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Calculation of Eddy Current Losses in Permanent Magnets of Servo Motor

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Abstract:
Eddy current losses are generated inside magnets of permanent magnet motors (PM motors), due to both of the high conductivity of the rare-earth magnet, neodymium-iron-boron (NdFeB), and to the harmonics of slot/tooth. These losses can increase the temperature inside the magnets that may deteriorate their material. The paper presents a calculation of the eddy current losses in the permanent magnets using the mathematical equations. The losses calculation depends on a 3D model of servo motor created using Autodesk Inventor program, and on the magnetic analysis of this servo motor. The magnetic analysis using program FEMM is applied to 2D model of servo motor created using AutoCAD program.

INTRODUCTION

The applications of PM motors increase more and more in various industrial fields. The applications of PM motors are in a broad power range from small power motors of mW to large power motors of kW. Rare-earth permanent magnets have also been recently used in large power synchronous motors rated at more than 1 MW. The PM motors are applied everywhere, in industry, medicine, power tools, public life such a pumps, fans, blowers, robots, catering equipment, washing machines and clothes dryers, heating and air conditioning systems, printers, plotters, scanners, facsimile machines, electric wheelchairs, rehabilitation equipment, drills, hammers, etc. PM motors have better properties in comparison with the induction motors. They do not pose electrical losses by the field excitation which means they have higher efficiency. They have better dynamic performance in comparison with an electromagnetic excitation, higher torque and higher output power, higher magnetic flux density in the air gap, simple construction and easier maintenance.

Paper focuses on an AC servo motor with permanent magnets. AC servo motors are typical synchronous machines with permanent magnets that often have high torque to inertia ratio at high acceleration ratings. These motors operate at a constant speed in absolute synchronism with the line frequency.

The synchronous motors with permanent magnets are usually built with one of the following rotor:

- Interior magnet rotor
- Surface magnet rotor
- Inset magnet rotor
- Rotor with buried magnets symmetrically distributed
- Rotor with buried magnets asymmetrically distributed

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. Generally, 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. Three basic types of servo motors are used in modern servo systems, AC servo motors, DC servo motors, and AC brushless servo motors. AC servo motors are of cylindrical or square shape, open or enclosed, and available in a variety of housing sizes and diameters.
Permanent magnets can keep their magnetic field stable under a proper application after they are magnetized, due to their high coercive force. They can produce a magnetic field in an air gap with no winding and no dissipation of electric power. PM materials are very sensitive to the temperature. They may lose all their magnetic properties if they are heated to a certain temperature. Their remanent magnetic flux density and coercive force decrease with the increasing temperature. Three main classifications of permanent magnet materials are used in the design of electrical machines:

- Alnico (Al, Ni, Co, Fe): the main properties of this material are high magnetic remanent flux density and low temperature coefficients.
- Ceramics (ferrites): Barium ferrite $BaO\times6Fe_2O_3$and Stroncium Ferrite $SrO\times6Fe_2O_3$. Their main properties are higher coercive force in comparison with Alnico, but lower remanent magnetic flux density. It has relatively high temperature coefficients.
- Rare-earth materials: Samarium-Cobalt (SmCo) and Neodymium-Iron-Boron (NdFeB). Their main properties are higher remanent magnetic flux density, high coercive force, high energy product, and linear demagnetization curve and low temperature coefficient. [1]

Neodymium magnets (Nd-Fe-B) are composed of neodymium, iron, boron and a few transition metals. These magnets are extremely strong for their small size, metallic in appearance and found in simple shapes such as rings, blocks and discs as follows

Fig. 1: Neodymium block magnets

Fig. 2: Neodymium disc magnets

Fig. 3: Neodymium ring/sphere magnets

Fig. 4: Neodymium disc magnets with adhesive

EDDY CURRENT LOSSES

Energy saving and natural resources protection are the focus of recent research, particularly in the field of electrical machines design by building high efficiency machines. Losses in an electrical machine can be classified into copper loss, core loss and rotor loss. In PM machines the core losses form a large portion of the total losses in comparison with the other machines. Therefore, satisfied prediction of core losses for the PM machine design and analysis is essential to reach high efficiency and better performance [6].

The magnet losses are usually neglected for the PM machines with plastic bonded or ferrite magnets, due to their very high resistivity, while the resistivity of the rare earth magnet material is much lower. Therefore it is very important to know these losses because they heat the rotor and may demagnetize the magnets if they are heated to a high temperature such 120 C° for NdFeB magnet [3].

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 coercivity and moderately high electrical conductivity. It is important to consider in PM machines such machines with a high-speed and/or high-pole number [4], [5].

STRUCTURE OF SERVO MOTOR M 718

PM servo motor M 718 is one of the VUES Brno Company products. It is built with surface magnet rotor.

Technical parameters of analyzed servo motor (M 718I) are as follows

- Voltage 280 V
- Current 11.56 A
- Nominal load 16.5 Nm
- Number of pole pairs 6
- Rotational speed 3000 rpm
- Output power 5174 W

The PM servo motor M 718 is designed of

- Stator with 18 slots
- Coils
- Solid rotor
- Permanent magnets mounted on the surface of the rotor.

Permanent magnet material applied to the PM servo motor M 718 belongs to the third type rare earth permanent magnet material NdFeB. It is called MagnetFabrik.

Key Advantages of NdFeB

Neodymium magnets are the most powerful commercially produced magnets.

- NdFeB magnets have a higher maximum energy product, $(B\cdot H)_{max}$.
- NdFeB magnets can replace SmCo magnets in the most cases, especially in cases where operating temperature is less than 80°C.
- Very high strength.
- High remanent magnetic flux density.
- High coercive force.
- Linear demagnetization curve.
- Relatively low cost.
- Compared to Alnico and SmCo magnets, relatively easy to machine.

The main properties of the MagnetFabrik material are presented in the following table [7].

Tab. 1: Properties of MagnetFabrik material

Material	***MagnetFabrik***
Density [kg/m^3]	7 600
Thermal conductivity [W/m·K]	8
Specific heat [J/kg·K]	440
Relative permeability μ_{rec}	1.1
Resistivity [10^{-6} Ωm]	1.6
Remanence [mT, type, at 20 °C]	1 110
Coercivity [kA/m, at 20 °C]	850
Energy product [kJ/m^3]	230
Curie temperature [°C]	350
Max. operation temperature [°C]	190

Design of the analyzed servo motor M 718 is presented in Figs. 5 and 6.

Fig. 5:Real PM servo motor M 718

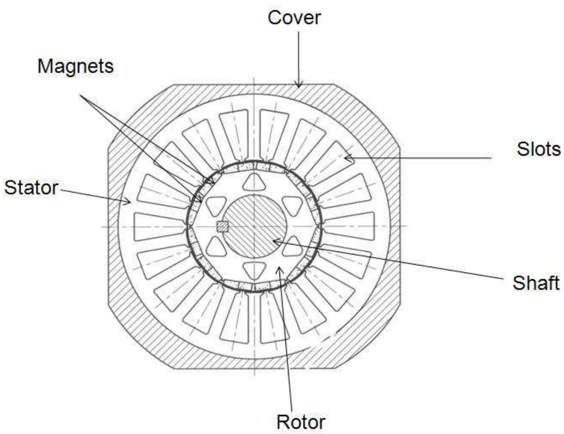

Fig. 6:Outline of servo motor M 718

CALCULATION OF EDDY CURRENT LOSSES IN THE PMs

At load operation, a three phase sinusoidal current system is applied to the three phase windings as a d-q current operation according to the actual rotor position as the rotor and stator field have to rotate synchronously. The variation of the magnet flux is increased due to the harmonics of mmf (magneto-motive force) of the stator field and depends on the relative position between stator and rotor field

Considering only fundamental field waves in synchronous machines, the rotor field is constant in steady state operation and thus no eddy current losses should occur in the magnets.

Actually, due to the modulation of the rotor field with the stator slotting permanence at no-load and at load, additional mmf space harmonics of the stator field, with amplitudes amplified by the slot openings, exist. That induces eddy current losses in the magnets [2].

Eddy-current losses per unit of magnet volume:

The current density in the magnets is calculated according to the second Maxwell's equation:

$$\oint E \cdot ds = -\frac{d}{dt}\iint_{s} B \cdot d\alpha \qquad (1)$$

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 = ρ_m.J. Thereby, the current density can be written as:

$$J_z(x) = \frac{x}{\rho_m}\frac{dB}{dt} \qquad (2)$$

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

$$k_m = \frac{1}{b_m}\int_{-b_m/2}^{b_m/2} \rho_m J_z^{\,2}(x)\,dx = \frac{b_m^{\,2}}{12\rho_m}\left(\frac{dB}{dt}\right)^2 \qquad (3)$$

The magnetic flux density, which causes the losses in the k-th magnet, can be written as

$$B_k = B(\alpha_k) = \hat{B}\cos(p(\alpha_k - \beta)) \qquad (4)$$

By replacing the flux density in equation (3), the eddy current losses per unit of magnet volume in the k^{th} magnet can be calculated as follows

$$k_{m,k} = \frac{b_m^{\,2}}{12\rho_m}\left(\frac{d}{dt}\left\{\hat{B}\cos(p(\alpha_k - \beta))\right\}\right)^2 \qquad (5)$$

The total magnet losses equals to summation of the magnet losses in total Nm magnets

$$P_m = l_s l_m b_m \sum_{k=1}^{N_m} \frac{b_m^{\,2}}{12\rho_m}\left(\frac{d}{dt}\left\{\hat{B}\cos(p(\alpha_k - \beta))\right\}\right) \qquad (6)$$

where:

- l_m: magnet thickness
- l_s: stack length of motor
- b_m: magnet width
- α_k: axis of k-th magnet lays at rotor coordinate
- ρ_m: magnet resistivity
- β: a function of time
- P: the number of pole pairs of the motor
- B: magnetic flux density

The eddy current losses in the magnets can be estimated as follows

$$P_m \approx \frac{V_m b_m^{\,2} \hat{B}_m^{\,2} \omega^2}{12\rho_m} \qquad (7)$$

where:

- ω: frequency
- ρ_m: magnet resistivity
- V_m: total volume of magnets
- B_m: magnetic flux density in the air gap

According to the Eqn. 7, eddy current losses in the permanent magnets of servo motor M 718 can be calculated depending on:

- Parameters of the permanent magnets (3D model)
- Physical properties of the permanent magnets (servo motor datasheet)

- Magnetic analysis of this servo motor (magnitude of the magnetic flux density in the air gap)

MODELING OF SERVO MOTOR

3D model of servo motor is created using Autodesk Inventor program according to the following servo motor dimensions in datasheet [7]

- **Stator**, designed of 18 slots
  Dimensions:
    Outer diameter 126 mm
    Inner diameter 63 mm
    Length 225 mm
- **Solid rotor** with PMs mounted on its surface
  Dimensions:
    Outer diameter 61.6 mm
    Inner diameter 30 mm
  Dimension of PMs:
    Number 9
    Length 25 mm
    Height 3.5 mm
    Width 14 mm
    Weight of PMs 1.05 kg
- **Coils**
    Insulation class F
    Pure wire weight 4.5 kg
- **Air gap**
    Width 0.7 mm

Both 3D model of servo motor and 3D model of the permanent magnets applied to the servo motor are presented in Figs. 7-8

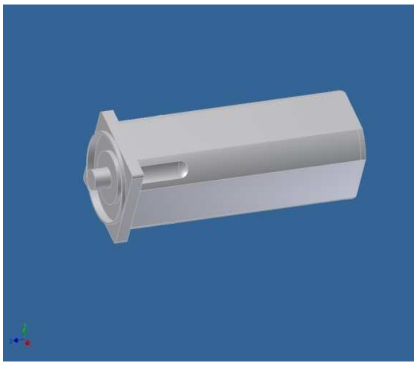

Fig. 7:3D model of PM servo motor M 718

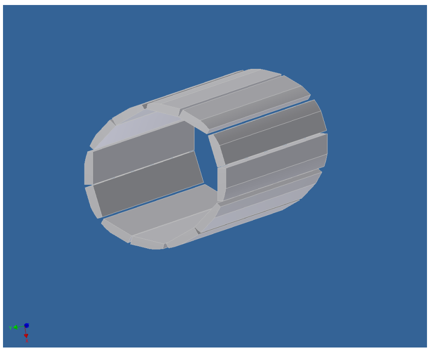

Fig. 8:3D model of permanent magnets applied to the servo motor M 718

From the 3D model, the total volume of the magnets V_m and the magnet width b_m are obtained

$$V_m = 1.0282\times10^{-5}\ m^3$$
$$b_m = 14\times10^{-3}\ m$$

THE MAGNETIC ANALYSIS OF PM SERVO MOTOR M 718

The magnetic analysis of PM servo motor M 718 is computed using FEMM (Finite Element Method Magnetics). For this analysis a 2D model of servo motor is created using AutoCAD program. Materials applied to the 2D model are chosen from the FEMM library.

The magnetic analysis is computed at the nominal load, and the results are as follows

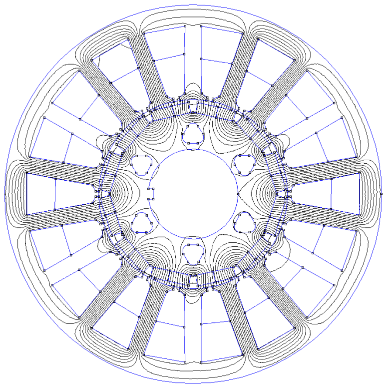

Fig. 9:Magnetic flux line distribution inside the servo motor

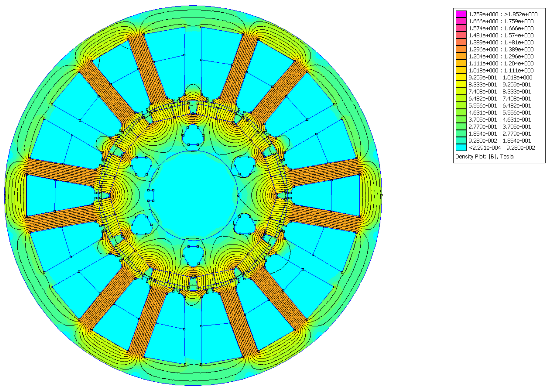

Fig. 10: Magnetic flux density distribution inside the servo motor

Figs. 9 and10 present the distribution of the magnetic field intensity and the distribution of the magnetic flux density inside the analyzed servo motor.

Two magnetic fields exist in the PM motors. The magnetic field produced by the windings in the stator and the magnetic field produced by the permanent magnets mounted on the rotor.

Fig. 11 presents the magnetic flux density in the air gap as a function of the air gap length in a form of an arc=180° in the air area around of the rotor.

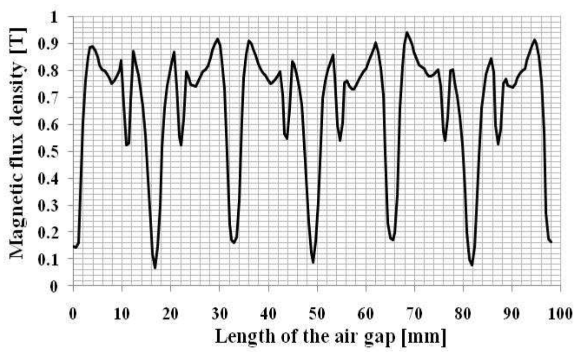

Fig. 11: The magnetic flux density according to the air gap length

From Fig. 11 it can be noted that the magnetic flux density in the air gap has non sinusoidal waveform. The approximated value of the magnetic flux density in the air gap is about B_m = 0.62 T.

By replacing the obtained values above in the Eqn. 7, the eddy current losses can be calculated.

Tab. 2: Calculation results

$P_{m\,(technical\ data)}$	$P_{m\,(calculated)}$	*Difference*
52 W	47.8 W	8 %

Tab. 2 presents a comparison between the calculated value of eddy current losses and the technical ones. The calculated value of these losses is about 47.8 W with about 8 % difference from the technical data of the analyzed servo motor.

CONCLUSION

The eddy current losses in the permanent magnets of servo motor M 718 using mathematical equations have been calculated. The difference between the technical data and the calculated one is due to three main reasons: the approximation made in the value of the magnetic flux density in the air gap, the approximation of the windings layout in the stator slots in the computational model, which differs a little bit form the real one and the error due to the combination of 2D and 3D models of the servo motor.

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