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FINITE ELEMENT METHOD MODELING OF BRUSHLESS DC SERVOMOTOR WITH FRACTIONAL NUMBER OF SLOTS PER POLE

BY

CRISTINA-NICOLETA DIACONESCU, GHEORGHE URSANU and GHEORGHE BĂLUŢĂ*

“Gheorghe Asachi” Technical University of Iaşi
Faculty of Electrical Engineering

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Abstract. The authors present in this paper the magnetic circuit modeling of a BrushLess DC (BLDC) servomotor with 9 slots and 10 poles using finite element method (FEM). They also present the optimization of BLDC servomotor which aims to reduce the cogging torque and to improve the electromagnetic torque. Therefore, it has been modified the slot’s area and opening. The magnetic circuit modeling of the proposed structure has been realized in FEMM4.2 program. To obtain the waveforms of electromagnetic torque, cogging torque and Back-ElectroMotive Forces (BEMF) for the three phases of servomotor it has been created a program in LUA scripting language, which is integrated into interactive shell of FEMM4.2.

Key words: BLDC servomotor; fractional number of slots per pole; FEM; cogging torque.

1. Introduction

The servomotors based on permanent magnets with high energy are used in most part of applications, in special in electrical drive systems. In present, it is intended to replace classical DC servomotors by brushless servomotors, either DC or AC. Therefore, brushless servomotors with special

*Corresponding author: *e-mail*: gbaluta@tuiasi.ro

structures, have been designed to achieve high performances (Dajaku & Gerling, 2011; Miller, 1989; Petrovska *et al.*, 2012).

In accordance with general theory of three phase electrical machines to realize a winding it is necessary minimum one slot per pole per phase. Therefore, for machines having 2 poles, 6 slots are necessary only to realize the winding but not to achieve high performances. To obtain medium performances 3 slots per pole per phase are necessary, which means 18 slots for a machine with 2 poles. In practice, the electrical machines are designed with more poles, usually with 6 or 8. There are also special machines which have over 40 poles. In this case, there are necessary from 48 to 72 slots or even 360 slots (Jula & Ursu, 2002).

The need to achieve high density of power and torque (power and torque *versus* total weight or total volume) made possible the design of special machines with fractional number of slots per pole and phase less than one, which is the equivalent of *fractional number of slots per pole* studied by Salmien (2004)

$$q = \frac{N_s}{2mp}, \tag{1}$$

where: N_s is the number of slots, m – the number of phases, and p – the number of pole pairs.

An electrical machine with fractional number of slots per pole offers some advantages, such as (Miller, 1989; Petrovska *et al.*, 2012; Salmien, 2004; Tangudu, 2011)

a) higher specific output power and density torque;

b) higher efficiency;

c) lower cogging torque achieved;

d) reduced winding mutual inductance between phases;

e) reduced mass and volume of machine by lowering the stator copper content;

f) high slot fill factor.

To meet actual requirements, the designers of electrical machines have been tried to reduce the number of slots as much as possible and in the same time to keep the possibilities of a proper operation of the servomotor (maintaining the waveforms of BEMF and electromagnetic torque developed to the shaft).

Taking into account the mentioned aspect, the paper presents the magnetic circuit modeling using FEM of a BLDC servomotor with fractional number of slots per pole (9 slots and 10 poles).

2. FEMM4.2 Program

Finite Element Method Magnetics (FEMM) is a suite of programs that solve low frequency electromagnetic problems on two-dimensional planar and axial-symmetric domains. The program currently addresses linear/nonlinear magnetostatic problems, linear/nonlinear time harmonic magnetic problems, linear electrostatic problems, and steady-state heat flow problems (Meeker, 2002).

FEMM program is divided in three parts: *interactive shell* (a Multiple Document Interface pre-processor and a post-processor for the various types of problems solved by FEMM), *triangle.exe* (breaks down the solution region into a large number of triangles, a vital part of the finite element process), and *solvers* (each solver takes a set of data files that describes problem and solves the relevant differential eqs. with partial derivatives (DEPDs) to obtain values for the desired field throughout the solution domain). It is based on FEM which means that the problem to solve is divided into a large number of regions, each region having a simple geometry (*i.e.* triangles). For these regions, the real solution for desired potential is approximated by a very simple function. The approximated potential is very closed to exact solution when small enough regions are used. On each element the solution is approximated using a linear interpolation of the values of potential at the three vertices of the triangle. The linear algebra problem is obtained by minimizing a measure of the error between the exact DEPD and the approximate DEPD as written in terms of the linear trial functions (Meeker, 2002).

3. BLDC Servomotor with 9 Slots and 10 Poles

The BLDC analysed servomotor was realized with 9 slots and 10 poles, its structure being presented in Fig. 1.

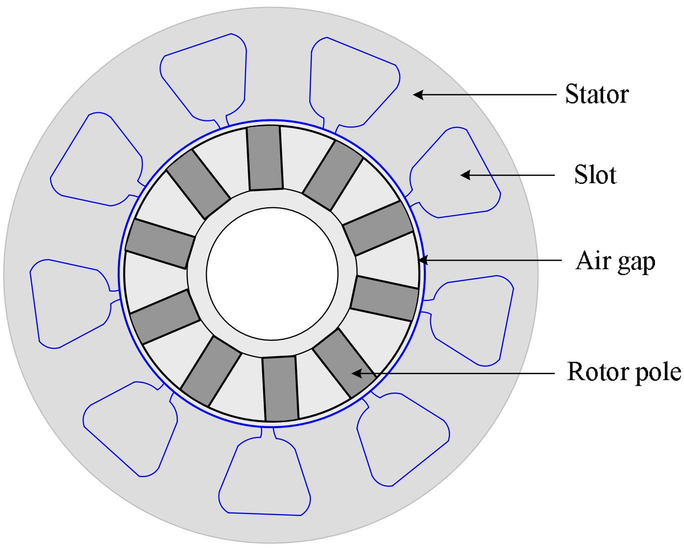


Fig. 1 – The configuration of BLDC analysed.

To be possible to realize the model in FEMM4.2 it is necessary to compute servomotor sizes. Therefore, it is necessary to compute the number of coil per phase and the number of turns per coil (Miller, 1989)

$$N_{cph} = \frac{N_s}{2m} = \frac{2mpq}{2m} = pq\,, \tag{2}$$

$$w_t = \frac{w}{N_{cph}} = \frac{w}{pq}\,, \tag{3}$$

where w is the number of turns per phase.

To realize the model in FEMM4.2, more stages have been studied (Meeker, 2002). In first stage it has been established the type of problem (two-dimensional planar problem) and the boundary for simulation. In next stage were defined the geometry of the servomotor and the materials used for each component of the servomotor. The rotor with 10 poles was modeled from NdFeB 35-SH permanent magnets, material with good magnetic properties and the stator were modeled with M-19 Steel. Each stator winding has 40 turns per phase and its resistance is 0.42 Ω. Also, for the rotor shaft 430 Stainless Steel was used and between the rotor poles 1117 Steel was used. The magnetic properties of the materials used in modeling are presented in Tables 1 and 2. In Fig. 2 are shown the magnetization curves of these materials.

Table 1

Magnetic Properties of Material Used in Modeling

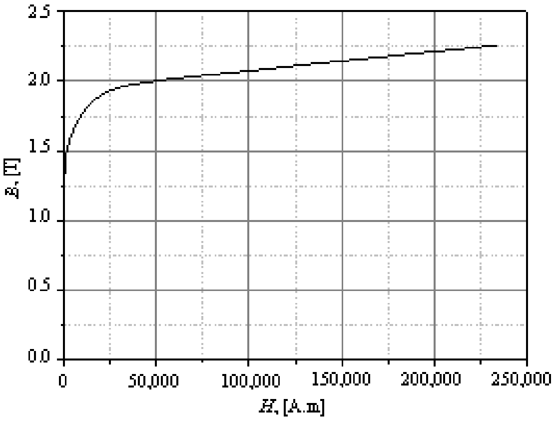
	Electrical conductivity MS/m	Relative permeability	Filling factor	Thickness mm
M19 Steel	1.9	4,416	0.98	0.635
430 Stainless Steel	0	409	1	0
1117 Steel	5.8	1,777	1	0

Table 2

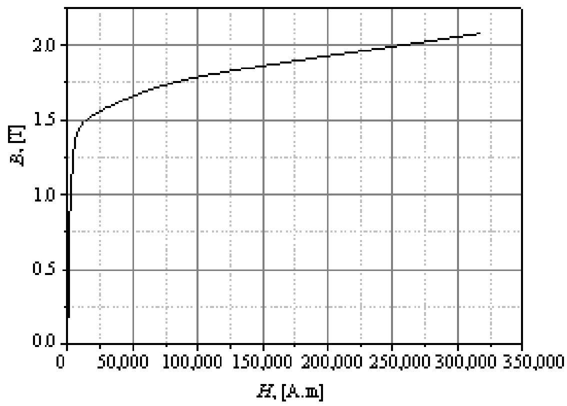
Magnetic Properties of NdFeB 35-SH

	Remanent field density, B_r T	Coercive force, H_{cb} kA/m	Coercive force, H_{ci} kA/m	Maximum energy product BH_{max}, [kJ/m^3]	Working temperature ^{o}C
NdFeB 35-SH	1,170...1,220	≥ 876	≥ 1,592	263...287	150

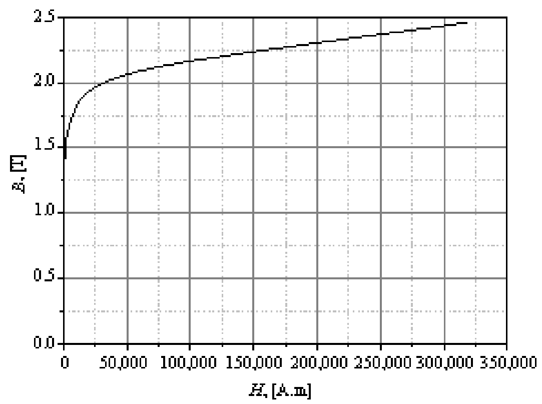
Using FEMM4.2 program, the surface that represents the servomotor was divided in a large number of triangular regions with small dimensions. Therefore, a mesh that allows solving the problem much easier was created. In this manner, on each element that was created, the solution is approximated by a linear interpolation of the values of potential at the three vertices of the triangle (Meeker, 2002). The structure achieved in FEMM4.2 consists of 4,966 nodes and 9,570 elements and is shown in Fig. 3.



a – M-19 Steel.



b – 1117 Steel.



c – 430 Stainless Steel.

Fig. 2 – *B*(*H*) curves of the materials used in modeling.

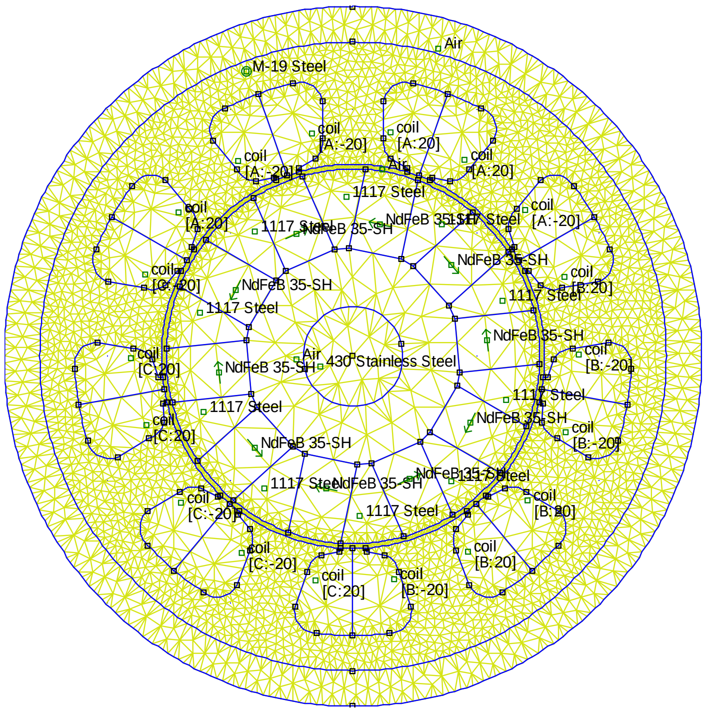


Fig. 3 – FEMM model of BLDC servomotor with 9 slots and 10 poles.

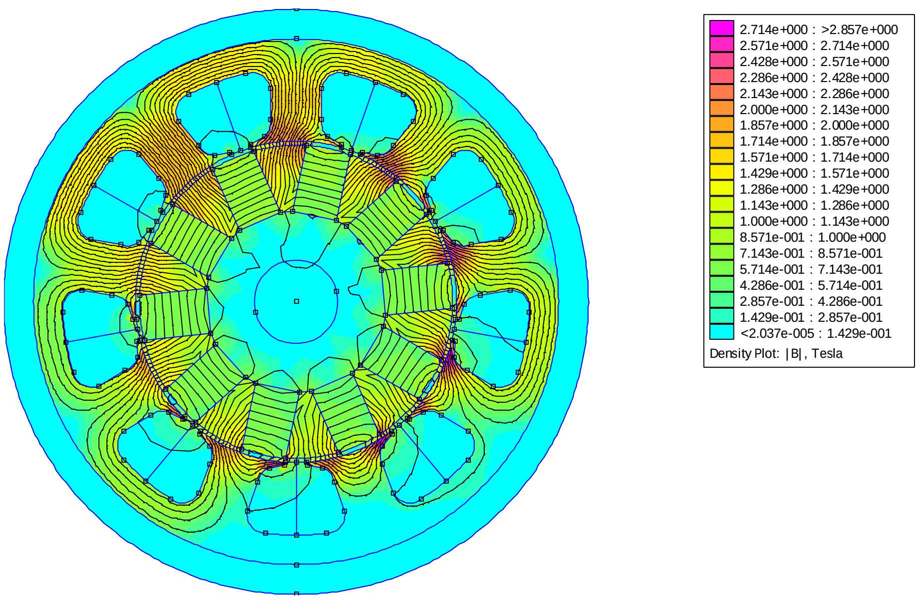


Fig. 4 – Radial model of BLDC servomotor with 9 slots and 10 poles.

As one can see, the servomotor's air gap consists of air with relative permeability μ_r = 1 H/m. Also, the working boundary consists of air. After the model of BLDC servomotor with 9 slots and 10 poles was run, the radial model of the servomotor was achieved (see Fig. 4). Based on radial model of BLDC servomotor one can obtain the variation of field density in air gap (s. Fig. 5).

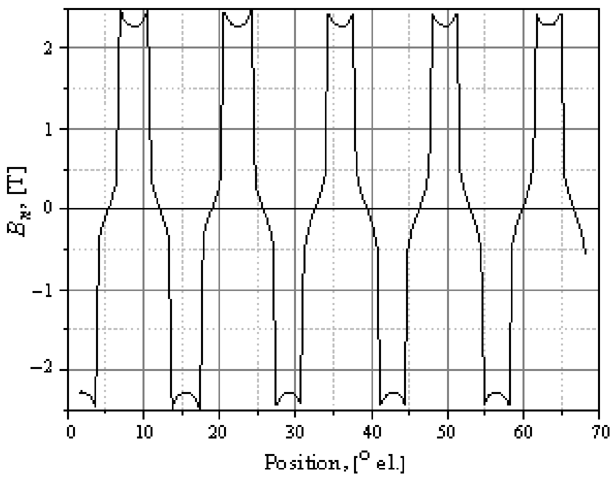


Fig. 5 – Field density in air gap

4. Simulation Results

To obtain the waveforms of BEMF, electromagnetic torque and cogging torque for BLDC servomotor with 9 slots and 10 poles was necessary to write a program in LUA scripting language, that is integrated into interactive shell of FEMM4.2 program (Meeker, 2002). As input parameters for this program were considered the number of pole pairs, *p*, the number of electrical integration cycles needed for computation (360 × 2/*p*) and the integration step.

Using LUA specific functions, the flux and electromagnetic torque (the difference between total torque and cogging torque) were computed. Having the flux on each phase, one can compute the BEMF (fluxes difference) for the three phases of servomotor. The BEMF depends on rotor position, so at each step the rotor position is incremented. The air gap of the servomotor is 0.4 mm.

To optimize the BLDC servomotor with 9 slots and 10 poles the size of the air gap was kept and the surface and the opening of the slots were modified; the final slot area is 770.61 mm^2 compared with the initial area of 719.564 mm^2. Therefore, in Figs. 6,…, 9 are presented the waveforms of electromagnetic torque, cogging torque and BEMF, respectively, before and after optimization.

After optimization one can see a decrease of cogging torque, its average value is about 10% lower than in initial case. Also, there is an increase of electromagnetic torque, its average value is of 2.060842 N.m compared to initial value of 2.021064 N.m.

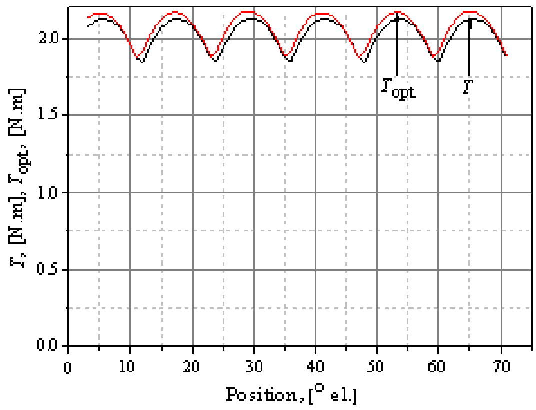


Fig. 6 – Waveforms of electromagnetic torque (before and after optimization).

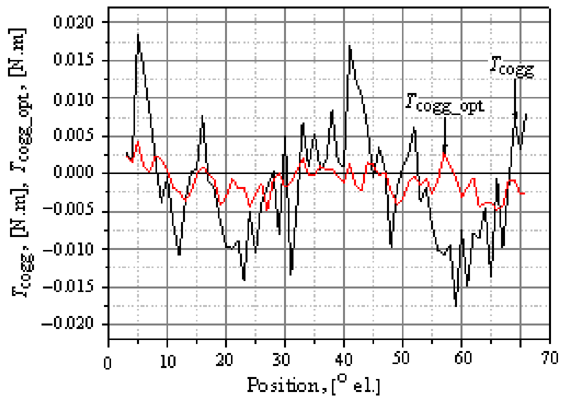


Fig. 7 – Waveforms of cogging torque (before and after optimization).

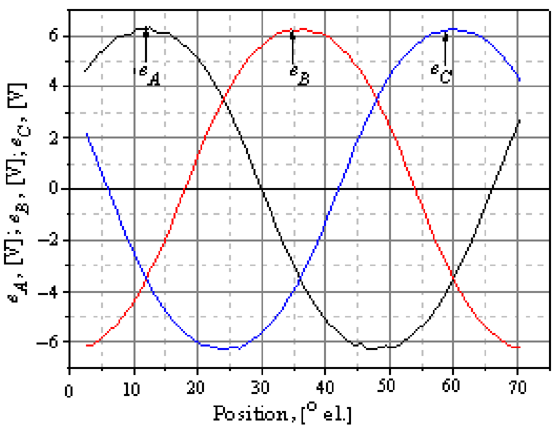


Fig. 8 – Waveforms of BEMF before optimization.

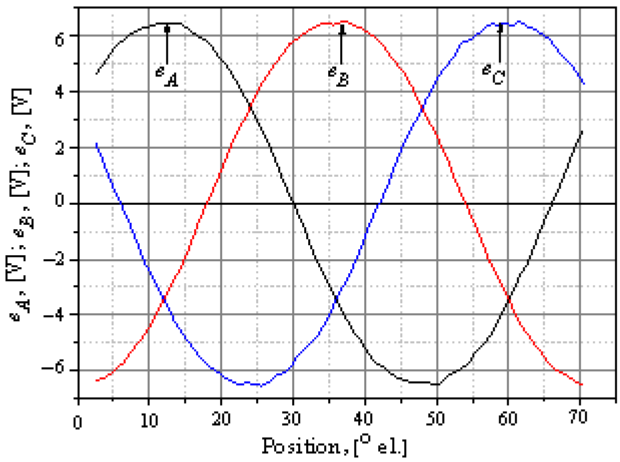


Fig. 9 – Waveforms of BEMF after optimization.

5. Conclusions

Currently, it exists the tendence to replace the clasical DC servomotors with brushless servomotors with special structures, either DC or AC due to their advantages. Therefore, the paper presents the magnetic circuit modeling and the optimization of a BLDC servomotor with fractional number of slots per pole (9 slots and 10 poles).

The authors aim to find an algorithm to improve the analysed servomotor by computing the optimal values for electromagnetic torque and cogging torque.

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MODELAREA PRIN METODA ELEMENTULUI FINIT A SERVOMOTORULUI DE CURENT CONTINUU FĂRĂ PERII CU NUMĂR FRACȚIONAR DE CRESTĂTURI PE POL

(Rezumat)

Se studiază modelarea circuitului magnetic al servomotorului de curent continuu fără perii, cu 9 crestături şi 10 poli, prin metoda elementului finit şi optimizarea acestuia. În acest sens au fost modificate suprafața şi izmul crestăturii. Modelarea circuitului magnetic al structurii propuse a fost realizată in pachetul de programe FEMM4.2, iar obținerea formelor de undă corespunzătoare cuplului electromagnetic, cuplului parazit de prindere magnetică (cuplul de „cogging") şi tensiunilor electromotoare (BEMF) pe cele trei faze ale servomtorului a fost realizată prin utilizarea limbajului de programare LUA, integrat în interfața interactivă a programului FEMM4.2.