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# 3D MODEL OF ARMATURE FIELD OF HELICAL (FAULHABER) WINDINGS INCLUDING ROTOR EDDY CURRENTS

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**Abstract**. Helical (Faulhaber) windings are widely used in low-power permanent magnet machines. The paper presents an analytical model of the armature reaction field of a machine with a helical winding, which takes into account induced eddy-currents in the rotor. The eddy-current losses are calculated applying the Poyting vector. The model has been verified by FEM.

**Keywords**: high-speed machines, analytical modeling, Faulhaber winding, second order vector potential, harmonic modeling approach.

## INTRODUCTION

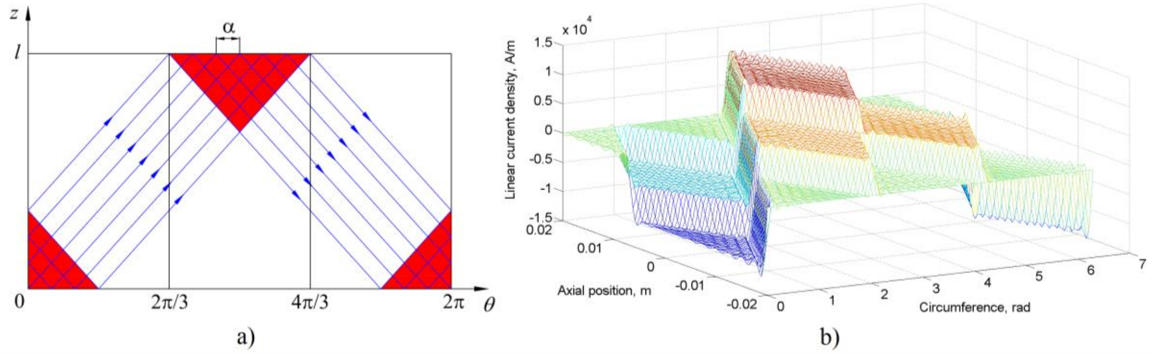
The history of helical windings started in 1947 when Dr. Fritz Faulhaber invented the winding. In many papers Faulhaber winding is also called “skewed” or “helical” winding. The winding was intended to be used in low-power electrical machines. Helical windings have inherent advantages such as absence of cogging torque, cheaper manufacturing of low-power machines and absence of end windings. However they also have disadvantages such as high copper losses and poor cooling capability [1].

Many researches have been working on analysis of Faulhaber windings. In [2] torque and force calculations of a Faulhaber winding in three-dimensional (3D) had been analyzed. The method of calculation of phase inductances of Faulhaber windings is proposed in [3], where authors have used Biot-Savart’s law to determine the armature field from a Faulhaber winding. In [4] the Faulhaber winding’s torque constant is determined by means integrating magnetic vector potential of a permanent magnet (PM) over the conductors of the winding. Additionally, the authors introduced an equation to determine the winding’s DC. Aforementioned papers are providing methods to analyze Faulhaber windings, however none of the papers are describing modeling of the armature reaction field and the rotor eddy-current losses calculation. Rotor eddy-current losses are important to consider in high-speed PM machines because of the risk of the PM demagnetization. This paper provides an analytical model of the magnetic field generated by the helical winding including induced eddy-currents. The magnetic field is solved by means of the second order vector potential (SOVP) in the Cylindrical coordinate system.

## METHOD OF MODELING

### Linear current density modeling

The first step in modeling the armature reaction field of a helical winding is the analytical expression of linear current density of the winding (Fig 1a). Linear current density of a helical winding has two components such as the axial component which produces torque and the azimuthal one which is only contributing to losses. The profile of axial linear current density obtained using the analytical expression which takes into account all three phases and is plotted in Fig. 1b.



a)

b)

**Figure 1**. a) General presentation of Faulhaber winding b) Axial linear current density distribution of Faulhaber winding.

### Magnetic field modeling

Analytical modeling of the magnetic field in a machine with the helical winding is a 3D problem. For the analysis of the magnetic field the Harmonic Modeling Approach (HMA) is applied. The method assumes the division of a machine into regions with its own governing equation. To non-conducting regions the Laplace equation is applied and to conducting regions, where eddy-currents take place, Helmholtz equation is applied. The magnetic field is expressed by means of the SOVP which is defined as:

$$\vec{B} = \nabla\times\left(\nabla\times\vec{W}\right) = \nabla\times\left(\nabla\times(\vec{e}_z W_1 - \nabla\times(\vec{e}_z W_2))\right), \tag{1}$$

where $B$ is flux density, $W_1$ and $W_2$ are components of the SOVP. Using the method of separation of variables to solve differential equations a general solution of the SOVP can be obtained. Unknown constants in the expression of the SOVP are found by solving a system of equations which is set by applying boundary conditions.

## RESULTS

To verify the method, the analytical and 3D FEM with the same parameters have been built. Comparing to the analytical model, FEM modeling requires significant amount of computational time, however the difference in results of FEM and analytical models does not exceed 5%. The radial component of the magnetic flux density which is obtained analytically is shown in Fig. 2.

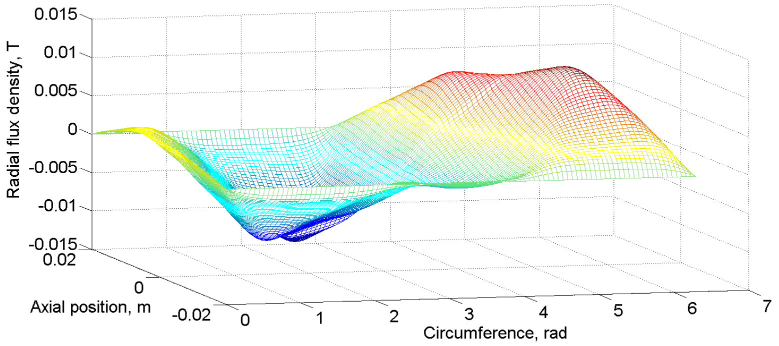


**Figure 2**. Radial component of air gap flux density calculated analytically.

## CONCLUSIONS

In this paper 3D electromagnetic model of a machine with a helical winding is described. The analytical model is compared with 3D FEM showing good matching (difference does not exceed 5%). The model takes into account eddy-currents induced in conducting regions, such as the PM or conductive sleeve, and their reaction field. The modeling plays an important role during design of a high-speed PM machine with a helical winding because of the risk of the magnet demagnetization. The most important advantage of the obtained analytical method lies in significantly lower required computational time while having similar accuracy in comparison with 3D FEM, which is highly important factor for practical implementation of a machine design optimization.

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