OPTIMIZATION OF THE PM ARRAY OF BRUSHLESS DC MOTOR FOR MINIMUM COGGING TORQUE

This paper deals with magnetic field calculations and model-based prediction of electromagnetic torque pulsations in a brushless DC (BLDC) motor. The impact of a multipolar excitation of permanent magnets is analysed. Measurement results from the prototype motors are well-compared with those obtained from the model calculations. It is shown that the cogging torque in the motor with the multipolar excitation of permanent magnets is reduced six times as compared with the conventional BLDC motor. For the computation of an optimal magnetic circuit shape a 3D finite element program was used and an evolutionary algorithm was implemented. In the evolutionary algorithm used for optimization, two parameters were taken into account. Several computer simulations were carried out and the results were compared with the previous prototype version of the motor.

1. INTRODUCTION

Nowadays, brushless direct current motors with permanent magnets (BLDC motor) are extensively used in a variety of industrial drives. Usually, these drives are characterised by relatively high torque ripples. Cogging torque reduction is an essential requirement in a wide range of high-performance motion control applications. Cogging torque is produced by the circumferential component of attractive forces between the magnet and the stator teeth. Many applications like servodrives or hard disk drive micromotors do not tolerate cogging torque of any level. The most effective means applied to reduce the cogging torque are skewing of slots and/or magnets [3]; optimization of such factors as magnet pole-arc to pole-pitch ratio [2]; slot number and pole number combination, including auxiliary teeth and slots [10]; slot opening width, airgap length, magnet thickness [11] and Halbach – like

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magnetization of permanent magnets [8, 9]. At present, the magnetic structures resulting from this work have become known as multipolar excitations of arrays. In the literature, a comparison between the multipolar and standard permanent magnet arrays has been extensively described [4, 5, 6].

Rotors of the BLDC motor to be analysed in this paper have radially magnetized array and three segments per pole with multipolar excitation of array. The application of multipolar cylinders to brushless motors has shown that a low level of cogging torque can be realized without recourse to conventional design features, such as distributed stator winding and/or skewing of the stator/rotor.

This paper presents an example of the application of an evaluationary algorithm (EA) to optimization of BLDC motors. The main task is reducing of the cogging torque in a small brushless motor with permanent magnet excitation by shape optimization of permanent magnets and distribution of the magnetization vector.

2. PROTOTYPES OF MOTORS FOR THE TORQUE CALCULATIONS

Calculations are performed for BLDC motors with radial permanent magnet magnetization (Fig.1) and with various widths of the magnets and for various distributions of the magnetization vector (Fig.2). Using the multipolar excitation of PMs allows for reducing of the cogging effect and allows get a higher average value of the electromagnetic torque, much better than the conventional motor with radial magnetization [4, 5].

![Fig. 1. Cross-section of BLDC motor with the radial magnetization (a) and the rotor of the prototype A of the motor (b)](image)

The motor pole structures are shown schematically in Figs.1 and 2. In the motor with multipolar excitation, each pole in the rotor is subdivided into three segments with various arc-pole widths described by the parameters $\gamma$ and $\beta$ (the angle of magnetization vector was equal to $45^\circ$).
Fig. 2. Cross-section of BLDC motor with the multipolar magnetization of PMs (a) and the rotor of the prototype B of the motor (b)

In Table 1, common parameters of BLDC PM motor prototypes with radial magnetization of PMs and with multipolar excitation of arrays are shown.

<table>
<thead>
<tr>
<th>Table 1. Main data of the motor prototypes</th>
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<tr>
<td>Air-gap length</td>
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<td>PM material</td>
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<tr>
<td>PM radial thickness</td>
</tr>
<tr>
<td>Stator outer diameter</td>
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<tr>
<td>Stator and rotor stack length</td>
</tr>
<tr>
<td>Residual flux density</td>
</tr>
<tr>
<td>Coercive magnetizing intensity</td>
</tr>
<tr>
<td>Rated Power</td>
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<tr>
<td>Rated nominal current</td>
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The mathematical model of the motor for calculation 3D magnetic field was presented in details in [4, 5]. The calculation of the electromagnetic torque developed by the motor is performed making use of virtual work method.

3. OPTIMIZATION PM ARRAY OF THE BLDC MOTOR

Evolutionary algorithm (EA) imitates the natural selection and the genetics of living organisms while searching the global extremum in $\mathbb{R}^n$. A typical EA consists of three heuristic operators, i.e. reproduction, crossover and mutation to provide the transfer of best features to the successive generations and to overcome a possibility of falling into a local minimum [1]. Evolutionary Algorithms are, in general, able to solve large-scale optimization problems applying these features.
The optimization task can be defined to find the best compromise between reduction of the cogging torque and/or maximization of electromagnetic torque. To ensure high accuracy in evaluation of the parameters of a BLDC motor while solving an optimization problem, the quasi-nonlinear 3D model of a BLDC motor is used. A 3D model is considered for magnetic field evaluation. In Fig. 3, variables for optimization algorithm are shown.

The objective function is defined in the form:

$$\min_x (T_{cogg\ max})$$

(1)

where $T_{cogg\ max}$ - maximum value of the cogging torque.

Figure 4 shows the minimal values of the objective function versus a number of generations (P).

Table 2 shows the results from EA. In the optimized prototype B, the maximum cogging torque is reduced by sixteen times whereas in the non-optimized prototype B only a six times reduction is obtained in comparison with prototype A. The torque ripple factor $\varepsilon$ was defined by Nakata at al. [7].
### Table 2. Comparison of torques for the prototypes of BLDC motor for I = 10A

<table>
<thead>
<tr>
<th>Prototypes of BLDC motor</th>
<th>Parameter ( [\circ] )</th>
<th>( T_{\text{cogg max}} ) [Nm]</th>
<th>( T_{\text{e max}} ) [Nm]</th>
<th>( T_{\text{e min}} ) [Nm]</th>
<th>( T_{\text{e av}} ) [Nm]</th>
<th>( \varepsilon ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype B – before optimization</td>
<td>( \beta = 45 ) ( \gamma = 22 )</td>
<td>0.11</td>
<td>0.11</td>
<td>3.94</td>
<td>3.32</td>
<td>3.67</td>
</tr>
<tr>
<td>Prototype B – after optimization</td>
<td>( \beta = 48 ) ( \gamma = 32 )</td>
<td>0.04</td>
<td>–</td>
<td>3.65</td>
<td>3.10</td>
<td>3.60</td>
</tr>
<tr>
<td>Prototype A</td>
<td>( \beta = 0 ) ( \gamma = 47 )</td>
<td>0.67</td>
<td>0.7</td>
<td>4.5</td>
<td>1.9</td>
<td>3.41</td>
</tr>
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</table>

Using the multi-polar excitation of PMs allows for reduction of the cogging effect much better than for prototype A (see Table 2). The main advantage is a higher average value of the electromagnetic torque. In addition, comparing the prototype B before optimization and the motor version after optimization, it can be observed that, for the latter, the average torque is lower by some 2%, but the relative ripple cogging torque is over 63% lower. The simulation results for the torques developed by the selected motor versions are illustrated in Fig. 5.

![Fig. 5. Electromagnetic torque (a) and cogging torque (b) versus angular position for prototype B (before and after optimisation) and motor version A.](image)

### 4. CONCLUSIONS

In this paper, an approach to minimization cogging torque by shape optimization of permanent magnets and distribution of the magnetization vector of BLDC motor has been presented. An effective model of BLDC motor for field evaluation has been developed and successfully applied for optimization using an evolutionary algorithm. The measurement results from prototype motors are well-compared with calculations. This confirms the usefulness of the computational approach presented for modeling of the BLDC PM motor performance.

The impact of inhomogeneous magnetization vector of PM and various pole width of rotor on the torque pulsations has been investigated. Results of the calculations
clearly show the existence of an optimal direction of the magnetization vector and an optimal division of rotor poles, at which the average torque remains high and pulsations are considerably reduced. The cost is a bit more complicated rotor structure, with a number of sleeves cut for the construction of the segments.

REFERENCES


OPTYMALIZACJA WZBUDZENIA SILNIKA BLDC ZE ZMIENNYM WEKTOREM MAGNETYZACJI

W pracy przedstawiono wyniki analizy momentu elektromagnetycznego i jego pulsacji w silniku bezszczotkowym prądu stałego ze zmiennym wektorem magnetyzacji magneów trwałych. Wyniki obliczeń zostały porównane z pomiarami na modelu fizycznym silnika, wykazujące dobrą zgodność. Optymalizację obwodu magnetycznego silnika przeprowadzono przy użyciu algorytmu ewolucyjnego, wykorzystując pakiet programowy FLUX3D oraz Matlab. W wyniku optymalizacji określono parametry magneów trwałych, zapewniające redukcję momentu zaczepowego silnika.

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