Modelling AC losses in a high-temperature bulk superconducting axial-flux synchronous machine

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***Abstract*— High-temperature bulk superconductors have been proposed as trapped field magnets to improve the performance of synchronous machines; however, under the influence of time-varying magnetic fields bulk superconductors can experience demagnetization that reduces the trapped magnetic field. This demagnetizing effect will reduce the machine performance during its operation. Studies of demagnetization due to AC fields have been modelled and verified with reasonable agreement; however, there has been little investigation under real operating conditions, such as in a rotating magnetic field or in a machine environment. For this purpose, we constructed a small-scale high-temperature bulk superconducting axial-flux synchronous machine, which has triangular-shaped GdBCO bulks as trapped field magnets in the rotor and regular solenoid copper coils to produce a magnetic field in the stator. A numerical model to reproduce the experiment has also been constructed using a coupled H-A formulation. This combined strategy will allow us to gain better insight into the demagnetizing effect inside the material and make better predictions of the long-term performance of the machine towards providing better strategies to prevent demagnetization in future bulk superconducting electrical machines.**

Keywords—AC losses, demagnetization, bulk HTS, HTS machine, numerical modelling, rotating machine.

I. INTRODUCTION

There is a worldwide interest in utilizing bulk superconductors as trapped field magnets, because they can provide significantly higher magnetic flux density than permanent magnets. Applications for their use include portable high-field magnet systems, ultra-light electrical machines, and compact desktop NMR/MRI systems [1].

In the case of electrical machines, the trapped field in bulk superconductors can decay due to time-varying magnetic fields that are produced by the stator windings. The incident alternating fields penetrate the superconductor, inducing a shielding current that interacts with the pinned magnetic flux vortices (and hence supercurrent) producing the trapped field. If the Lorentz force exceeds the pinning force, then flux vortices leave their pinning sites and a redistribution of currents occur in the volume where the alternating magnetic fields have penetrated and where the flux vortices have been displaced, as discussed in [2]. These effects due to AC fields in the superconductor have been widely studied with experiments, but often these have been done with fields acting either in parallel or perpendicular to the superconductor. However, this is far from the real operating conditions a bulk superconductor would experience in a machine and while attempts have been tried [3], this is still an area of opportunity to carry out more realistic studies and gain a further understanding of the phenomena and its impact on machine performance, as well as use numerical modelling tools to create better strategies to reduce trapped field decay. Our numerical model and experimental setup aim to fulfil such purpose.

II. EXPERIMENTAL SETUP

The experimental setup, representing a small-scale high-temperature bulk superconducting axial-flux synchronous machine, consists of six triangular-shaped GdBCO bulks that are fixed in a copper rotor to help thermal conductivity from the LN_2 bath acting as a coolant. To produce the rotating magnetic field, the machine has a double stator arrangement with six solenoid copper coils above and below the rotor of the machine. The housing and shaft of the motor are made from stainless steel, with some holes in the housing to allow the flow of the coolant in the LN_2 bath. A picture of the device is shown in Fig. 1 and a detailed summary of the components is provided in Table 1. The parameter values given for the bulks, which were fabricated by the top seeded melt growth method [4, 5], are based on an average estimate and may vary slightly between samples. The triangular shape of the bulk was selected because this shape maximizes the volume to be occupied by the superconducting material in the rotor and likewise this geometry should produce a higher force as a consequence of the Lorentz force produced by the radially flowing supercurrent and the incident perpendicular field from the stator coils. This geometry should be more representative of practical trapped field magnets in future electrical machines.

To measure the magnetic field during the operation of the machine, one Hall sensor is installed at the centroid on the top surface of one bulk, while another bulk has three Hall sensors installed in a line along the top surface to study the trapped field profile during operation. Finally, another Hall sensor is located at the centre at the end of one of the stator (solenoid) coils. The bulk at magnetized by field cooling as described in [2], and the stator coils are energized with a signal produced by an Agilent DSO-X 2004A that is amplified using a KEPCO bipolar operational power supply. The speed of the rotor was kept constant using an external DC motor connected to the shaft.

III. MODELLING FRAMEWORK

The numerical model is implemented using the finite element method in COMSOL Multiphysics 5.4. Only one sixth of the motor geometry is modelled by exploiting the symmetry of the geometry, as shown in Fig. 2.

TABLE I. GENERAL PARAMETERS FOR THE SYNCHRONOUS MACHINE

HTS bulks	***Side length, a***	20 mm
	Thickness, t_b	8 mm
	Corner fillet radius, r_f	2 mm
	Critical current density, J_c [Self-field, 77 K]	2.29 x 10^8 A/m^2
Rotor	***Rotor diameter, d_r***	42.85 mm
	Rotor thickness, t_r	8 mm
Stator	***Coil internal radius, d_i***	4 mm
	Coil external radius, d_e	10 mm
	Coil height, h	35 mm
	Copper coil wire diameter, d_c	0.63 mm
	Number of turns, n_i	495

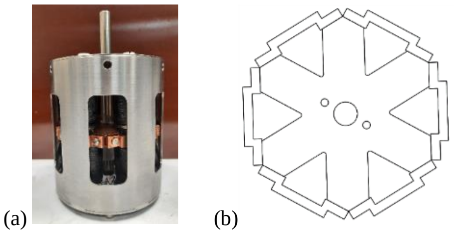

Fig. 1. (a) Small-scale high-temperature bulk superconducting axial-flux synchronous machine outside the LN_2 bath. (b) Top view of the rotor plate where the triangular-shaped GdBCO bulks are fixed.

For the different parts of the model, different formulations of Maxwell's equations were used, as described in [6]. In our model, we solved the domains in the geometry with three different formulations. First, the magnetic scalar potential formulation solves the domains separating the stationary and rotational parts of the model, as this improves its convergence. The H-formulation is used in the domain with the HTS bulk and its surrounding domain. The A-formulation is used in the domains where the stator coils and the surrounding volume are located, as well as the domains surrounding the H-formulation domains and the interface between the H-formulation and the magnetic scalar potential domains. To exploit the symmetry, the periodic boundary conditions were imposed in the A-formulation domain surrounding the H-formulation, thus reducing the size of the model. The coupling between the A and H formulations works by imposing the electric field from A to H, and the magnetic field from H to A. For clarity Figs. 2 (a) and (b) show the different domains coloured according to the formulation used in the model.

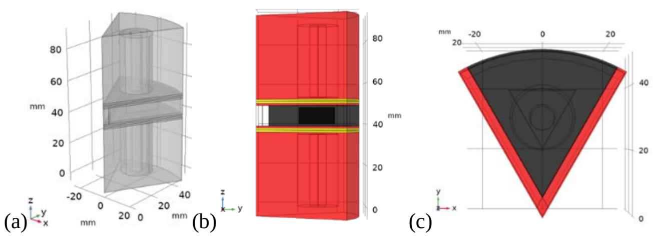

Fig. 2. (a) Geometry of the high-temperature bulk superconducting axial-gap synchronous machine finite-element model reduced to one sixth of the geometry by exploiting symmetry. (b) Side view with the A-formulation domain around the H-formulation domain hidden, (c) The top of the machine with the top vector and scalar potential domains removed for clarity, the vector potential to the right and left side of the H-formulation domain have the symmetric boundary conditions imposed. The A-formulation domains are shown in red, the magnetic scalar potential domains are yellow and the H-formulation domains are black.

IV. PRELIMINARY RESULTS & DISCUSSION

In our preliminary run of the model, it can be observed that demagnetization effects are lower when the external magnetic field is rotating with respect of the superconductor, contrary to the stationary case. This is to be expected as when the bulk experiences the Lorentz force from the stator, it is free to rotate which reduces the experienced Lorentz force on the pinning sites until the system reaches an equilibrium. This trend can be observed in Fig. 3. The modelling framework will allow us to investigate the the impact of loads, frequencies ranging from 8 to 50 Hz and different magnetic field amplitudes from the stator from 25 to 100 mT, to compare with experimental results. Likewise, in the future, these analyses will guide the appropriate operating strategies to reduce AC losses.

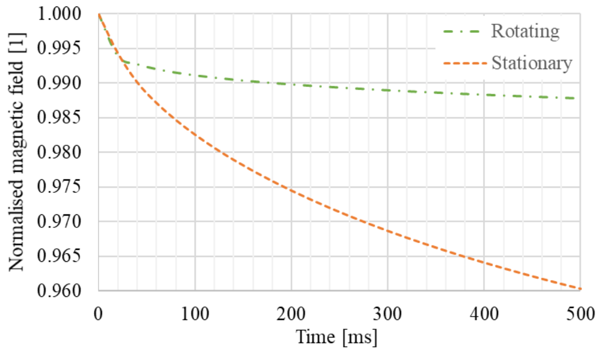

Fig. 3. Results for the simulated trapped field decay: (a) when the bulk experiences an oscillating AC field with a fixed stationary rotor (orange dashed line), (b) when the rotor is rotating at its synchronous speed (green dot-dashed line).

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