Preliminary Studies and Test Results of a Superconducting Hysteresis Motor with Multiphase Windings and Variable Number of Magnetic Poles

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Abstract. In this paper a procedure for determining the number of different synchronous speeds that can be obtained from the stator of a drum motor as a function of the number of slots is presented. This preliminary study is foreseen for a hysteresis high-temperature superconducting motor, but the approach is directly applied in conventional motors. The targeted device has multiphase windings, in order to achieve full flexibility in torque-speed space through electronic variation of magnetic poles. Simulations are performed in order to achieve a qualitative understanding of the behaviour of the motor, namely in what concerns to torque and settling times from initial to synchronous speed. A prototype with eighteen slots in the stator and a bulk YBCO rotor is described and built, and experimental values of torque are obtained.

Keywords: Superconducting hysteresis motor; Electronic pole variation; multi-phase motor.

1 Introduction

For electric motors the need for changing speed and the corresponding torque and power as a way to adapt machines to the contexts of variable load is almost an inevitable situation. A variety of techniques for changing and control speed of electric motors have been proposed for decades, including virtual gearboxes, i.e., electronically changing the number of magnetic poles of stator windings during motor operation in multiphase motors [1,2].

On the other hand, the exploitation of hysteresis in high temperature superconducting materials, when this material builds the rotors of electric motors, results in higher torque values than those obtained in hysteresis motors with ferromagnetic rotors, i.e., higher power density is obtained in comparison with conventional hysteresis motor [3,4,5,6,7].

Conventional hysteresis motors are known to be reliable and with the most simple fabrication process among electric motors types [8,9]. Yet these motors are normally applied in relatively low power contexts, where the low noise and constant torque during asynchronous operation are the two main parameters determining its selection.

As previously mentioned, higher power density is achieved when using superconductor hysteresis rotors, thus allowing considering applications as transportation or variable load winch drives, where the changing of power and torque are the normal operating conditions.

The synchronous speed of an electric motor depends on the number of magnetic poles of the stator winding and supply voltage frequency. Changing synchronous speed is commonly achieved by acting on the latter, trough power electronic inverters, which is a well established process [10]. Synchronous variation through changing number of magnetic poles is a more complex process, and hardly ever used. This can be implemented mechanically [11], typically with ratio 2:1, by the following approaches: a stator with a single set of windings divided in sectors, where number of poles is set by commutation of those sectors; a stator with two independent sets of windings; a stator with two independent sets of windings, each divided in sectors, which allows other ratios. Besides maintenance and reliability issues, mechanical commutation limits flexibility, as all possible pole configurations are established after the machine is built.

Techniques for electronic commutation of poles have already been defined, such as Pole Amplitude Modulation [12] or Pole Phase Modulation [13]. However, these still raise some difficulties, as limited pole changing ratios, namely p: p-1, where p is the number of pairs of poles; discontinuous stators with asymmetrical windings, which are hard to build; or inefficient use of stator slots.

The technique foreseen in this paper was described elsewhere [2], and solves some of the previous problems. It uses as much windings as slots, allowing operation in a large number of poles configurations. Power electronics is used to generate supply voltages with controlled frequency and phase shift, allowing obtaining different configurations of stator poles.

In this paper, preliminary design of multiphase motor, aiming the previous strategy is described. Since the number of armature and rotor poles must be the same, only asynchronous (conventional) or hysteresis (either conventional or superconducting) motors are eligible. A superconducting hysteresis motor is selected.

Considerations about the number of different synchronous speeds and configuration of a multiphase motor are detailed in next section. Dynamic simulations of different topologies under a qualitative approach are subsequently presented, followed by the details of the prototype manufactured. First experimental results are then shown, and conclusions and future work are drawn in the last section.

2 Contribution to the Internet of Things

Hysteresis motors with conventional stators but rotors made of high temperature superconductors in a cylindrical shape are machines of simple design and construction, which preserve the robustness characteristics of the conventional hysteresis motor. The possibility for changing the configuration of the windings, through the number of phases, the number of poles and by the frequency change of the electrical currents, allows the adjustment of speeds and torques to the application context. These variables are key factors for knowledge enhancement of the hysteresis motor in transport applications, for example, where the adaptation of torques and speeds to the context demands are very important features. Adequate interface devices and software for communication and control allows the abstract representation of the motor, aiming the control of its variables through the internet communication infrastructure. Data may be obtainable through different variables in a number to be defined and developed accordingly to research work.

3 Theory of Variable Poles and Phases

Power converters allow generating multiphase voltages, with controlled phase angles and equal amplitudes. As in conventional three-phase stators, symmetry must prevail, arising from equal spacing or equal number of stator slots between active conductors of a phase, from equal values of currents and frequencies in all phases and a constant relationship between geometrical slot position of a phase and the time difference between phase currents. The result is a rotating magnetic field with constant magnitude where its speed depends on the value of supply frequency and number of magnetic poles. Changing phase angles allows changing the number of magnetic poles on the stator [2]. This imposes not only different motor speeds, but also different torque and power. It is important to mention that the number of different voltages generated by the power converter depends on the value of the phase angles of each voltage, e.g, 24 voltages with phasors displaced by 30º builds a 12-phase system.

To improve magnetic field paths within the motor, electric phase coils fill stator slots and they are thus determinant in the number of phases and the number of poles in each phase. Table 1 shows the relationship between the number of slots, poles and phases in a stator with 18 slots and a single layer of conductors in each slot. There are thus three possible synchronous speeds with this configuration, corresponding to 2, 6 and 18 poles, although the theoretical single phase corresponding to 18 poles is meaningless, as it corresponds to a pulsating field, thus with zero speed. Figure 1 illustrates the particular case of three phases and six poles, within a stator of 18 slots.

Table 1: Number of different speeds achieved with a motor with 18 slots, single layer windings, and different number of phases. There are thus three different possible speeds, although one corresponds to nil speed

Number of poles	Number of different supply voltages (phases)
2	3, 9
4	-
6	3
8	-
10	-
12	-
14	-
16	-
18	1

The number of different synchronous speeds in Table 1 is obtained by counting the number of integer divisions of the number of slots and the even numbers of poles, $C/2p$, where C is the number of slots and p the number of pairs of poles. With 18 slots, two different synchronous speeds are thus possible.

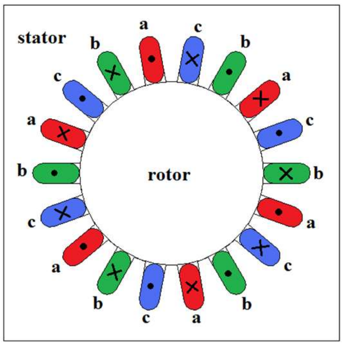


Figure 1: Winding configuration for a stator with 18 slots, in a three phase and six poles configuration.

The relationship between the number of slots and possible different speeds is illustrated in Figure 2, for stators up to 200 slots. It can be observed in also that the number of different speeds is roughly limited by the root of the number of slots.

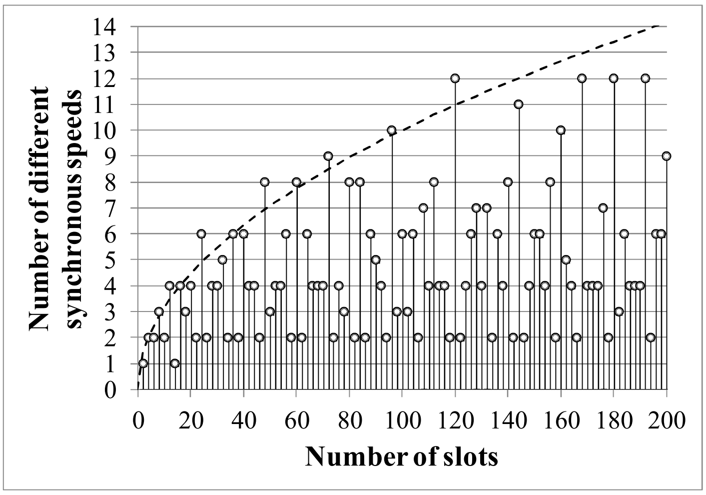


Figure 2: Number of different speeds as function of the number of stator slots. There is an envelope on the number of speeds given roughly by $\sqrt{C}$, where C is the number of slots available in the stator.

The magnetomotive force (MMF) produced by an m-phase symmetrical system, F_{tot}, where each phase is geometrically displaced by $2\pi/m$ rad, with $2p$ poles per phase, and current in phase j is given by

$i_j(t) = I_{max}\cos(\omega t + \theta_j)$, where I_{max} is the amplitude, $\omega = 2\pi f$ is the angular speed, f is the frequency, and θ_j is the phase angle, is

$$|F_{tot}| = \sum_{i=1}^{m} |F_i| = \frac{m}{2}\frac{4}{\pi}\left(\frac{N}{2} I_{max}\right)\cos(\omega t - p\theta) \quad (1)$$

where N is the number of conductors in each winding, $4/\pi$ corresponds to the fundamental amplitude of each squared MMF and θ is the geometric angle over stator surface.

The slots occupied by each phase are related with the number of poles in the same phase. After the previously explained calculation, it is now possible to regroup the slots in each phase, thus changing the number of poles but not the number of phases. As an example, the six poles/three-phase stator illustrated in Figure 1 can be rearranged in a two poles/three-phase system, as shown in Figure 3.

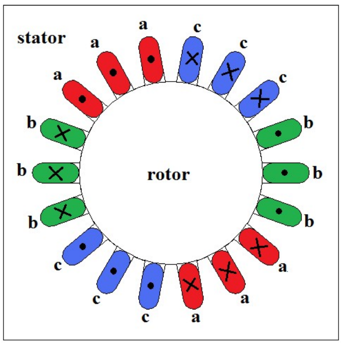


Figure 3: Regrouping slots allows changing a three-phase hexapolar motor into a three-phase bipolar configuration.

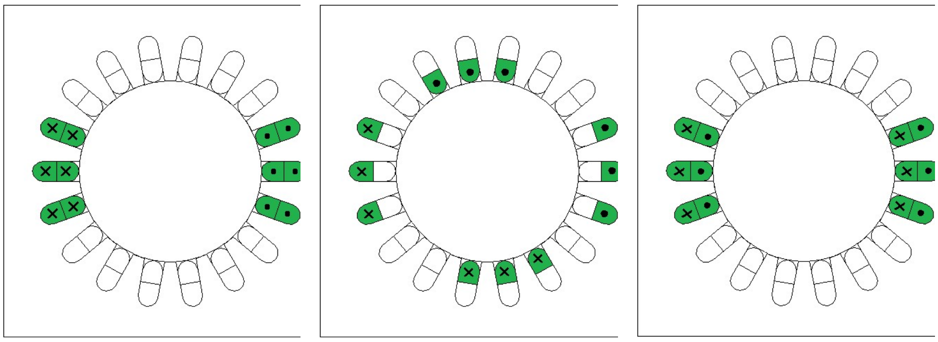
It is possible to regroup the slots per each phase if the condition $N_p = 2p \times G$ applies, where N_p is the number of slots occupied by each phase and G the number of adjacent slots. In Figure 1, $N_p = 6$, $p=3$ and $G=1$. In Figure 3, N_p remains equal to 6, $p=2$ and $G=3$. The total number of different speeds calculated according to Table 1 is not altered.

Despite the unchanged total number of different speeds, when regrouping phase slots the total MMF force amplitude is changed as result of

$$|F_{tot}| = \sum_{i=1}^{m} |F_i| = G\frac{m}{2}\frac{4}{\pi}\left(\frac{N}{2} I_{max}\right)\cos(\omega t - p\theta) \quad (2)$$

Different torque values are possible with the same speed, which improves the number of different values of available power. In (2), the effects of geometrical displacement of adjacent coils in a regrouped phase are not taken in account. Adjacent coils are considered to be a lumped parameter.

In Figure 1 each phase occupies the whole volume of the slot, in a single layer configuration. In a double layer configuration, (1) still applies. The number of phases remains the same but there are more than one set of coils for each phase electrically connected in parallel. Each set of coils of each phase may be geometrically displaced throughout the slots and each MMF interacts with the other subsets of coils of the same phase. Figure 4 illustrates the geometric displacement and correspondent interaction between the two sets of coils of the same phase, when each coil occupies half of a slot.



a) b) c)

Figure 4: Geometrical displacement of two windings of the same phase, in a double layer stator.

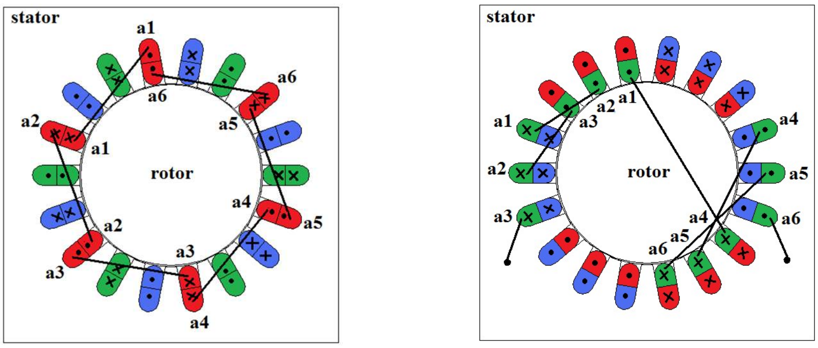
In Figure 4, from left to right, there is a reinforcement of MMF in the left (Figure 4.a)) and a full opposition on the right (Figure 4.c)). The total MMF produced from the N coils of the same phase is given by

$$F_{tot} = F\sum_{i=1}^{N}\cos(\theta_i) \tag{3}$$

where F is the MMF of each individual coil, and θ_i is the geometric angle between the phase windings subsets. Despite the MMF combination the number of poles remains unchanged no matter the geometrical displacements between the sets of coils within a phase.

4 Qualitative Simulation of Bulk Superconductor Rotor Dynamics

The concept of changing number of poles (either electronically, either mechanically) is only possible in devices where stator poles correspond to rotor poles, which is achieved with induction or hysteresis motors. In the present work, a HTS hysteresis motor with 18 slots and 18 independent windings in the stator is foreseen. Coils are assembled in double layer configuration, each one spanning by four slots. In practice, as shown later, all the terminals are available outside the motor, allowing maximum freedom in connections amongst coils. Simulations with Flux2D from Cedrat Company were first carried out in order to qualitatively analyse the dynamic behaviour of the device. Three-phase superconducting hysteresis motors have been extensively described elsewhere [5,6].



a) Six poles configuration, T_1.

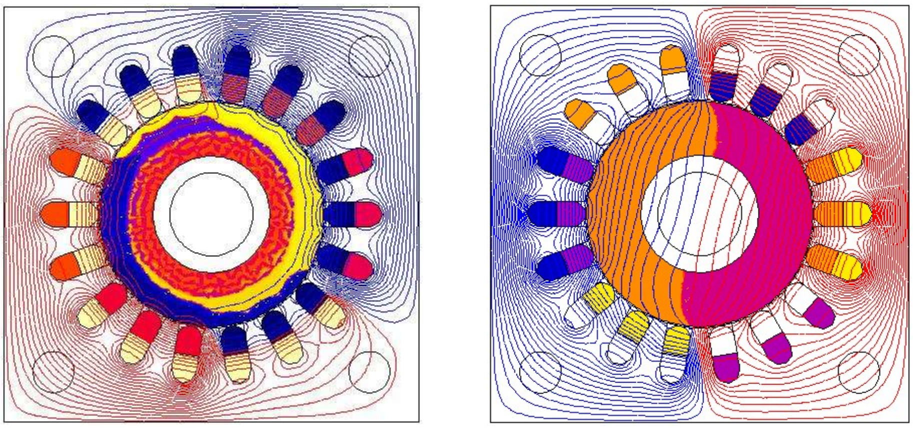
b) Two poles configuration, T_2.

Figure 5: Different configurations in a stator with 18 slots and 18 independent coils, allowing maximum degrees of freedom in connections between windings. The stator is supplied by a three-phase system.

In this study, two three-phase topologies are studied, namely T1, corresponding to six poles, and T2, corresponding to two poles. Winding arrangements are represented in Figure 5.a) for topology T1 and in Figure 5.b) for topology T2. The superconducting rotor is 52 mm height, 52 mm external diameter and 30 mm internal diameter. In these simulations only qualitative and relative results are foreseen, for which superconducting parameters (critical current density and n parameter) are not determinant.

4.1. Simulation of Topology T_1

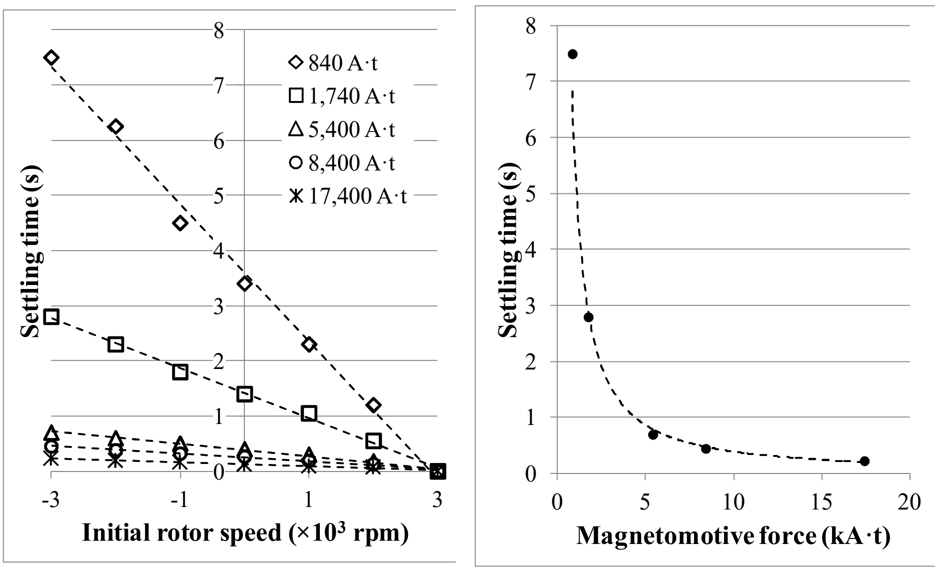
For MMF forces with amplitudes bellow the full penetration threshold (840 A.t in the simulations, naturally dependent on the characteristics of the HTS material), only partial magnetization in the rotor is achieved. This situation is represented in Figure 6.a). In these regimes the developed torques are considerably lower (in this case, bellow 10^{-4} N·m). Only when flux fully penetrates the rotor, see Figure 6.b), significant torques are developed.



(a) (b)

Figure 6: Profiles of current density in the rotor, for different values of MMF amplitude, corresponding to (a) partial penetration (170 A·t) and (b) full penetration (840 A·t). These values depend on the superconducting properties, which is not a concern in simulations, only qualitative results.

Settling times (time needed to reach synchronous speed) were obtained by simulations for different starting speeds and different MMF. For c (3000 rpm synchronous speed) settling times are illustrated in Figure 7.



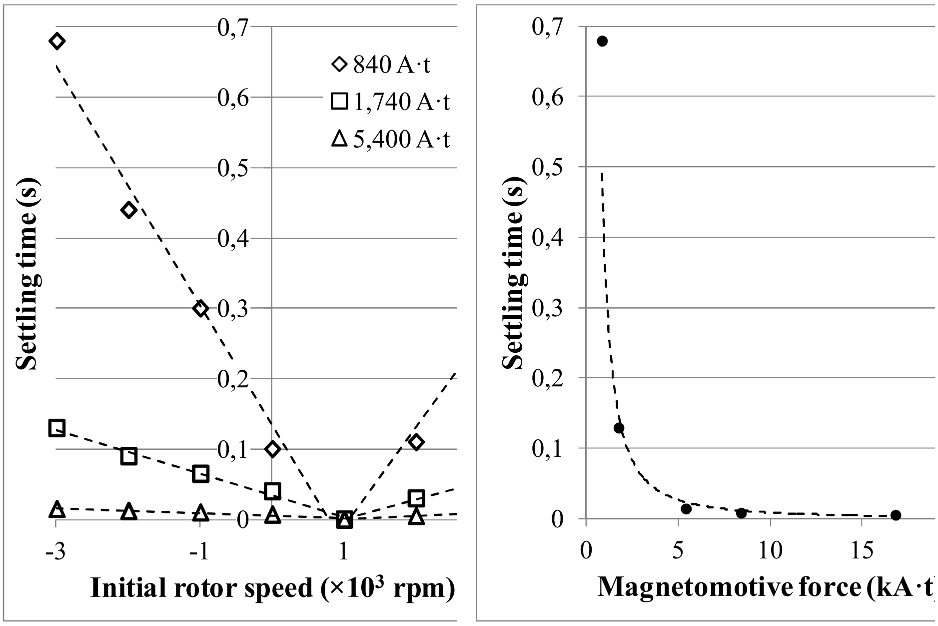
(a) (b)

Figure 7: Settling times for topology T_1 (bipolar), as a function of (a) MMF and initial speed and (b) as a function of MMF for -3,000 rpm initial speed. Synchronous speed is 3,000 rpm.

Considerably longer settling times were registered when the external magnetic flux was not able to fully penetrate the rotor material. In this region there is a high nonlinearity between settling time and MMF, thus conditioning the performance of the motor and demanding a higher control complexity. Nevertheless, torque is linear with MMF, as shown later.

4.2. Simulation of Topology T2

Due to lower magnetic fields produced in topology T_1 (bipolar) when compared with T_2 (hexapolar), settling times are higher on the later for the same MMF produced by each coil, as illustrated in Figure 8.



(a) (b)

Figure 8: Settling times for topology T_2 (hexapolar), as a function of (a) MMF and initial speed, where results above 5,400 A·t are not shown as they overlap, and (b) as a function of MMF for -3,000 rpm initial speed. Synchronous speed is 1,000 rpm.

4.3. Comparison of Topologies

Time responses observed in the previous subsections are related to torque differences as illustrated in Figure 9. As expected, torque produced with an hexapolar topology is considerably higher than with bipolar.

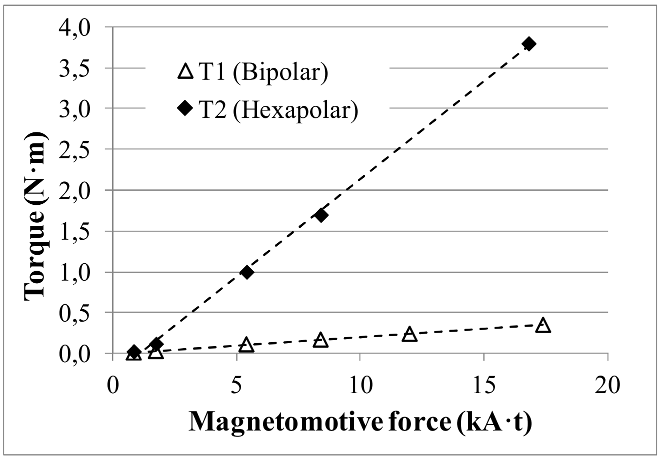


Figure 9: Comparison of developed static torques for topologies T_1 and T_2. Torque is linear with MMF.

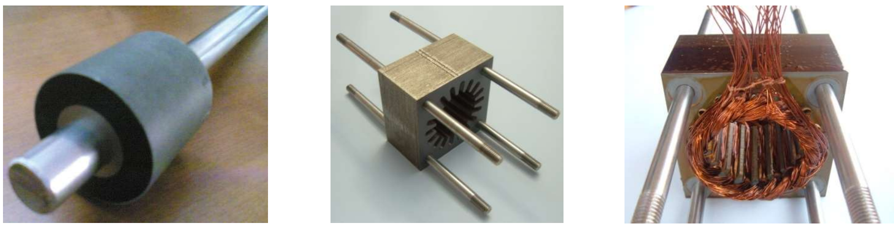
5 Motor Construction

In order to investigate pole changing techniques applied to superconducting hysteresis motors, and to validate the previous results, a motor was built, with a HTS YBCO rotor supplied by ATZ GmbH Company. This rotor, with a stainless steel shaft applied, is shown in Figure 10.a). The cylinder diameter, with outside protection bandage is 54 mm.

The stator was built with stacked laminations of non-oriented silicon iron (M15), see Figure 10.b). Each lamination is 0.5 mm thick and quadrangular shape with 10 cm side. The stator is 52 mm height, the same dimension of the rotor, and the airgap is 0.3 mm.

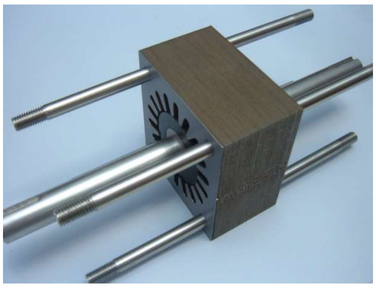
The stator has 18 slots, and 18 independent coils, each one spanning for four slots, see Figure 10.c).

The complete assembled motor is shown in Figure 11.

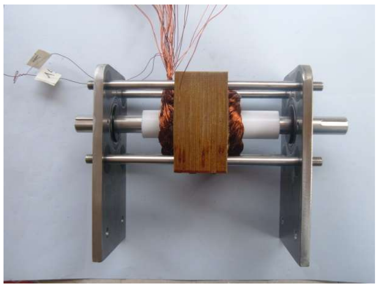


(a) **(b)** **(c)**

Figure 10: Constitutive parts of the assembled motor, namely (a) HTS rotor from ATZ GmbH Company with stainless steel shaft inserted; (b) stator built by stacked laminations of non-oriented silicon iron; and (c) stator windings inserted in slots, where each of the 18 coils spans along four slots, and is independent form the others.



(a)



(b)

Figure 11: Assembled motor, namely (a) stator with HTS rotor inserted; and (b) view of the motor with terminals of 18 independent coils available.

6 First experimental results

First experiments on the motor, at liquid nitrogen temperature, were performed, using a 1 kW asynchronous split phase motor as load. This machine was used to impose a mechanical load to the superconducting motor, and torque was controlled through stator current. The experimental results for the motor working in bipolar configuration (topology T_1) are shown in Figure 12. As expected, there is a linear relation between torque and stator MMF.

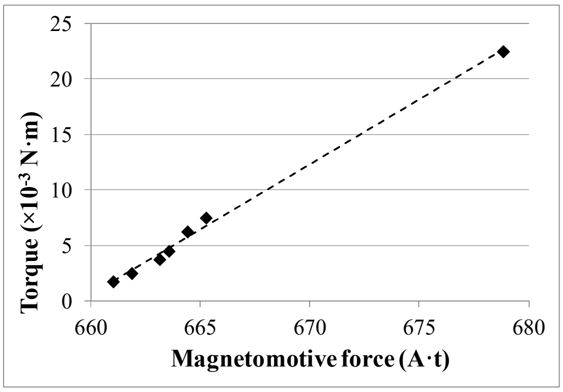


Figure 12: Comparison of developed static torques for topologies T_1 and T_2. Torque is linear with MMF.

7 Conclusions and Future Work

In this paper, a procedure for determining the number of synchronous speeds available in a motor is presented. This systematic procedure is recommended for the correct planning of stators for motors with dynamic change of speed, torque or power.

To be effective the process has a standard approach sequence: number of different phases; possible regrouping; coil slot occupation with eventual geometrical offsets.

Dynamic configuration of windings is strongly dependent on power electronics and commutation techniques. The performances of different topologies of a multiphase hysteresis motor were simulated, in order to compare them in a qualitative approach. A motor was assembled and first experiments were carried out. Future work includes measuring characteristics of the HTS material (critical current and n parameter) in order to perform quantitative simulations. Future work includes also building a power electronic converter that can supply 18 independent phases, in order to investigate the performance of the motor with any configuration of poles.

Acknowledgements. This work was supported by National funds through FCT (Fundação para a Ciência e Tecnologia) under the framework of PEst-OE/EEI/UI0066/2011 project.

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