Small Power Synchronous Machine with SMC PM Excited Rotor – Experimental and Simulation Results

Abstract: The work presented in this paper relates to an Interior Permanent Magnet Synchronous Motor (IPMSM) experimental and simulation results. The stator of the machine is a mass-produced one with classic assembly. The rotor has been previously optimized, designed and constructed and made of Soft Magnetic Composites (SMC). There is presented a method of measuring inductances at different load currents. Particularly self and mutual winding inductances as well as $d$ and $q$ axis inductances were evaluated. The value of torque was evaluated for different currents and power angles. Experimental results were compared with simulation ones. On the test stand there was also evaluated efficiency map.

Keywords: PM electrical machines, $d$, $q$ inductances

1. Introduction
To protect the environment, there exists a strong demand to develop very efficient electric motors with high torque/mass ratio [1-3]. Special design with high overall performance and wide speed operation capabilities [3, 4] make particular machines suitable for all automotive applications where weight and geometry dimensions are very important. An IPMSM with permanent magnets buried inside the rotor that is properly designed, fulfill foregoing requirements.

Main positive feature of SMC applied in magnetic cores is that it can be easily shaped in complex forms. The other advantage is its isotropic properties and low losses at high speed/frequencies. SMC mixed with epoxy resin makes machine structure robust to mechanical stresses. With proper technology it is possible to achieve high relative permeability up to 1000.

2. Machine geometry
The case of study is represented by a 4-pole IPMSM with fixed stator geometry and winding parameters. Stator and assembly are mass-produced ones taken from an induction motor. The machine is equipped with NdFeB magnets, oriented in the radial direction, mounted inside the rotor. Such structures are referred as IPM machines [3, 5]. The rotor is made of SMC (relative permeability approximately 40). During initial works there have been implemented optimization procedure in Matlab environment which used a genetic algorithm that ran and evaluated FE models in Maxwell tool [2, 5]. After optimization process the machine has been built and tested.

The analyzed geometry (optimized one without SMC poles) has been depicted in Fig. 1 and Fig. 2.

Selected machine parameters has been presented in the table 1.
3. Simulation results

Simulations were conducted with a 2D FE model that did not consider any losses which caused some errors but on the other hand shortened calculation time. Characteristics of steel were taken from datasheet and were modeled as a nonlinear B-H curve. Magnet parameters were as follows (B_r=1.23T, H_c=-890kA/m). Fig. 3. shows torque waveforms as a function of power angle for two different current amplitude values. Electromagnetic torque consists of two main components according to (1):

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

Where: \( I_d, I_q \) – \( d \) and \( q \) axis currents, \( \Psi_{pm} \) – magnet flux. The first one is a PM torque (that is proportional to quadrature axis current and flux in air gap developed by magnets), and the second one is a reluctance torque (that is proportional to the difference between direct and quadrature axis inductance, and currents product). The value of torque for nominal current and optimal power angle was about 3.1 Nm which is comparable with basic (induction motor) design (3.6 Nm).

![Fig. 3. Torque waveforms for different currents](image-url)
Secondly $L_A$ and $L_{AB}$ values over different rotor position have been estimated using that method described in details in [6]. It must be emphasized that inductance values should be increased with end-winding inductances that has not been simulated in 2D model [7]. Recalculated results are shown in Fig. 4.

![Fig. 4. Self and mutual inductance waveforms](image)

$L_d$ and $L_q$ were 65mH and 150mH respectively. A method for calculation of $d$ and $q$ axis inductances values was described in [6]. Despite big magnet volume the PM flux value was relatively low - 400mWb.

Knowing machine parameters and power supply constraints it is possible to evaluate Constant Power Speed Range (CPSR). It has been defined as:

$$\text{CPSR} = \frac{\omega_{\text{max}}}{\omega_{\text{nom}}}$$  \hspace{0.5cm} (2a)

Theoretical considerations showed that proposed geometry has small CPSR (1.3), because it does not fulfill optimal field weakening condition:

$$I_a = \frac{\Psi_{\text{PM}}}{L_d}$$  \hspace{0.5cm} (2b)

Torque and power curves are depicted in Fig. 5.

![Fig. 5. Torque and power curves](image)

Nominal speed of a proposed geometry was higher than for induction motor. For this reason it was possible to stay at even higher power level with smaller torque value.

4. Experimental results

For experimental evaluation of the machine parameters and characteristics, a proper test stand has been designed and programmed (Fig. 6). It consists of the optimized IPM prototype and a B&R servo motor (8LSA44 - 1451W, 3000rpm) clutched and mounted on a aluminum plate, and several measurement devices. The B&R was controlled via application developed for Power Panel 45.
Inductance were measured with the scheme shown in Fig. 7.

\[ L_A(\phi) = \frac{\left(\frac{U_A}{I_A}\right)^2 - R^2}{2\pi f} \quad (3a) \]

\[ L_{AB}(\phi) = \frac{U_B}{(2\pi f)I_A} \quad (3b) \]

where

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

Fig. 8. shows self and mutual inductances values for different rotor positions and two AC currents – nominal and 1.5 times nominal value. It occurred that the machine was not saturated – for different currents there was nearly any change in the inductance values. It was caused by the relatively big air-gap length and low permeability of SMC.
According to results shown in Fig. 10 the highest efficiency was about 96%.

![Torque waveforms comparison](image)

**Fig. 10. Torque waveforms comparison**

The last result show comparison of cogging torque waveforms (Fig. 12.). Experimental data needed some mathematical transformations, because torque level was very small and noise signal had a strong impact on a measured signal. Maximum value of cogging torque was about 2% of a nominal value so it was at acceptable level.

![Cogging torque waveforms comparison](image)

**Fig. 11. Cogging torque waveforms comparison**

5. Summary

Simulation results were validated experimentally. The prototype offered very high nominal efficiency (about 88% in contrary to induction motor efficiency – 73%) with very small maximum cogging torque value (about 0.05Nm – 2% of nominal value).

All these features were achieved due to PM excitation and rotor made of SMC. Negligible influence of current on d and q axis inductances values have been observed. It was caused by low permeability of SMC and high air gap length. Serious disadvantage of such solutions is small value of L_{db}, which results in limited field-weakening capabilities.

During experimental evaluation it was not easy to keep constant temperature of windings – the copper wires were overheated in the high torque regions. Whole measurement procedure took about 8h for a qualified engineer. In the future there is planned a special test stand development that would simplify and automatize measurement procedures.

6. Literature


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