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Analysis of an on-line superconducting cryofan motor for indirect cooling by LH₂

V Climente-Alarcon¹, A Baskys¹, A Patel¹ and B A Glowacki^{1,2,3}

¹ Department of Materials Science and Metallurgy, University of Cambridge, Cambridge CB3 0FS, UK

² Institute of Power Engineering, 02-981 Warsaw, Poland

³ Epoch Wires Ltd. Cambridge CB22 6SA, UK

E-mail: vc363@cam.ac.uk

Abstract. This work relates to the study of an electrically powered cryofan for circulating closed-loop cooling helium gas for superconducting applications with the following features:

- Absence of any seal that can leak the pumped fluid or provide a path for heat transfer and require maintenance and/or is prone to failures.
- The use of high temperature superconducting (HTS) stacks on the fan-rotor that, below critical temperature, can be magnetized contributing to the driving torque.

The absence of electrically connected equipment as well as the lack of any seal, makes this arrangement especially suitable for reliable cryogenic helium gas circulation. Because HTS stacks cannot provide magnetic flux above T_c , during the initial stages of operation, in the presented study we analyse the torque that will be provided by the passive iron components of the machine (reluctance torque, due to the saliency of the rotor) and by auxiliary permanent magnets or alternatively magnetizing coils.

1. Introduction

The pumping of cryogenic fluids offers a stimulating environment for the commercial application of superconductors [1]. Up to certain limits, the task of cooling the motor can be left to the transferred fluid, liberating the machine of ancillary equipment that increases cost and reduces the expected time-to-failure of the equipment.

Thus, works on the matter have been proposed recently. For instance, in [2] an induction motor is designed for moving a liquid nitrogen circulator to cool down a high-temperature superconducting power transmission cable. The design procedure is carried out for a conventional, resistive, rotor cage, which was latter replaced by an HTS winding, this approach showed the characteristics that motors under this kind of applications must exhibit compared to larger (i.e. ship propulsion) ones: simplicity in the rotor and absence of connections of this element to external devices. This is especially critical in applications that involve liquid hydrogen, which can be used for cryogenic refrigeration, combustion, or in hybrid transfer lines application [3], where ignition sources in contact to the fluid must be avoided as far as possible.



Hereof, the authors propose further simplifying the structure of the machine's rotor by employing newly developed superconducting stacks [4]. Stacks of superconducting tape layers can trap fields exceeding the performance of bulk superconductors due to their laminated structure [4, 5], in which the superconducting material is deposited on, among others, a metallic layer that provides mechanical stiffness, improves thermal conduction, and may add other important material characteristics that affect the operating characteristics of an electrical motor (such as an increase in magnetic permeability). Below T_c , the superconducting stacks perform the role of permanent magnets, supplying the magnetic flux density \mathbf{B} that interacts with the stator currents to produce torque. For sinusoidal current and flux, the average tangential stress in the air gap, which, when acting on the rotor surface, is responsible for the torque provided by the machine, can be expressed as follows [6]:

$$\sigma_{tan} = \frac{\hat{A} \hat{B} \cos \zeta}{2} \quad (1)$$

where \hat{A} is the peak value of the surface stator current, \hat{B} is the peak value of the magnetic flux density and ζ is the phase angle between both waves. Hence, a way of increasing the power density of a superconducting electrical motor is to attain values of \hat{B} higher than the ones supplied by permanent magnets based on rare-earth materials (~ 1.3 T); such values can be easily surpassed using superconducting stacks, provided that the rest of the magnetic circuit is able to sustain that flux density (iron-cobalt commercial alloys will, for instance, saturate at 2.35 T).

Furthermore, electromagnetic losses in the motor's iron decrease the machine performance and even more dramatically affect its size, due to the square-cube law that relates the surface needed to release those losses to the environment with its volume. Divided in to hysteretic, eddy current and excess losses, they can be calculated from their corresponding tabulated coefficients, k_h , k_e , k_{ex} and also $\alpha(f)$ following expressions such as equation 2 [7]:

$$\frac{h_{losses}}{m_{iron}} = k_h(f) f B^{\alpha(f)} + k_e f^2 B^2 + k_{ex} f^{1.5} B^{1.5} \quad (2)$$

where m represents mass, f is the frequency and B the root mean square value of the corresponding magnetic flux density harmonic. In superconducting applications, the heat released by these effects should be minimized and the remaining transferred, preferably away from the working fluid.

2. Proposed solution

The proposed solution consists of a homopolar inductor machine [1], which could be considered as two radial synchronous machines coupled by the same shaft, one having in the rotor the north poles and the subsequent one the south poles, (hence its name) presented schematically in figure 1. The magnetic circuit is closed between both halves by two iron sockets, one mounted in the rotor and other on the stator, with the magnetic flux flowing axially through them. Enough clearance is left in the latter to install an axially centered coil endowed with the task of providing the field excitation. A rugged synchronous machine with no electric components in the rotor is thus obtained, which simplifies its operation and maintenance and allows higher rotational speeds. The main drawbacks of such a configuration stem from the difficulty in computing the 3D magnetic fields needed for its design (the magnetic flux moves radially between stator and rotor and axially between both halves of the machine) and its bulky construction, which yields a low power density. Nowadays, conventional versions of this kind of machine are being considered for applications in flywheel energy storage systems, taking advantage of the inertia of its relatively large rotor.

What the authors propose in this work is keeping the advantages of this design whilst increasing its power density by combining the latest advances in superconductor materials with the machine's intended use as a cryogenic fluid circulator. Superconducting stacks mounted on the rotor immersed in the cryogenic fluid provide a magnetic flux density for the operation of the motor as a permanent magnet

machine under cryogenic conditions. Above them, the axial field coil would supply a magnetizing flux, and the slightly higher magnetic permeability of the superconducting stacks would provide the necessary flux direction to move the rotor when the temperature of the motor is above T_c , although at a reduced torque (see figure 1).

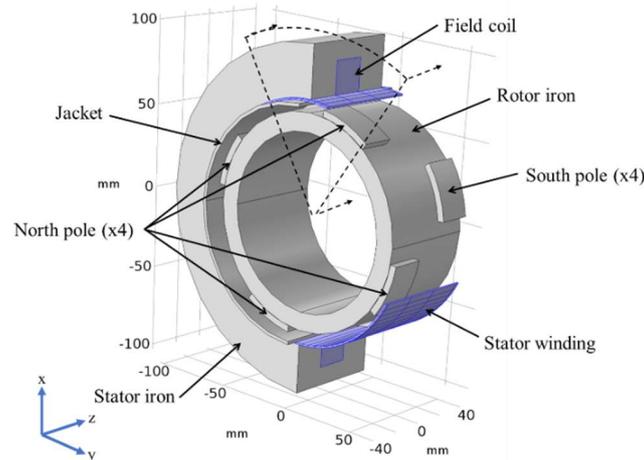


Figure 1. Basic design of the proposed homopolar inductor motor. In blue it is shown the stator winding and the concentric field coil. The poles are formed by superconducting stacks.

In addition, this axial field coil can provide the magnetic flux density necessary for magnetization of the stacks. This flux will follow the lower reluctance path set by the iron and the slightly ferromagnetic stacks, entering the latter radially from the air-gap. Pulsed magnetization will be studied but field cooling may also be possible using this arrangement.

Regarding the heat and mass transfer characteristics, in the proposed design a 2 mm thick fixed non-conductive jacket separates rotor and stator, allowing the former to move inside the cryogenic fluid with no necessity for inserts that could leak. Heat generation is minimized since in the rotor the magnetic flux density is roughly constant, which yields very small losses in the iron. Higher losses are expected in the stator iron behind the winding according to equation (2), since in this part of the machine the flux is changing as the rotor poles sweep the armature (stator) winding, but this part of the machine can be easily refrigerated from outside.

In order to reduce the Joule heating coming from the stator windings, following equation (1) a high magnetic flux density during normal operation of the machine is intended, which would diminish the losses in the conductors. A small value of \hat{A} also allows a simplified winding, with just one layer and no necessity of stator teeth. The relatively wide air gap entails a powerful field coil to keep the machine magnetized above T_c and magnetize the stacks below this value; however, its heat generation can easily be dissipated outwards through the stator iron, which in this part of the machine needs not to be laminated, since the magnetic flux density there is constant.

Despite the fact that the lack of stator teeth will smooth the flux in the air gap and increase the survivability of the superconducting stacks to demagnetization, this field coil will be available during operation below T_c to top the flux up in these elements if needed.

3. Preliminary design procedure

The cryofan has been designed to circulate 60 m³/h of helium at 35 K and 20 atm, increasing its pressure around 2 kPa. For a specific speed of 10,000 (axial), these parameters yield a machine, rotating at 1,800 rpm with a load torque of 0.346 N·m, (with an efficiency of the fan of 55%). Assuming a speed of the fluid of 1 m/s at the impeller, the internal diameter of the machine is 52 mm. From this value, the magnetic circuit is designed following the standard analytical procedure devised for permanent magnet machines. The magnetizing current during operation above T_c establishes the dimensions of the field

coil. The stator winding is designed in a single layer, fixed between the stator iron and the insulating jacket, connected in four parallel paths. The characteristics of the machine are presented in table 1.

Table 1. Geometric characteristics of the machine shown in figure 1

Number of phases	3
Number of pole pairs	4
Total number of stator turns	96
Number of parallel branches	4
Number of field coil turns	500
Inner diameter	53 mm
Rotor yoke width	11.3 mm
Stack height	4 mm
Air gap length	0.5 mm
Insulating jacket width	2 mm
Stator winding width	1 mm
Field coil dimensions	20 × 20 mm

Two finite element (FE) 2D models have been used to validate the initial analytical calculations of the 3D design represented in figure 1. The first one describes a section of the machine in x - y coordinates where the North and South pole stacks have been represented at the same $z = 0$ level in order to compute stator currents and torque. The other is used to check the field coil current needed to magnetize the machine above T_c , assuming a permeability, μ_r , for the stacks of 10, thus studying it in the perpendicular direction to the first z - y plane with $x = 0$. The results summarizing the outcome of both approaches are shown in table 2.

Table 2. Characteristics of operation

	Superconducting operation	Conventional operation
B_{rem} (stacks)	1.33 T	0 T
Field current	0 A (DC)	1 A – 2 A (DC)
Stator current	10 A (rms)	10 A – 20 A (rms)
Back-EMF	2.98 V (square)	0.394 V – 0.779 V (square)
Torque	0.376 N·m	0.05 N·m – 0.2 N·m

According to the FE simulations, the machine can produce the required torque with a current of 2.5 A circulating in each branch of the stator windings during superconducting operation, if the trapped flux is ~ 1.3 T. Above T_c , the torque is reduced to 13.3% of the superconducting one maintaining the same stator current (10 A). However, if the currents in the stator winding and field coil are doubled (something especially feasible for the former since there the current density is low due to the diameter of the motor), the conventional yielded torque can reach 53.2 % of the superconducting one. Furthermore, the reduction of back-EMF facilitates this increase of current from the point of view of the variable speed drive that would control the motor. Figure 2 presents frame captions (at 0.01s) of the time-stepping FE simulations performed showing low saturation of the magnetic circuit indicated by values in the colour-coded bars. A 3D model may be needed to confirm these values.

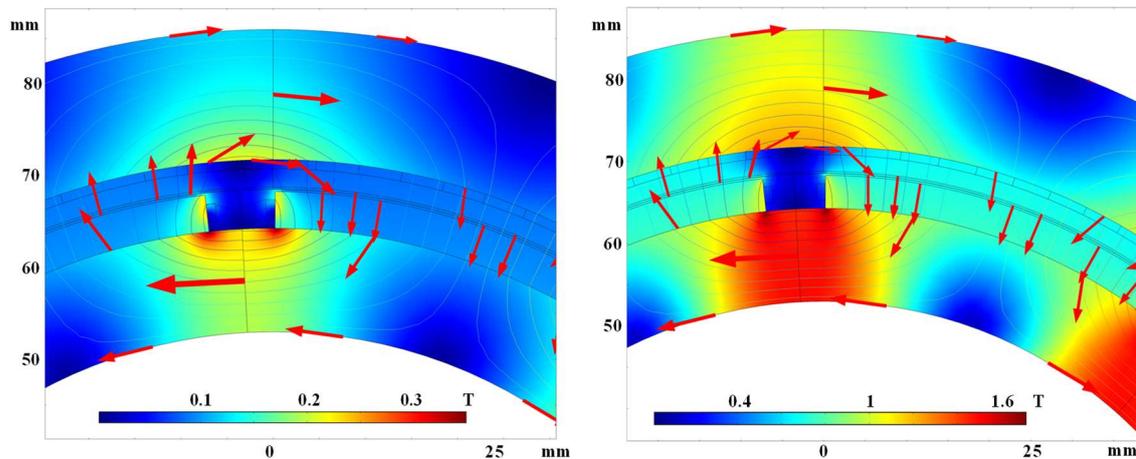


Figure 2. 2D xy -plane finite element analysis of the motor operating with the field coil energized (left) and with stacks magnetized (right) represented in both cases at the same z level. These figures show a 2D approximation to the radial effects in the machine for the area between the dotted lines in figure 1.

4. Conclusions

This contribution presents a design of a superconducting machine applicable to a cryofan circulator, able to operate above T_c using stacks of HTS tape with a higher magnetic permeability than air. In conventional mode, a field coil winding mounted coaxially on the stator provides the required magnetic flux density, whose path is guided by the stacks. Below T_c , the flux trapped in them provides the excitation, with the field coil being used intermittently to top up that flux following any eventual demagnetization. The machine does not require any seal, nor is there any leakage path for the fluid, or any electric circuit in the rotor, making it especially suitable for pumping LH₂. The design is in its preliminary stage, but, in principle, values of magnetic remanence of 2.35 T could be obtained, roughly doubling the ones currently used in permanent magnet motors. This work will be used to develop a fully functional efficient on-line cryofan for electric plane applications.

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