ELECTROMECHANICAL CONVERSION IN A SINGLE-POLE AXIAL FLUX VARIABLE RELUCTANCE MOTOR USING 3-D FEA AND THE NOTIONS OF LOAD ANGLE AND ELECTROMECHANICAL CYCLE

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REZUMAT. Se tratează procesul de conversie electromecanică pentru o maşină cu reluctanţă variabilă, unipolară cu flux axial utilizând analiza prin metoda elementelor finite, MEF. Particularitatea motorului, şi anume structura unipolară, este cea care face ca atunci când alimentarea se face de la frecvenţa reţelei de 50 Hz, motorul funcţionează la turaţia de 6000 rot/min. Pentru o privire mai detaliată asupra procesului de conversie se utilizează noţiunile de unghi intern şi ciclu electromecanic.

Cuvinte cheie: motoare cu reluctanţă variabilă, metoda elementului finit, unghi intern, ciclu electromecanic.

ABSTRACT. The paper presents the electomechanical conversion process for a variable reluctance, single-pole, axial-flux machine using the finite element method, FEM. The particularity of this motor is ensured by the single-pole structure, which makes the motor to operate at the speed of 6000 rpm when supplied from a voltage source with the industrial frequency of 50 Hz. For a clearer insight into the conversion process the notions of load angle and electromechanical cycle are introduced.

Keywords: reluctance motors, finite element method, load angle, electromechanical cycle.

1. INTRODUCTION

Variable reluctance motors are synchronous motors that operate on the principle of variable reluctance, which implies that the production of an energy transfer between its systems is based on the variation of the reluctance. This variation is obtained by design with the help of a non-uniform airgap, or by employing a salient-poles construction. Most often, variable reluctance motors have only one winding per phase, but may also make use of a system or a group of windings, [1], [2].

Due to its functional particularities it is important to evidence the physical mechanism of the power conversion, and the conditions for which this conversion occurs.

A 3-D model, (Fig. 1), was implemented in the FEM software in order to analyze the characteristics of the motor.

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. The rotor consists of three modules placed along the shaft. Each module has the shape of a disc, approximately half of ferromagnetic material and the other half of non-magnetic material, [3], [4], [5], [6].

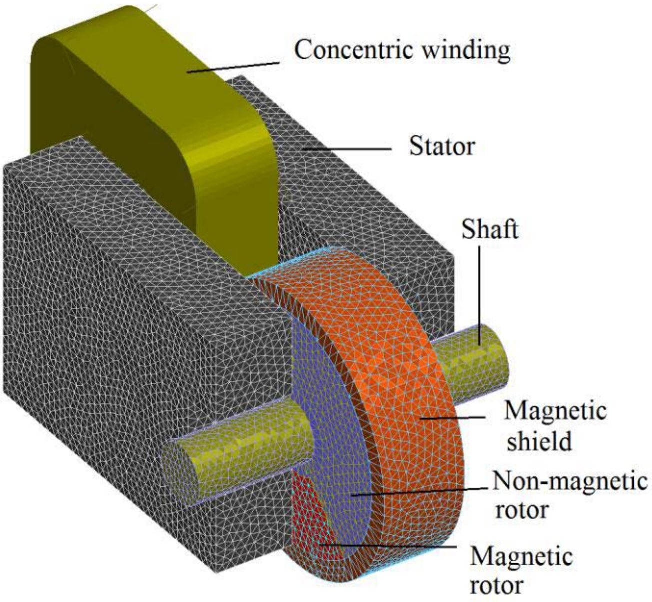

Fig. 1. 3-D model of the variable reluctance machine and the mesh implemented for analysis.

2. TIME-STEPPING ANALYSIS USING 3-D FEM

In order to study the behavior of the motor when it is fed from an alternate voltage supply a time-stepping analysis was employed. All the three comprising systems of the motor: electrical, magnetic and mechanical, are in this way modeled.

The electrical system is modeled with the help of an equivalent electrical circuit presented in Fig. 2.

The voltage supply was defined as follows:

$$u = 230\sqrt{2}\,\sin(2\pi f t). \tag{1}$$

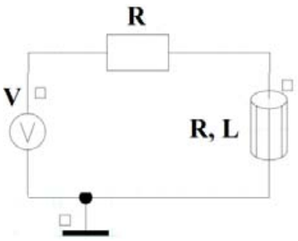

Fig. 2. Equivalent electrical circuit.

The mechanical system is modeled using the moving equation:

$$J\frac{\mathrm{d}\omega}{\mathrm{d}t} = T_e - T_r(\omega) = T_e - T_L - B\cdot\omega, \tag{2}$$

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.

Simulations were performed for different loads. In Fig. 3 are presented the the waveforms for speed, electromagnetic torque and current at maximum load.

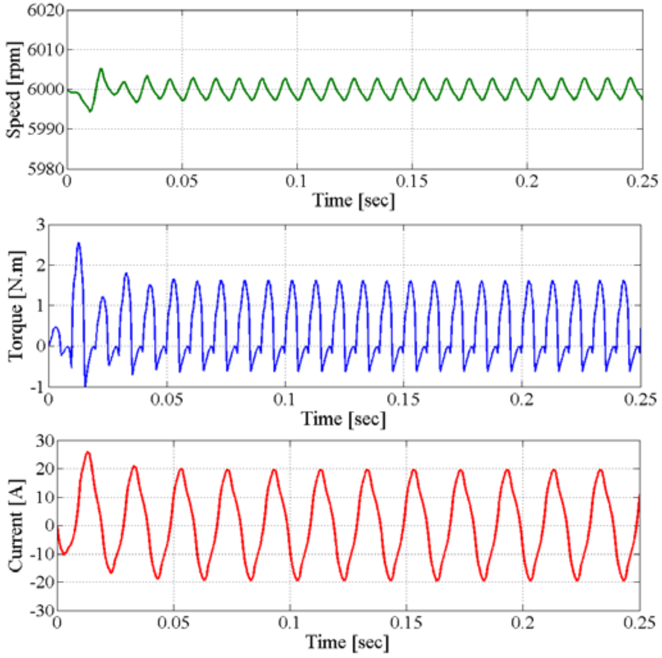

Fig. 3. Speed, torque and current at full load.

It can be observed that also negative torque is created on the falling slope of the current and in order to be able to discuss over a positive mean value of the torque it is important to introduce the notion of load angle.

3. ANALYSIS USING LOAD ANGLE AND ELECTROMECHANICAL CYCLE

If it is considered that the motor operates at synchronous speed at no-load and in the ideal case without friction, (B = 0, coefficient of fiction), the longitudinal axis of the rotor has the tendency to allign with the stator polar axis. In other words, because there is no transfer of energy from the electromagnetical system to the mechanical system, the mean torque is equal to zero, the peak value of the current corresponds temporaly to the moment when the inductance of the circuit is maximum, L_{max}. Because of the symmetry that the inductance characteristic has over the rising slope and the falling slope, the current flowing through the winding will generate a positive torque over the rising slope of the inductance and an equivalent negative torque over the falling slope. Such a case is illustrated in Fig. 4, where the mean electromagnetic torque is approximately zero, more exactly: $T = 0.046$N·m.

The load angle is defined as the angle between the longitudinal axis of the rotor and the stator polar axis, θ, measured at the moment when the fundamental of the current has its maximum value, divided by two to be in accordance with the variation of the inductance, whose frequency is twice the frequency of the current, [7]. In Fig. 4, the load angle is $\delta = \theta/2 = 4.5$ degrees.

Also, a graphical representation of the load angle is shown in Fig. 5, presenting the magnetic flux density color map for the moment when the fundamental of the current reaches its maximum value.

The energy absorbed in the first instance is returned in the second, not considering the Joule losses, Fig. 6.

A more suggestive representation is that of the electromechanical cycle, Fig. 7, whose area represents the magnetical energy involved into the conversion process and corresponds to the mechanical energy transfered to the shaft, [7], [8].

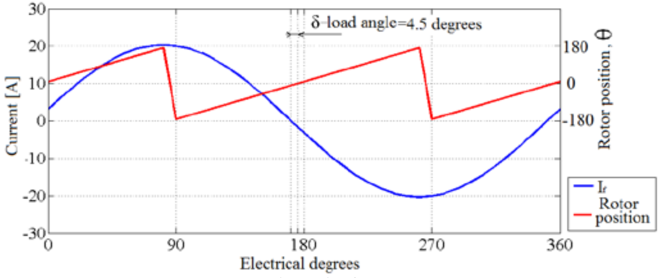

Fig. 4. Load angle for $T = 0.046$N·m.

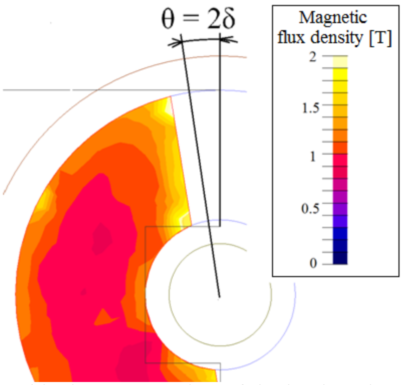

Fig. 5. Graphical representation of the load angle and of the magnetic flux density, δ =4.5°.

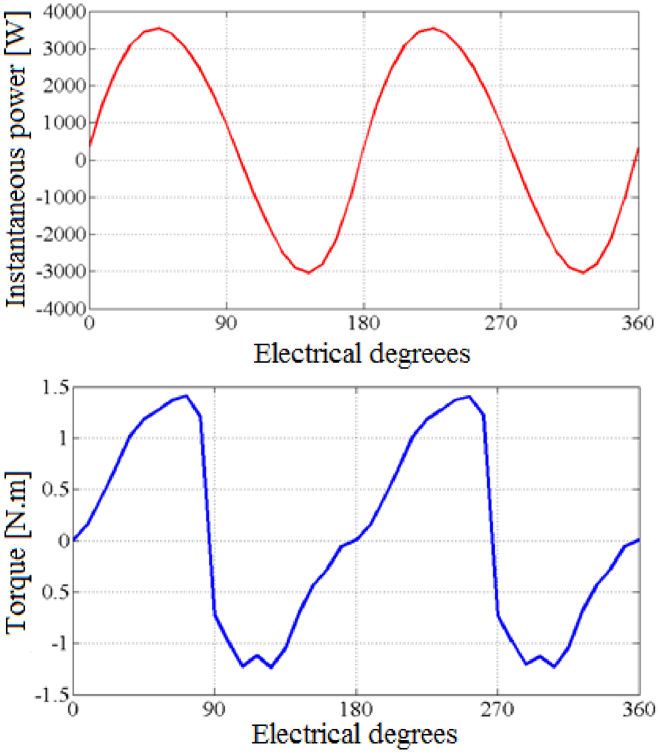

Fig. 6. Instantaneous power and torque, (load angle δ =4.5).

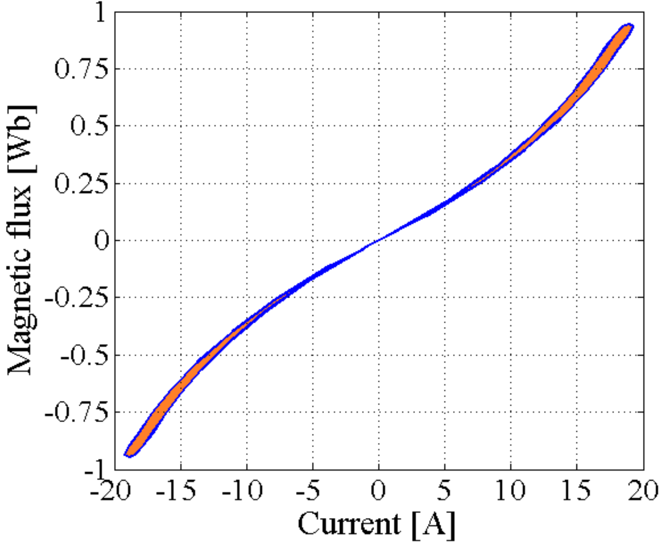

Fig. 7. Electromechanical cycle for T=0.046N.m and δ =4.5.

In the case when mechanical power is delivered to the shaft, the load angle δ has the tendency to increase so as through the relative displacement of the peak value of the current towards the increasing slope of the inductance a positive mean electromagnetic torque is generated. In this way, the load angle δ is determined by the load and characterizes the electromechanical conversion process.

In Fig. 8 it is represented the case when the mean electromagnetic torque has its maximum value, i.e. T = 0.6517 N·m.

Fig. 9 illustrates graphically the load angle and the color map for the magnetic flux density in the case of T = 0.6517N·m and a load angle δ =32.85°.

In Fig. 10 are represented the instantaneous power and the electromagnetic torque for a period. The mean value of the electromagnetic torque is equal to 0.065N·m and it is the maximum torque that could be generated. The load angle for which this torque is obtained is δ =32.85°.

It is possible to represent the dependency ψ = ψ(i), over a period of the supply voltage, T, and obtain the electromechanical cycle, whose surface represents the mechanical energy obtained through conversion. Fig. 11 illustrates the electromechanical cycle for δ = 32.85°

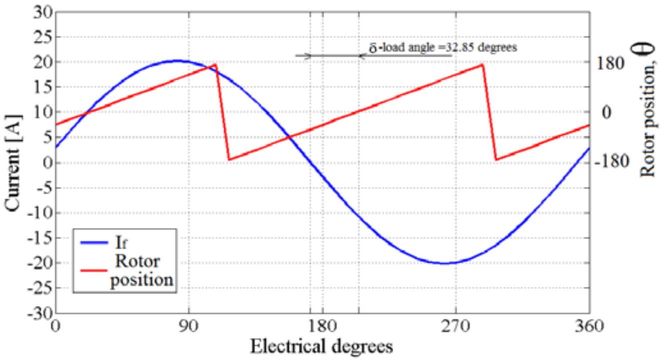

Fig. 8. Load angle for T = 0.6517N·m.

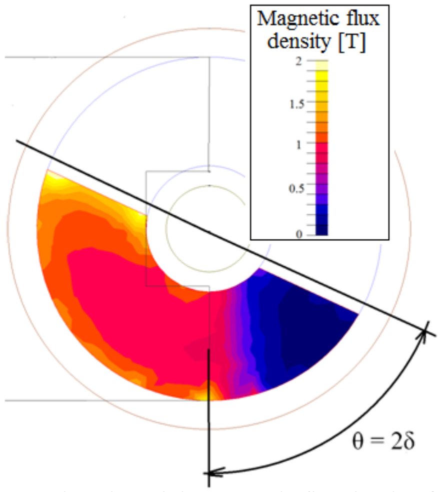

Fig. 9. Load angle and the magnetic flux density, δ =32.85°.

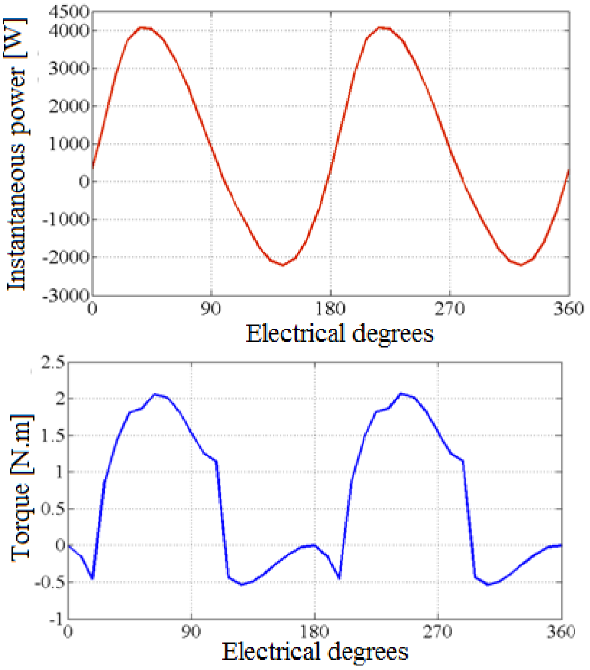

Fig. 10. Instantaneous power and torque, (load angle δ =32.85).

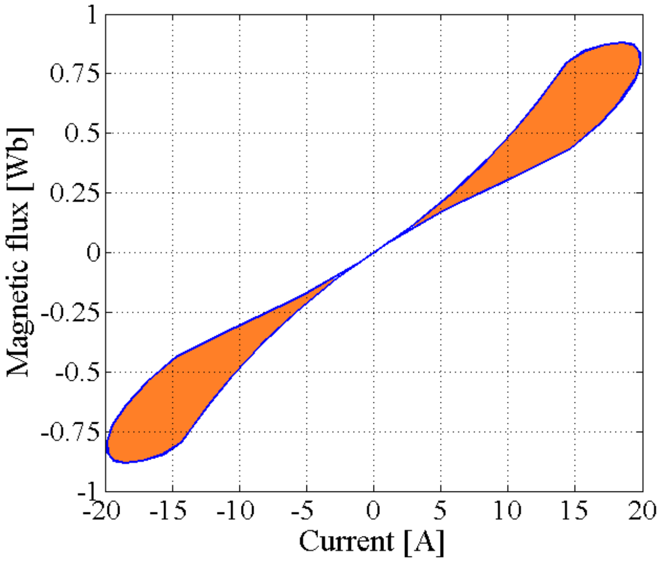

Fig. 11. Electromechanical cycle for T=0.65N.m and δ =32.85.

In Fig. 11 it can be observed that the surface of the electromechanical cycle has increased, which means as opposed to the case presented in Fig. 7 that mechanical work is performed. In the case of a static single-phase circuit or in the case when the motor operates ideally neglecting the friction losses ($\delta = 0$) the area of the electromechanical cycle would be zero.

In the case when the motor operates at a load angle different to zero, $\delta \neq 0$, the conditions for electromechanical conversion are satisfied and mechanical work is done at the shaft through the tendency of the system to achieve the position of stable equilibrum, for which the energy stored in the magnetic field is maximum (the inductance is maximum or $W_{max} = \frac{1}{2} I_{max} \psi_{max}$, where W_{max} – the maximum magnetic energy of the system). In these conditions an amount of the stored magnetic energy is converted into mechanical energy, the greater the internal angle, the greater the surface of the electromechanical cycle.

The dependency $T = f(\delta)$ is called torque − load angle characteristic of the variable reluctance machine. In Fig. 12 it is represented the torque − load angle characteristic of the studied machine, [1].

The increase of the load angle, δ, determines a modulation of the current waveform, and as a result the machine absorbs active power from the source both through the fundamental of the current and through its harmonics, [1]. In Fig. 13 it is represented the dependency $P = f(\delta)$, where P is calculated using eq. (3):

$$P = \frac{1}{T} \int_0^T u \cdot i \, dt. \tag{3}$$

The reactive power is calculated using eq. (4):

$$Q = \sqrt{S^2 - P^2},. \tag{4}$$

where Q is the reactive power, S – apparent power and P – active power.

The motor changes reactive power with the source regardless of the operating regime, more exactly regardless if it is operating at no-load or at full-load, [7]. The reactive power – load angle characteristic is represented in Fig. 14. It can be observed a small decrease of the reactive power changed with the source with the increase of the load angle, that is with the increased absorbtion of active power, but not significantly.

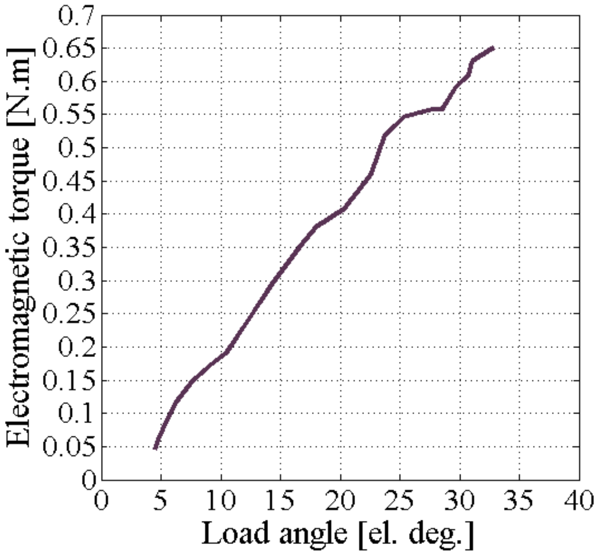

Fig. 12. Torque − load angle characteristic of the variable reluctance machine, $T = f(\delta)$.

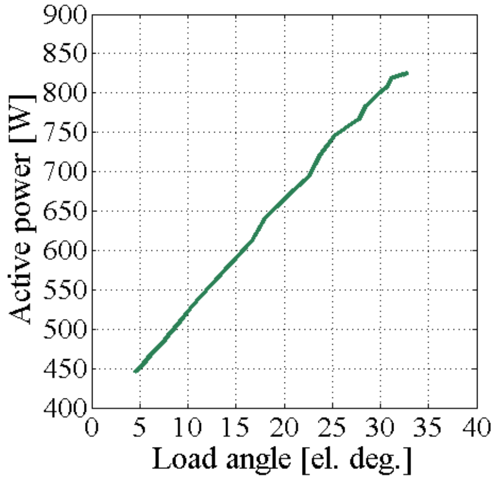

Fig. 13. Active power – load angle characteristic of the variable reluctance machine, $P = f(\delta)$.

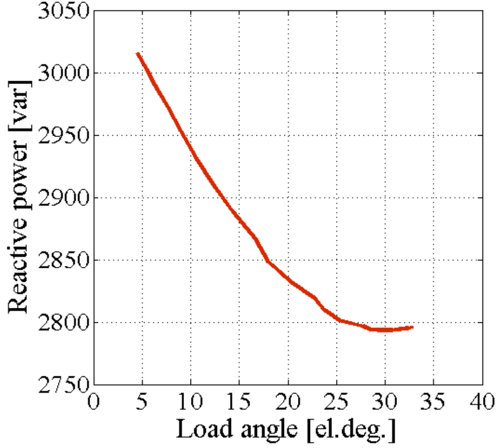

Fig. 14. Reactive power – load angle characteristic of the variable reluctance machine, $Q = f(\delta)$.

4. CONCLUSIONS

The electromechanical conversion in a variable reluctance machine is conditioned by synchronism. Also, the amount of converted energy is self-regulated according to the load in a range determined by the load angle. Ideally, the angle varies sinusoidally with the maximum value for torque obtained at 45°. Nevertheless, in our case, the maximum torque of 0.6517 N·m is achieved at 32.85°, which suggest parasitic torques overlapping the fundamental, and caused by a non-sinusoidal variation of the inductance between the two extreme positions.

The small power factor caused by the reduced ratio between the two extreme inductances reflects in an increased change of reactive power with the source.

Considering the coefficient of friction $B = 0.0006$ N·m·s it results in an usefull torque at the shaft of only 0.25 N·m, in which case the usefull mechanical power is 157W. A possible solution to improve the performances would be to use a modular construction (more modules placed on the same shaft). In this way the torque oscillations would be reduced and with an adequate control strategy (either vectorial control or as a switched reluctance motor – SRM), the overall performances of the motor would be increased; not to mention the starting problem which would also be solved.

ACKNOWLEDGMENT

This paper was realized with the support of POSDRU CUANTUMDOC “DOCTORAL STUDIES FOR EUROPEAN PERFORMANCES IN RESEARCH AND INOVATION” ID79407 project funded by the European Social Found and Romanian Government.

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