MODELING AND SIMULATION OF A PERMANENT MAGNET SYNCHRONOUS MOTOR FOR BRAKE-BY-WIRE TECHNOLOGY IN AUTOMOTIVE APPLICATIONS

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KEYWORDS

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ABSTRACT

The present paper approaches a three-phase Permanent Magnet Synchronous Motor (PMSM) analytical design, modeling and simulation for an electromechanical brake system in automotive applications. Analytical design of the electrical machine is validated by static simulation using JMAG-Studio, (a Finite element method based software). The Magnetic Equivalent Circuit (MEC) method is an accurate yet simple method for predicting the flux density distribution for iterative design procedures. The MEC technique gives fast (minutes) and acceptably accurate results. It provides a trade off between conventional, empirical methods, having fast simulation times, limited accuracy and flexibility, and the Finite Element Method (FEM), which requires long simulation times (hours), but offers high accuracy and flexibility.

INTRODUCTION

Electromechanical Brake (EMB)

Electric actuation is one of the actual trends in the automotive industry, due to its high reliability, energy efficiency and controllability. 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 Electro-Mechanical Braking System (EMB). EMB system has already begun replacing the hydraulic one. This not only reduces the weight of vehicles, but also has the potential for a large number of new features.

In the EMB case (Fig.1), the idea presented is to replace completely the hydraulic system in order to transmit the commands through the wire. For that, the braking force is generated directly at each wheel by high-performance electric motors controlled by an Electronic Control Unit (ECU), and executed by signals from an electronic pedal module, which includes 4 intelligent braking actuators [10].

Electrical motor proposed for EMB actuation

As a major issue in automotives is represented by the need for improved fuel efficiency and much more flexibility concerning latest technologies used in X-By-Wire's, the current 14 V bus has become insufficient. Therefore, car manufactures has come to the conclusion that the solution is to increase the voltage and implement a new 42 V bus in the system. Some aspects have to be considered during the design of the brake by wire drive systems: reliability, performance, thermal and acoustic behavior, energy efficiency and cost.

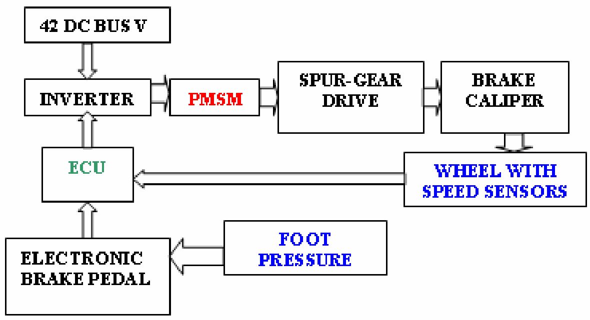

Figure 1: System layout of an electromechanical brake

These applications require high performance motors with high torque/volume ratio, low inertia, high dynamic, low torque pulsations and low radial forces. In this paper a surface-mounted PMSM has been considered as a driving motor for brake-by-wire application because it offers the advantage of low rotor inertia (provide high torque at lower rotational speed), high efficiency, convenient heat dissipation structure and reduction of the motor size [2], [4], [9].

DESIGN OF THE PROPOSED PMSM

Analytical Design

The analytical design of a PMSM is a complex process, which includes literature studying for adopting optimal design methods for different targets as obtaining a lighter prototype, a minimum cogging torque variation, a higher torque and low losses.

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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 are given in Table 1 and Fig.2 presents the torque-speed characteristic of an electrical motor for EMB [6].

Table 1: General requirements for a PMSM used in EMB application in Automotives

Parameter	Units	Value
Peak stall torque	Nm	3.0
Base speed	1/min	1000
Maximal speed	1/min	3000
DC-bus voltage	V	42
Duty cycle	-	S3-5%
Environment temperature	C degree	-40…125

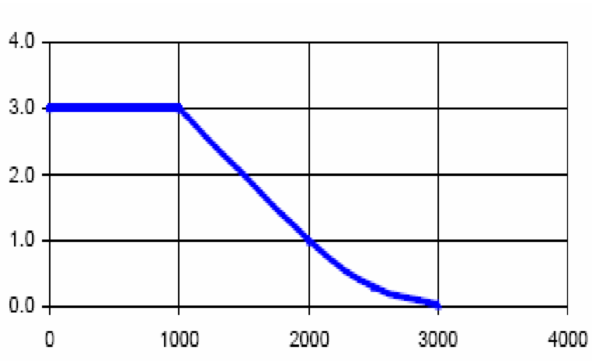

Figure 2: Torque vs. speed curve of an electrical machine for EMB

In addition to these requirements, several constraints must be met. These constraints address limited size, lower weight, low torque ripple content, fault tolerance. A three-phase, four-pole surface mounted PMSM was chosen with the topology presented in Figure 3.

The design starts with the set of initial data that includes the input parameters presented in Table 2, the material data of the magnet, iron and conductors. The main dimensions of the stator lamination and rotor core were computed via an analytical design procedure, following the input data [1], [5], [8]. First step in sizing the motor implies the estimation of the stator inner diameter using:

$$D = \sqrt[3]{\frac{S_n \cdot 60}{C_1 \cdot \lambda_m \cdot n_s}} \qquad (1)$$

where: S_n - rated power; C_1 - machine constant; λ_m - the geometric form factor; n_s - rated speed.

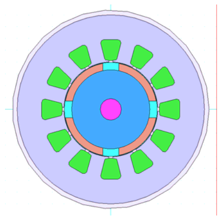

Figure 3: Cross-section of the proposed PMSM

Table 2: Inputs parameter of the proposed PMSM

DC voltage [V]	42
Rated power [VA]	460
Pole pair number	2
Rated speed [rpm]	1000
Torque [Nm]	3

The necessary permanent magnet volume results from:

$$V = \frac{2}{\pi} \cdot \frac{k_\phi \cdot k_{ad} \cdot (1+\varepsilon)}{f \cdot k_{lm} \cdot B_r \cdot H_C \cdot \eta_m} \cdot k_m \cdot S_n \qquad (2)$$

k_Φ - shape coefficient of the permanent magnetic field; k_{ad} - shape coefficient of the magnetic field on d-axis; ε - motor excitation rate; f – frequency; k_{lm} - shape coefficient of the magnetic field; B_r – remanence of the permanent magnet; H_c – coercivity of the permanent magnet; η_n- efficiency; $cos\Phi$ - power factor; k_m - motor overloading factor; P - rated active power.

The permanent magnet material used for this application is a NdFeB with B_r = 1.2T and H_c = 868000 A/m. The chosen geometry of the permanent magnet influences the magnetic flux distribution in the machine [12]. For this reason, it is presented in Figure 4.

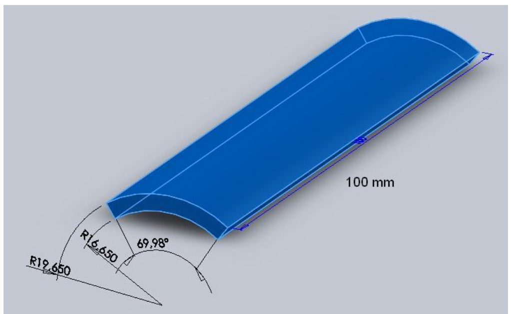

Figure 4: Permanent magnet geometry

Two geometrical dimensions were imposed, with the third dimension calculated considering the total magnet volume obtained in the previous step, divided to 4. The final dimensions of the magnets are the result of several iterations, following the minimization of the cogging torque criteria.

Third step of the design procedure approaches the computation of the air gap magnetic flux density (3) and dimensioning of the stator tooth geometry. The air gap magnetic flux density results from:

$$B_\delta = \frac{B_r}{\sigma \cdot \dfrac{S_p}{S_m} + \dfrac{1}{\mu_0} \cdot \dfrac{B_r}{H_c} \cdot \dfrac{2 \cdot \delta \cdot k_c \cdot k_s}{h_m}} \tag{3}$$

with S_p- pole surface; S_m- permanent magnet surface ; δ- air gap length ; k_c - Carter factor ; k_s - magnetic circuit saturation ratio.

The analytical design procedure ends with the analytical calculus of the magnetic flux values in different parts of the core. The formulas for the magnetic flux density in the rotor yoke and in the stator yoke are defined by the general formula below:

$$B_x = \frac{B_\delta \cdot \tau}{2 \cdot h \cdot k_{Fe}} \tag{4}$$

τ - polar pitch and h - rotor/stator/tooth height.

Table 3: Obtained values PMSM

STATOR : Stator Core		
Number of Slots	12	
Tooth Width	6	
Slot Opening Width	1.7	
Outside Diameter	80	
Coil Inside Diameter	41.4	
Inside Diameter	40	
Coil outside Diameter	59	
ROTOR : SPM Rotor		
Number of Poles	4	
Magnet Interval	6.86	
Rotor Diameter	33.3	
Outside Diameter	39.3	
Stack length	100	
MATERIALS		
Stator Core	Category	NiponSteel
	Type	50H600.hb
Rotor Magnet	Category	TDK-Nd-FeB
	Type	NEOREC41
	Magnetization	Parallel
Rotor Core	Category	NipponSteel
	Type	50H600
CIRCUIT		
Phase Current Amplitude [A]	17.6	
Phase [deg]	0	
Phase resistance [ohm]	0.334	
Electromotive force [V]	23.57	

Carrying out the analytical design calculations, the dimensions obtained for the studied machine are gathered and presented in Table 3 and the distribution of the turns in the stator slots, according to the 4 poles topology is presented in Figure 5.

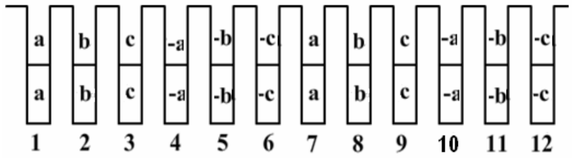

Figure 5: Stator winding distribution

To prove the analytical design procedure accuracy, EMC and FEM model analysis will be also applied and the results obtained will be compared and discussed.

Magnetic Equivalent Circuit Analysis (MEC)

Regarding the permanent magnet as a flux source, the stray magnetic field from the motor can be included in the magnetic circuit of the motor, as it can be seen in Figure 6.

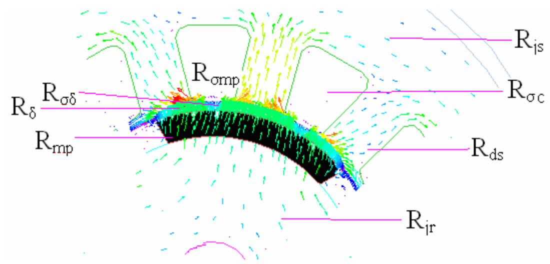

Figure 6: Magnetic flux line distribution

Also, the equivalent magnetic circuit for one pole is presented in Figure 7, where:

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

The magnetic “voltage drop” across the magnet can be expressed as in equation (5), based on the analytical expression of the demagnetization curve presented in equation (6).

$$H_{mp} \cdot l_{mp} = \left(\frac{B_{mp}}{\mu_{mp}} - H_c \right) \cdot l_{mp} = R_{mp} \cdot \Phi_{mp} - F_{mp} \tag{5}$$

$$B_{mp} = \frac{B_r}{H_c}\left(H_{mp} + H_c\right) = \mu_{mp}\left(H_{mp} + H_c\right) \tag{6}$$

where l_{mp} represents the length of the considered one pole surface magnet.

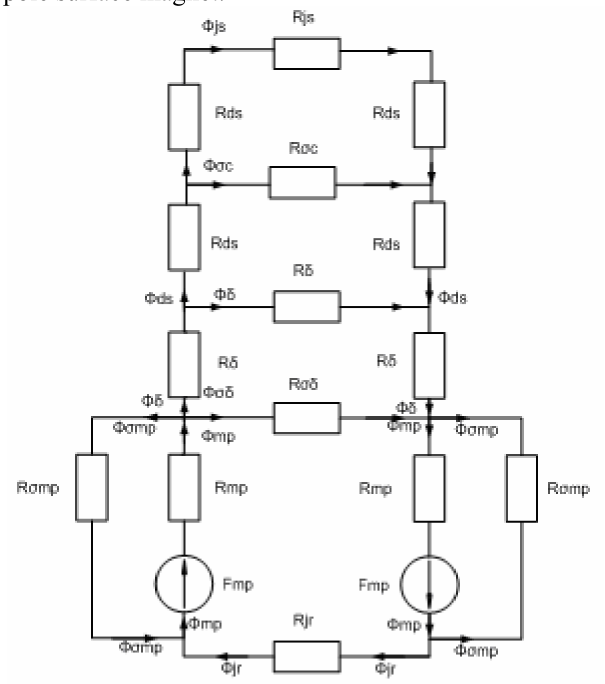

Figure 7: The magnetic equivalent circuit

As it can be seen from the above expression, the demagnetization curve of the magnet was considered linear, which comes as a particular property for rare-earth NdFeB magnet. The flux density values in different parts of the magnetic circuit of the machine result by solving the equation system based on EMC. These final values, obtained with an iterative process, represent the first validation method of the analytical design procedure.

FEM modeling

Numerical techniques often give straight forward answers to problems that are difficult or impossible to solve with analytic methods. Thus, a model of the optimized PMSM was implemented in JMAG in order to both verify the analytical procedure accuracy and to obtain basic characteristics of the motor.

JMAG-Studio is an electromagnetic field modeling and simulating software package developed by JRI Solutions, which supports the design and development of motors, actuators, and other electric products. Highly accurate modeling is essential to correctly examine the phenomena occurring inside of an electromechanical design [11]. For this purpose, FEM was applied to the proposed topology, following the algorithm presented in Fig.8.

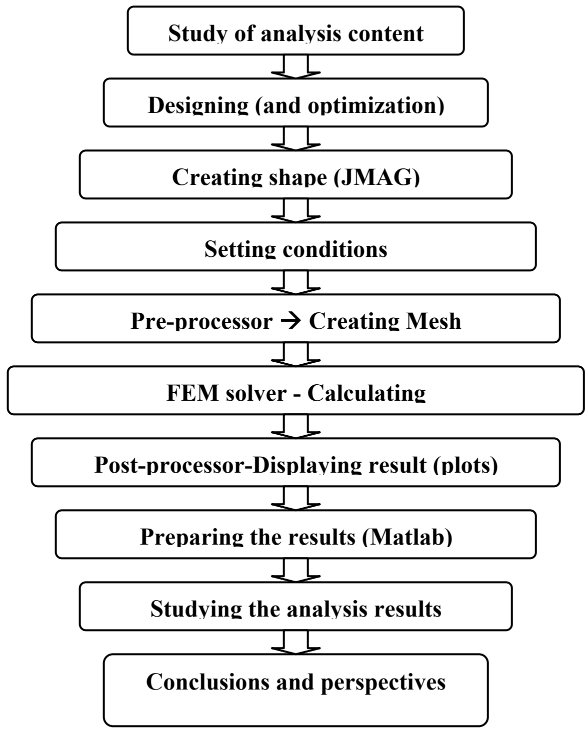

Figure 8: JMAG Basic steps in FEM modeling

When conducting analysis of rotating machine, it is recommended to generate the mesh suitable for the application. The basic role of mesh is to calculate in different points of the motor, the values for magnetic flux density. Since the torque is proportional to the square of magnetic flux density, it is greatly influenced by the number of mesh division of the air gap in the circumferential direction. Therefore, the number of the divisions should be made as large as possible in particular parts of the motor.

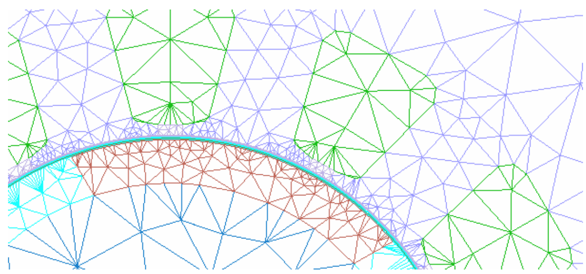

Figure 9: Mesh network in the machine

A magnetic field analysis was carried on for no-load regime in JMAG. The magnetic Flux Density distribution is shown in Fig 10.

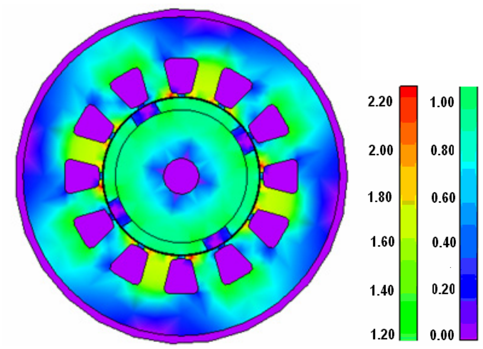

Figure 10: Mesh lines and Magnetic Flux Density distribution

The cogging torque for the rated speed (1000 rpm) is depicted in Figure 11. By applying Fourier Transform, the harmonic content of the cogging torque can be analyzed. Thus, the cogging torque can be expressed as a Fourier series:

$$T_{cog} = \sum_{k=1}^{\infty} T_{mk} \sin(mk\theta) \tag{7}$$

where m is the least common multiple of the number of stator slots (N_s) and the number of poles (N_p), k is an integer, and T_{mk} is a Fourier coefficient. It is seen that the cogging torque has m periods per mechanical revolution of the rotor and has a direct relationship to the number of slots and poles. For the proposed PMSM, m=12.

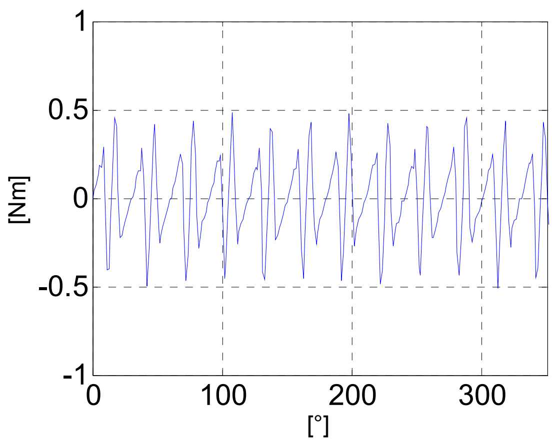

Figure 11: Cogging torque at 1000 rpm

As it can be noted from Figure 12, the main harmonics of the cogging torque are for 200Hz, 400Hz, 600Hz and 800Hz.

In order to get optimal torque quality, the shapes of the induced Electromotive force (EMF) and the feeding currents should be similar. As the no-load induced EMF shape (Figure 13) is closer to a sinusoidal waveform, sinusoidal feeding currents will be supplied for static analysis of the proposed PMSM for rated load regime.

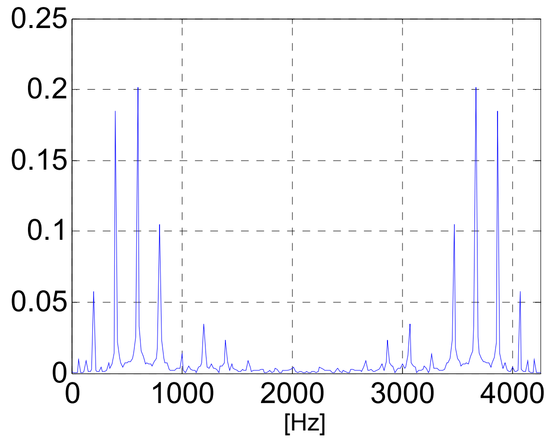

Figure 12: Harmonic content of the cogging torque

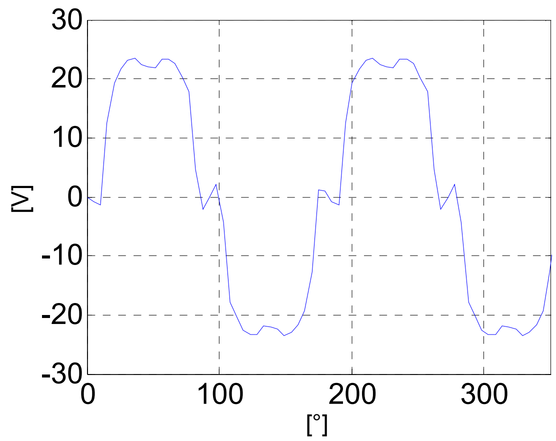

Figure 13: Electromotive force at no-load regime

The magnetic flux density distribution across the cross-section of the machine, for the same rotor position as in Figure 10 is depicted in Figure 14.

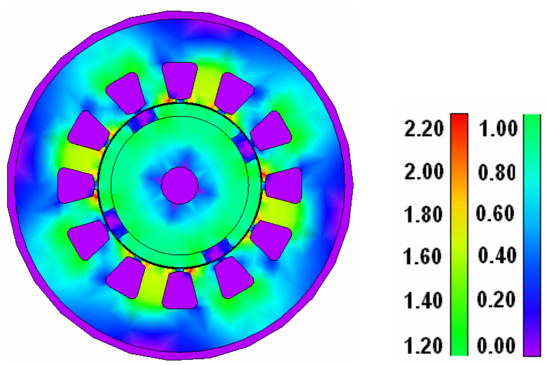

Figure 14: Magnetic Flux Density distribution

The developed electromagnetic torque is presented in Figure 15, for a 360° mechanical rotation. The periodicity of the torque ripple is given by the number of stator slots.

For the proposed PMSM, the torque ripple represents 50%, with 12 peaks for a complete mechanical rotation.

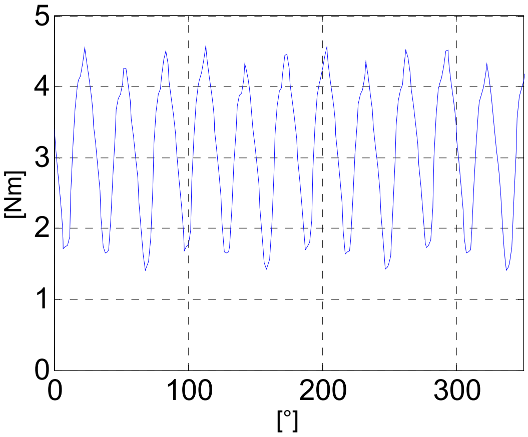

Figure 15: Electromagnetic torque for 1000 rpm

Applying (8) to the developed electromagnetic torque a T_{av}= 3.13 Nm average torque results, corresponding to the required by the EMB actuation at the rated speed. The air gap magnetic flux density is also presented in Figure 17.

$$T_{av} = \frac{1}{2\pi} \cdot \int_{0}^{2\pi} T(t)dt \tag{8}$$

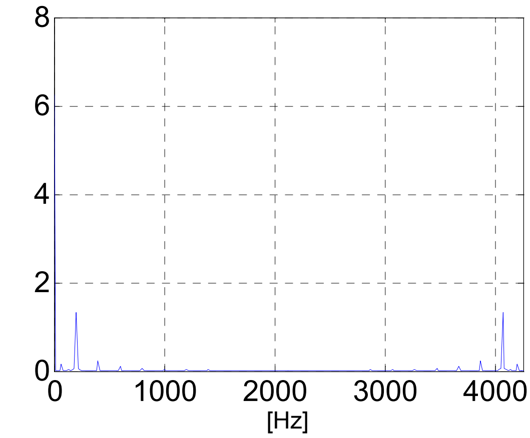

Figure 16: Harmonic content of the electromagnetic torque at the rated speed

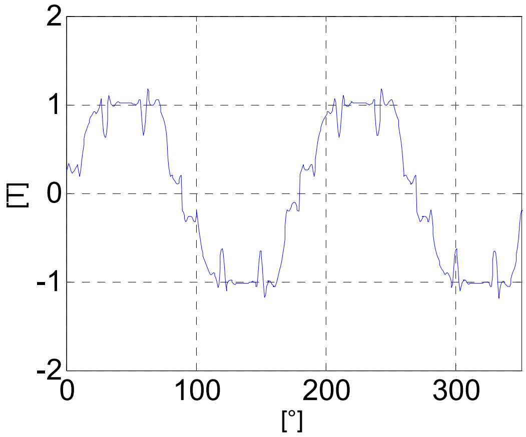

Figure 17: Air gap magnetic flux density

CONCLUSIONS AND FURTHER WORK

In this paper a PMSM design procedure is presented in order to serve for the EMB actuation in automotive applications. Basic principles used in a developed analytical sizing procedure are presented. The final results of this process are both the machine's dimensions and the flux density values for different regions, based on the geometry aspect. Also, the torque and the EMF analysis were performed.

Further on, a MEC and FEM analysis applied to the proposed PMSM are presented and the results are compared in order to validate the previous analytical technique. The differences are due to the fact that 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 5.

Further work will be oriented on the analysis and development of Matlab-Simulink model for the dynamic simulation of the machine and for testing different control strategies according to the specificity of the applications. A PMSM prototype will be built and tested on a test-bench using the Hardware-in-loop approach, implemented by using LabAmesim software.

Table 5: Flux density values and Electro-motive-force from the three determination models

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

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