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Comparison of Two Synchronous Motors with Interior Magnets

Abstract. *The paper presents two prototypes of Interior Permanent Magnet Synchronous Motor (IPMSM) and their experimental and simulation results comparison. After the optimization, two different rotors have been constructed and tested. Particularly self and mutual winding inductances as well as d- and q-axis inductances were evaluated. The torque values for different currents and power angles, as well as induced voltage, were measured and compared with calculated values. Finally self and mutual waveforms of inductances of a phase windings were measured and simulated.*

Streszczenie. *W pracy przedstawiono porównanie wyników symulacji i pomiarów dwóch prototypów maszyn synchronicznych z zagnieżdżonymi magnesami trwałymi (IPMSM). Wykorzystując wyniki wcześniejszych optymalizacji zbudowano i następnie przebadano dwa różne wirniki. Wyznaczono wartości indukcyjności własnych i wzajemnych, a także indukcyjności w osiach d- i g-. Dokonano obliczeń i pomiarów wartości momentu elektromagnetycznego dla różnych prądów, a także indukowanego napięcia, momentu zaczepowego i funkcji sprawności. Ostatecznie zmierzono i zasymulowano przebiegi indukcyjności własnych i wzajemnych uzwojeń fazowych. (**Porównanie dwóch wariantów maszyny synchronicznej z zagnieżdżonymi magnesami trwałymi**).*

Keywords: PM-excited electrical machines with embedded magnets, cogging torque.
Słowa kluczowe: maszyny elektryczne z magnesami trwałymi zagnieżdżonymi, moment zaczepowy.

Introduction

Increasing electric motor parameters is an ongoing task for the electric motor designers – it can be achieved with proper design of a motor, proper winding dimensioning, magnets selection and optimized geometry. In particular, use of rare-earth magnets with high energy product, it is possible to develop high power density machines with high overall efficiency. Surface and radially-laminated PMS-machines have limited or zero flux-weakening capability (main demand for proper application for pure electrical vehicles drives). Properly designed IPMS-machines are capable of operating in Constant Power Speed Region – such machines perform also inverse saliency – their *q*-axis inductances are larger than *d*-axis inductances. Other obvious advantage of IPM rotor is that centrifugal forces cannot damage magnets because of their location. With special constructions (spoke designs) it is possible to achieve very high torque densities.

Machine Geometry and Equations

The case of study is represented by two 4-pole IPMS-machines with fixed stator geometry and winding parameters. The stator and housing of both machines are mass-produced ones for 550 W AC machine (50 Hz power supply frequency) with 24 slots. Rotors are made with electrical steel laminations (type M400-50A) and equipped with NdFeB magnets (B_r = 1,23 T, H_c = −890 kA/m), mounted inside the rotor and oriented in the radial direction. There is no skewing both for stator slots and rotor magnets. During initial works some unique optimization procedures in Matlab and Maxwell environment were used in order to optimize geometry and select the best one based on several requirements.[1-4]. The connection between these two packages allows very efficient geometry analysis as well as effective results evaluation. The only problem that occurred was a stability of a connection between two packages. It has been improved in further versions of FEM software, and works much more stable nowadays. Finally two different rotors which differ very smoothly in their shapes have been developed and built as a part of two MA-Theses done in the Department of Power Systems and Electrical Drives, West Pomeranian University of Technology, Szczecin, Poland in 2015 [5, 6]. Figure 1 presents main components of the rotor and the opened housing of the machine with a rotor and the stator stack.

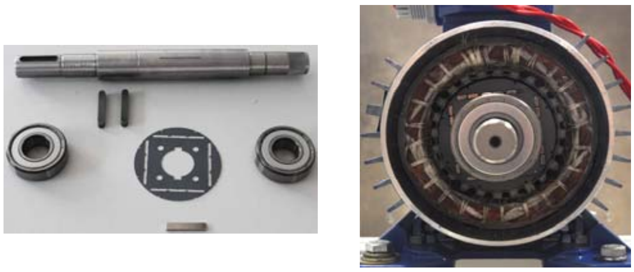

Fig.1. Components of the IPMSM (left) and the opened housing (right)

Main mechanical and electrical parameters of the machine are following: stator outer diameter: 120 mm, air gap length: 0,5-1,5 mm, packet length: 55 mm, nominal power: 550 W, phase voltage: 230 V, nominal torque: 3 Nm, nominal current: 1,6 A. Figure 2 shows details of both rotors, where special slots on the rotor's surfaces were manufactured. They allow proper assembly of magnets within the rotor and additionally result in reduction of the cogging torque. Disadvantage is that the holes cause increasing torque ripple with increasing current.

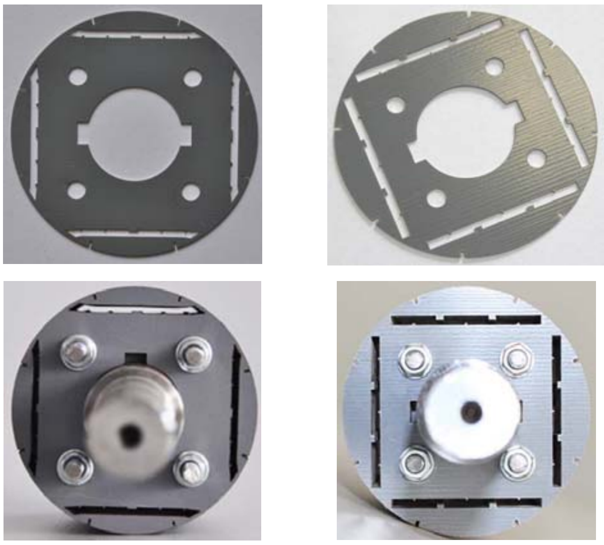

Fig.2. Rotor geometries: prototype A (left) and B (right)

Static model of IPMS-machines is given by the following equation set [7, 8] under several assumptions:

$$(1)\qquad U_d = RI_d + \frac{d\Psi_d}{dt} - p\Omega_m\Psi_q,$$

$$(2)\qquad U_q = RI_q + \frac{d\Psi_q}{dt} + p\Omega_m\Psi_d,$$

$$(3)\qquad \Psi_d = L_d I_d + \Psi_{PM},\quad \Psi_q = L_q I_q,$$

$$(4)\qquad T_{em} = \frac{3}{2}p\left[\Psi_{PM} I_q + \left(L_d - L_q\right) I_d I_q\right].$$

where: U_d, U_q – *d*- and *q*-axis voltages, I_d, I_q – *d*- and *q*-axis currents, R – stator phase winding resistance, Ψ_d, Ψ_q – *d*- and *q*-axis magnetic fluxes, Ψ_{PM} – magnetic flux of permanent magnets, Ω_m – mechanical rotor speed, p – number of pole pairs, T_{em} – electromagnetic torque.

These equations are typically used for the precise control of IPMS-machines [7-10], thus all coefficients in these equations have to be determined via field calculations or measurements. One of main problems of the proposed model is that it neglects higher harmonics of voltages and currents which causes some difficulties in parameters evaluation.

FEM and Experimental Results

In the first step static torques, induced voltages as well as phase and mutual inductances were evaluated with FEM ([6, 7]). Figure 3 shows the FE-meshes used for the field computations.

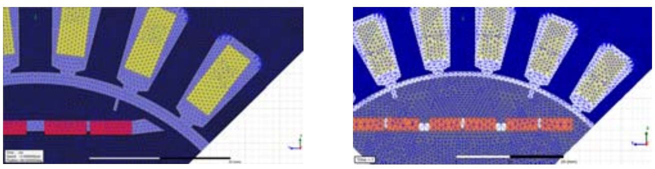

Fig.3. FE-meshes. Prototype A (left) and Prototype B (right)

Comparison of exemplary magnetic field distributions within both machines at no load and rated operation has been shown in Fig.4 and Fig.5.

As can be seen in above figures, even small geometry differences in the machine structure, cause relatively big differences in the magnetic field distribution.

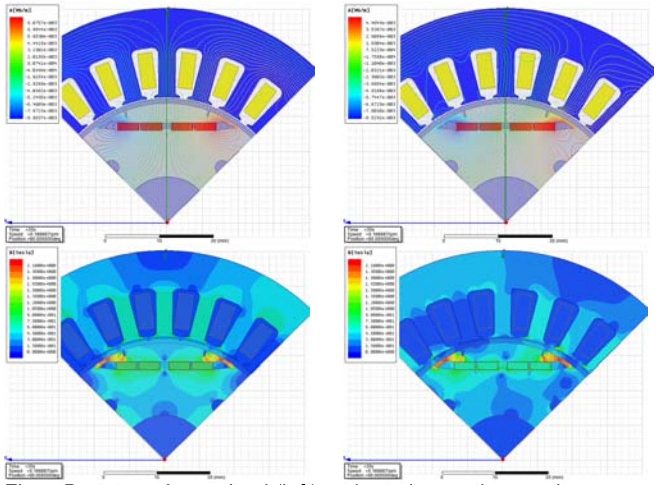

Fig.4. Prototype A – no load (left) and rated operation results

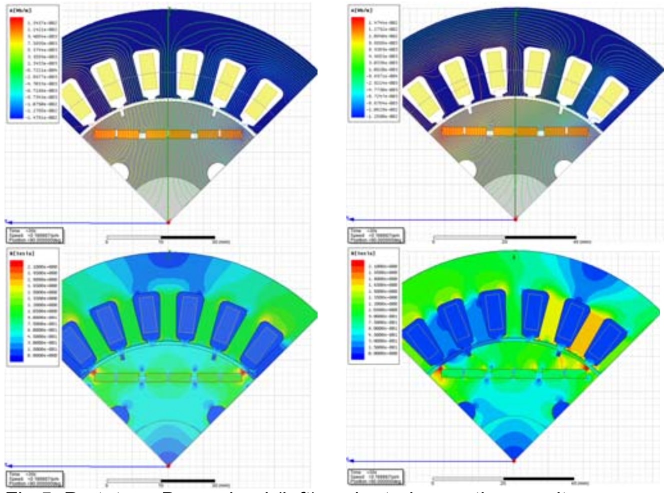

Fig.5. Prototype B – no load (left) and rated operation results

Simulation results were validated experimentally. Experimental test stand has been designed with a B&R servomotor and drive unit (ACOPOS with PowerPanel 45). The test stand and the operator panel view have been shown in Fig.6.

Next figures show measurements of the static torque and phase induced voltage at 1000 *rpm* and gives the comparison between both machines.

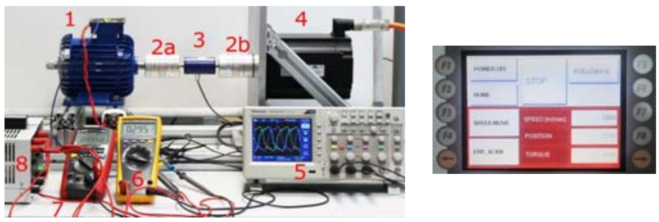

Fig.6. Test stand (left), operator panel (right)

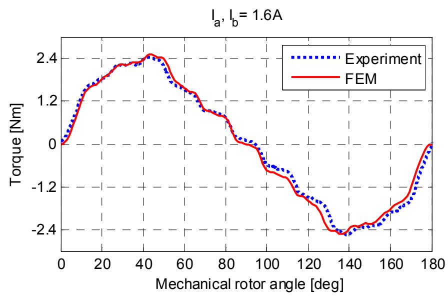

Fig.7. Static torque values – prototype A

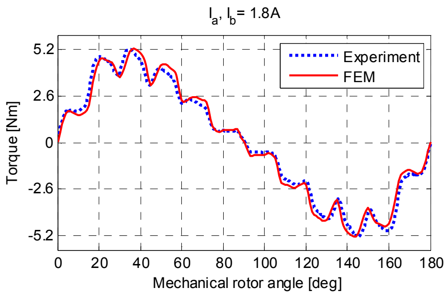

Fig.8. Static torque values – prototype B

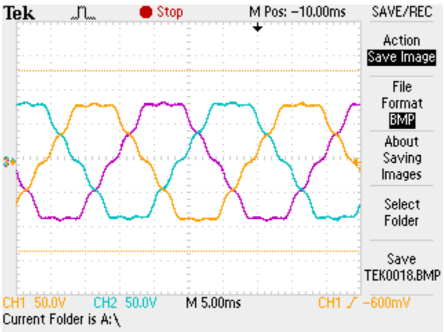

Fig.9. Induced voltage – prototype A

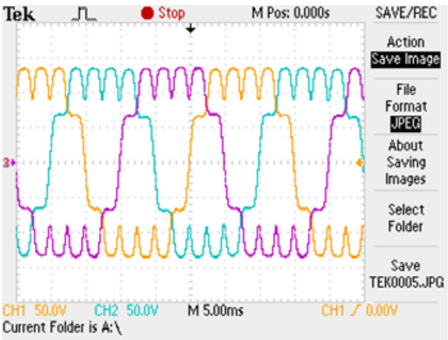

Fig.10. Induced voltage – prototype B

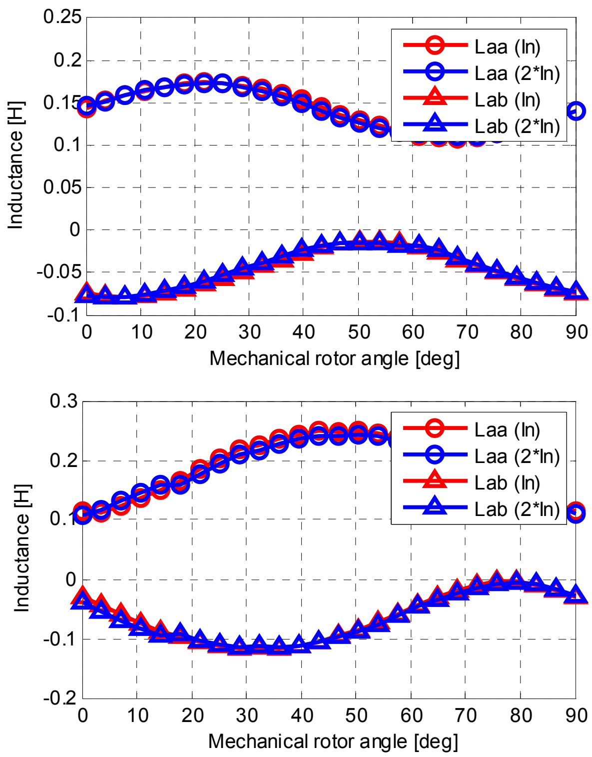

Fig.11. Self and mutual inductances; A (top) and B (bottom) - measurement results

The exact quantitative comparison of both machines is difficult, because they have different air gap flux densities, but, as it can be seen from above figures, even small geometry differences in the machine structure result in big differences in the torque values and induced voltages. It should be stated that the prototype A gives for both examined quantities much smoother dependences, having smaller local oscillations. This results from the better position and shape of permanent magnets in the rotor and smaller magnet volume. In fact, prototype B was strongly saturated and had much higher air-gap flux density.

Table 1 presents selected values of self and mutual inductances and the maximum cogging torque value.

Table 1. Inductances and cogging torque comparison

Prototype	Min L_{aa} [mH]	Max L_{aa} [mH]	Min L_{ab} [mH]	Max L_{ab} [mH]	T_{cogg} [%]
A	110	180	-77	-15	2,0%
B	105	240	-130	-5	1,5%

Figure 12 shows the comparison of cogging torque waveforms. The aim of the geometries optimization was to reduce the cogging torque below 2% of a nominal torque. The goal has been achieved but proposed solution (small slots on the rotor surface) increased torque ripples.

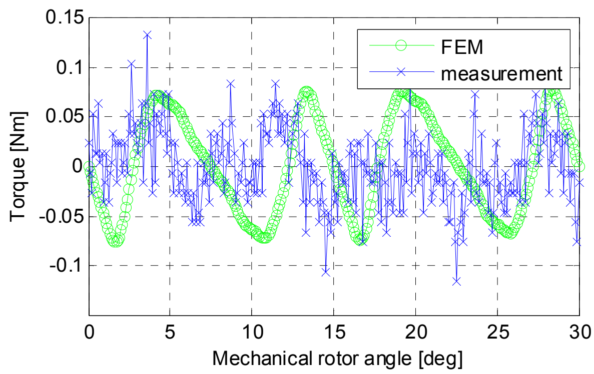

Fig.12. Cogging torque verification (prototype B)

Inductances were measured with a common method that uses special phase connection and AC power supply source with constant frequency. Based on the *RL*-circuit voltage equation it is possible to calculate the phase and mutual inductances. If needed L_d and L_q inductances may be recalculated using commonly proposed methods [e.g. Freescale or Dal Y. Ohm]

Summary

Both prototypes have offered very high nominal efficiency (about 88% (work without fan) in contrary to the typical induction motor efficiency – 73%). with very small maximum cogging torque value (less than 2% of nominal value). All these features were achieved due to proper rotor geometry design. Negligible influences of current on d- and q-axis inductances values have been observed. They were caused by the relatively big air gap compared to number of amper-turns. In fact classic AC machines in this frame size use reduced air-gap length. Disadvantage of both designs are higher harmonics in induced voltage. This has been caused by the shape of stator teeth and lack of methods of reduction of higher harmonics (like pseudo-skewing or magnet shaping). In many applications it is needed both for the proper work of control algorithms as well as for reduction of losses, vibrations, noise and torque ripples. Prototype A has a small magnetic loading while prototype B has a relatively high magnetic loading. It is not easy to compare machines with different nominal torques (with same sizes). In the future authors will show fully optimized, improved construction.

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