An Analytical and Numerical Model to Predict Static and Dynamic Performance of a Torus Machine with Two Permanent Magnets Topologies

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Abstract — An axial-flux permanent magnet brushless machine, Torus type, was designed, built and tested. This article shows the analytical and numerical model developed and its results for two different topologies of permanent magnets. Analytical modeling of the machine is extremely important because it allows to visualize easily variables and therefore it is the main tool for improvement and optimization. On the other hand, numerical modeling is a good tool of analysis as it deals well with nonlinearity.

I. INTRODUCTION

A great variety of devices are studied looking for high torque density, beside this, comes the search for devices for specific applications, like electric vehicles, for example. In this context, appears the Torus machines, with their variety of configurations and special features. Considering the low-cost and easily of construction of this kind of machines, their reduced axial length and -their high energy product because of the use of NdFeB permanent magnets, that leads to a machine with high torque density. These machines are interesting for applications with restrict volume, mainly because in many cases they don't need mechanical transmission to drive devices [1]-[2]-[3]-[4].

Motivated by the features above described, was designed a Torus Machine at the Laboratory of Electrical Machines, Drives and Energy of the Federal University of Rio Grande do Sul. The device was analyzed with two different shapes of permanent magnets (square and sectoral), with three focus: flux density (magnetic induction), electromotive induced force (EMF) and torque developed by the device.

Here are presented the analytical and numerical model of the magnetic induction and EMF, important to characterize the machine and its behavior. For the square magnets results are complete, however the analytical model of sectoral magnets is still in development, considering the higher complexity of the method adopted (explained in chapter III). These results compound a master thesis in development that aims to study the machine as generator and regenerative braking mode.

II. TORUS MACHINE

The Torus machine presented is an axial-flux permanent magnet brushless machine, disc-type, with a sandwich topology, where a stator is mounted between two external rotors [4]. The stator has a toroidal shape, and is composed by 18 toroidal coils, energized sequentially in 3 sets of 6 coils in series. Each rotor has 6 neodymium-iron-boron NdFeB permanent magnets disposed 60 degrees between each other, in alternating polarity NS; the poles of the permanent magnets on one rotor are mirrored by the ones at the same angular position on the other rotor. Figure 1 shows the assembled machine and its parts.

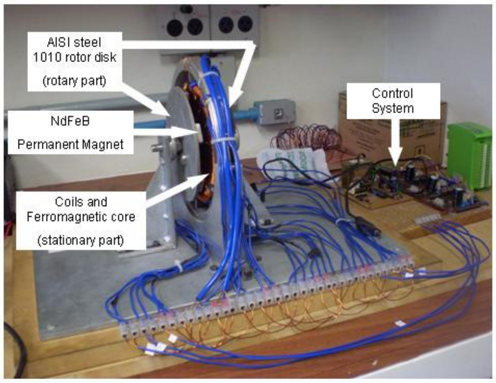

Fig. 1. Torus machine prototype.

This device was studied in motor operation with the permanent magnets in square shape, and actually has been studied as motor and generator with permanent magnets in sectoral shape. The dimensions of the two types of permanent magnets can be seen in Fig. 2.

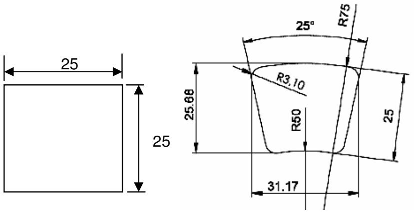

Fig. 2. Permanent magnets dimensions in millimeters. (a) square; (b) sectoral.

The magnetic inductions of permanent magnets interact with the current of the stator coils, which is drived by a control system developed specifically for this application.

III. ANALYTICAL MODEL

In order to obtain the field equation in the air gap due to the permanent magnets and EMF, an analytical model was developed based on an analysis of a 3D model.

For the analytical model, considering the square magnets, the solution adopted uses Lie symmetries, which are changes of variables that do not alter the form of differential equations and obtaining an exact solution from another solution of the original equation.

The magnetic induction model was developed in rectangular coordinates and to calculate the EMF was converted into polar coordinates, obtaining a distribution consistent with that found in the machine [5]-[6]. The magnetic induction **B** of permanent magnets is obtained by replacing the magnetic scalar potential Ψ in (1), followed by an application of Lie symmetry of scale.

$$\mathbf{B} = \mu_0 \mathbf{H} = \mu_0 \nabla \psi \qquad (1)$$

The EMF was calculated using Faraday's Law (2), from the expression obtained by induction of the permanent magnets [7], where d**S** is the infinitesimal area delimited for the displacement of the projection of the wires on the magnet.

Replacing the scalar magnetic induction and performing variable substitution, extracting the real part and applying symmetries, we obtain the expression of EMF.

$$e = -\int_s \frac{\partial \boldsymbol{B}}{\partial t} d\boldsymbol{S} \qquad (2)$$

For the sectoral magnets, we chose to utilize the method of spatial harmonics adopting cylindrical coordinates due to the format characteristics of the magnets [5]-[6],. This step is in development.

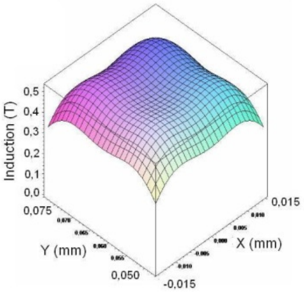

Fig. 3. Flux density at the middle of the air gap, analytical method, square magnets.

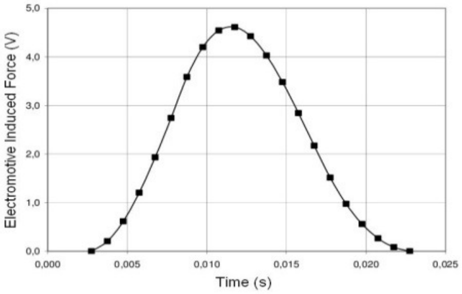

Fig. 4. Calculated EMF induced at 450 RPM for square magnets.

IV. NUMERICAL MODEL

The 3D model of the machine was built in order to be analyzed by the finite element method (FEM). The mapping of magnetic flux density at the middle of air gap in front of polar surface of permanent magnets is showed in figures 5 and 7; the EMF induced is showed in figures 6.

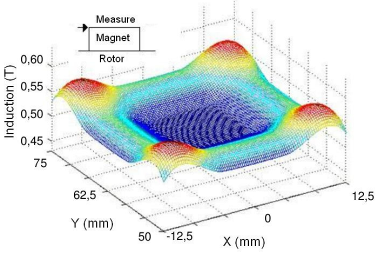

Fig. 5. Flux density at the middle of the air gap, FEM, square magnets.

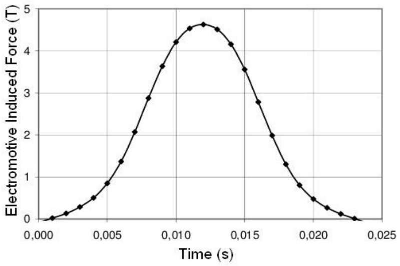

Fig. 6. FEM result of EMF induced at 450 RPM for square magnets.

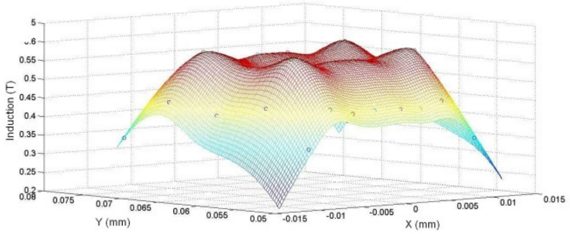

Fig. 7. Flux density at the middle of the airgap, FEM, sectoral magnets.

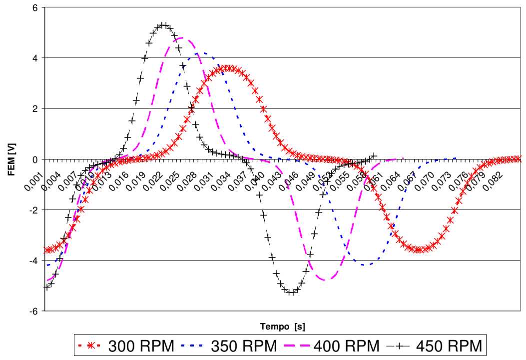

Fig. 8. FEM results of EMF induced at 4 speeds for sectoral magnets.

V. CONCLUSION

The analysis demonstrates consistency of the comparisons made between the results obtained analytically with the ones obtained numerically.

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