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IPMSM WITH SMC ROTOR – OPTIMIZATION AND EXPERIMENTAL RESULTS

MASZYNA SYNCHRONICZNA Z WIRNIKIEM PROSZKOWYM – OPTYMALIZACJA I WYNIKI EKSPERYMENTALNE

A b s t r a c t

The work presented in this paper relates to an Interior Permanent Magnet Synchronous Motor (IPMSM) experimental results and optimization procedure programed in Matlab and Maxwell environments. The stator of the machine is a conventional stator with distributed winding. The subject of the first optimization stage was the geometry of the IPM machine, concerning average torque value maximization and maximum cogging torque value minimization under physical and technological constraints. The optimized rotor core is made of from Magnetic Powder (SMC). It was tested in a generator regime.

Keywords: *PM electrical machines*, *IPMSM optimization*, *FEM*, *experimental research*

S t r e s z c z e n i e

Artykuł podejmuje temat badań eksperymentalnych oraz optymalizacji maszyn synchronicznych z magnesami zagnieżdżonymi z wykorzystaniem narzędzi Matlab i Maxwell. Stojan badanej maszyny jest typowym stojanem silnika asynchronicznego klatkowego z uzwojeniem rozłożonym. Dokonano optymalizacji geometrii wirnika maszyny, z uwzględnieniem maksymalizacji wartości średniej momentu elektromagnetycznego i minimalizacji maksymalnej wartości momentu zaczepowego oraz ograniczeń geometrycznych i technologicznych. Zoptymalizowany rdzeń wirnika został wykonany z proszku magnetycznie miękkiego. Zaprojektowaną maszynę przebadano w stanie generatorowym.

Słowa kluczowe: *maszyny z magnesami trwałymi*, *optymalizacja*, *MES*, *badania eksperymentalne*

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1. Introduction

To protect the environment, there exists a strong demand to develop very efficient motors with a high torque/mass ratio. Thanks to the rapid advancement of power electronics, material engineering, digital signal processors and control algorithms, PM-excited and switched reluctance motors find more and more applications and have replaced the traction systems of most present hybrid and electrical vehicles because they offer high performance over other DC and AC machines [1–3]. In particular, owing to the development of rare-earth magnets with high energy production, it is possible to develop high power density machines with improved overall efficiency. Furthermore, extended high speed capabilities, demanded in a highway cycle, are achieved thanks to proper rotor geometry designs, and field weakening control strategies [3–8]. Surface and radially-laminated Interior PM synchronous machines with conventional structures have limited or zero flux-weakening capability [5, 6]. Properly designed IPMSMs are capable of operating in CPSR (constant power speed region) – such machines also perform inverse saliency, i.e. the *q*-axis inductance is larger than *d*-axis inductance. Consequently, it provides an additive torque value, reluctance torque, that may be exploited to extend CPSR. Another positive feature of the IPM rotor is that centrifugal forces cannot damage magnets, thus the whole construction is mechanically robust. Small cogging torque reduces noise and mechanical vibrations which causes increased reliability and user-friendly operation [9–13]. PM excited machines can fulfill all the above requirements [1–4].

A proposed geometry has NdFeB magnets oriented in a radial direction. Such structures are referred to as IPM machines [5, 6]. Its rotor is made of Soft Magnetic Powder. The authors have implemented the optimization procedure in the Matlab environment with a genetic algorithm that runs and evaluates FE models using Maxwell (Ansys). After the optimization process, the machine has been built and tested.

2. PMSM mathematical model

Torque generated in IPM machines can be described as follows:

$$T_{em} = \frac{3}{2} \cdot p_b \cdot \left[\Psi_{PM} \cdot I_q + \left(L_d - L_q \right) \cdot I_d \cdot I_q \right] \tag{1}$$

where:
T_{em} – electromagnetic torque average value,
p_b – number of pole pairs,
Ψ_{PM} – PM caused magnetic flux,
I_d, I_q – *d*- and *q*-axis currents,
L_d, L_q – *d*- and *q*-axis inductances.

Electromagnetic torque may be divided into two components. The first term in the equation (1) is the PM torque, and the second term is the reluctance torque which is proportional to difference between stator inductances, L_d and L_q. In the analyzed IPMSM, L_q is higher than L_d (due to the lower reluctance in the *q*-axis direction), because magnetic flux flowing along the *d*-axis has to cross the air gap and magnet, while the magnetic flux of *q*-axis crosses only air gap. The *d*-axis is also basically magnetized with PM [5, 6]. The inductance difference increases torque and extends CPSR. The mathematical model of IPM machines is commonly defined by the following equation set:

$$U_d = RI_d + \frac{\mathrm{d}\Psi_d}{\mathrm{d}t} - p_b \Omega_m \Psi_q \tag{2a}$$

$$U_q = RI_q + \frac{\mathrm{d}\Psi_q}{\mathrm{d}t} + p_b \Omega_m \Psi_d \tag{2b}$$

$$\Psi_d = L_d I_d + \Psi_{PM} \tag{2c}$$

$$\Psi_q = L_q I_q \tag{2d}$$

where:
U_d, U_q – *d*- and *q*-axis voltages,
R – stator phase winding resistance,
Ψ_d, Ψ_q – *d*- and *q*-axis magnetic fluxes,
Ω_m – mechanical rotor speed.

The control strategy applied for such motors meets several limitations:

$$U_d^2 + U_q^2 \le U_N^2 \tag{3a}$$

$$I_d^2 + I_q^2 \le I_N^2 \tag{3b}$$

where U_N, I_N denote base harmonic voltage and current RMS values.

In high speed regions, a flux developed by magnets gives electro-motive force that exceeds supply voltage (2). Using the classic field weakening method, the main flux is decreased by the *d*-axis negative current (2c) and thus it is possible to stay within the voltage limit (3a). The optimum flux-weakening condition can be written as:

$$I_N = \left| \frac{\Psi_{PM}}{L_d} \right| \tag{4}$$

Such designs are called optimal field-weakening IPM machines and theoretically exhibit unlimited CPSR.

3. Design problem

The case of this study is represented by a 4-pole IPMSM with a fixed stator geometry and winding parameters. The rotor is equipped with NdFeB magnets (B_r = 1.23 T, size: 50x20x40 mm) and is made of SMC (relative permeability of about 40). In contrary to the previous research [11], classical geometry (without magnets segmentation) was chosen in order to achieve high electromagnetic torque value. In IPMSM designs, magnet volume should be rather high and segmented geometry will cause PM flux leakage. A small PM flux leakage is strongly demanded especially for rotors made of SMC (with rather low relative permeability values of 30–100 [2]).

Some of the IPM parameters are kept constant – these are presented in Table 1. Selected design variables were chosen according to the available technological abilities – these are presented in Table 2. The analyzed geometry (optimized geometry without SMC poles) is depicted in Fig. 1.

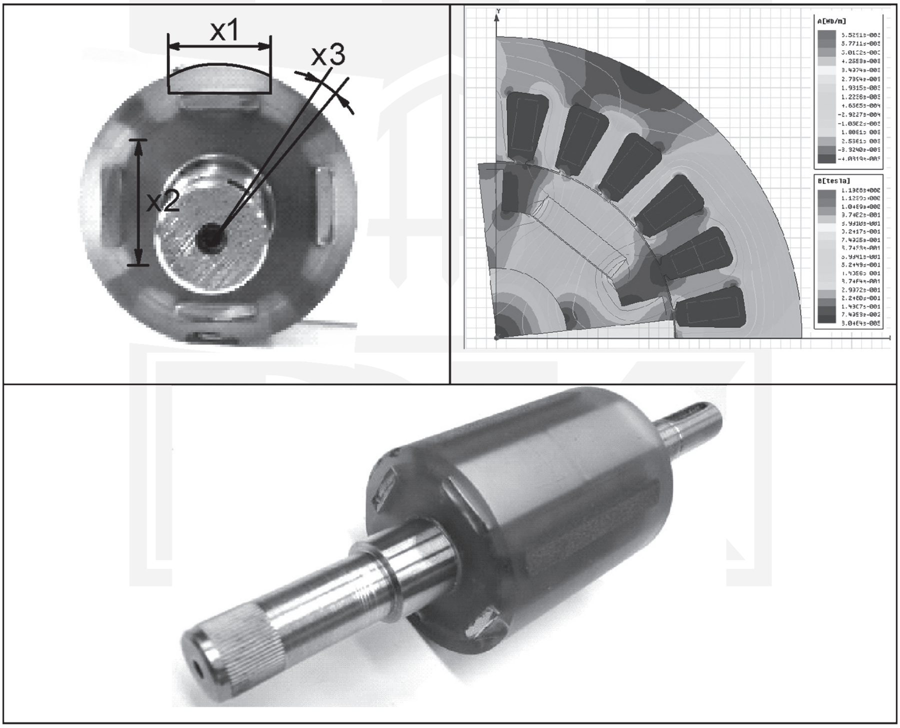

Fig. 1. Initial rotor geometry (without iron poles)

Table 1

Machine parameters

Rotor outer diameter [mm]	Air gap length [mm]	Stator outer diameter [mm]	Rotor length [mm]	Nominal current [A]	Phase resistance 20° [Ohm]
67.5	1.5	120	55	1.6	12.7

Table 2

Design variables constraints

$x1$ [mm] Pole width	$x2$ [mm] Cutter width	$x3$ [deg] Tooth angle
5–26	13–16	0–20

4. Optimization process

In the optimization procedure, a genetic algorithm (GA) was used. This heuristic technique based on a struggle between individuals, commonly known as GA, mimics natural selection that exists in nature were the strongest individuals survive, because they fit to the present demanding [11, 13]. Details of the used genetic algorithm have been given in [14].

The optimization problem described in the paper is a typical multi-objective optimization problem (MOP) subject to a set of constraints. For the proposed geometry, the following objective functions are defined:

$$f_1(x) = \max(T_{cogg}(\varphi)) \tag{5a}$$

$$f_2(x) = -\text{mean}(T_{em}(\varphi)) \tag{5b}$$

where:
T_{cogg} – cogging torque,
T_{em} – electromagnetic torque,
φ – rotor angle.

All the above quantities should be minimized. After solving the MOP, a set of optimal non-dominated solutions were generated creating a Pareto front shown in Fig. 2. This is a set

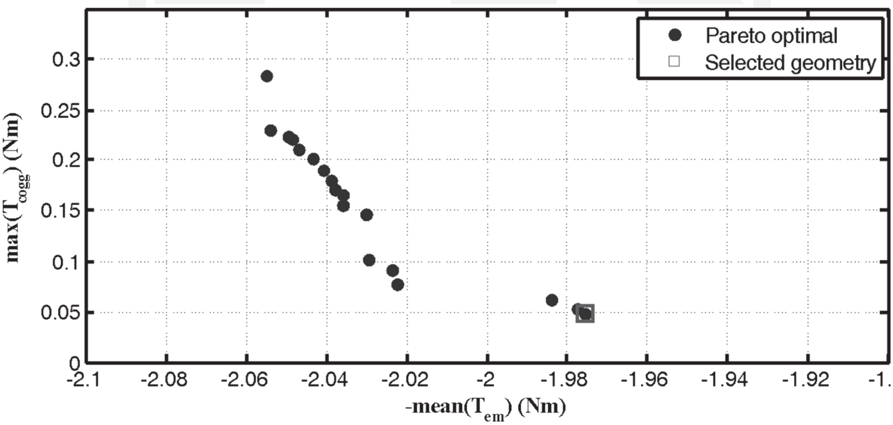

Fig. 2. Pareto front

of models that acts as an area for a selection of best individual. The final selection should be made taking into account other features that the motor should have [1, 11] – in this particular design problem, the highest possible difference between L_d and L_q values as well as proper L_d value (4). Details of the presented methodology are described in [11]. The GA have used 30 individuals in each population and 30 generations. The whole optimization process lasted for about 15 h on a high performance PC. The results of the optimization are shown in Fig 2. One individual that was designed and created for experimental evaluation is also depicted.

5. Experimental results

For the experimental evaluation of the machine parameters and characteristics, a proper test-stand has been designed (Fig. 3). It consists of the optimized IPM prototype and a B&R servo motor (8LSA44 – 451 W, 3000 rpm) clutched and mounted on a aluminum plate, a torque meter, load resistors, voltage and current meters and a digital oscilloscope. The B&R was controlled via an application developed for Power Panel 45.

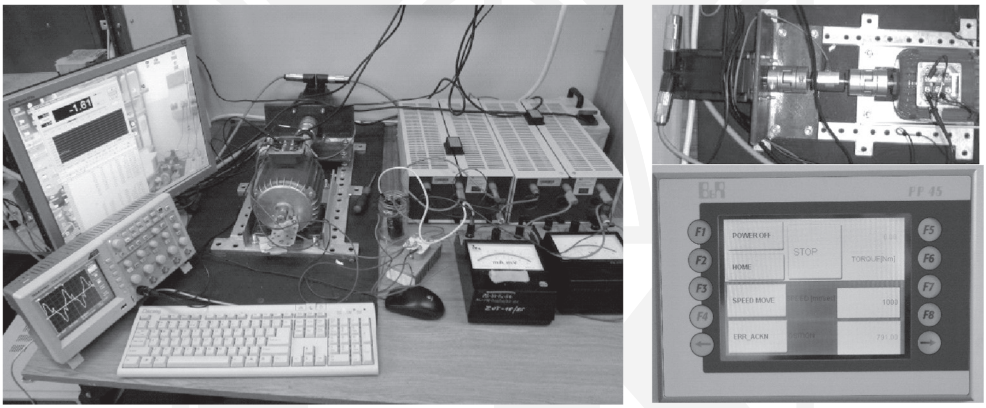

Fig. 3. Test stand

All crucial parameters of the optimized rotor are shown in Table 3.

Table 3

Optimized Design variables values

$x1$ [mm] Pole width	$x2$ [mm] Cutter width	$x3$ [deg] Tooth angle
25.2	15.5	6.5

Cogging torque was measured for various rotor positions. Experimental and simulation results are presented in Fig. 4.

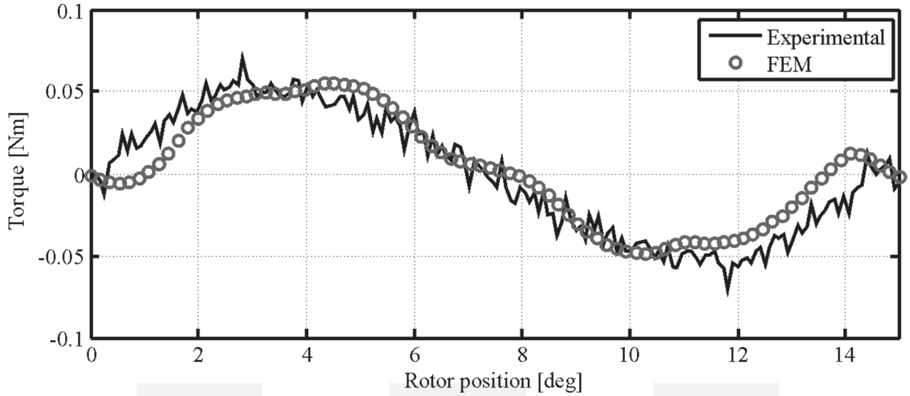

Fig. 4. Cogging torque waveform

Inductance was measured with the scheme shown in Fig. 5.

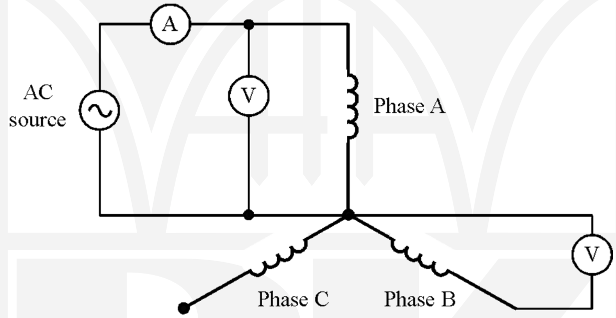

Fig. 5. Inductance measurement scheme

The inductances values were calculated with the following formulas:

$$L_A(\varphi) = \frac{\sqrt{\left(\frac{U_A}{I_A}\right)^2 - R^2}}{2\pi f} \tag{6a}$$

$$L_{AB}(\varphi) = \frac{U_B}{(2\pi f) I_A} \tag{6b}$$

where:

U_A, U_B – A and B phase RMS voltage value,
L_A, L_{AB} – self and mutual inductance,
f – AC source frequency.

Figure 6 shows self and mutual inductances for different rotor positions and two AC currents – nominal and 1.5 times the nominal value. It occurred that the machine was not saturated – for different currents there was nearly any change in the inductance values. This was caused by the relatively big air-gap length.

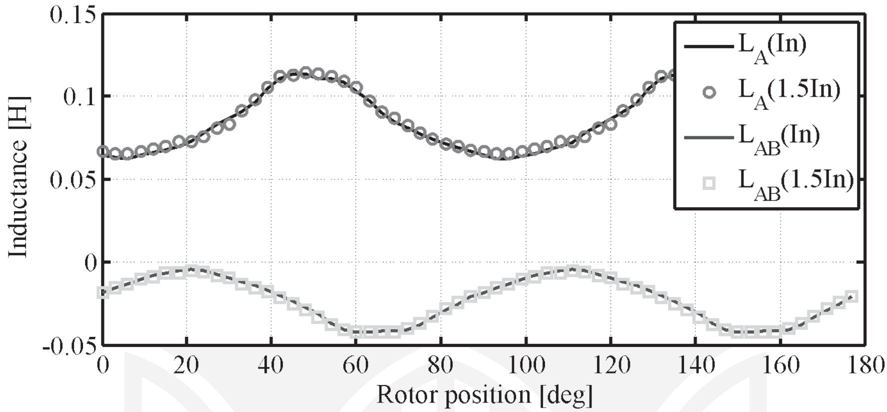

Fig. 6. Measured inductances for different current values

The calculated values of self and mutual inductances during simulation were increased with the end-connection inductance value. The results for the nominal current value are presented in Fig. 7.

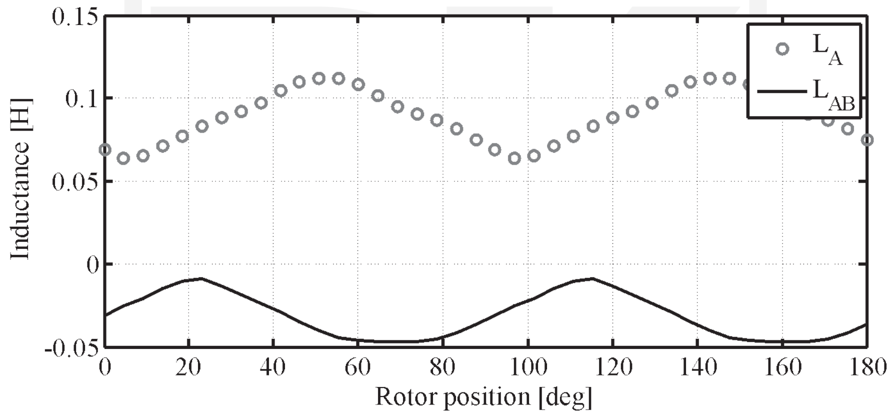

Fig. 7. FEM calculated inductances for nominal current

After simple mathematical calculations, L_d and L_q values may be obtained [15]. The value of L_d was 65 mH and L_q was 150 mH. Small inductance in the *d*-axis cannot assure proper field-weakening capabilities according to equation (5). Its small value is caused by the small permeability of the SMC and large air-gap length. Efficiency of the generator was 91% for 1500 rpm rotor speed and nominal current, so it was 19% higher than for the IM motor with the same stator and windings. During the experimental tests, torque for different current values was also evaluated. Two phases were connected in series and supplied with a DC current. For each rotor position, the shaft was stalled and the torque value was measured. A comparison between simulation and experimental results for nominal current is presented in Fig. 8.

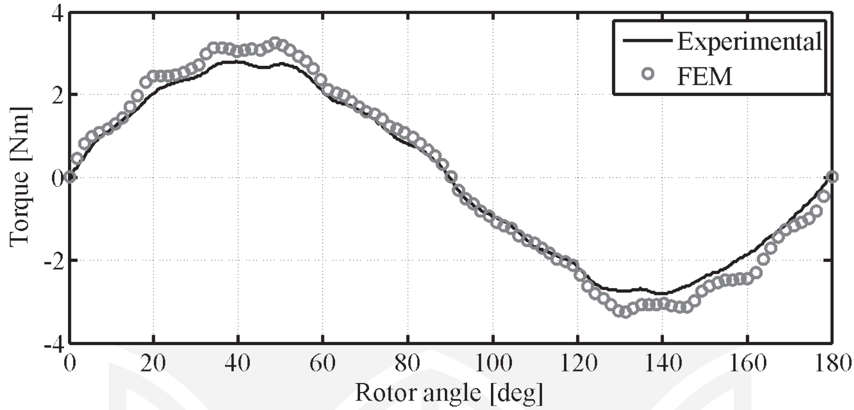

Fig. 8. Torque waveforms for nominal current

6. Summary

The authors applied Maxwell and Matlab tools for the SMC rotor geometry optimization process of the interior permanent magnet synchronous motor. The connection between these two packages allowed a flexible FE model geometry definition and analysis as well as effective results evaluation. The simulation points out the benefits of the optimization using a genetic algorithm.

Simulation results were verified on the experimental test stand. Efficiency, mechanical torque, cogging torque and L_d and L_q values have been measured.

The prototype offered very high nominal efficiency (about 91%) with very small maximum cogging torque value (about 0.05 Nm – 2% of nominal value). All these features were achieved due to PM excitation and the rotor made of SMC. A negligible influence of the current on *d*- and *q*-axis inductances values was observed. A serious disadvantage of such solutions is the small value of L_d, which results in limited field-weakening capabilities – further work will be focused on better high speed features of IPM with SMC. Surely, this could be achieved with optimized rotor geometry and higher relative permeability of used magnetic powder.

During simulation and experimental tests, the authors encountered several problems. The first was to apply proper mesh settings in order to shorten the whole optimization calculation time, and assure correct FEM calculation results. Particularly, the mesh should be more dense in the air gap region, and thinner over the stator and rotor cores. Secondly, the simulation did not consider any losses, it caused a difference between the measured and simulated torque values of approximately 10%. The main problem during experimental tests was to assure a nominal temperature of windings.

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