corresponds to the geometry of the HTS dynamo presented in [9], [10]. The remanent field of the PM is increased from zero, and again B_p is determined for a range of I_c values. There is still linearity between B_p and I_c, but it is clear that magnetic shielding is present in the tape at much higher fields than the Brandt model predicts, due to the finite size of the magnet and the consequent decrease in applied field at the coated conductor.

TABLE I
Modelling Parameters

Stator	Width, e	12 mm
	Thickness, d	1 μm
Critical current, I_c [self-field, 77 K]	28.3 A, 56.6 A, 113.2 A, 283 A, 566 A, 1132 A, 2264 A	
Magnetic field ramp rate		5 mTs^{-1}
Homogeneous n-value		120
Inhomogeneous n-value		20
Permanent magnet (PM)	Width, a	6 mm
	Height, b	12 mm
Flux gap, c		3.7 mm

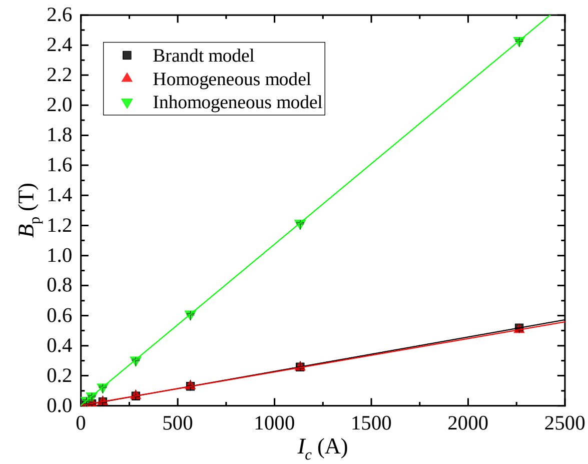

Fig. 2. Applied magnetic field strength at which a superconducting strip is no longer fully shielded, B_p, for a range of critical currents, I_c. The solid lines are linear fits to the data.

Further results will show the effects of adding $J_c(B, \theta)$ considerations, changing the flux gap and field ramp rate, and changing the PM geometry - including the presence of a flux-focusing effect when using a PM with a much smaller width than the coated conductor tape. Ultimately, this study targets improved understanding of the flux penetration behaviour which arises from a finite-sized permanent magnet, in order to better understand the operation of the HTS dynamo and other such devices.

References

[1] E. H. Brandt, and M. Indenbom, “Type-II-superconductor strip with current in a perpendicular magnetic field,” Phys. Rev. B, vol. 48, no. 17, pp. 12893-12906, Nov. 1993.

[2] E. H. Brandt, “Superconductors of finite thickness in a perpendicular magnetic field: Strips and slabs,” Phys. Rev. B, vol. 54, no. 6, pp. 4246-4264, Aug. 1996.

[3] X. Zhang et al., “Study of Critical Current and n-Values of 2G HTS Tapes: Their Magnetic Field-Angular Dependence,” J. Supercond. Nov. Magn., vol. 31, pp. 3847–3854, Apr. 2018.

[4] K. Tsuchiya et al., “Critical current measurement of commercial REBCO conductors at 4.2 K,” Cryogenics, vol. 85, pp. 1-7, May 2017.

[5] L.J.M. van de Klundert, and H.H.J. ten Kate, “Fully superconducting rectifiers and fluxpumps Part 1: Realized methods for pumping flux,” Cryogenics, vol. 21, no. 4, pp. 195-206, Apr. 1981.

[6] L. Schultz et al., “Superconductively levitated transport system - the SupraTrans project,” IEEE Trans. Appl. Supercond., vol. 15, no. 2, pp. 2301-2305, June 2005.

[7] COMSOL, Inc., Burlington, MA, USA, COMSOL version 5.5 [www.comsol.com]

[8] R. Brambilla, F. Grilli, L. Martini, M. Bocchi, and G. Angeli, “A Finite-Element Method Framework for Modeling Rotating Machines With Superconducting Windings,” IEEE Trans. Appl. Supercond., vol. 28, no. 5, pp. 1-11, Aug. 2018.

[9] M. D. Ainslie et al., “A new benchmark problem for electromagnetic modelling of superconductors: the high-Tc superconducting dynamo,” Supercond. Sci. Technol., vol. 33, no. 10, pp. 105009, Aug. 2020.

[10] R. C. Mataira, M. D. Ainslie, R. A. Badcock, and C. W. Bumby, “Origin of the DC output voltage from a high- Tc superconducting dynamo,” Appl. Phys. Lett., vol. 114, no. 16, Art. no. 162601, Apr. 2019.