

DEVELOPMENT AND RESULTS OF AN IRONLESS HIGH SPEED ELECTRONICALLY COMMUTATED PERMANENT MAGNET MOTOR

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ABSTRACT

There are some items to be considered when selecting the most suitable kind of motor for a small power high speed spindle application like performance, cost, size, weight, etc. These applications could include aerospace, automotive and textile industries.

Squirrel Cage Induction Motors and Hysteresis Motors can be used, however they present the drawback of having moderate power factor and moderate efficiency ($\cong 70\%$) which results in a larger motor due the need of more copper in the stator (larger current).

In order to obtain a small high speed motor with high efficiency ($\cong 90\%$) and power factor ($\geq 90\%$), it was decided to develop an Ironless Electronically Commutated Permanent Magnet Motor (Ironless Motor) with high energy rare-earth magnets. This motor has no iron in the stator and consequently no iron losses.

It was designed an Ironless Motor to have a maximum speed of 24000 rpm. The design considered a fixed diameter and used available $SmCo_5$ magnet blocks. Both motors were then analyzed by the Finite Element Method (FEM), and flux lines, flux densities wave forms and values are shown. Experimental electromechanical characteristics of both motors are compared and some conclusions are presented.

1. Introduction

Choosing electric spindle motors for high speed applications it's not an easy task. Motors have advantages and drawbacks for this task.

Squirrel cage motors are robust, but are limited by the mechanical strength of rotor material. In terms of electromechanical characteristics, this motor has the drawbacks of moderate load power factor ($\cong 70\%$) and moderate load efficiency ($\cong 80\%$).

Hysteresis motors are most robust because of rotor's mechanical simplicity. The rotor is cylindrical without slots and cage. This results in a very well balanced rotor. It has a moderate efficiency ($\cong 70\%$) and low power factor ($\leq 40\%$).

Reluctance motors are simple in their rotor but they have to be laminated, which limit their application high speed, and due their rotor saliency their mechanical balance are not so good. They have good efficiency and power factor ($\cong 80\%$).

In order to improve the electrical characteristics, it is possible to use the permanent magnet electronically commutated motor, which presents high efficiency and power factor (values greater than 90% can be obtained). The mechanical drawback is the costly construction, mainly due the shaped permanent magnet rotor. For very high speeds, this good performance can be kept, by using the ironless stator construction (stator without iron), which eliminates the iron losses. Others advantages are the absence of radial forces and cogging torque.

In this paper it is shown some aspects of development and experimental results of an iron and ironless motors.

2. Iron Motor

An iron permanent magnet motor was designed¹, having a pre-established gap diameter¹, and was analyzed by an analytical electromagnetic model based on Hague² and Boules³ equations and by the FEM⁴ (figure 1). The angle of 39 mechanical degrees of the magnets was determined making the "plateau" of the flux density maximum, for magnets with parallel magnetization.

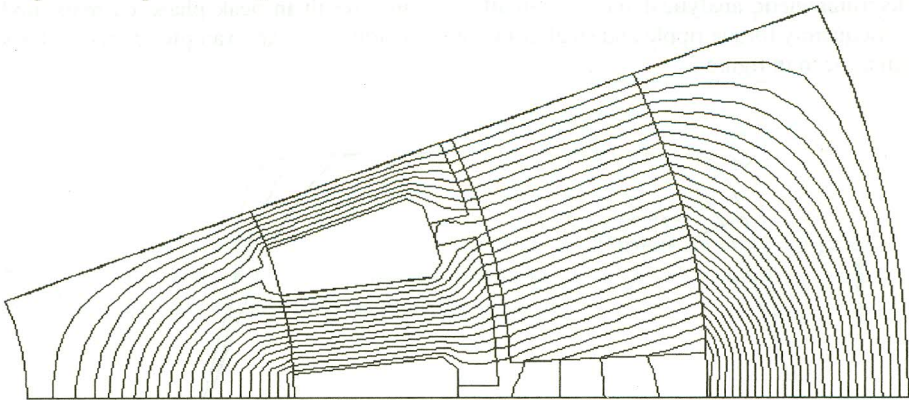


Figure 1 Magnetic flux lines of the iron motor (half pole).

The flux density wave form can be seen in fig. 2. The basic formulas used in order to obtain the theoretical electromechanical characteristics can be obtained in Scheibig¹

A comparison between the flux density waveform obtained by the FEM and the electromagnetic analytical model (motor without skew), based on Hague and Boules equations are shown in figure 2.

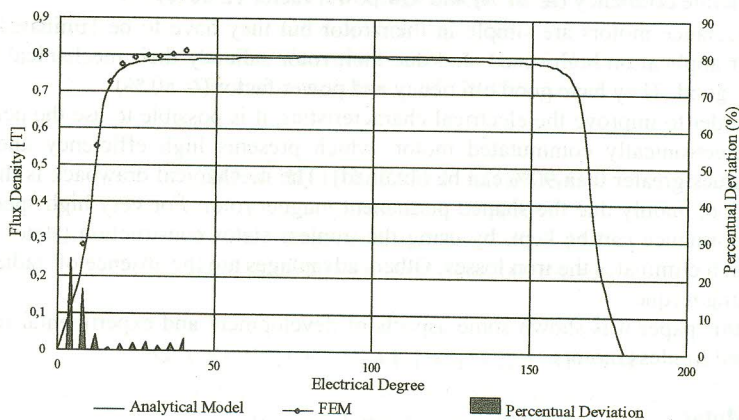


Figure 2 Comparison between Flux Density obtained by the FEM and the analytical model for the iron motor in the medium air gap diameter.

In this motor there is a compromise between the "plateau" of the induced voltage wave form and the cogging torque. The "plateau" decreases when stator's slots inclination increases (slot's skew). The influence of slot's inclination can be analysed by the electromagnetic analytical model¹. Small "plateaus" result in peak phase currents, and consequently torque ripple and smaller motor's performance. An example of this analysis can be seen in figure 3.

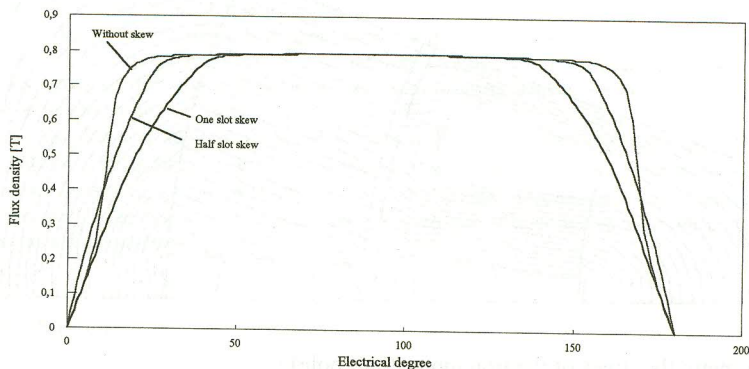


Figure 3 Variation of Flux density with slot's inclination.

As can be seen from figure 3 , increasing the slot's inclination (the skew), reduces the "plateau". This three phases motor needs 120 degrees "plateau" in one pole air gap magnetic flux density. The inclination of one slot results in a 100 degrees "plateau". The motor was constructed with less than one slot inclination. Some characteristics of the motor are shown in table 1 and 2.

| <i>Characteristics</i> | |
|------------------------|--|
| Type of motor | Iron Electronically Commutated Permanent Magnet |
| Power | 550 W |
| Rotation | 24.000 r.p.m |
| DC Link Voltage | ≈ 300 V |
| Type of drive inverter | Full Bridge |

Table 1 General characteristics of the drive

| | | |
|--------|---------------------------------------|---|
| STATOR | Material which support the conductors | 0,1 mm Laminated iron |
| | Number of phases and connection | 3 phase star connected |
| | Number of slots | 24 |
| | Peak current | 2 A |
| | Kind of sensor | Position Hall sensor |
| ROTOR | Type | Exterior rotor (Cup type motor) |
| | Poles | 8 SmCo5 magnets (parallel magnetization) |
| | Magnet arc pole | 39 degrees |
| | Support | 4140 steel |

Table 2 Physical characteristics of the iron motor.

3. Ironless motor

The ironless motor was based on the design of the iron motor. Bidimensional analysis⁵ were used. Making the relative permeability of the iron equal to "one", the motor was analyzed by the FEM, resulting the figure 4.

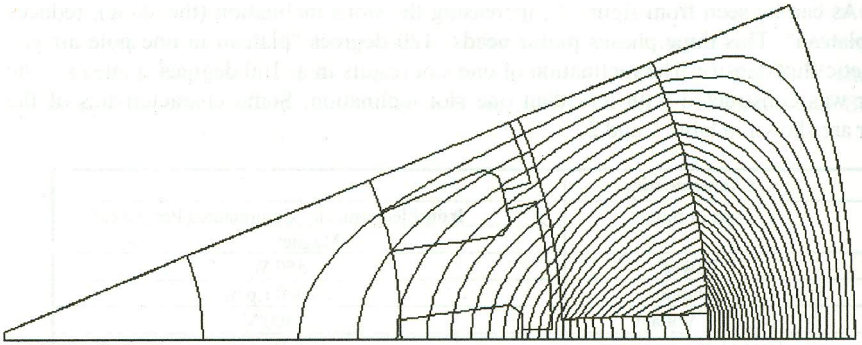


Figura4 Magnetic flux lines of the ironless motor (half pole).

From this figure it can be seen that the back iron of the magnets are not saturated (admissible values). The thickness of the back iron can be reduced, however it was kept the same as the iron motor.

A comparison between the flux density waveform on three radius conductor's obtained from the analytical model and the FEM can be seen in figure 5.

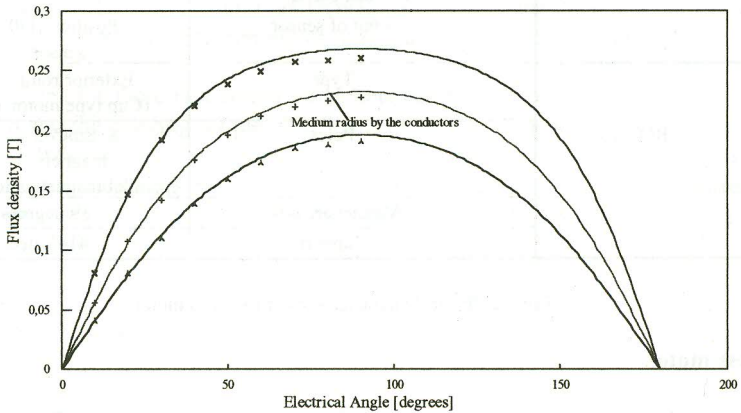


Figure 5 Comparison between flux densities values obtained by the analytical model and the FEM, for the Ironless Motor conductors (3 radius are shown).

In figure 5 the global medium deviation between the two methods is 1,8 %.

As we can see, from figure 6 the flux density waveform obtained is not more trapezoidal (like Iron motor) and looks more sinusoidal. The maximum medium radius value of flux density is approximately 0.23 T. A model to get the theoretical electromechanical characteristics are given in Scheibig¹. Tables 3 and 4 show some characteristics of the ironless motor.

| <i>Characteristics</i> | |
|------------------------|--|
| Type of motor | Ironless Electronically Commutated Permanent Magnet |
| Power | 300 W |
| Rotation | 24.000 r.p.m |
| DC Link Voltage | $\cong 300$ V |
| Type of drive inverter | Full Bridge |

Table 3 General characteristics of the drive

| | | |
|--------|---------------------------------------|---|
| STATOR | Material which support the conductors | Plastic |
| | Number of phases and connection | 3 phase star connected |
| | Number of slots | 24 |
| | Peak current | 1 A |
| | Kind of sensor | Position Hall sensor |
| ROTOR | Type | Exterior rotor(Cup type motor) |
| | Poles | 8 SmCo5 magnets (parallel magnetization) |
| | Magnet arc pole | 39 degrees |
| | Support | 4140 steel |

Table 4 Physical characteristics of the ironless motor.

4. Tests and Results

The induced phase or phase to phase voltages were measured by a memory digital oscilloscope. The net torque was measured by the stator reaction with the motor on load by an eddy current brake. The drag torque, due the induced currents in the iron lamination or in the copper for the ironless motor (these induced currents in the conductor's ironless motor appears also with motor's terminals open⁴) was measured disconnecting the electronic drive and measuring the reaction torque and subtracting the bearing torque. The mean electromagnetic torque is given by the sum of the net and drag torque. The rotation values were obtained by an optical sensor. Voltage, rms currents and power factors values were measured by a digital rms meter. Comparisons between electromechanical characteristics of both motors are shown on figure 6, 7, 8 and 9.

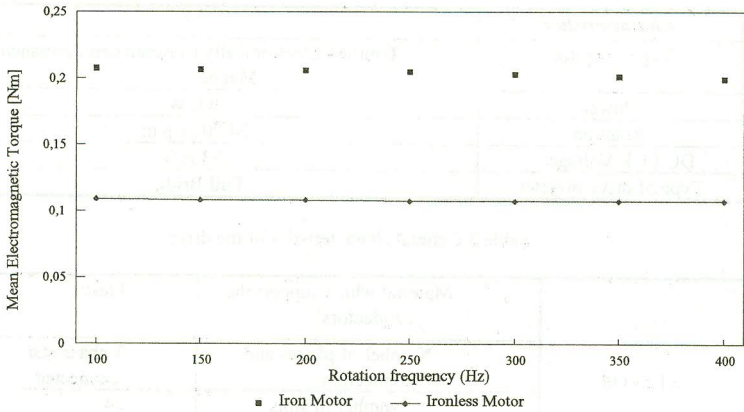


Figure 6 Experimental comparison between mean electromagnetic torque for iron and ironless motor

Due to the fact of the iron absence in the stator of the ironless stator motor the maximum magnetic flux density, in the "air gap" reduces from 0,8 T to 0,23 T (a reduction of 29 %). On the other hand, the ironless motor has approximately half of the mean torque (for the same current density in the copper 4 A/mm^2). This is explained mainly due to the more conductor's number in the ironless motor. The absence of iron, which reduces the magnetic flux density, are compensated in part by more copper.

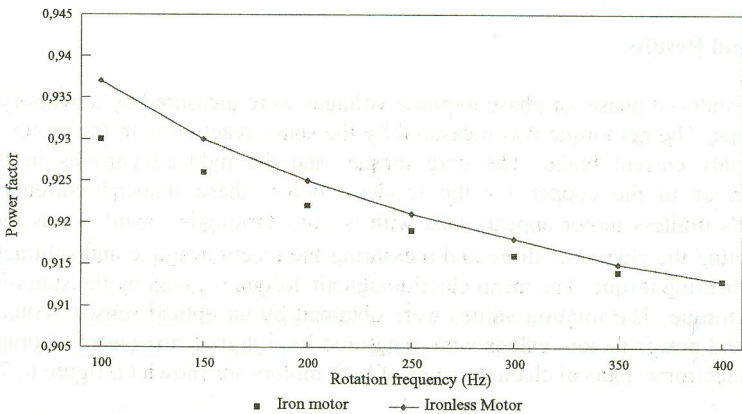


Figure 7 Experimental comparison between power factor between iron and ironless motor.

Power factors are as the same for both motors in the rotation range considered.

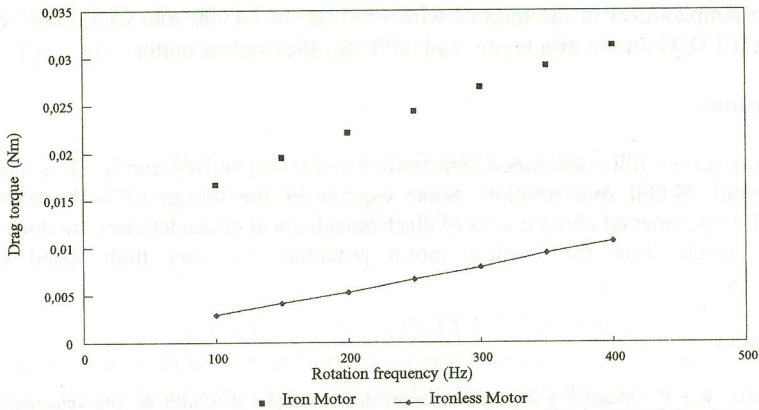


Figure 8 Experimental comparison between drag torque for the iron and ironless motor.

The drag torque in the ironless motor is smaller than in the iron motor. In the ironless motor this can be reduced using smaller diameter copper wire in parallel⁴ for one conductor. In the iron motor it is necessary to reduce the lamination thickness, which is difficult to get (it has been used 0,1 mm thickness). This drag torque influences directly the efficiency.

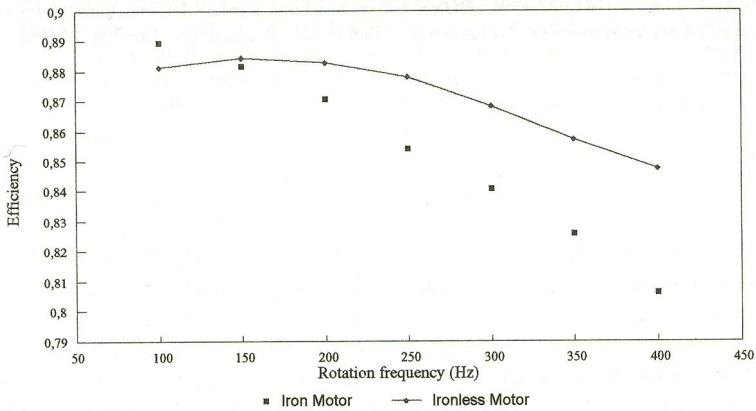


Figure 9 Experimental comparison between efficiencies for the iron and ironless motor.

The ironless motor presents efficiency greater than the iron motor for rotation frequencies higher than 150 Hz. The ironless efficiency can be improved by decreasing the drag torque.

The temperatures in the motor's wire windings at 24.000 rpm ($4A/mm^2$ current density) are $131^{\circ}C$ for the iron motor and $90^{\circ}C$ for the ironless motor.

5. Conclusions

It was successfully developed, constructed and tested an Iron and Ironless motor to running until 24.000 rpm rotation. Some aspects of the design of both motors are explained. Experimental comparisons of electromechanical characteristics are done.

The result show the Ironless motor potential, for very high speed spindle applications.

6. References

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