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3-D FINITE ELEMENT ANALYSIS OF A SINGLE-PHASE SINGLE-POLE AXIAL FLUX VARIABLE RELUCTANCE MOTOR

BY

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Abstract. This paper presents a special topology of variable reluctance motor. 3-D Finite Element Analysis is used in order to obtain the magnetization characteristics and the static torque curves. The performances of the motor are analysed considering the obtained results and conclusions are drawn.

Key words: 3-D FEM; special topology motor; variable reluctance motor.

1. Introduction

Variable reluctance machines are a category of electrical machines for which one of the windings is missing, usually the one on the rotor. The electromagnetic torque appears as a consequence of the difference between the reluctances on the two symmetry axes of the machine. This leads to inherent advantages such as: simple construction, reduced costs and safety in operation. Due to the fact that the performances of the machine are strictly related to the ratio between the two extreme inductances, a great deal of researches have been conducted in this direction (Simion, 1993).

The paper introduces a special topology variable reluctance machine. It presents only one phase, one pole and the magnetic field lines are closing parallel to the shaft.

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For a correct estimation of the machine performances it is necessary to perform a 3-D finite element method analysis. The study in 2-D was not possible because the machine presents no axial symmetry. The study aims to obtain the magnetization and torque characteristics, $\psi(i,\theta)$ and $T(i,\theta)$, respectively (Krishnan, 2001; Miller, 2002).

2. Geometry of the Motor and Principle of Operation

The stator of the motor is assembled from a stack of “U” shaped laminated steel sheets and presents a concentric winding. The winding has 144 turns with the diameter of the copper wire of 1.19 mm. Because the insulation layer used for the wires is thick, it resulted in a fill factor of the coil only of 0.15. The resistance of the winding is 0.6 Ω (Dabija *et al*., 2012).

The rotor is a disc, half of ferromagnetic material, which aligned with the polar axis of the stator gives the minimum reluctance position, also called the *d*-axis. The other half is made of non-magnetic material, which aligned gives the maximum reluctance position, or the *q*-axis (Simion, 1993).

The geometry of the motor is presented in Fig. 1.

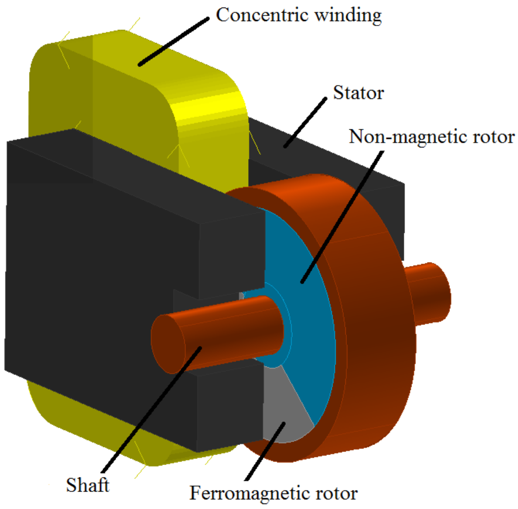

Fig. 1 – Geometry of the motor.

When a current flows through the coil it generates a magnetic field whose lines are closing over the minimum reluctance path. Therefore a torque occurs with the tendency to move the rotor towards the position of minimum reluctance or maximum magnetic energy of the system (Biro *et al*., 2005).

The voltage eq. is

$$u = Ri + L\frac{\mathrm{d}i}{\mathrm{d}t}, \tag{1}$$

where u represents the voltage applied at the terminals, R – the resistance of the winding, i – the current flowing through it and L – the inductance.

The inductance, L, varies both as a function of angular position, θ, and current, i, thus the magnetization characteristics, $\psi(i,\theta)$, present a nonlinear variation.

The electromagnetic torque, T_e , can also be computed as the derivative of the magnetic energy with respect to the angle θ. This can be written as follows:

$$T_e = \frac{\mathrm{d}W_m}{\mathrm{d}\theta}, \tag{2}$$

knowing that the magnetic energy can also be written as

$$W_m = \frac{1}{2} L I^2. \tag{3}$$

In eq. (3) if current I is considered constant, the variation of the inductance, L, is the one responsible for the variation of the magnetic energy, and, therefore, creates electromagnetic torque (Simion, 1993).

3. Finite Element Analysis

The finite element method was used in order to perform field computations necessary with the view to identify the parameters of the machine. It was intended to obtain the magnetization and the torque characteristics, $\psi(i,\theta)$ and $T(i,\theta)$, respectively. Magnetostatic field computations were performed. For a given current, the rotor position, θ, was varied from 0 to 360 degrees with a step of 5 degrees. The current, I, was also varied from 3 A to 18 A, in steps of 3 A.

The magnetization characteristic offers valuable information about the performances of the machine. The magnetic flux, or rather the variation of the magnetic flux according to the rotor position, gives the overal variation of the magnetic energy of the system. Therefore, the bigger this variation is the better the performances of the electrical machine (Biro *et al*., 2005; Krishnan, 2001; Miller, 2002).

The obtained magnetization characteristic is presented in Fig. 2.

The area enclosed by the magnetization curve when the motor is operating represents the magnetic energy converted into mechanical energy through the variation of the co-energy of the system. A better explanation is that when a current is applied, ideally in the position where the magnetic flux would be minimum, that is the q-axis, the current generates a magnetic flux. The rotor moves from the q-axis towards the d-axis, with the current being kept constant, and when the d-axis position is reached, ideally the current would have to be rapidly falling to zero in order to prevent negative torque generation. This can be achieved by using special controllers, which are using a position sensor and a current regulator. In this case the motor operates as a switched reluctance motor (Krishnan, 2001; Miller, 2002).

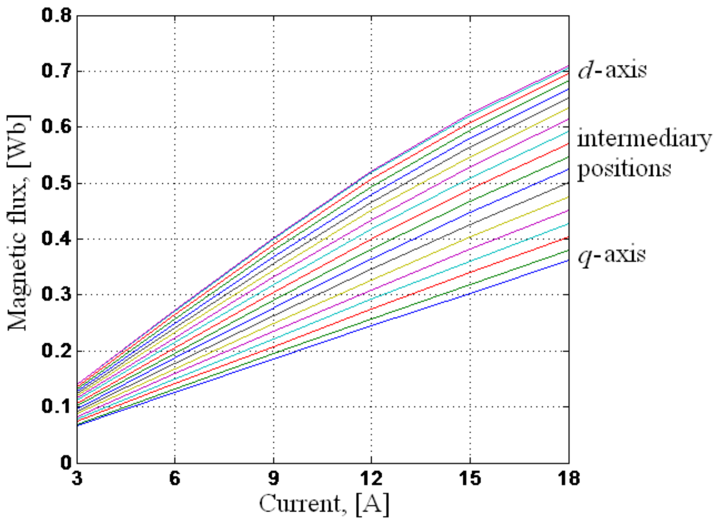

Fig. 2 – Magnetization characteristic.

Perhaps the most important feature of this single-pole motor is that by supplying it with an alternative voltage with the frequency of 50 Hz it has the ability to produce torque both on the positive and on the negative current's alternation. Of course, the condition being that of the rotor to rotate at the synchronous speed, that is 6,000 rpm. This is possible mainly because the torque does not depend on the sign of the current, but rather on its square value (Simion, 1993).

Finite element analysis software computes the static torque curves according to eq. (2). The static torque curves as obtained from the finite element analysis are given in Fig. 3. The motor has the capability to develop torque only for half of rotation, corresponding to the rising slope of the inductance. When the motor is supplied by an alternative voltage, the peak of the current sets to the maximum at a value of the inductance slope when the generated torque counterbalances the effect of the resistive torque. The conclusion that rises is that when supplied by an alternate current the slope of the inductance should be maximum at the middle of the torque generation area. This could be achieved by optimizing the rotor geometry, so that the slope of the inductance to have a sinusoidal variation (Irimia *et al*., 2012; Simion, 1993).

On the other hand, this is not the case when the motor is controlled as a switched reluctance motor; in that case the best variation of the inductance slope would be a linear one. This happens because the current is controlled to have the same constant value during the torque production area. In the constructive variant presented in this paper, the slope has almost a linear variation, being thus suitable for a switched reluctance motor operation.

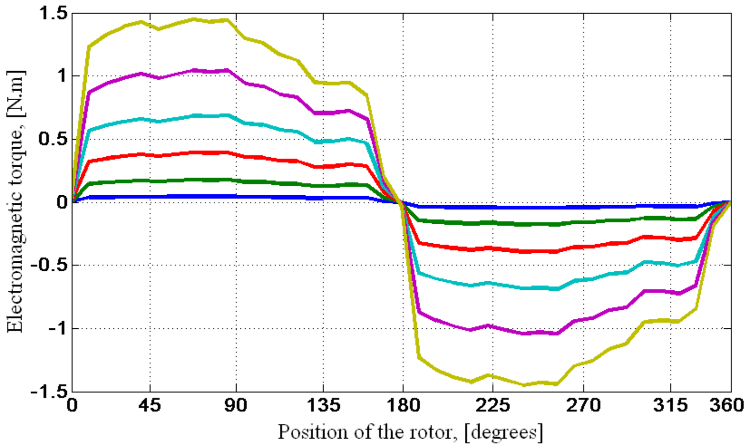

Fig. 3 – Static torque curves.

Of great importance is also the magnetic circuit. When considering an optimization of the geometry, it is important to be able to see the areas where the magnetic core saturates (Kang *et al*., 2000; Letelier *et al*., 2005).

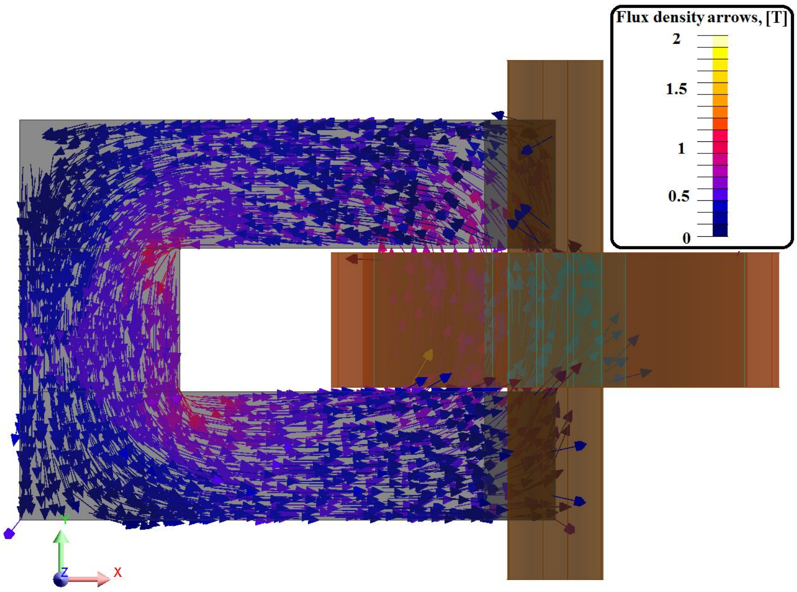

Fig. 4 – View from the top of the flux density arrows.

Fig. 4 presents a view from the top of the flux density arrows. The rotor is in the *d*-axis position and the flux lines are closing through the shortest path, the reluctance being thus minimum. From the flux density arrows presented in Fig. 4 it is also possible to observe the areas where saturation occurs. One can see that saturation mostly occurs on the inner side of the “U” shaped magnetic stator core. When considering an optimization of the magnetic circuit in order to obtain the desired performances for the machine it is essential to be able to see the areas where saturation is present (Hennen *et al.*, 2006; Zhao *et al.*, 2011).

A closer view of the way the magnetic flux density is distributed over the ferromagnetic part of the rotor is depicted in Fig. 5.

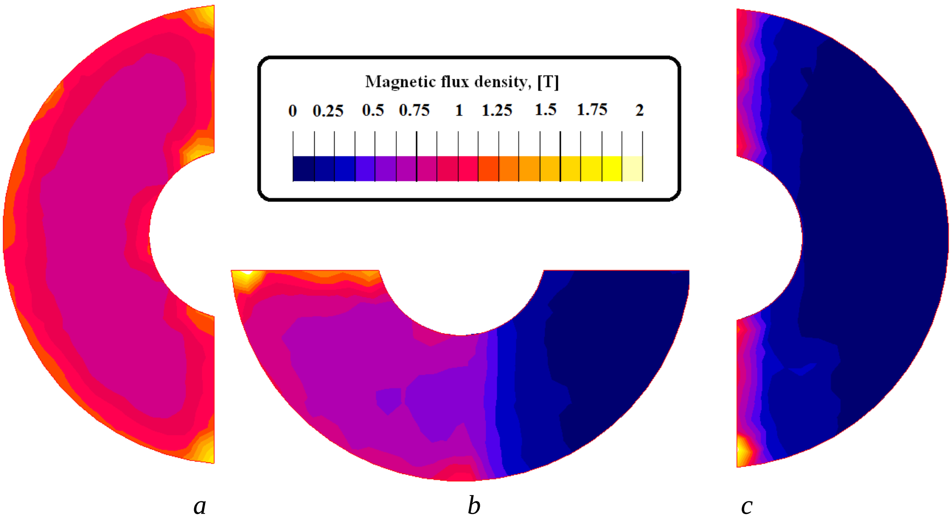

Fig. 5 – The map for the magnetic flux density over the ferromagnetic part of the rotor for different positions: *a* – *d*-axis position, *b* – intermediary position, *c* – *q*-axis position.

The way the magnetic flux density varies with respect to the rotor position allows us to consider a different shape for the ferromagnetic part of the rotor. This way the inductance could be modeled to have a sinusoidal variation.

4. Conclusions

This paper presented a special constructive variant of a variable reluctance motor with passive rotor. The geometry is a special one consisting of only one stator phase and one single pole. This special feature permits the motor to operate at a speed of 6,000 rpm, under special conditions described in the paper. An other distinctive attribute of this special topology is that the flux lines are closing axially with the rotor shaft.

Due to the increased torque generation area, which in this case is 180 degrees, optimization of the rotor geometry could be taken into account, so that the inductance to have a sinusoidal variation and thus to be more suitable for an alternate current supply. Finite element analysis could be successfully used in this endeavour.

In order to reduce the torque ripples the motor could be built modularly. Many stators and rotors could be implemented and by obtaining a multiphase motor the overall performances of the motor ameliorated.

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ANALIZA PRIN METODA ELEMENTULUI FINIT ÎN 3-D A UNUI MOTOR CU RELUCTANȚĂ VARIABILĂ, MONOPOLAR MONOFAZAT ŞI CU CÂMP AXIAL

(Rezumat)

Se prezintă un motor cu reluctanță variabilă, de construcție specială. Analiza prin metoda elementului finit în 3-D este folosită pentru a obține caracteristicile de magnetizare şi cele ale cuplului static. Performanțele motorului sunt analizate în urma rezultatelor obținute, iar în final sunt prezentate concluziile.