CALCULATION OF PARAMETERS OF PERMANENT MAGNET MOTOR WITH POWDER MAGNETIC CORE USING EDGE ELEMENT METHOD

Abstract: In the paper the potential application of soft magnetic composite material (Somaloy 500) in permanent magnet motor is presented. The influence of material parameters on electromagnetic torque and emfs of permanent magnet motor are discussed. Two types of permanent magnet motors have been considered: (a) rotor with powder magnetic core and (b) rotor with laminated magnetic core. Parameters of permanent magnet motor have been calculated using reluctance network method. Reluctance network is formed using the interpolation function of edge and facet elements. The presented edge element method and reluctance network is suitable to analyses isotropic, anisotropic materials and non-homogenous regions.

1. Introduction

Permanent magnet machines (PMM) are widely applied in industrial applications. Recently, in order improve the performance of PMM the new powder magnetic materials have been proposed. Currently, two types of those materials are available, respectively with soft and hard magnetic properties [5]. In opposite to laminated cores (made of traditional magnetic sheets) the soft magnetic composite (SMC) powder materials have 3D-flux carrying capabilities. Application of those 3D magnetic properties is a key to success with an SMC core motors. This technology gives the possibilities for the designer to use new topologies with shape, winding and assembly solutions which are beyond today’s standards and opens up for benefits such as better performance, reduced size and weight, fewer parts and lower cost [5]. In the paper the PMM with core made of SMC powder material Somaloy 500 has been investigated.

In the paper two types of PMM have been considered: (a) rotor with powder magnetic core and (b) rotor with laminated magnetic core. The 3D edge element method (EEM) has been applied for calculations of magnetic field in the motors. The edge element equations represent the loop equations of reluctance network (RN) [4]. RN is formed using the interpolation functions of edge and facet elements [1,4].

2. Edge element equations

In order to describe the distribution of the magnetic field the edge element method using the vector magnetic potential \( \mathbf{A} \) has been applied. In the presented approach the motor has been subdivided into curved rectangular parallelepipeds (Fig. 1).

The equations of used EEM represent the loop equations of reluctance network. The branches of RN connect the centres of neighbouring elements. The branch fluxes of RN represent the face values of flux. The loop flux \( \varphi_{ij} \) represents the edge value of \( \mathbf{A} \), for edge \( P_iP_j \) – see Fig. 1. The branch reluctances are calculated using the interpolation functions of facet element,

\[
R_{\mu_{ij}} = \int_{V_e} w_{ij}^T \mathbf{w}_{ij} dV
\]  

(1)

Here, \( w_{ij} \) and \( w_{sj} \) are interpolation functions of a facet element for the face \( S_i \) and \( S_j \) [4]. \( V_e \) is the volume of element. In contradistinction to the classical RN, the reluctance network formed by EEM has mutual reluctances.

![Fig. 1. 12-edge curved rectangular parallelepiped element](image-url)
Here, $\mathbf{R}_{\theta g}$ is the matrix of branch reluctances, $\mathbf{R}_c$ is the transposed loop (mesh) matrix for RN, $\mathbf{\theta}_g$ is the vector of branch mmfs, $\mathbf{\theta}$ is the vector of loop mmfs.

The branch mmfs can be defined by the edge values of the current vector potential $\mathbf{T}_e$ for region with windings [6] and the edge values of magnetizing vector $\mathbf{T}_m$ for region with magnets [2]. To calculate RN equations the block overrelaxation method has been employed.

The electromagnetic torque for RN is obtained from finite difference approximation of the magnetic energy derivative versus the virtual moving [3]. The finite difference approximation gives

$$T(\alpha) = -\frac{1}{2\beta}(W(\alpha+\beta)-W(\alpha-\beta))$$  \hspace{1cm} (3)

Where, $W(\alpha\pm\beta)$ is the magnetic energy for discrete rotor positions $\alpha\pm\beta$, $\alpha$ is an considered rotor position, $\beta$ is the angular width of element see Fig 1.

To calculate $T(\alpha)$ characteristics the band with curved rectangular parallelepipeds has been placed in the air-gap of 3D PMM model. The element edges are parallel to the axis of a cylindrical co-ordinate system $r$, $z$, $\psi$. The trace of the elements in the plane perpendicular to the axis $z$ is the grid with quadrangles of identical angular length of the base $\beta$ (Fig.1). The band is subdivided into $m$ layers of thickness $\Delta l_q$ in direction $z$ (Fig.1). For the band, formula (7) has been expressed as follows

$$T(\alpha) = \frac{1}{2\beta} \left\{ \sum_{q=1}^{m} R_{p,q} \sum_{i=1}^{n} \phi_{q,i-1} \left[ \phi_{q,i-1} - \phi_{q,i+1} \right] \right\}$$

$$+ \frac{1}{2\beta} \left\{ \sum_{q=1}^{m} R_{z,q} \sum_{i=1}^{n} \phi_{z,q,i} \left[ \phi_{z,q,i} - \phi_{z,q,i+1} \right] \right\}$$  \hspace{1cm} (4)

Here, $\phi_{q,i-1}$ is the value of flux in branch $P_{p=q}$ for position $\alpha\pm\beta$ and $\phi_{z,q,i}$ is the value of flux in branch $P_{z=q}$ for position $\alpha\pm\beta$, see Fig. 2. $R_{p,q}$ and $R_{z,q}$ are the reluctances associated with the band, see Fig. 2. Subscript $q$ denotes the reluctances and the branch fluxes related to the $q$-th layer.

As a result we obtain equation that represents the stress tensor formula for torque calculation using RN and EEM [3].

A 4 pole motor with 6 slots per pole has been designed. Permanent magnets are not skewed and are mounted on rotor with powder magnetic core – see Figure 3.

Figure 4 shows the magnetic property comparison between the ferromagnetic sheets and SMC material – Somaloy 500.
A single-layer winding is composed of 4 multi-turn coils per phase. The coils are connected in series. 3-phase stator windings are star connection. The motor is equipped with rare-earth NdFeB-type permanent magnets. The stator core of the machine is laminated, see Fig. 5.

In order to model this core in 3D it is assumed that reluctivity \( \mu_z \) in the direction parallel to shaft axis \( z \) differs from the reluctivity \( \mu_r, \mu_\phi \) in the direction orthogonal to axis \( z \), i.e. the core reluctivity is considered to be orthogonally anisotropic. The values of \( \mu_z \) and \( \mu_r, \mu_\phi \) have been obtained from the formulas that describe the equivalent reluctivity of the system composed of two reluctances: the reluctance for the flux which penetrates the ferromagnetic sheets and the reluctance for the flux that penetrates the isolation. This approach gives

\[
\nu_z = (1-k_z)\nu_0 + k_z\nu_{Fe} \approx (1-k_z)\nu_0 + k_z\nu_{Fe}\]

where, \( k_z \) is the stacking factor, \( \nu_{Fe} = \nu (B) \) is the reluctivity of isotropic ferromagnetic sheet.

In order to model rotor with powder magnetic core it is assumed that reluctivity \( \nu_z \) and reluctivity \( \nu_{r,\phi} \) are equal to reluctivity of SMC materials (\( \nu_{SMC} \)).

4. Results

The method presented above has been used in the analysis of two types of PMM: (a) rotor with powder magnetic core, (b) rotor with laminated magnetic core. The considered region has been subdivided into \( \approx 200\,000 \) elements per pole.

In this paper the results of electromagnetic torque and \emph{emfs} calculation are given. In the case of torque calculation it was assumed that the phase currents are sinusoidal, i.e. \( i_q = 13.85 \sin (\omega t + (q-1)120) \) (\( q = 1,2,3 \)), and torque angle \( \delta = 90^\circ \). The calculations have been performed for the motors of different core length \( l_c \) (see Fig. 3). Here, the results for the motor of external stator diameter \( d \) equal to \( 3l_c \) are presented. The 3D and 2D models have been considered (2D – see Fig. 6a and 3D – see 6b). The waveforms of electromagnetic torque are shown in Fig. 6. The torque waveforms are related to the rotor with powder magnetic core \( T_{SMC} \) and rotor with laminated magnetic core \( T_{FS} \).

![Fig. 6. The waveforms of electromagnetic torque (a) 2D model (b) 3D model (\( d/l_c = 3 \))](image)

The calculated average \( T_{av} \) maximum \( T_{max} \) torque values and maximum \( T_{cmax} \) cogging torque values are summarized in Table 1 for 2D model and Table 2 for 3D model. Additionally, in the Tables 1 and 2 the differences between values of calculated torques \( (T_{av, T_{max}, T_{cmax}}) \) for different ratio \( d/l_c \) have been shown.

<table>
<thead>
<tr>
<th>Type of motor</th>
<th>ratio ( d/l_c )</th>
<th>( T_{av} ) [Nm]</th>
<th>( T_{max} ) [Nm]</th>
<th>( T_{cmax} ) [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotor with powder magnetic</td>
<td>3.0</td>
<td>5.601</td>
<td>6.221</td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>22.386</td>
<td>24.882</td>
<td>0.196</td>
</tr>
<tr>
<td>rotor with laminated magnetic</td>
<td>3.0</td>
<td>5.686</td>
<td>6.309</td>
<td>0.049</td>
</tr>
<tr>
<td>core</td>
<td>0.75</td>
<td>22.724</td>
<td>25.236</td>
<td>0.195</td>
</tr>
</tbody>
</table>

![Fig. 5. Anisotropic structure of laminated stator core](image)
Table 2. Calculated values of torque and cogging torque (3D model)

<table>
<thead>
<tr>
<th>Type of motor</th>
<th>Ratio</th>
<th>$T_{av}$ [Nm]</th>
<th>$T_{max}$ [Nm]</th>
<th>$T_{cmax}$ [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotor with powder magnetic</td>
<td>3.0</td>
<td>5.239</td>
<td>5.758</td>
<td>0.045</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>22.065</td>
<td>24.439</td>
<td>0.193</td>
</tr>
<tr>
<td>rotor with laminated magnetic core</td>
<td>3.0</td>
<td>5.325</td>
<td>5.843</td>
<td>0.044</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>22.403</td>
<td>24.798</td>
<td>0.191</td>
</tr>
</tbody>
</table>

Next the results of emfs calculation are given. In Fig. 7 the emfs waveforms are presented. The emfs characteristics (Fig. 7) have been interpolated by FFT method. The amplitudes of calculated harmonics are presented in Fig. 8.

5. Conclusions

Soft magnetic composites materials have the potential to be applied to electrical machines. Analysis of permanent magnet motor with powder magnetic core shows that it is possible to design motor with such a soft magnetic circuit. The benefits of replacing the conventional laminated cores in the electrical motors with the powdered iron composites are as follows: significant reduced production costs, due to the simplified design and essentially unity iron stacking factor.

The used method in the paper is universal and can be successfully applied in the analyses isotropic, anisotropic materials and non-homogenous regions.

6. Bibliography


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