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Design and analysis of a permanent magnet synchronous machine for automotive electromechanical braking system

Abstract. The present paper will approach the design and analysis of a permanent magnet synchronous motor (PMSM) for automotive electromechanical braking (EMB) system. Due to technological and cost constraints, for the PMSM prototype a slightly different topology of the rotor is proposed. Finite element method will be used for analyzing the static performances of the former topology, and compare them with the designed one. The dynamic performances, the losses and the thermal behavior of the two topologies machine will be also analyzed in a comparative manner.

Streszczenie. *Artykuł przedstawia projekt i analizę maszyny synchronicznej z magnesami trwałymi dla systemu elektromechanicznego hamowania w samochodach. Z powodu technologicznych i ekonomicznych ograniczeń zmieniono topologię winika maszyny. Za pomocą symulacji komputerowej (MES) porównano działanie przy starej topologii i nowej dla pracy statycznej. (**Projekt i analiza maszyny synchronicznej z magnesami trwałymi dla elektromechanicznego systemu hamowania w samochodach**).*

Keywords: synchronous motor, thermal analysis, brake by wire.
Słowa kluczowe: silnik synchroniczny, analiza termiczna.

Introduction

The need for faster brake responding, better fuel economy, simplified system assembly, easy maintenance, more environmentally friendly and improved safety design has resulted in new EMB, that has already begun replacing the hydraulic one in automotives. The alternative to the electro-hydraulic system is the electro-mechanical implementation. When the hydraulic system is removed completely, the EMB approach is so called Brake-by-Wire. In this case, the braking force is generated by high power electric motors at each wheel. These are controlled from an electronic control unit where the driver input would again be from a suitable sensor similar to the electro-hydraulic system. In addition, an actuator at the input (e.g. the brake pedal) would provide feedback to the driver.

Brake-by-wire technology not only reduces the weight of vehicles, but also has the potential for a large number of new features. These applications require high performance motors with high torque/volume ratio, low inertia, high dynamic, low torque pulsations and low radial forces Also, the thermal issue of electric vehicles is an important criterion for the design of the motor and for choosing the adequate cooling system to assure proper actuating performance and reliability. The thermal behavior of motor depends on the heat sources and on the motor geometry.

Concerning latest technologies used in X-By-Wire's in Automotives, the current 14 V DC bus has become insufficient and the car manufactures have concluded that the solution is to increase the voltage. Therefore, respecting the newest tendency in Automotives, 42 V bus in the feeding system of the present proposed PMSM will bring increased power, reduced currents, longer life, much more flexibility and last but not least - higher level of safety.

The present paper will approach the design and analysis of a three-phase four-pole permanent magnet synchronous motor for electro-mechanical brake in automotives. In order to justify that PM synchronous motor is a productive election for Brake-by-Wire actuation, relevant properties of a general PMSM have been studied. For example, the fact that this type of motor assures a high torque for a reduced motor volume – comes as an advantage concerning the attention paid for the weight of the vehicle (which is required as low as possible). In addition, having high dynamic capacity, this motor bears up completely to faster brake responding request. Further, another effective characteristic is represented by the low torque pulsation.

Electrical machine design and analysis

A basic configuration of an EMB system was analyzed in order to establish the specification data and the demanded torque-speed curve for the PMSM. These requirements for a brake-by-wire EPAS system as described in literature [2] are presented in Table 1 and Figure 1. In addition to these requirements, several constraints must be met. These constraints address limited size, lower weight, low torque ripple content, fault tolerance. In order to propose a productive new prototype, an analytical design was based on the imposed rated power and on the several criteria, which must be considered while designing a PMSM used in EMB application.

Table 1. EMB EPAS System

Peak stall torque [Nm]	3
Maximal speed [rpm]	1000
DC-bus voltage [V]	42
Duty cycle	S3-5%
Ambient temperature	-40...125°C

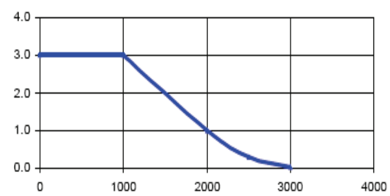


Fig.1.Electromagnetic torque(Nm) vs. speed (rpm)

The analyzed topology is a 12-stator slots/4 rotor poles one, with the cross section and flux line distribution presented in Figure 2. The main dimensions of the machines resulted from the analytical design procedure are presented in Table 2, while the cogging torque for rated speed is depicted in Figure 3.

The analytical design is a closed loop procedure based on the imposed parameters, optimizing targets, technical catalogs, and engineer abilities in order to achieve improved quality/price factor. The stator inner diameter is directly connected to the necessary magnet volume, while the shape of stator's teeth and the shape of magnet influence the quality of the output electromagnetic torque of the machine.

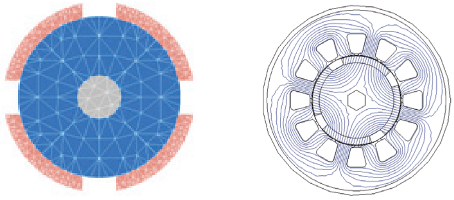


Fig.2.Crossed section of the analyzed topology

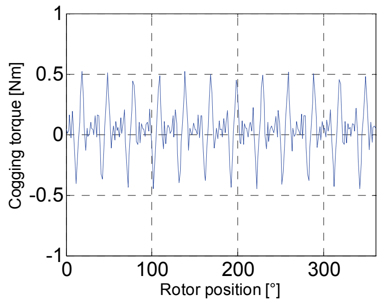


Fig.3.Cogging torque for rated speed

The optimization of the prototype is made by using Magnetic Equivalent Circuit method. Regarding the permanent magnet as a flux source, MEC is based on the equations of the Magnetic Flux Law, which is similar to Ohm's law for closed electric circuits. The most important elements of MEC are represented by the reluctance and magneto-motive force values. Although FEM analysis provides more accurate field solutions for already designed geometry, MEC analysis assures quick suggestions for changes to dimensions, materials, excitations. The first validation for the previous analytical design, concerns the magnetic field and static performances analysis carried on by using 2D Finite Element Method based software (JMAG-Studio). The differences are because the mathematical model is a linear conditioned model, while the FEM model is based on both linear and nonlinear conditions. The magnetic flux densities values obtained via three methods (analytical, MEC and FEM) are presented in Table 3 and the magnetic equivalent circuit is described in Figure 4.

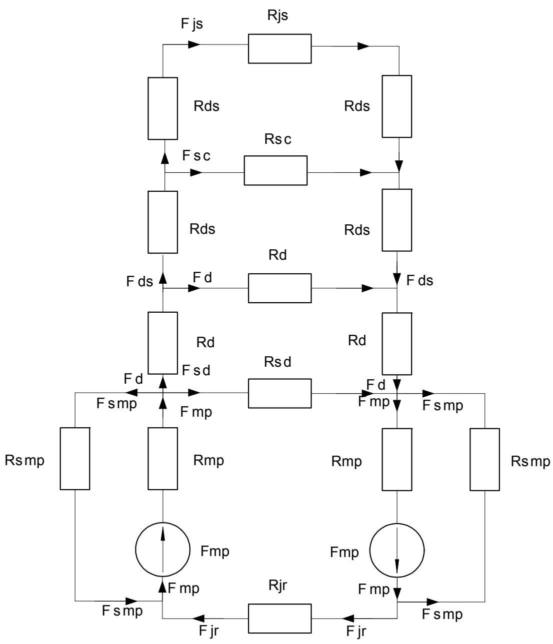


Fig.4.Magnetic Equivalent Circuit

R_{mp} - permanent magnet reluctance;
R_{δ} - air gap reluctance;
$R_{\sigma\delta}$ – air gap leakage reluctance;
R_{ds} – stator tooth reluctance;
R_{js} – stator yoke reluctance;
R_{jr} – rotor yoke reluctance;
$R_{\sigma mp}$ – permanent magnet leakage reluctance;
$R_{\sigma c}$ – slot leakage reluctance;
Φ_{mp} – permanent magnet flux;
$\Phi_{\sigma mp}$ – permanent magnet leakage flux;
Φ_{δ} – air gap flux;
Φ_{js} – stator yoke flux;
Φ_{jr} rotor yoke flux;
F_{mp} – magneto-motive-force.

Table 2. Main PMSM Dimensions

Stator outer diameter	80 mm
Stator inner diameter	40 mm
Stator slots	12
Stack length	100 mm
Rotor outer diameter	35 mm
Main air-gap width	0.35 mm

Table 3. Magnetic Flux Densities

Magnetic FluxDensity [T]	Analytical Design	MEC	FEM
Air gap	0.63	0.7419	0.7374
Rotor yoke	1.0122	0.9605	0.8374
Stator tooth	1.7371	1.9365	1.89
Stator yoke	0.9926	1.1065	0.92
EMF [V]	23.57	23.55	22.30

According to the prototyping facilities and due to technological and cost constraints, the chosen rotor topology to be built is presented in Figure 5, together with the flux line distribution. In order to estimate the prototype's static, dynamic and thermal performances, the magnetic field analysis was performed by using the same FEM-based software. At the same time the losses and then the thermal aspects of the machine were analyzed. The cogging torque of the new prototype for the same 1000 rpm rated speed is presented in Figure 6.

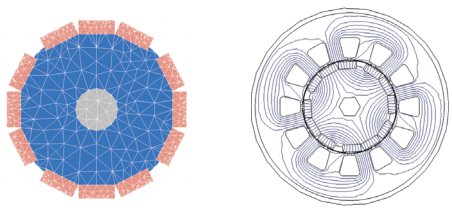


Fig.5.Crossed section of the chosen topology to be built

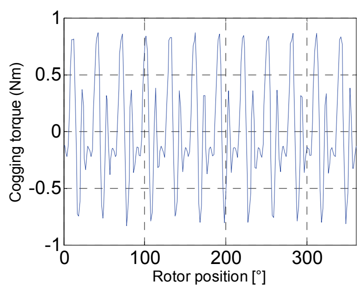


Fig.6.New prototype cogging torque

In Figure 7 the electro-motive force and the air gap magnetic flux density are depicted for the machine with full surfaced magnets (first and third figures) and for the machine with partial buried rectangular magnets (second and forth figures), at load regime.

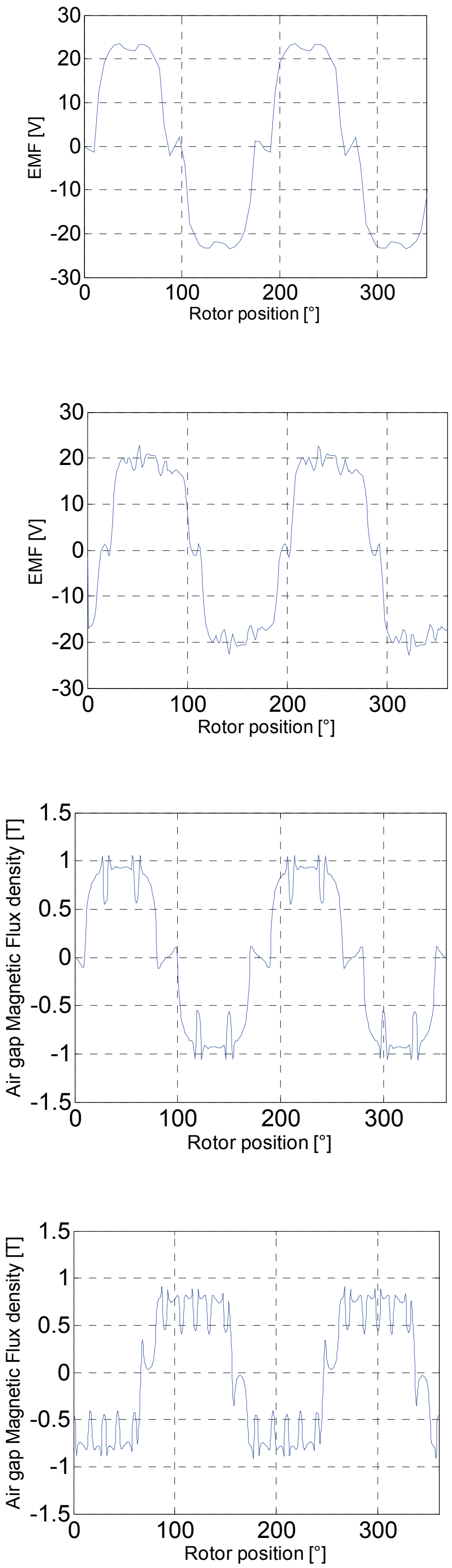


Fig.7 Electromagnetic force and Air-gap magnetic flux density of the PMSMs

A stator loss analysis was made in a comparative manner for both cases. The results of the iron loss analysis in the stator core (both yoke and teeth structure) are presented in Table 4.

Table 4. Loss Analysis

Stator Losses [W]	Surface arched magnets	Partial rectangular burried magnets
Hysteresis Loss	2,51	3,21
Eddy currents Loss	0,881	1,34
Iron Loss	3,39	4,56

The hysteresis loss due to the material properties and the joule loss due to the eddy current distribution are the main components of the total iron loss in the stator. The values are different as the denture magnetic flux density is directly influenced by the shape of the rotor magnets. As these differences don't present important issues for the performance of the machine, the prototype with the partial buried magnets has been considered an appropriate election in terms of efficiency. Another important issue in designing an electric motor with permanent magnets is the temperature distribution. The quality of the magnet properties is directly influenced by the thermal stress in time due to the demagnetization risk of the magnets. In order to verify if the new proposed prototype should offer a proper thermal behavior, a 3D thermal tool of JMAG-Studio FEM software have been created by coupling the thermal 3D model support with the relevant condition and results from the previous 2D magnetic field and iron loss analysis.

The most important elements concerning a thermal analysis are represented by several material properties (such as thermal conductivity, specific heat and density), the heat transfer coefficients and the contact thermal resistance between the coil and the stator slot (c-s) surface, between the motor axis and the rotor surface (a-r) and between the magnet and the rotor core (m-r), following the general formula (1).

$$R_{x-y} = \frac{d_{x-y}}{\lambda_{x-y} \cdot S_{x-y}} \qquad (1)$$

where:

$d_{x-y}[m]$ – Width between x and y

$\lambda_{x-y}[W/m^2 \cdot K]$ – Heat transfer coefficient

$S_{x-y}[m^2]$ – Contact surface

In Figure 9 the Temperature Distribution of the machines is presented and compared for the same step 800 of the simulation. In case the magnets are rectangular and partial buried in the rotor core, the temperature in the magnets is reduced and so the losses in the magnets are subdued.

In figures 10 the temperature behavior is presented for both cases in the stator core (a), coil structure (b) and also in the magnet core (c) – in a comparative manner.

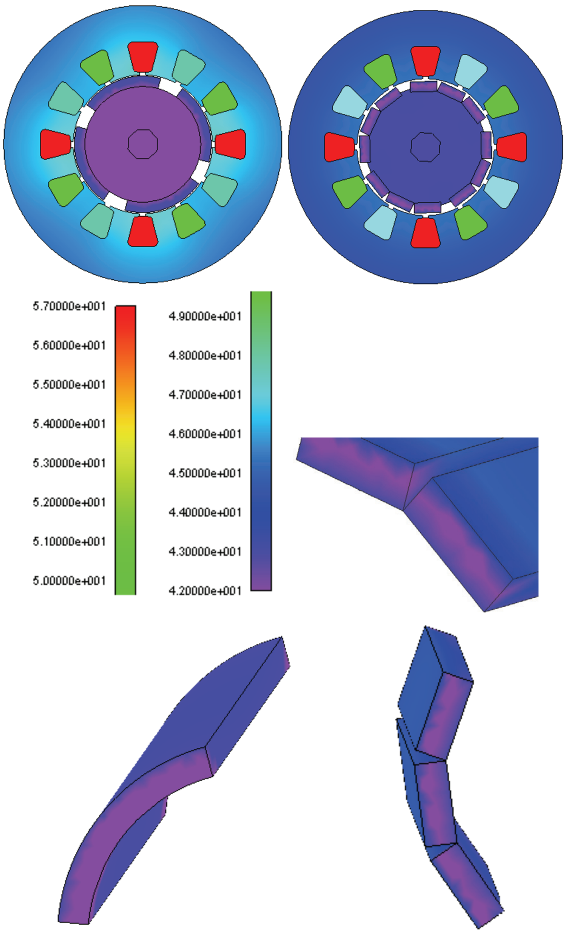
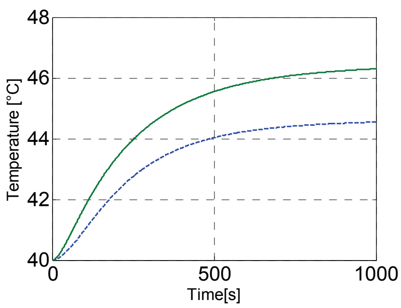
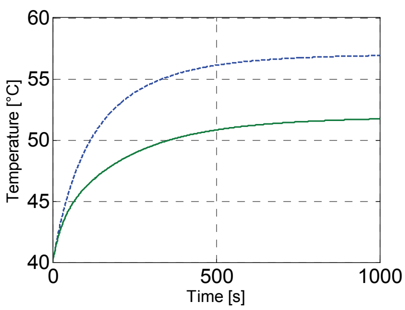


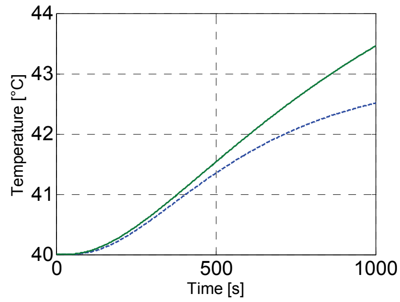
Fig.9 Temperature distribution (ºC) for both PMSMs



a) Stator core



b) Coil Structure



c) Magnet core

Full surfaced magnets
Partial buried rectangular magnets

Fig.10.Temperature behavior (ºC) for both PMSMs

Conclusions

Following the specific EMB system requirements, the present paper approaches the design and analysis of a PMSM for this kind of application. The influence of the rotor topology on the machine static and dynamic performances, as well as on the thermal behavior was studied in order to build a prototype by following the given main specifications and under some technological and cost constraints.

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