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A Novel Approach of Shape Optimization in Spoke Type Permanent Magnet Motors

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ABSTRACT: A novel approach of shape optimization to reduce pulsating torque components in spoke type permanent magnet motors is developed in this paper. This method is demonstrated on the iron pole shape optimization of an 8-pole/18-slot spoke type motor. The results of experiments show the effectiveness of the presented method.

KEYWORDS: Spoke type motor, Pulsating torque, iron pole shape optimization.

1 INTRODUCTION

Nowadays, permanent magnet motors are widely used in industrial automation because of their efficiency and power density. In particular, the spoke-type motor, which can focus flux from permanent magnets, has a high torque density per unit volume resulting from its high reluctance torque and structure for concentrating flux from permanent magnet. However, cogging torque and torque ripple can be increased due to a distortion of air gap flux density distribution in the spoke type motors. This drawback is due to its asymmetric magnetic reluctance on the edge of the permanent magnet.

There have been some developments for iron pole shape optimization. Cogging torque reduction in IPM motors was performed using a rotor with flux barriers [1]–[3]. Eccentric pole design was proposed to compensate the armature reaction for reducing torque ripple [4]. To obtain better performance, the rotor pole shape was varied and divided into three parts. These consist of two end parts of eccentric surfaces and one uniform surface. Response surface methodology (RSM) was used during the design process [5]. The continuum shape design sensitivity formula and the finite element method are employed to calculate the sensitivity of flux linkage to the design variables, which determine the shape of iron pole piece [6]. They used B-Spline parameterization to optimize the design variables in order to provide the back-EMF waveform as close as possible to a sinusoidal form.

The main challenge of current optimization methods, especially for complex one, is the number of design variables required for rotor pole shape optimization and the generality of the procedure. The first method has poor performance due to the loss in flux barriers. The second method is only suitable for motor rotation in one direction. Also, the later method is not a general approach to achieve the optimum rotor pole shape profile.

A novel algorithm applicable for a larger class of problems is developed in this research and it is conducted to rotor pole shape optimization of a 3-phase spoke type motor with 8 pols-18 slots. An innovative, comprehensive way of using an efficient design variables linking method, termed as reduced basis technique [7], is demonstrated for rotor pole shape optimization. In the reduced basis technique, many initial rotor pole shapes, called basis shapes, are combined linearly by assigning weight factors. Different resultant shapes can be generated by changing their weight factors. Therefore, the number of design variables required to define the shape is reduced to the number of basis shapes. So, the weights assigned for each basis shapes are the design variables and the optimization goal is to find the best possible combination of these weights to minimize a cost function.

The presented algorithm focuses on the Taguchi method which is the combination of mathematical and statistical techniques used in the empirical study of relationships and optimization, in which several independent variables influence a dependent variable or response. The choice of an experimental design to build the model depends on the objectives of the experiment and the number of factors to be investigated.

2 SHAPE OPTIMIZATION METHOD

2.1 INITIALIZATION

The iron pole shape optimization of a 8poles-18slots spoke type motor is demonstrated in this work. A cross-section of the motor in which rotor shape is circular is shown in Fig. 1 and characteristics of the motor are listed in table 1. The problem can be solved in multiple levels as shown in Fig 2, such as the optimization procedure guides the designer progressively in selecting viable basis shapes.

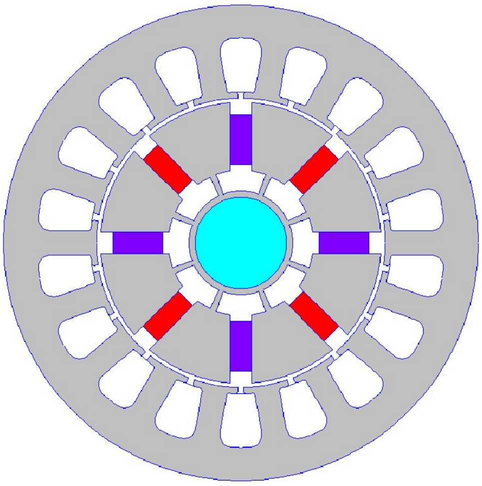


Fig. 1. Cross section of 8P18S IPM motor

Table 1. Specification of the investigated IPM motor.

Parameter	Value
Outer Diameter	60 mm
Pole number	4
Slot number	24
PM flux density	1.05 T
Rotor outer diameter	37 mm
Magnet thickness	3 mm
Stator length	65 mm

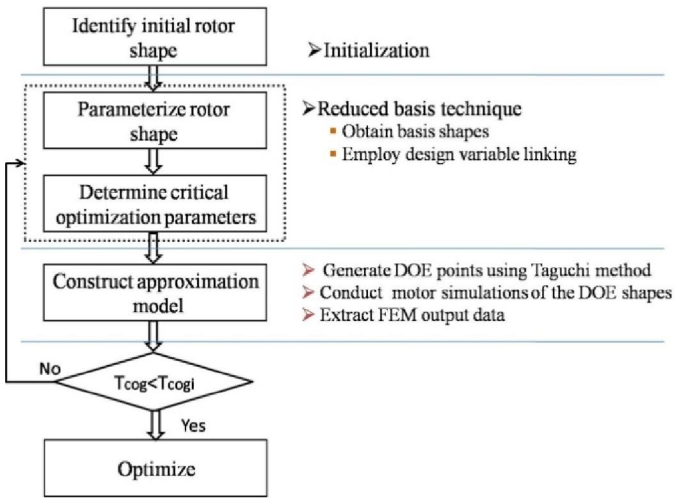


Fig. 2. Flowchart of design optimization process

2.2 SHAPE PARAMETERIZATION

The second step is to define design parameters. Based on geometrical nature of the motor (see fig. 3), it is enough to consider one pole piece. Since the rotation of rotor is bidirectional, the rotor pole shape should be symmetrical; therefore, only one half rotor pole shape is defined. The geometrical features of basis shapes can be defined in polar system in which, a point called the centre point is considered at centre of the rotor and many radial lines that have the same angle from each other ($\theta_1 = \theta_2 = \ldots = \theta_n$) meet the boundary of basis shape. The radial co-ordinates ($r_1, r_2, \ldots, r_n$) of these boundary points define the basis vector (R).

$$R = \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_n \end{bmatrix} \tag{1}$$

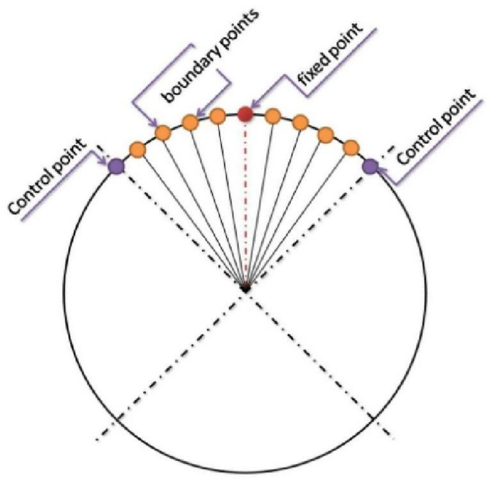


Fig. 3. Basis vector definition

2.3 OBJECTIVES AND CONSTRAINS

The objective function in this research is to minimize cogging torque value. Since this value is not constant respect to rotation angle of rotor, pack to peak value is considered as cost function. Also, during simulation of motor, it is assumed that energy error of the system be lower than 0.2%.

Based on problem geometry and characteristics, geometrical constraints can be defined for ease of solution. As shown in Fig. 3, the rotor shape has three control points. One of them assumed to be fixed and the other two points, have symmetry respect to the fixed point, therefore, only one point is considered in computations.

2.4 REDUCED BASIS TECHNIQUE

In this paper, a rotor pole shape optimization method to reduce cogging torque, in IPM motors is investigated by using the reduced basis technique. The primary objective of the method is to reduce the enormous number of design variables required to define the rotor pole shape. The reduced basis technique is a weighted combination of several basis shapes. The aim of the method is to find the best combination using the weights for each rotor pole shape as the design variables. A multi-level design process is developed to find suitable basis shapes or trial shapes at each level that can be used in the reduced basis technique. Each level is treated as a separated optimization problem until the required objectives – minimum cogging torque– is achieved. The process is started with geometrically simple basis shapes that are defined by their shape co-ordinates.

2.5 BASIS VECTOR CONSTRUCTION

This step of optimization procedure it is to select appropriate basis shapes. Fig. 4 shows three basis shapes assumed as different spline curves in this process. Spline curves are smooth, empirical and can be manufactured by CNC machines. For all cases, the fixed point is on $(r,\theta)=(37mm,0^{\circ})$ and co-ordinates of second point for Basis 1, Basis 2, and Basis 3 are $(36mm,45^{\circ})$, $(35mm,45^{\circ})$, and $(34mm,45^{\circ})$, respectively. Each basis shapes is defined by one radial boundary point and basis vectors of each basis shape, R1,R2 and R3, is constructed.

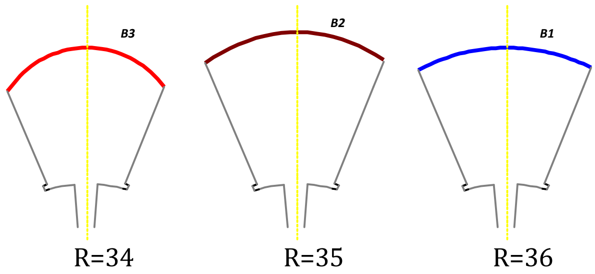


Fig. 4. The selected Basis shapes

2.6 FINITE ELEMENT ANALYSIS

This step is to perform 2-D FEA simulations of the basis shapes to find the cogging torque for preliminary analysis as shown in Fig. 5. The peak to peak cogging torque value of the basis shapes are 0.084585, 0.096331, and 0.098793 (N.m), respectively.

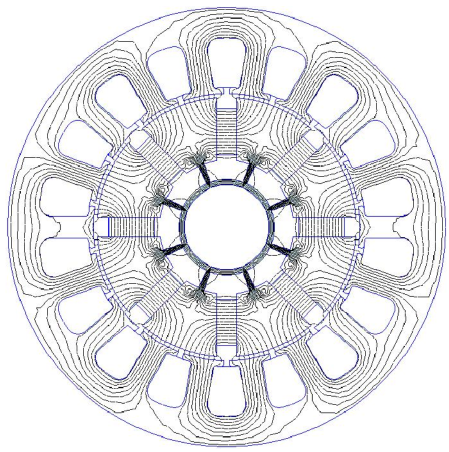


Fig. 5. Finite element analysis of the model

- Design variable linking

These basis vectors is combined with the weighting factors, w_1, w_2, and w_3 that correspond to each basis vector based on the following equation

$$R=\frac{\sum_{i=1}^{n} w_i R^i}{\sum_{i=1}^{n} w_i} \quad (1)$$

where, $0\le w_i \le 1$, and n is number of radial boundary points.

If the number of shape variables required to define a basis shape is $m=30$, then by applying the reduced basis method, the number of design variables is decreased from $m=30$ to $n=3$ (equal to the number of weighing factors). By changing these weights, it is possible to obtain various resultant rotor pole shapes for the optimizer to find the best combination of these weights.

From the preliminary analysis, it can be said that the Basis 1 is more successful than the other two shapes in reducing the cogging torque. Therefore, the contribution of Basis 1 must be more than the other basis shapes, which must be recognized by the optimizer.

2.7 SURROGATE MODEL CONSTRUCTION

The experimental design of Taguchi method [8] is used to build the approximation model and to perform optimization. This methodology, in which several independent variables (here, weighting factors) influence on a dependent variable (here, cogging torque), is the combination of mathematical and statistical techniques used in the empirical study of relationships and optimization. The goal of Taguchi method is to secure an optimal combination. Having performed the analysis of results, the predicted optimum result must be verified through carrying out experiments at optimum combination of factors. If the result of optimum experiment is within the permissible limit, the predicted result will be verified and otherwise, the DOE experiments must be redesigned.

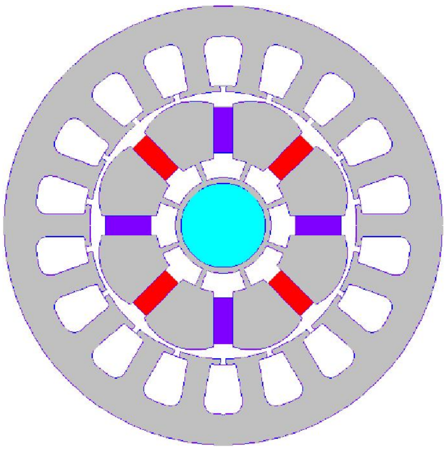
9 DOE points are generated to conduct simulation. Simulations are conducted at these DOE points to find the cogging torque and to build the Taguchi models for optimization. Optimization is performed in QualiTek-4 software to minimize the cogging torque. Weight factors and Levels are listed in table 2. The optimum weights are 0.9, 0.7, and 0.6, respectively. The cogging torque of the resultant shape is 0.034741 N.m. It can clearly see that most of the contribution is from Basis 1. There is also a significant contribution from Basis 2. A comparison of peak to peak cogging torque between basis shapes and optimum shape is shown in table 3.

Table 2. Weighting factors and their selected values

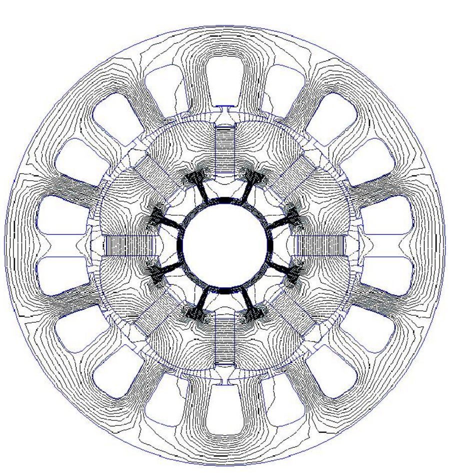
Factor	Level 1	Level 2	Level3
A1	0.8	0.9	0.95
A2	0.5	0.7	0.8
A3	0.4	0.6	0.75

Table 3. A comparison of cogging torque for several curves

Rotor shape	Cogging Torque
Initial	0.138486
Spline-1	0.084585
Spline-2	0.096331
Spline-3	0.098793
Optimum	0.034741



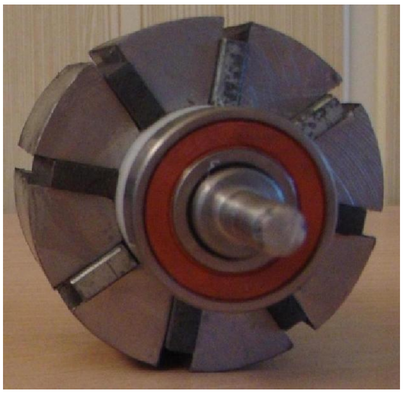
(a)



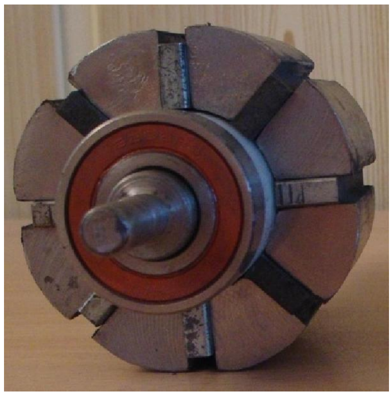
(b)

Fig. 6. Optimum resultant shape, (a) geometrical model, (b) finite element model

The geometrical and finite element model of the optimal rotor is shown in Fig. 7. Fig. 8 shows two fabricated rotor which are based on the initial and optimal shapes. The history of cogging torque reduction is experiments and is compared in Fig. 9.



(a)



(b)

Fig. 7. The fabricated motors, (a) initial design, (b) optimized design

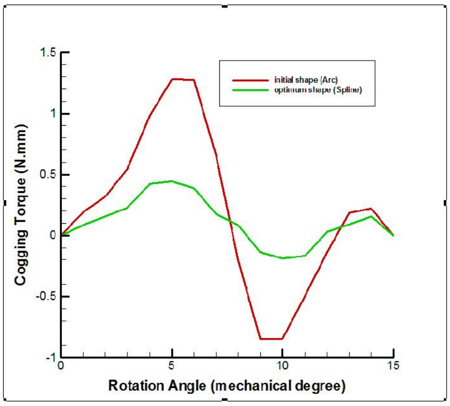


Fig. 8. History of cogging torque reduction

3 CONCLUSION

A two-dimensional rotor pole shape optimization method for a permanent magnet motor is introduced in this paper using the reduced basis technique. This design technique can be used for iron pole shape optimization. The concept of a multi-level design process is introduced, which aids the designer in the selection of practical basis shapes that will give cogging torque reduction, but this will also increase the number of FEA simulations. It is important to mention that if expert knowledge is available, then practical basis shapes can be selected and the optimum rotor pole shape can be obtained in a single level. Increasing the number of basis shapes also enables the designer to obtain a better rotor pole shape, but the computation time also increases to build an approximation model. The reduced basis method aids in the use of the ANOVA models for optimization. Most rotor pole shapes obtained by this method are practical. However, if the motor geometry is complicated, it is prudent to start from very simple starting shapes. The developed algorithm has been applied on a 8poles-18slots PM motor, as a case study. An optimum rotor pole shape has been achieved by the implemented algorithms, starting from three basis shapes (splines). The cogging torque has been reduced significantly (from 0.138486 to 0.034741 N.m) by this optimization method after 10 iterations.

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REFERENCES

[1] B. Y. Yang, K. Y. Yun, and B. I. Kwon, “Designing method of flux barriers in rotor for reducing cogging torque,” in *COMPUMAG2005*, Shenyang, China, June 2005, IV-26, PG1-7.

[2] D. H. Kim, I. H. Park, J. H. Lee, and C. E. Kim, “Optimal shape design of iron core to reduce cogging torque of IPM motor,” *IEEE Trans. Magn*., vol. 39, no. 3, pp. 1456–1459, May 2003.

[3] T. U. Jung and H. Nam, “Rotor design to improve starting performance of line-start synchronous reluctance motor,” *J. Elect. Eng. Technol*., vol. 1, no. 3, Sep. 2006.

[4] Jang-Sung Chun,Hyun-Kyo Jung, and Joong-Suk Yoon, “Shape optimization of closed slot type permanent magnet motors for cogging torque reduction using evolution strategy,” *IEEE Transactions On Magnetics*, vol. 33, no. 2, Mar 1997.

[5] Kyu-Yun Hwang, Sang-Bong Rhee, Byoung-Yull Yang, and Byung-Il Kwon, “Rotor Pole Design in Spoke-Type Brushless DC Motor by Response Surface Method, ” *IEEE Transactions on Magnetics*, vol. 35, no. 3, May 1999.

[6] Joon-Ho Lee, Dong-Hun Kim, and Il-Han Park “Minimization of Higher Back-EMF Harmonics in Permanent Magnet Motor Using Shape Design Sensitivity With B-Spline Parameterization ,” *IEEE Transaction on Magnetics*, vol. 39, no. 3, May 2003.

[7] N. Thiyagarajan, and R. V. Grandhi, “Multi-level design process for 3-D preform shape optimization in metal forming,” *Journal of Material Processing Technology*, 170 (2005) 421-429.