Prediction of Eddy Current Losses of Surface Mounted Permanent Magnet Servo Motor

R. Deeb, M. Janda, Z. Makki

***Abstract* -- Eddy current losses are generated in a magnetic material when it is excited by an AC magnetic field. These losses increase the temperature of the magnets, which causes demagnetization, then deterioration of these magnets. This paper deals with calculation of eddy current losses of a servo motor with permanent magnets. Eddy current losses are calculated using two methods for both two and three dimensional models of the PM servo motor. These losses have been calculated according to the permanent magnets properties and to the magnetic flux density distribution in the air gap between the stator and the rotor of the analyzed servo motor. Finally, a comparison of the different results is performed.**

***Index Terms* -- Eddy currents, Finite element methods, Magnetic losses, Permanent magnet motors, Servomotors.**

I. Introduction

Applications of electrical machines with permanent magnets (PM machines) have remarkably increased in many industrial applications. Their excellent properties make them preferred to the induction machines. PM machines have no electrical losses with the field excitation which means increasing of their efficiency. This paper focuses on modeling and simulation of PM machines, particularly on an AC servo motor with permanent magnets.

AC servo motors are typical synchronous motors with permanent magnet that often have high torque to inertia ratio at high acceleration ratings. AC servo motors have an output shaft that can be positioned by sending a coded signal to the motor. As the input of the motor changes, the angular position of the output shaft changes as well. In general, AC servo motors are small but powerful for their size and easy to control. Servo motors have a wide power range from 0.2 kW up to 5 kW. AC servo motors are of cylindrical or square shape, open or enclosed, and available in a variety of housing sizes and diameters. These motors are used in robotics, servo drives and many other applications. Applying of permanent magnet materials to the electrical machines brings benefits such as increasing of their torque and output power and increasing of their efficiency. Three types of permanent magnet materials exist, Alnico, Ferrites and rare earth magnet material [1].

The eddy current losses are generally small in comparison with the copper losses and the iron ones. But they can heat the permanent magnets because of their relatively poor heat dissipation coming from the rotor and result in partial irreversible demagnetization, especially for NdFeB magnets that have relatively high temperature coefficients of remanent and coercive force and moderately high electrical conductivity [2].

Eddy current losses are generated in magnetic material when it is excited by an AC magnetic field. It consists of classical eddy current losses and excess eddy current losses [3, 4].

A. Classical eddy current losses

They are well known. It can be expressed as

$$P_c(t) = \frac{d^2}{3\pi\rho}\left(\frac{dB(t)}{dt}\right)^2 \tag{1}$$

where d is the thickness perpendicular to the direction of the magnetic field and ρ is the resistivity of the magnet material.

For a sinusoidal varying magnetic field with angular frequency ω_s, Eq.1 can be written as:

$$P_c = \frac{d^2}{6\pi\rho}\omega_s^2 B^2 \tag{2}$$

From Eq.2, it can be noted that classical eddy current losses are a function of the second power of the frequency and the flux density.

In more general periodically varying flux density with a time period $T=1/f$, the average loss density is expressed as:

$$P_c = \frac{d^2}{3\pi\rho}\frac{1}{T}\int_0^T\left(\frac{dB}{dt}\right)^2 dt \tag{3}$$

$$T = \frac{1}{f} = \frac{4\pi}{p\omega_m} \tag{4}$$

where, P is the number of pole pairs and ω_m is the mechanical speed.

B. Excess eddy current losses

These are additional losses known as anomalous or excess eddy current losses. They are less known than the classical eddy current losses. The origins of this mechanism are the magnetic domains that exist inside a magnetic material. According to Bertotti statistical theory of excess eddy current losses, these can be expressed as

$$P_{ex}(t) = \sqrt{\frac{A\alpha n_0}{\rho}}\left(\frac{dB(t)}{dt}\right)^{3/2} \tag{5}$$

where, α is a numerical constant, A is the area of the cross section, and n_0 characterizes the statistical distribution of the local coercive fields.

Comparing Eq.2 and Eq.5, it can be noted that excess eddy current losses depend on 3/2 power of the flux density and frequency, while classical eddy current losses depend on square of the flux density and frequency.

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Total eddy current losses are given as:

$$P_e = P_c + P_{ex} \tag{6}$$

Calculation of the eddy current losses in the permanent magnets machines has been treated by many researches. Some of these researches calculated these losses for surface magnet motors under load condition using analytical methods and focused on the increase of eddy current losses with motor load. Eddy current losses are related to a fictitious voltage induced in a one-turn coil wound around a stator tooth. A simple way is used to calculate part of the load currents for this voltage [5].

Paper [6] presents analytical and finite element method (FEM) approaches to calculate eddy current losses in conductive non-magnetic sleeves (cans) of synchronous or induction machines. In the FEM modeling approach, a geometric model of the machine is created and fine mesh is generated, then the magnetic and electric fields within the model are determined. 2D transient model was created to determine eddy current losses in the rotor and stator sleeves. The stator and rotor sleeves were defined as coils within the model and were short circuited. This technique neglects end effects of the sleeve. A comparison of analytical and FEM calculation results were performed.

Paper [7] presents a comparison of analytical and Finite Element (FE) calculation of eddy current losses. The model is applied to calculate the losses in the solid back-iron of the linear PM generator of the Archimedes Wave Swing (AWS) for different combinations of poles and teeth number. FE calculation is achieved using a general purpose software environment for the finite element solution of Partial Differential Equations (PDEs) akin to MATLAB for numerical linear algebra.

A new analytical approach of eddy current losses calculation in permanent magnet synchronous machines PMSM with tooth windings is presented in the paper [8]. A different analytical method is used. Two different points exist in this method: the field is calculated using an all-in-one method, so the simultaneous calculation of stator and no-load field is possible, finite magnet dimensions are taken into account, the calculation of an easy-to-use correction factor for endless dimensions is introduced. Calculation also included the losses caused by stator slotting and stator harmonics.

Paper [9] presents an investigation and evaluation of eddy current losses in conductive retaining sleeves of permanent magnet synchronous motors (PMSMs). Paper dealt with eddy current calculation of high speed motors with surface magnet rotors. To fix the magnet on rotor surface, a bandage of stainless steel sleeve can be used. Eddy current losses in this region are investigated. The losses are evaluated in several different no-load and loaded working conditions. Analytical results are compared with Finite Element Method (FEM) simulations of two and three dimensional models.

In the paper [10], an investigation of rotor core eddy current losses in interior permanent magnet (IPM) synchronous machines is presented. Analytical insight is developed, and the major design parameters that have the most significant impact on these losses are identified. A comparison of the predicted eddy current losses of IPM machines with one and two layer rotors coupled with concentrated and distributed winding stators.

In the paper [11], a core-loss model for the PM motor is presented. In this model, flux variation loci in different parts of the motor are predicted by carrying out a finite-element transient analysis. Because of complexity of flux variation pattern, an improved equation based on the conventional three-term expression is used for losses calculation. A comparison of calculation and experiments results on a high-speed PM motor has been presented.

C. *Eddy current losses per unit of magnet volume*

The eddy current losses are generated in the permanent magnets due to the time-harmonics by non-sinusoidal input waveform and to the space-harmonics by non-constant reluctance because of stator slotting. These losses may cause significant heating of the permanent magnets, due to the relatively poor heat dissipation from the rotor, and result in partial irreversible demagnetization, particularly of NdFeB magnets, which have relatively high temperature coefficients.

The current density in the magnets is calculated according to the second Maxwell's equation [12].

$$\oint E \cdot ds = -\frac{d}{dt}\iint_s B \cdot d\alpha \tag{7}$$

In this equation, some assumptions are made: The effect of eddy currents in the magnets on the magnetic field is negligible. The end effects are negligible, then the current density has only a component in z-direction, and the two sides of the closed path parallel to the x-direction is much larger than the width of magnet b_m. The magnet segments are small, therefore the magnetic flux density can be considered constant over the magnet width. Consequentially, the current density is an odd function of x: $J_z(-x)= -J_z(x)$.

The electric field strength can be replaced by the product of the current density and the resistivity of the magnet: $E = \rho_m.J$. Thereby, the current density can be written as:

$$J_z(x) = \frac{x}{\rho_m}\frac{dB}{dt} \tag{8}$$

The eddy current losses per unit of magnet volume are calculated as:

$$k_m = \frac{1}{b_m}\int_{-b_m/2}^{b_m/2} \rho_m J_z^{\,2}(x)\,dx = \frac{b_m^{\,2}}{12\rho_m}\left(\frac{dB}{dt}\right)^2 \tag{9}$$

Losses in magnets are caused by the space harmonics of the stator windings and stator slotting. The magnetic flux density causing the magnet losses can be written as:

$$B(\alpha_r) = \hat{B}\cos(p(\alpha_r - \beta)) \tag{10}$$

where p is number of pole pairs, β is a function of time.

The magnets are numbered from 1 to N_m, since the magnetic flux density, which causes the losses in the kth magnet can be written as:

$$B_k = B(\alpha_k) = \hat{B}\cos(p(\alpha_k - \beta)) \tag{11}$$

By replacing the flux density in Eq. 9, the eddy current losses per unit of magnet volume in the kth magnet can be calculated as the following:

$$k_{m,k} = \frac{b_m^{\,2}}{12\rho_m}\left(\frac{d}{dt}\left\{\hat{B}\cos(p(\alpha_k - \beta))\right\}\right)^2 \tag{12}$$

The total magnet losses equal to summation of the magnet losses in total N_m magnets:

$$P_m = l_s l_m b_m \sum_{k=1}^{N_m} \frac{b_m^{\ 2}}{12\rho_m} \left(\frac{d}{dt} \left\{ \hat{B} \cos(p(\alpha_k - \beta)) \right\} \right)^2$$
$$\approx 2pr_s l_s l_m \frac{b_m^2}{12\rho_m} \tag{13}$$
$$\times \int_{-\alpha_m/2}^{\alpha_m/2} \left(\frac{d}{dt} \left\{ \hat{B} \cos(p(\alpha_r - \beta)) \right\} \right)^2 d\alpha_r$$

Eq. 13 can be written as follows:

$$P_m = \frac{r_s l_s l_m b_m^2}{12\rho_m}$$
$$\times \left\{ (p\alpha_m + \sin(p\alpha_m)) \left(\frac{d}{dt} \left\{ \hat{B} \cos(p\beta) \right\} \right)^2 \right. \tag{14}$$
$$\left. + (p\alpha_m - \sin(p\alpha_m)) \left(\frac{d}{dt} \left\{ \hat{B} \sin(p\beta) \right\} \right)^2 \right\}$$

where, l_m is the magnet thickness, l_s is the stack length of motor, b_m is the magnet width, ρ_m is the magnet resistivity, α_m is the magnet pole arc, r_s is the air gap radius and B is the magnetic flux density in the air gap. Axis of kth magnet lays at the rotor coordinate α_k.

For each time harmonic of stator currents, the magnetic flux density can be written according to Eq. 10, and the magnet losses may be calculated using Eq. 14.

The relationship for the eddy current losses in the magnets can be simplified as (see Eq. 9):

$$P_m \approx \frac{V_m b_m^{\ 2} \hat{B}_m^{\ 2} \omega^2}{12\rho_m} \tag{15}$$

where, ω is frequency, V_m is magnet volume.

II. Air Gap Magnetic Flux Density

The main magnetic field is produced by the permanent magnets mounted on rotor when the motor works in no-load. When the current is applied to the windings, the main field is affected by the fundamental wave of the armature magnetic potential produced by the armature winding current. A distortion is produced in the main magnetic field because of the armature reaction. Eddy current losses in PM machines are caused by air gap permeance variation due to stator slotting, space harmonics in the stator winding distribution, and time harmonics in the stator current waveform. Air gap magnetic flux density has a non-sinusoidal waveform containing a series of harmonic components described using FFT. The first harmonic of the air gap magnetic flux density is given as:

$$B_{mg1} = \frac{2}{\pi} \int_{-0.5\alpha_i\pi}^{0.5\alpha_i\pi} B_{mg} \cos\alpha d\alpha$$
$$= \frac{4}{\pi} B_{mg} \sin\frac{\alpha_i \pi}{2} \tag{16}$$

where, the saturation of the magnetic circuit is neglected, the magnetic flux density $B_{mg} = \mu_0 F_{exc} / (g' k_C)$ under the pole shoe can be found on the basis of the excitation MMF F_{exc}. Where, g' is equivalent air gap that includes the permanent magnet height h_M and Carter's coefficient k_C.

Coefficient α_i is defined as the ratio of the average to maximum value of the normal component of the air gap magnetic flux density.

III. Properties of the Analyzed PM Servo Motor

PM servo motor M 718 is produced by VUES Brno company. The motor is designed with surface magnet rotor.

The main properties of this servo motor are as follows:

Voltage	280 V
Current	11.56 A
Nominal load	16.5 Nm
Rotational speed	3000 rpm
Output power	5174 W

Real PM servo motor and its cross-section are presented in Fig. 1 and Fig. 2, respectively.

Fig. 1. Real PM servo motor of M 718 type [13].

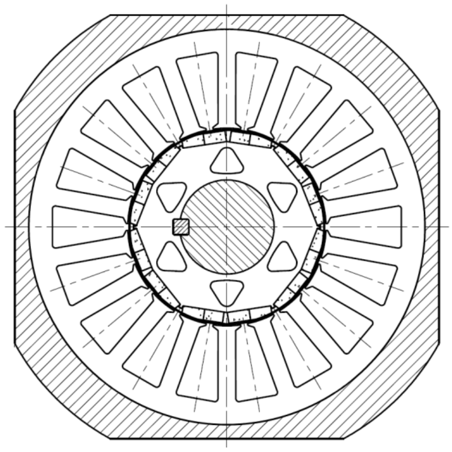

Fig. 2. Cross-Section of the PM servo motor of M 718 type [13].

TABLE I
CLASSIFICATION OF PM SERVO MOTOR M 718

Number of pole pairs	6
Number of slots	18
Stator inner radius [mm]	31.5
Rotor inner radius [mm]	30
Air gap length [mm]	0.7

Permanent magnet (PM) can produce a magnetic field in the air gap with no field excitation winding and no dissipation of electric power. The permanent magnet material applied to this servo motor is of the rare earth NdFeB type. These magnets are now produced in increasing quantities. They are characterized by a high remanence B_r, high coercivity H_c, high strength and very high energy product $(B{\cdot}H)_{max}$. On the other hand, the demagnetization curves, especially the coercive force, are strongly temperature dependent. If eddy current losses are high, the magnets may become so hot that they demagnetize.

The main properties of the applied permanent magnet materials are presented in the following table.

TABLE II
PROPERTIES OF APPLIED PERMANENT MAGNETS

Magnet width [mm]	13
Magnet thickness [mm]	3.5
Magnet resistivity [$10^{-6}\,\Omega$m]	1.6
Relative permeability of magnet	1.1
Remanence [mT]	1110
Coercivity [kA/m]	850
Max. operation temperature [°C]	190
Curie temperature [°C]	350

Table II presents the main properties and dimensions of the permanent magnets applied to the analyzed motor.

IV. Finite Element Method Analysis

Both two and three dimensional analyses of the servo motor are computed. Distribution of the magnetic field inside the motor is presented in addition to the circumferential distribution of the magnetic flux density in the air gap center. These performed analyses are computed for the case of nominal current is applied to the armature winding.

A. 2D FEM analysis of the magnetic field of the PM servo motor M 718.

Two dimensional (2D) model of the PM servo motor M 718 is created using Autodesk Inventor program. The magnetic field of this motor is computed using finite element method magnetics program (FEMM). Materials applied to the created model are chosen from the FEMM library, considering of the properties and polarization of the applied permanent magnets. In the material properties definition, the magnetizing direction of the permanent magnet must be established correctly (radial magnetizing direction of the permanent magnet). Boundary conditions are applied to the model by setting A_z=0 to a stator shell as boundary. All magnetic fluxes are considered in the shell ideally. The magnetic analysis is performed for the case of nominal current I_n = 11.56 A is applied to the servo motor armature winding. According to the finite element method, free mesh has been generated for the whole model. Grid subdivision of the analyzed motor is presented in Fig. 3.

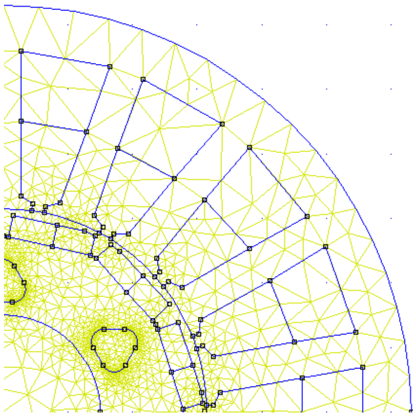

Fig. 3. Grid subdivision.

Better results can be reached by improving the mesh quality. Distribution of the magnetic flux density and lines in the permanent magnets and in the stator slot are presented in Figs. 4 and 5.

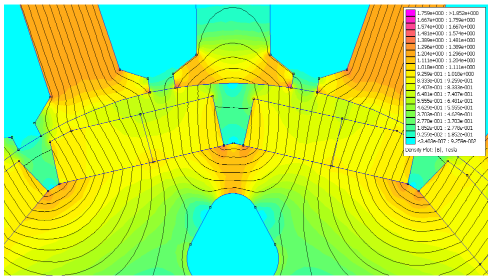

Fig. 4. Distribution of the magnetic flux density in the permanent magnets.

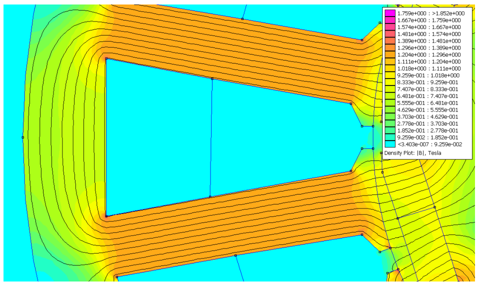

Fig. 5. Distribution of the magnetic flux density in the stator slot

Figs. 4 and 5 present the distribution of the magnetic flux density in the permanent magnets and in the stator slot, respectively. The values of magnetic flux density are between 0.09-1.759 T.

The distribution of the magnetic flux density according to the air gap length is presented in Fig. 6.

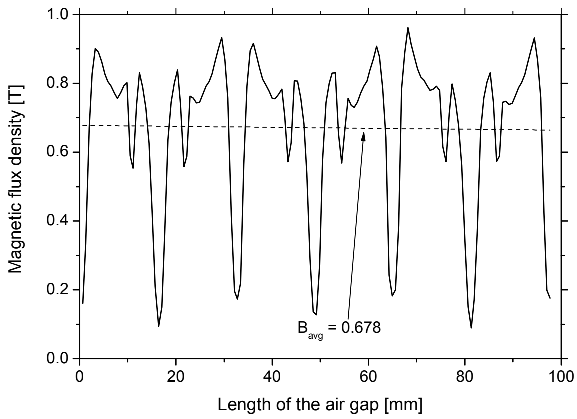

Fig. 6. Circumferential distribution of the magnetic flux density in the air gap center for the 2D analysis.

Fig.6 presents the magnetic flux density in the air gap. Average value of the magnetic flux density is about 0.678 T.

An irregular distribution of the magnetic field is caused by the fractional slot winding structure.

B. 3D FEM analysis of the magnetic field of the PM servo motor M 718

Three dimensional model (3D) of the PM servo motor M 718 is generated using RMxprt program and presented in Fig. 7. The model of the permanent magnets is shown in Fig. 8.

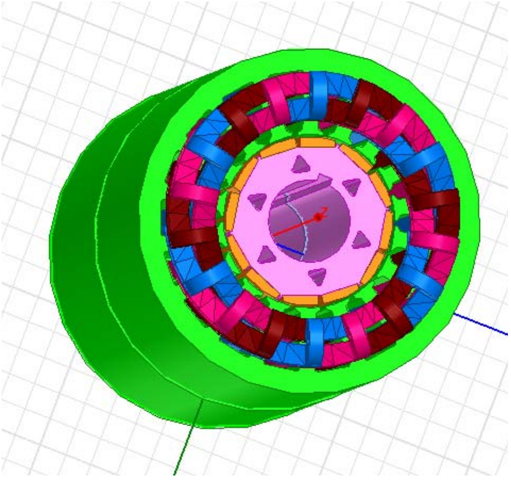

Fig. 7. Generated 3D model of the analyzed PM servo motor.

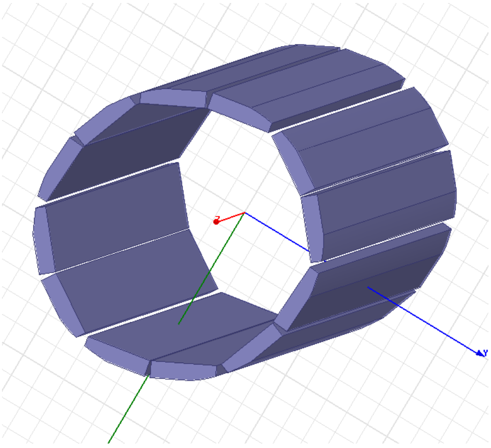

Fig. 8: 3D model of permanent magnets.

The magnetic field is computed using Maxwell package. This software treats the electromagnetic field problems by solving Maxwell's equations in a finite region of space with appropriate boundary conditions or with user specified initial conditions in order to obtain a solution with guaranteed uniqueness.

Magnetics is the solution type set to this analysis. The used materials are chosen from the Maxwell library, considering the properties and polarization of the applied permanent magnets. According to the finite element method, the 3D model is meshed. The fine mesh is generated automatically by the program. The performed analysis has been computed for the case of nominal current of I_n = 11.56°A is loaded to the three phase armature winding shifted from each other with angle of 120 degrees. Grid subdivision of the 3D model of the analyzed motor is presented in Fig. 9.

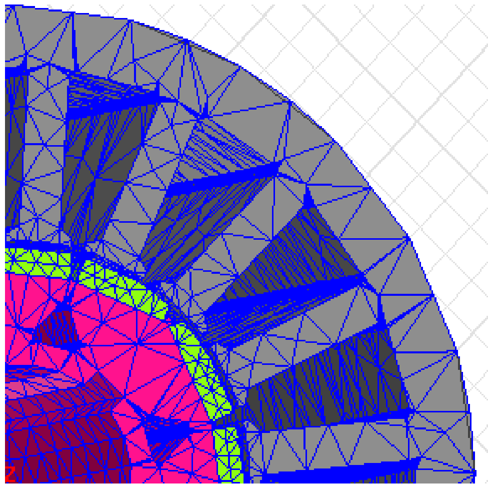

Fig. 9. Grid subdivision.

The distribution of the magnetic flux density can be shown more clearly in the cross section of the servo motor as presented in Fig. 10.

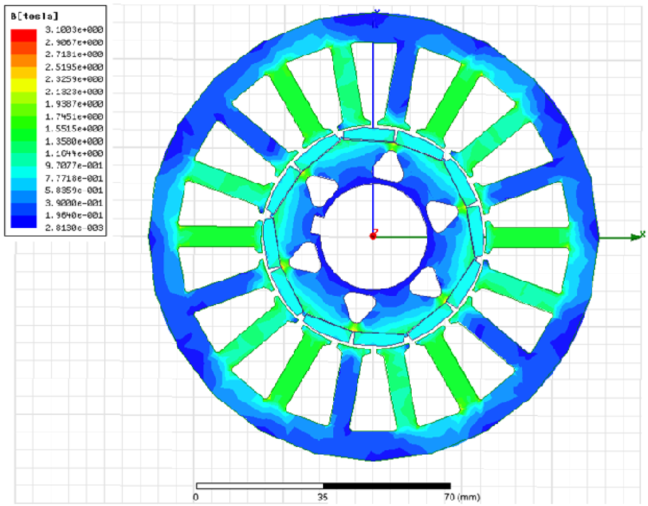

Fig. 10. Distribution of the magnetic flux density along the cross section of the PM servo motor M 718.

The value of the magnetic flux density obtained from Fig. 10 is between 0.003-3.1 T.

To get the distribution of the air gap magnetic flux density, a polyline is drawn in the center of the air gap. The magnetic flux density B is plotted along the created polyline as presented in Fig. 11.

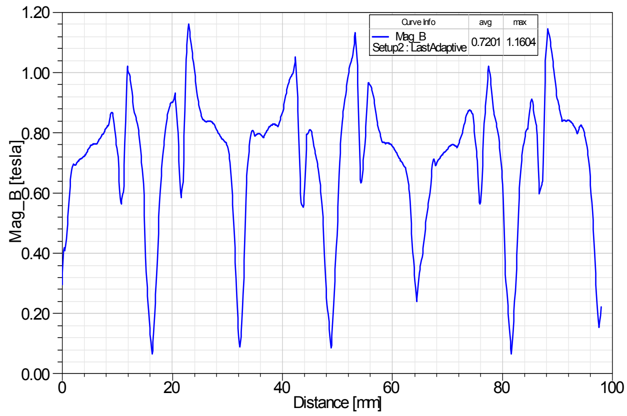

Fig. 11. Circumferential distribution of the magnetic flux density in the air gap center for the 3D analysis.

From Fig. 11, it can be shown the magnetic flux density at air gap center along circumferential. The obtained values of the maximum and average magnetic flux density are as follows:

$$B_{max} = 1.1604 \text{ T}, B_{avg} = 0.7201 \text{ T}.$$

The 2D magnetic field distribution is different from the actual 3D one. In the two dimensional analysis, machine shield consists of ferro magnetic material covers just the straight axial portion of racetrack shaped field coil, while in 3D model; the machine shield covers all the axial portion of the field coil, which results in higher excitation voltage than in 2D design result. That is because machine shield just covers the axial straight portion of field coil, so the flux linkage between field and armature coil decreases at the coil end portion.

V. Calculation of Eddy Current Losses

Eddy current losses which associated with a uniform change of magnetization shown in Figs. 6 and 11 have been calculated. Calculations are achieved in dependence on applied permanent magnets properties and dimensions, and the air gap magnetic flux density. The losses are calculated using two methods. In the first method, the magnetic field of the PM servo motor M 718 is computed using FEMM program. FEMM is freeware software that can be used for two dimensional static analyses only. In the second one, the magnetic field is computed using ANSOFT Maxwell program. This program offers different static and transient analyses in both 2D and 3D applications. Calculated and measured values of total eddy current losses are presented as follows:

TABLE III
MEASURED AND CALCULATED EDDY CURRENT LOSSES OF THE PM SERVO MOTOR M 718

Eddy current losses	2D	3D
Measured	52 W	52 W
Calculated	47.8 W	54 W
Difference	8 %	3.8 %

VI. Conclusion

The calculated value of eddy current losses using FEMM is about 47.8 W, while using ANSOFT this value is about 54 W. The difference between calculation and measurements provided by the manufacturer [14] is about 8 % using FEMM (2D) and about 3.8 % using Maxwell (3D).

The difference between the two above computations is due to many reasons such as the different approach to the magnetic flux density distribution and the variations of mesh generation. Maxwell gives more accurate results because this program uses an auto adaptive algorithm for meshing and can be applied without any simplifications of geometry. FEMM generates mesh with lower quality using a simple algorithm. Calculation of the eddy current losses using a dedicated ANSOFT simulation, and the results comparison with the presented ones will be the next step in this research.

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VIII. Biographies

Ramia Deeb was born in Aleppo (Syria) and graduated from Tishreen University – Faculty of Mechanical and Electrical Engineering (Syria). She continues in PhD study at Brno University of Technology. The research field of her study concerns a modeling and simulation of electrical machines with permanent magnets.

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Marcel Janda was born in Pisek (Czech Republic). He has received master and Ph.D. degrees at the Department of Power Electrical and Electronic Engineering at the Brno University of Technology (Czech Republic). His research field of interests concerns cooling systems of electrical machines and their diagnostics.