CIRCUIT COUPLED – 3-D FEM ANALYSIS OF A SINGLE-POLE AXIAL-FLUX VARIABLE RELUCTANCE MACHINE AND EXPERIMENTAL VALIDATION

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REZUMAT. Se prezintă studiul unui motor cu reluctanţă variabilă cu flux axial, monopolar şi monofazat utilizând metoda elementului finit (MEF) în 3-D şi rezultatele sunt validate experimental. Se folosesc două strategii de alimentare: mono şi bialternanţă obţinându-se datorită structurii monopolare a motorului dublul vitezei de sincronism în cazul celei de a doua strategii de alimentare. După o scurtă introducere cu privire la geometria specială şi principiul de funcţionare ale motorului se realizează studiul electromagnetic utilizînd MEF 3-D. Rezultatele sunt mai apoi validate experimental.

Cuvinte cheie: motoare cu reluctanţă variabilă, metoda elementului finit.

ABSTRACT. This paper presents the study of a single-pole single-phase axial-flux variable reluctance motor using 3-D FEM and experimental validation. The motor is supplied using two strategies: by means of a half-wave rectifier and by using alternating current. For the second strategy a synchronous speed of 6000 rpm is obtained due to the single-pole structure of the motor. After a short introduction regarding the special geometry and principle of operation of the motor the study is performed using 3-D finite element method. The results are then experimentally validated.

Keywords: reluctance motors, finite element method.

1. INTRODUCTION

Variable reluctance motors are synchronous motors that function on the principle of the reluctance torque. This torque manifests itself as a consequence of the different reluctances that the motor presents for the two extreme positions and with the tendency to align the rotor in the position of minimum reluctance [1], [2].

Usually, the construction of this category of motors is simple. The rotor has no winding or permanent magnets, reducing thus the costs and losses. The stator often has only a concentric winding, but may also make use of a distributed winding in the case of the so called synchronous reluctance motors where the magnetizing flux is created by a rotating magnetic field [1], [2].

The single-pole, single-phase, axial flux variable reluctance motor presented in this paper was modelled and its behavior was simulated using a dedicated software that employs finite element method (FEM). It was necessary to use a 3-D model because the motor has no axial symmetry [3].

The simulations were performed using circuit coupled – 3-D FEM, therfore they account both for the electrical circuit that was used to feed the motor and for the magnetical circuit along with its nonlinearities. Two strategies were used to supply the single phase winding of the motor: by means of a half-wave rectifier and by using alternating current that also implies the rotor to rotate at double the synchronous speed, namely 6000 rpm, given the single-pole structure of the motor.

The results obtained from simulation are also validated by the results obtained in the laboratory, where the prototype was tested.

2. CHARACTERIZATION OF THE MOTOR

The geometry of the motor is simple. The stator is made out of a stack of "U" shaped laminations. The rotor has the shape of a disc, half of ferromagnetic material and the other half of non-magnetic material. When the ferromagnetic half is aligned with the polar axis of the stator the reluctance of the magnetic circuit is minimum. The opposite situation is reached after the rotor is rotated with 180 degrees and the reluctance is maximum [1], [4].

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.

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

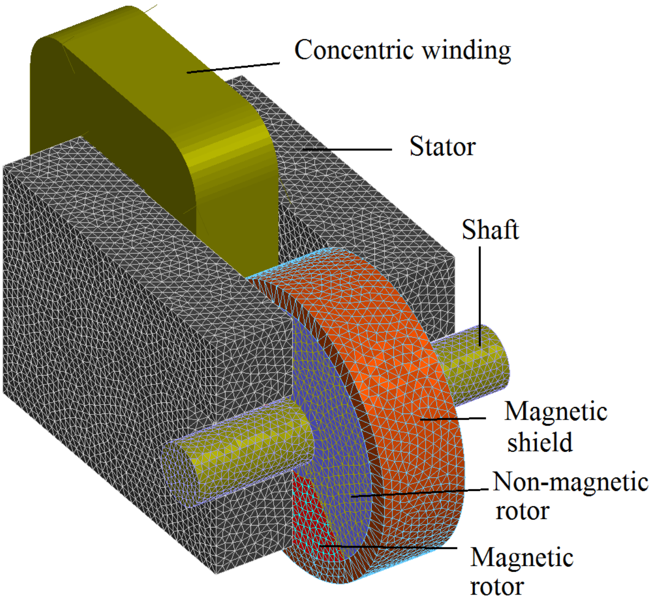

Fig. 1. Geometric model and meshing for circuit coupled – 3-D FEM simulation.

The inductance, L, varies firstly as a function of angular position θ, and secondly in the case when the magnetic circuit is saturated as a function of current i.

3. PRINCIPLE OF OPERATION WHEN SUPPLIED BY A.C. VOLTAGE SOURCE

The electromagnetic torque, T_e, is given by eq. 1:

$$T_e=\frac{1}{2}i^2\frac{dL}{d\theta}. \qquad (1)$$

$\theta_{ref}=0$ is considered the reference position when the ferromagnetic portion is unaligned with the polar axis of the stator. For $\theta \in (0,\pi)$ the slope of the inductance is always positive, meaning that the produced electromagnetic torque will be positive throughout the entire interval. On the other hand for $\theta \in (\pi, 2\pi)$, $dL/d\theta$ will always be less than 0, which results in negative torque generation.

For a given current the torque generation capability is determined by the slope of the inductance. When the motor is fed using an alternative voltage source, the peak value of the current is reached in the relative position of the rotor where the torque generated through the interaction between the magnetic field and the slope of the inductance is sufficient to counterweight the resistent torque [1].

The motor is supplied using two strategies: by means of a half-wave rectifier, at a synchronous speed of 3000 rpm and by using alternating current, obtaining a synchronous speed of 6000 rpm, given the single-pole structure of the motor. Both strategies can only be applied when the motor runs at synchronous speed. The motor, given its operational nature, may also be controlled as a switched reluctance motor. This is achieved using a special converter, which controls the current through the winding according to a prescribed value and to the rotor position.

4. SIMULATION USING CIRCUIT COUPLED - 3-D FEM ANALYSIS

Circuit coupled – 3-D FEM analysis stands for an electromagnetic field problem solved by means of finite element method and at the same time it is connected with an equivalent electric circuit. Between the circuit elements and the regions from the electromagnetic field problem there is a strong correlation. A time-stepping analysis can be set up and at each time step both the field equations and the equivalent circuit equations are solved. Also, the movement equation is taken into consideration. This equation is:

$$J\frac{d\omega}{dt} = T_e - T_r(\omega) = T_e - T_L - B\cdot\omega, \qquad (2)$$

where J represents the momentum of inertia, ω – angular speed, T_e – electromagnetic torque, T_r – resistant torque, T_L – load torque, B – coefficient of viscosity friction.

The momentum of inertia J = 0.007 Kg·m^2 and the coefficient of friction B = 0.0006 N·m·s.

The first case study was concerned with supplying the motor by means of a half-wave rectifier, the speed in this case being half of the synchronous speed of a single-pole motor at 50 Hz, i.e. 3000 rpm. The initial speed of the motor was considered 3000 rpm. The equivalent circuit used for simulation in this case is presented in Fig. 2.

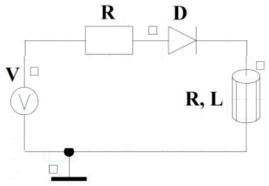

Fig. 2. Equivalent electrical circuit.

The voltage supply was defined as follows:

$$u = 230\sqrt{2}\sin(2\pi f t). \qquad (3)$$

The resistance R was used with the purpose to limit the current to a rms value of 15A. Its value was set to5Ω.

In order to optimize the magnetic circuit of the motor one should consider the magnetic flux density distribution in different areas of the machine. Such an analysis is usually performed in the design stage of the motor when magnetostatic field computations are performed [5]. Anyway, valuable information about the magnetic flux density distribution can be obtained through a circuit coupled – 3-D FEM analysis. The color map for the magnetic flux density for the moment when the electromagnetic torque is maximum, at an angle of approximately 45 degrees is presented in Fig. 3.

The speed variation for a simulation time of 4 seconds is presented in Fig. 4.

From Fig. 4 it is noticeable that the speed has a low frequency oscillation around the synchronous speed. This oscillation is caused by the fact that the motor has no damping winding and it takes a long time until the speed stabilizes, especially when the motor is operated under no-load regime.

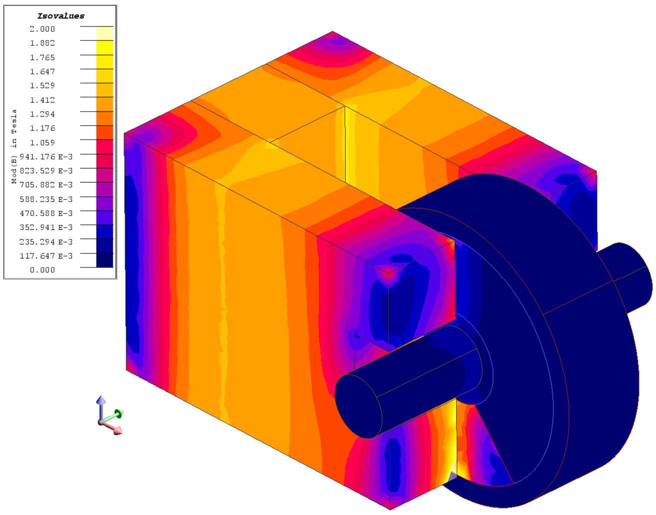

Fig. 3. Color map for the magnetic flux density.

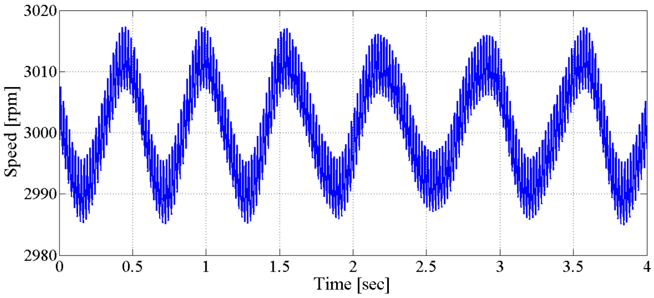

Fig. 4. Speed variation during simulation (no-load).

Because the inductance varies with the position it results in a different value of the inductance slope each time the current reaches its maximum value. The speed has also another oscillation of smaller amplitude and with the frequency of double the supply frequency. This is due to the electromagnetic torque, which is generated only for the rising slope of the inductance. It can be deduced that for a reluctance machine, if the value of the resistance R is neglected, the electromagnetic torque is:

$$T_e = \frac{X_d - X_q}{X_q} \sin(-2\theta), \tag{4}$$

where X_d and X_q are the reactances corresponding to the two symmetry axes, and θ is the load angle [1].

The mean value of the torque is self regulated according to the resistance torque. In the case of no-load operation the electromagnetic torque must counterbalance only the resistive torque caused by friction. When the machine is operating under load condition the mean value of the electromagnetic torque is greater than in the case of no-load condition. The electromagnetic torque is presented for both operating condition, no-load in Fig. 5, and under load in Fig. 6.

The waveforms for current, voltage and speed are presented in Fig. 7. Only the positive half-wave of the current is allowed to flow through the circuit. The current is limited by the impedance of the circuit. On the falling slope of the current the magnetic energy stored in the magnetic field is eliminated. Nevertheless, because of the time constant of the circuit, a current is still flowing after the rotor has passed the minimum reluctance position, and thus the appearance of a negative torque can not be prevented.

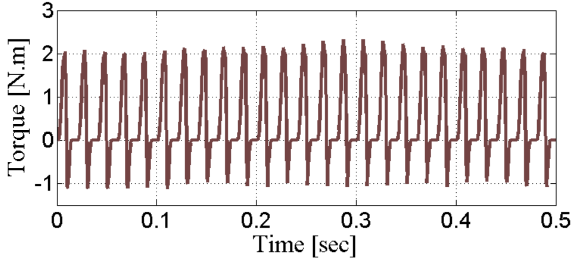

Fig. 5. Electromagnetic torque no-load condition.

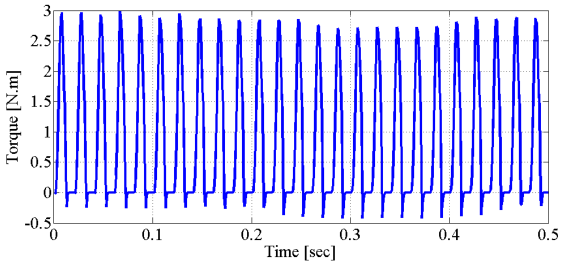

Fig. 6. Electromagnetic torque under-load condition (resistant torque 0.45 N.m).

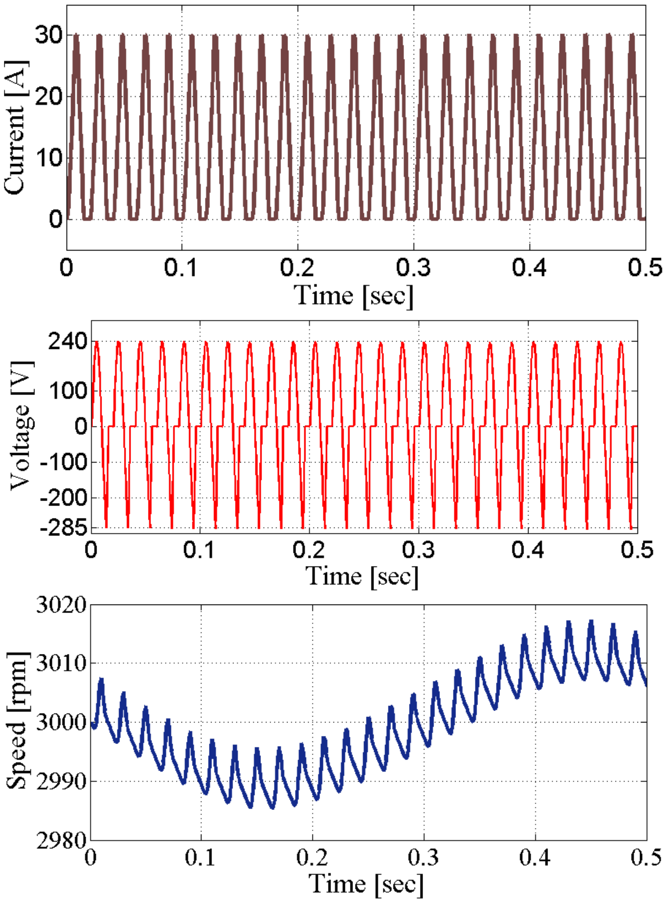

Fig. 7. Waveforms for current, voltage and speed (no-load).

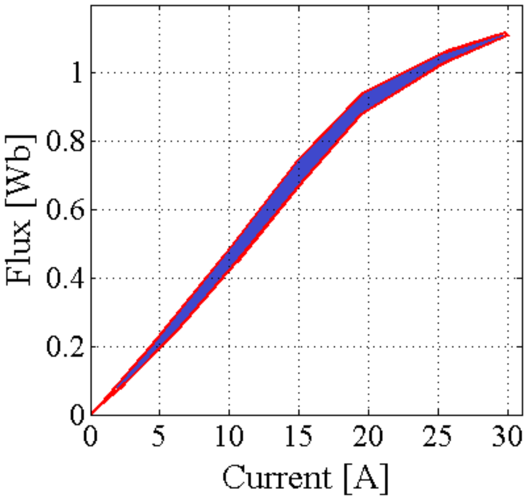

Fig. 8. The magnetic energy converted into mechanical energy for a conversion cycle (no-load).

The magnetic energy converted into mechanical energy for a conversion cycle is determined by the surface enclosed when the magnetic flux varies as a function of current for a complete rotation of the rotor [3], [6]. The energy converted for such a conversion cycle is illustrated in Fig. 8.

The second strategy used to supply the motor is by using both the negative and the positive half of the a.c. wave. Considering the single-pole structure of the motor it results in a synchronous speed of 6000 rpm at the frequency of 50 Hz [1], [5]. The speed can be seen in Fig. 9.

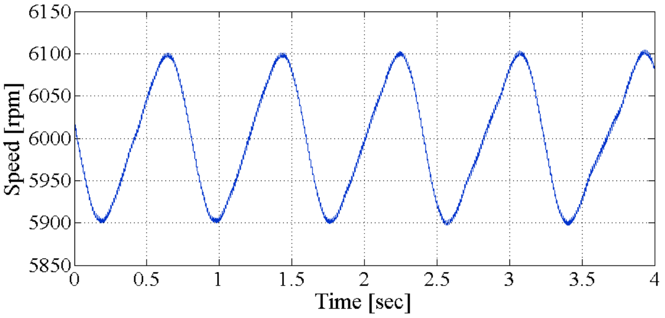

Fig. 9. Speed of the motor by using both the negative and the positive half of the a.c. wave.

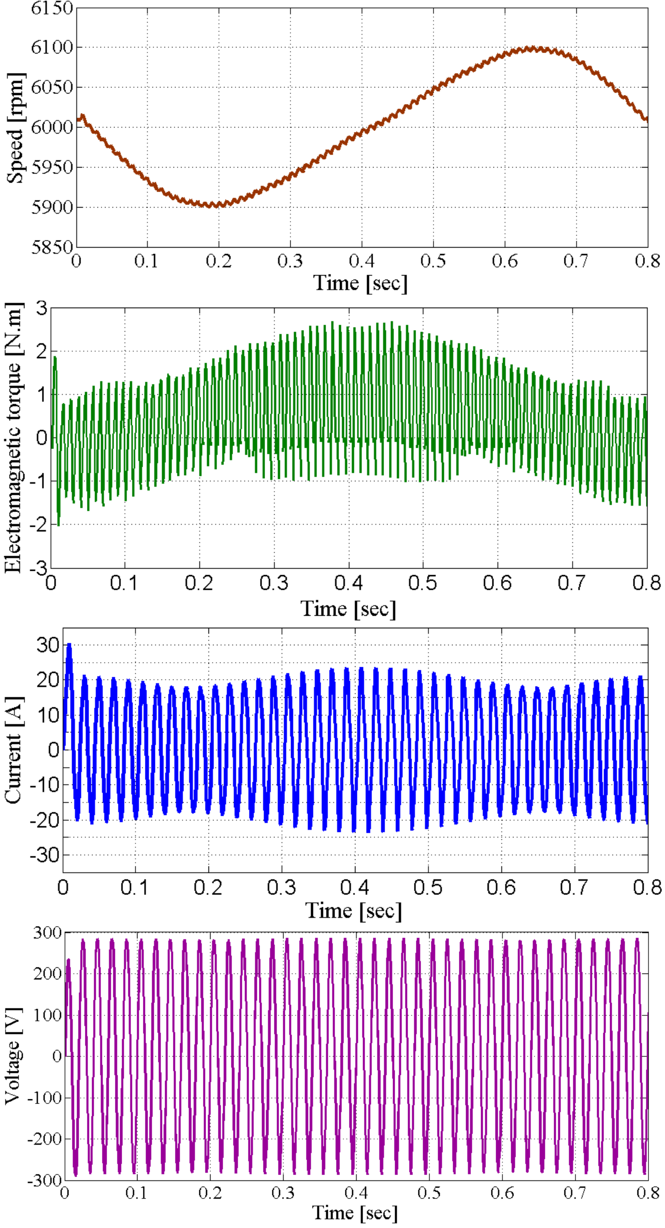

Fig. 10. Waveforms for speed, electromagnetic torque, current and voltage, – alternating current at synchronous speed of 6000 rpm.

The simulation is performed without a mechanical load. The only resistant torque is created by friction.

The speed has again as in the first case of simulation two types of oscillaton. The first oscillation with the frequency of approximately 0.8 Hz is attributed to the absence of any electrical damping and the oscillation will have to be attenuated through mechanical damping. The second oscillation is caused by the reluctance torque, which as stated earlier and evidenced by equation (4) acts with double the supply frequency, in this case 100 Hz.

The rms value of the current is approximately 15 A, as in the case of positive half-wave supply. Nevertheless, the peak value of the current is less when both the negative and the positive wave of the current are used and as a consequence the maximum electromagnetic torque generated.

Also, because the current prolongs itself on the negative slope of the inductance it results in imminent negative electromagnetic torque generation [1], [5], [6].

5. EXPERIMENTAL RESULTS

The tests were conducted in the laboratory and the test bench contained the following components:

- a D.C. motor provided with transduceres for torque and speed;
- a control unit used with the D.C. motor, which allows the speed to be controlled in the interval 0÷4000 rpm.; it also offers the possibility of displaying and aquisition of torque, speed and power;
- a diode, used for half-wave rectification;
- a resistor;
- a data aquisition board together with a virtual instrument installed on a computer;

Because it was needed that the motor to be brought to synchronous speed, i.e. 3000 rpm, the D.C. motor was employed. With the help of the control unit the D.C. motor drives the reluctance motor to the synchronous speed and then the winding of the reluctance motor is supplied from the power supply through the half-wave rectifier and resistor. At the same time the control unit goes from the control mode to monitor.

The speed in the case of no-load operation is presented in Fig. 11. Because the motor does not have any type of damping winding the speed has oscillations around the synchronous speed. These oscillations would eventually be damped.

In order to better visualize the waveforms for speed, current and voltage they are presented in Fig. 12 only for half a second.

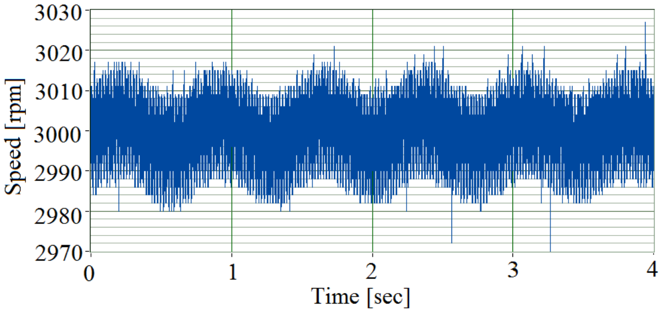

Fig. 11. Speed from data aquisition.

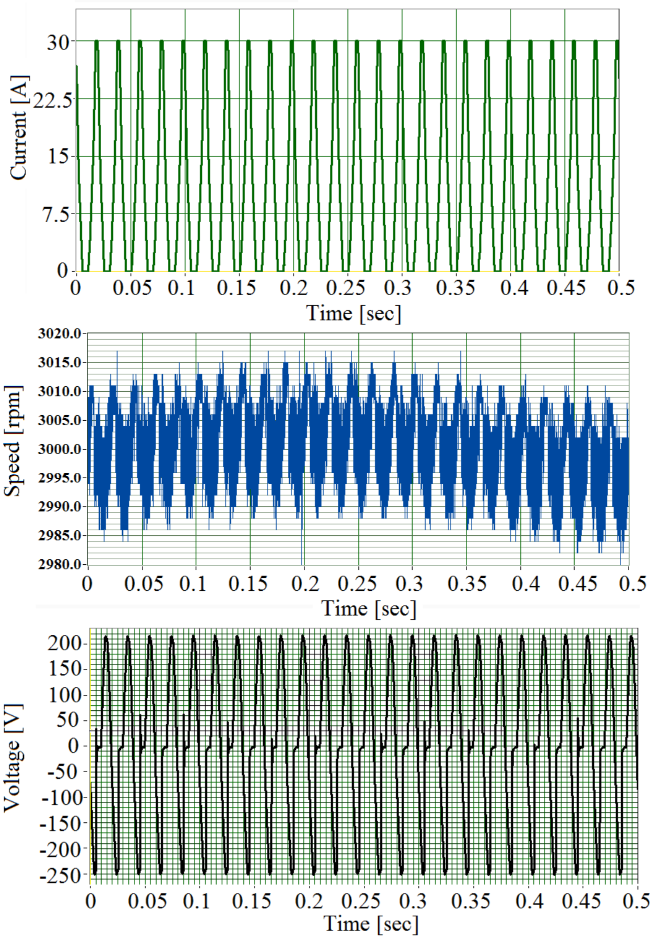

Fig. 12. Waveforms for the case of no-load operation.

6. CONCLUSIONS

The paper presented the study of a single-pole reluctance motor using circuit coupled – 3-D FEM and experimental validation. It was necessary to employ a 3-D model because the motor has no axial symmetry.

Two energizing strategies were used. First, with the help of a half-wave rectifier only the positive half-wave of the current is used. In this case, given a frequency of the power supply of 50 Hz it results in a synchronous speed of 3000 rpm. For the second case, both the positive and the negative half-wave of the current is used. In this way, the synchronous speed is 6000 rpm, which is a unique feature of this type of motor.

The slope of the inductance is responsible along with the current for the electromagnetic torque generation. Therefore, an optimization of the rotor geometry so that the inductance to present a sinusoidal variation is to be considered for a future work. It is to be expected that the maximum torque to be obtained at the middle of the inductance slope when its derivative is maximum.

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