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Design considerations for electric motors using stacks of high temperature superconducting tape as permanent magnets

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Abstract. High temperature superconducting (HTS) tape can be cut and stacked to form composite bulks capable of generating fields as high as 17.7 T, the highest of any trapped field magnet. This makes them the most powerful permanent magnets accounting for the need to maintain a cryogenic temperature. This cryogenic penalty is increasingly being justified due to the significantly higher power densities ($>10\text{ kW/Kg}$) fully superconducting motors can enable by using magnetized stacks of tape on the rotor and HTS coils on the stator. Design considerations for a motor using magnetized stacks for aerospace applications will be presented including FEM modelling in COMSOL and experimental prototype results for candidate designs. The rotor AC loss due to heating by ripple fields will be discussed based on these results and its interdependence with stator AC loss in a fully superconducting motor which has not always been appreciated in previous partially superconducting motor designs.

1. Introduction

The application of high temperature superconductors (HTS) to commercial devices has been troublesome despite the advantages offered by this kind of materials discovered decades ago. The material and electrical engineering worlds have been evolving separately no matter the efforts made to join them. Nowadays the increasing requirements of capital intensive industries, nuclear [1] and aerospace [2], might be opening further application fields. However, these developments from the demand point of view should be also corresponded by advances in the manufacturability and usability of superconductive arrangements.

In this sense, stacks of superconductive tape, consisting of layers of tape soldered together taking advantage of the metallic substrate on the superconducting layer is deposited, offer a stimulating opportunity for its application on electromagnetic devices as substitutes of permanent magnets. Mechanically, they roughly behave as their substrate, which in some cases is Hastelloy (i.e. Superpower tapes), materials well known in the industry; unlike bulks, any random defect in the material should not affect its electromagnetic behavior, since this is averaged among all the layers, there are plenty of suppliers nowadays, and the assembling of stacks is a process so easy that can be carried out in the laboratory with no need of specialized equipment or skills. Recently a world record of a trapped field of 17.7 T has been achieved using superconducting stacks (figure 1) [3].



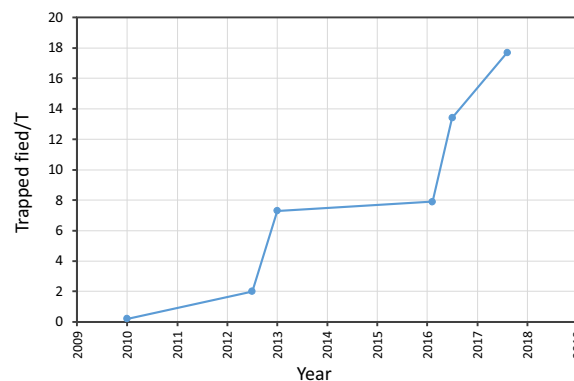


Figure 1. Evolution of maximum trapped magnetic field density in a superconductive stack during the last decade.

Electric motors is a field where the application of HTS materials has been especially studied. Initially, these works were focused on ship propulsion, an area in which weight savings can be achieved whilst maintaining the flexibility and fuel efficiency of the diesel-electric arrangements. The substitution of the field coils of synchronous machines by HTS wound ones could provide higher values of the magnetic flux density (values, for instance, up to 2.2 T [4]) but besides the necessity of surrounding the rotor by a cryostat, the machine remains a conventional one.

In an initial stage of the design of an electrical motor, its power output P can be approximated as [5]:

$$P = n_s V_r \hat{A} \hat{B} \cos \zeta \quad (1)$$

where n_s is the rotational speed, V_r is the volume of its rotor, \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 angle – spatial phase shift – between both waves; so maintaining all the remaining conditions constant, any rise in B achieved with HTS would increase the yielded power proportionally, up to the point of the saturation of the iron (around 2.35 T for the best iron-cobalt alloys being currently manufactured). From (1) it is clear that in order to reach a breakthrough in the use of electrical motors (i.e. plane propulsion), a more radical design, fully superconducting one, must be achieved, acting also on the stator current \hat{A} without increasing the weight, size and losses of the stator windings. Nevertheless, such an advanced design should also keep its complexity as low as possible and hence it seems advantageous to install in the rotor HTS stacks in order to act as a supply of constant magnetic flux density (act as permanent magnets, although at a much higher values of flux) with no need of electrical circuit arrangements in this part of the machine.

2. Magnetization of the stacks

Unlike permanent magnets (PM), generally magnetized after assembling the motor during the manufacturing process, this procedure should be carried out on the HTS stacks prior to operation, hence in similar conditions under which the machine is going to function. Two strategies exist: zero field cooling, followed by the imposition of an external magnetic field that should fully penetrate the stack; and field cooling, when the magnetic field is constant, and the temperature of the sample is decreased to reach a superconducting state (figure 2 a)).

Commonly to both methods, the superconducting electric motor will have, compared to conventional ones, an additional mode of operation to be designed for, a transient, in which electromagnetic and thermal variables are coupled. Sequential magnetization of the poles might also create cogging torque and induce stresses that must be considered during the design stage of the machine. Furthermore, pulsed magnetization would cause sharp changes in those variables (figure 2 b)) being necessary to perform fully coupled multiphysic simulations to ascertain the outcome of such process.

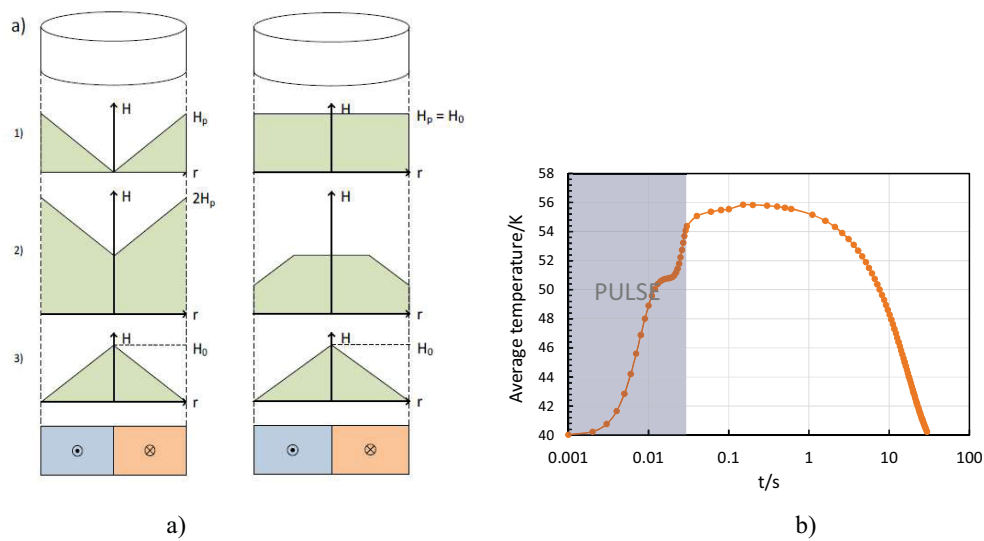


Figure 2. a) Magnetic field and currents in the superconductor during and after zero field cooling and field cooling magnetization according to Bean's theory. b) Temperature's rise during pulsed magnetization.

Consequently, the magnetic circuit of the machine must be adapted to this mode of operation. Leakage paths, routes that can be used by the magnetic flux to skip its desired course, have thus an increased impact in superconducting motors. In figure 3, a Finite-Element computed result simulating the magnetization of a stack mounted on the rotor (below) using the stator (above) currents, can be appreciated how part of the flux fully skips the rotor by jumping from tooth tip to tooth tip. Several strategies may be used to prevent this, but all must be devised in the designing stage of the machine.

Furthermore, the necessity of compensating for the flux leaked might compel to feed the stator with higher currents. Zero field cooling magnetization would also work in the same way. This would have the effect of rapidly saturating the iron present in the magnetic circuit.

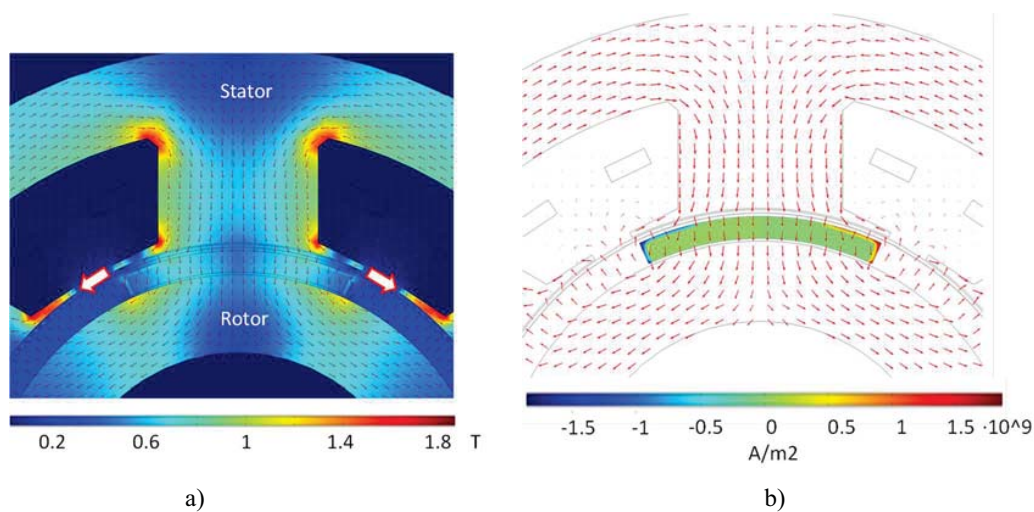


Figure 3. Simulation of the magnetization of a stack mounted on the rotor of a radial electrical machine. a) Magnetic flux density after magnetization showing the leakage paths and b) superconducting current density inside the stack.

Commercial software programmed to solve the electromagnetic state of the section of an electrical machine (2D, radial machine) can be used to compute this kind of problems as long as the common A -formulation can be coupled to the H -formulation needed in the superconducting areas [6].

3. Demagnetization of stacks

Obviously, the same phenomena that accounts for establishing the current vortexes in the superconducting layers of the stacks can disturb them, perturbing the correct operation of the machine. The designer must take into account the intricate magnetic environment in the airgap of a radial electrical machine, where even the smoother fundamental component of the magnetic flux density produced by a carefully tailored rotor is modulated by winding and saliency harmonics caused respectively by the discrete distribution of the stator coils and the stator teeth used to accommodate them.

On one hand, high frequency harmonics, created, for instance, by the stator teeth when passing over the stacks, are especially damaging, causing heating if applied in the normal direction and demagnetization, if their incidence is tangential [7]. A mitigation strategy in this case would consist of adding some shielding in the form of ferromagnetic material that establishes a preferential direction for the magnetic flux density and some leakage paths; however, this could easily constitute a conflicting requirement with the previous point: magnetization. Furthermore, the ferromagnetic material alters the saliency of the rotor, shifting the same phenomenon tried to be avoided in the rotor to the stator windings, if they are superconductive (figure 4). At this point, a sensible approach seems to require the removal of the stator teeth and the operation of the stacks at higher superconducting current densities to maintain the same magnetic flux density in the airgap.

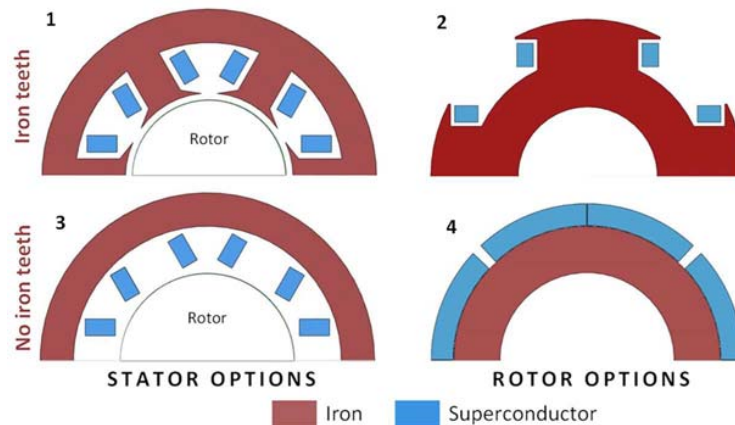


Figure 4. Shielding options to avoid demagnetization on the rotor stacks (2, 4) and increased losses in the stator winding (1,3) of a fully superconducting rotating electrical machine.

For instance, the impact of using the stators 1 and 3 on the rotor 4 of figure 4 is assessed in the following table, where the maximum variation of the normal (facing the airgap) and tangential components of the magnetic flux density on the surface of the stator winding and the rotor stacks is presented.

Table 1. Variation of $|\vec{B}|$ on the stator and rotor SC

Stator configuration	Stator winding		Rotor stacks	
	ΔB_n	ΔB_{tan}	ΔB_n	ΔB_{tan}
Teeth (1)	0.124	0.221	0.193	0.13
No teeth (3)	2.08	0.336	0.0252	0.011

Despite the fact that the stator iron yoke or corona hasn't been eliminated, the effect on the stator windings when the stator teeth are removed is quite severe. In order to obtain an optimal design, further design considerations, such as the capacity of cooling to remove those losses (more difficult in the moving rotor) should be taken into account.

4. Conclusions

The use of superconducting stacks acting as permanent magnets can simplify the construction of fully superconducting electrical machines, aimed at achieving a breakthrough from existing technology although conflicting requirements seem to plague its design. Two different modes of operation must be taken into account: magnetization and normal operation. The magnetic circuit of such device must be carefully designed, probably departing from solutions devised in the past century, decreasing the amount of iron to achieve higher, smoother flux levels and thermal considerations, in the form of coupled thermal computation at the design stage, should accompany any electromagnetic calculation.

Acknowledgments

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