An electrical gearbox by means of pole variation for induction and superconducting disc motor

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Abstract. In this paper, a poly-phase disc motor innovative feeding and control strategy, based on a variable poles approach, and its application to a HTS disc motor, are presented. The stator windings may be electronically commutated to implement a 2, 4, 6 or 8 poles winding, thus changing the motor’s torque/speed characteristics. The motor may be a conventional induction motor with a conductive disc rotor, or a new HTS disc motor, with conventional copper windings at its two iron semi-stators, and a HTS disc as a rotor. The conventional induction motor’s operation principle is related with the induced electromotive forces in the conductive rotor. Its behaviour, characteristics (namely their torque/speed characteristics for different number of pole pairs) and modelling through Steinmetz and others theories are well known. The operation principle of the motor with HTS rotor, however, is rather different and is related with vortices’ dynamics and pinning characteristics; this is a much more complex process than induction, and its modelling is quite complicated. In this paper, the operation was simulated through finite-elements commercial software, whereas superconductivity was simulated by the E-J power law. The Electromechanical performances of both motors where computed and are presented and compared. Considerations about the systems overall efficiency, including cryogenics, are also discussed.

1. Introduction
The use of HTS materials in the construction of electrical machines presents some characteristics that make them worthwhile in a wide range of applications when compared with conventional conductor materials. Among their fundamental properties it is highlighted the ability to carry large currents (in the order of 104 A.cm-2) with minimal losses when compared with copper conductors of the same cross section, and the consequent generation of high magnetic fields (up to 10T).

The output power, $P_{out}$, of any rotating machine can be expressed as [1]:

$$P_{out} \propto B_{g,\text{max}} \times A_{s,\text{max}} \times N \times V$$  \hspace{1cm} (1)

where $B_{g,\text{max}}$ is the maximum flux density in the air-gap, $A_{s,\text{max}}$ is the maximum stator load current, $N$ is the rotor speed and $V$ is the rotor active volume. Ferromagnetic materials are used in conventional motors in order to increase flux density. However flux density is limited to about 1.5 T, owing to materials saturation. On the other hand, current limits are imposed not only by the ability to dissipate Joule effects energy, but also by the available space to accommodate the conductors. Since HTS materials can also carry large currents in smaller sections, with reduced losses, they do not present the heat dissipation and space availability limitations. Thus, it is possible to achieve a reduction in machine dimensions that can go as far as 70% [2] and an increase in the overall efficiency up to 0.8%,
including the cryogenic system costs. The disc motor described in this paper is a HTS hysteresis disc type. This machine presents two operating regions, a synchronous and an asynchronous one. Two control strategies are considered: by variation of the input frequency and variation of the number of poles. The first one is usually done by power invertors [3] while the second is a complex process that generally consists in the following approaches [4]: one stator winding with commutable sections with ratio 1:2; two commutable independent stator windings; two independent stator windings, each one with two commutable sections with ratio 1:2, creating 2, 4, 3 and 6 poles. Power electronics can supply different number of phases [5] that together with an appropriate armature design [6] might change this approach, making the control more versatile.

Since the integration of disc motors with fuel cells in electric vehicles is a modern trend, this control method may implement an electrical and compact gearbox. The use of liquid hydrogen as fuel in electric vehicles may be a possibility in a near future [7], allowing also to cool HTS materials to 20 K, instead of 77 K obtained with liquid nitrogen (LN2). These cryogenics temperatures can also be used to cool power electronic circuits. A performance increase is expected when compared with the usual performance at ambient temperature, e.g. by the reduction of ohmic losses [8].

The proposed disc motor is built by two half-stators with conventional copper conductors. In this project’s first stage, the rotor is built by aluminium and in the second stage HTS materials (YBa2Cu3O7-x or YBCO) cooled by LN2 are used. The superconductor disc motor has a fragile rotor due to the ceramic nature of the HTS material, and also it needs cooling to cryogenic temperatures (≈ 92 K in YBCO), but a high specific torque is its expected advantage.

2. Motor Topology

The disc motor has an excellent torque/speed characteristic and a fast response [9]. The proposed disc motor’s stator (see figure 1) is built by two double layer half-stators. The rotor will be an aluminium disk in the conventional motor, or a disk of HTS bulk material in the superconductor motor. The performances of both motors, differing in their rotors, will be computed and compared [10].

Each half-stator has 24 slots, where the slot pitch, , is given by:

\[ \sigma = \frac{360^\circ}{\text{slots number}} = \frac{360^\circ}{24} = 15^\circ \text{mec} \]  

(2)

The width of each slot, , is given by

\[ c = \frac{p_{\text{avg}}}{48} = \frac{2\pi r_{\text{avg}}}{48} = \frac{\pi D_{\text{avg}}}{48} \]  

(3)

The inner and outer diameters were determined by a maximizing torque rule-of-thumb.
According to figure 1c), being $D_{outer} = 200$ mm the rotor’s external diameter, it results $D_{inner} = 115$ mm for the internal diameter (4) and $D_{avg} = 157.7$ mm for the average diameter. Consequently the slot width is $c = 10.31$ mm (3).

The linearised version of the motor is presented in figure 2. This will be used in the finite elements simulations. According to figure 1 c) and figure 3 the area of copper conductors is $S_{geom\_Total} = 2c^2 = 212.6$ mm$^2$. The area of the copper conductors for only one layer is $S_{geom\_layer} = c^2 = 106.3$ mm$^2$. With a stacking factor $\alpha = 0.5$, the number of conductors per slot with a copper cross section $S_{Cu} = 1.5$ mm$^2$ is $N_{Cu} = \frac{S_{geom\_layer}}{S_{Cu}} \times \alpha = \frac{106.296}{1.5} \times 0.5 \approx 35$ conductors per layer and $\approx 70$ conductors per slot.

The pole-pitch, $P_p$, depends of on the machine poles pair’s number, $p$, leading to

$$P_p = \frac{360}{p} \quad (6)$$

Figure 3 shows some details of the coils’ connections.

The motor was designed with a vertical axis, to make easier its operation in liquid nitrogen. Figure 4 shows details of the motor’s design, including details of its windings.

![Figure 3. Linearised version of the motor (six slots shown) and coils connections.](image)

![Figure 4. Vertical axis disc motor and windings coils.](image)

### 3. Control System

For a given pole configuration (and a corresponding torque/speed characteristic) the motor speed can be modified through the input frequency. On the other hand, the torque/speed characteristic is modified by an alteration of the number of poles: the higher the number of poles, the lower is the synchronous speed and higher is the developed torque. This is similar to the usual operation of a gearbox.

In this work the number of poles is varied “virtually” with the help of power electronics, instead of mechanically changing the windings connections, as described previously and depicted schematically in the blocks diagram of figure 5.
Figure 5. Components and control scheme.

The PIC controls the power electronics (with MOSFET or IGBT), which creates 24 currents with the same amplitude and frequency and with the necessary 24 phases to make the intended number of poles; these currents are injected in the respective coil. The coil’s current phase depends on the number of poles required, i.e.,

$$\phi(k) = -k \times \frac{N_{\text{poles}}}{N_{\text{slots}}}$$

where $k$ is the half-stator slot number ($k = 1, 2, 3, \ldots, 23, 24$), $N_{\text{poles}}$ represents the number of poles (2, 4, 6 or 8 poles) and $N_{\text{slots}}$ it’s the number of slots in each semi-stator (motor construction parameter - fixed).

Each semi-stator has 24 slots and each slot has two coils; through the magnetomotive force “space-time” characteristic we can determine the machine’s number of poles.

The schematic of the coils’ connections is represented in the figure 7.

Figure 6. Coil pitch, $\tau = 4$ slots.

The coil pitch is $\tau = 4$ slots, i.e., it has a 4 slots space shift and the mathematical equation is:

$$I_{\text{lower}}(k) = I_{\text{upper}}(k + \tau) = I_{\text{upper}}(k + 4)$$

In this work the number of poles is varied “virtually” with the help of power electronics, instead of mechanically changing the windings connections, as described previously. The evolution of the currents in the upper and lower semi-stators and of the developed magnetomotive forces, as functions of the slots number, for 2, 4, 6 and 8 poles, and for instant $t = 0$, are show in Figure 7 to 10; these results were obtained with MatLab®. As expected, the mmf and the torque increase with the number of poles. At the same time, synchronous speed decreases.

Flux line simulations were made using a commercial finite elements software (Flux2D) and the corresponding air-gap flux density distributions were obtained and are shown in Figure 11 to 14.
Figure 7. MMF and current distribution for 2 poles configuration.

Figure 8. MMF and current distribution for 4 poles configuration.

Figure 9. MMF and current distribution for 6 poles configuration.

Figure 10. MMF and current distribution for 8 poles configuration.

Figure 11. Flux lines and Airgap flux density for 2 poles.

Figure 12. Flux lines and Airgap flux density for 4 poles.
4. Performance comparison of a Disc Motor with Aluminium Rotor versus YBCO Rotor

The aluminium rotor motor is an asynchronous motor, where the rotor angular speed, $\omega_m$, is given by:

$$\omega_m = \omega_s (1 - s) = \frac{2\pi f}{p} (1 - s)$$  \hspace{1cm} (9)

where $\omega_s$ is the angular speed of the stator rotating, $f$ is the stator currents frequency and $s$ is the slip.

According to (9) it is clear that the speed may be controlled by changing the frequency and number of poles. The linearised disc motor when the rotor is aluminium is the LIM (Linear Induction Motor) and the travelling field velocity is given by:

$$v = \frac{2\tau f}{p}$$  \hspace{1cm} (10)

where $f$ represent the input currents frequency and $\tau$ is the magnetic pole pitch and $p$ represents the stator poles pairs.

One the other hand, the motor with YBCO rotor is the equivalent of a conventional hysteresis motor. Simulation and experimental results on hysteresis drum and disc motors [11] show that its torque/speed characteristic is rather complex, with synchronous and asynchronous regions. These are determined by the HTS material pinning properties. Flux lines penetrate the material in discrete quanta supported by current vortices which are pinned in heterogeneities, thus magnetising the rotor. A torque is generated and the rotor follows the rotating field with synchronous speed, leading it by a certain angle. If the synchronous speed is “high” the pinning forces act as of those of a viscous fluid and a slip appears and then the motor’s behaviour is asynchronous.

Using the finite elements program Flux2D some characteristics’ are presented.

Figure 13. Flux lines and Airgap flux density for 6 poles.  
Figure 14. Flux lines and Airgap flux density for 8 poles.

Figure 15. Time evolution of the linear speed 2, 4, 6 and 8 poles.  
Figure 16. Comparison of Aluminium rotor and YBCO rotor motors time-speed characteristics.
Figure 15 shows the expected variation of synchronous speed with the inverse of the number of poles (equation 10). In figure 16, also as expected, it is seen that the aluminium rotor motor is an asynchronous motor, never reaching synchronism and keeping a slip towards the field, while the HTS rotor motor is a synchronous motor, running at synchronous speed.

Under load conditions, the simulated behaviours of the designed LIM with 2, 4 or six poles, with aluminium rotor or with YBCO rotor are comparable (figures 17-20). The figures show that under the same conditions, the HTS rotor motor develops higher force than its aluminium rotor counterpart.

![Figure 17. Couple load behaviour of disc motor with aluminium rotor.](image1)

![Figure 18. Couple load behaviour of disc motor with YBCO rotor.](image2)

![Figure 19. Force vs time for 4, 6 and 8 poles and for Aluminium rotor and YBCO rotor.](image3)

![Figure 20. Dynamic behaviour for 4, 6 and 8 poles and for Aluminium rotor and YBCO rotor.](image4)

5. Conclusion and future work

A variable poles control strategy that implements a compact electrical gearbox is presented in this paper. Its goal is the control of induction and HTS disc motors. I also compare the performances of disc motor with aluminium rotor (induction motor) and with HTS materials (hysteresis motor).

Simulations are currently running on Flux2D in order to fully characterise both motor configurations. Result will be integrated with Simulink® in order to optimize control parameters. Stator design is being optimized as HTS rotor which is built by textured polycrystalline YBCO.

After motor assembly, experiments will be carried out.

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