A Noble Method for Minimization of Cogging Torque and Torque Ripple for Interior Permanent Magnet Synchronous Motor

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***Abstract*— In the paper, a novel method for minimizing cogging torque and torque ripple of interior permanent magnet synchronous motor (IPMSM) is proposed and its effective calculation method of torque distortion is also suggested by using finite element method. Asymmetric barrier in a permanent magnet rotor is designed without permanent magnet skew by adopting optimal design, which has simple manufacturing process. The proposed method is compared with general skew method by calculating torque characteristics in order to verify the effective minimizing method for decreasing torque distortion.**

***Index Terms*— Permanent magnet motors, Minimization, Torque, Finite element methods**

I. INTRODUCTION

Interior permanent magnet synchronous motor (IPMSM) is effective to maximize torque density owing to reluctance torque as well as magnetic torque because of its salient structure of permanent magnet rotor. However, torque distortion such as torque ripple and cogging torque would be generated with ease due to its saliency. Therefore, it is difficult to use IPMSM in an application to servo system in which noise and vibration due to torque distortion are critical problem.

In order to decrease torque distortion, it is general to adopt magnet skew in a rotor by analyzing appropriate skew angle. However, it has a disadvantage of decreasing average torque as well as torque distortion. In order to complement this drawback, many studies have been done for reducing torque ripple [1], [2].

In the paper, a novel method for minimizing cogging torque and torque ripple of IPMSM is proposed and its effective calculation method of torque distortion is also suggested by using finite element method. Asymmetric barrier in a permanent magnet rotor is designed without permanent magnet skew by adopting optimal design, which has simple manufacturing process. The proposed method is compared with general skew method by calculating torque characteristics in order to verify the effective minimizing method for decreasing torque distortion.

II. ANALYTICAL METHOD FOR TORQUE RIPPLE

Average torque of IPMSM can be calculated by (1) considering reluctance torque and magnetic torque. In case of torque ripple, it can be calculated by (2) considering variation of inductances and linkage flux according to rotor position in addition to cogging torque [3].

$$T = 1.5p[\psi_m I_q - (L_q - L_d) I_d I_q] \quad (1)$$

$$T = 1.5p[\Delta\psi_m(\theta) I_q - \Delta L_{qd}(\theta) I_d I_q] + T_{cogging}(\theta) \quad (2)$$

Torque ripple is influenced by cogging torque and cogging torque is generated by angular rate of accumulated energy in airgap by (3) [4], [5]. Accumulated energy can be calculated by using inductance in (4) as well.

$$T_{Cogging}(\theta) = -\frac{\partial W(\theta)}{\partial \theta} \quad (3)$$

$$W = \frac{1}{2} L I^2 \quad (4)$$

The analytical method for torque ripple and cogging torque is effective to analyze the parameters related to torque distortion. However, it is difficult to adapt it to minimizing torque distortion according to rotor shape such as barriers and permanent magnets.

III. PROPOSED CONCEPT FOR MINIMIZING TORQUE DISTORTION

Fig. 1 shows the base IPMSM model for the analysis. In order to decrease cogging torque and torque ripple, the IPMSM model with asymmetry barriers instead of skewing in permanent magnet is proposed as shown in Fig. 2. In axial direction, there exist two parts of lamination stack. First is the asymmetry model in Fig. 2 (a) and second is the asymmetry model in Fig. 2 (b) which is just overturning model of Fig. 2 (a) without magnet skew.

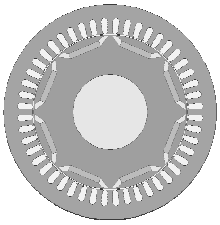
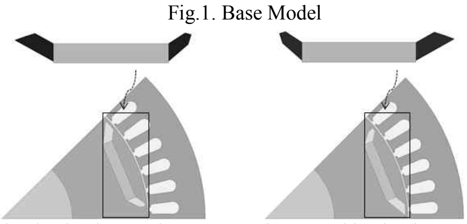


Fig.1. Base Model



(a) First lamination stack part (b) Second lamination stack part

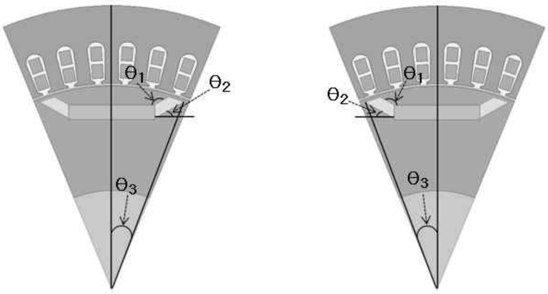
Fig.2. Proposed lamination stack in axial direction in order to decrease torque distortion.

In order to minimize the torque distortion, Taguchi method is used with three design parameters related to asymmetric barrier shape as shown in Table I.

TABLE I

THREE DESIGN PARAMETERS FOR OPTIMAL DESIGN

Variable	Level
θ1	147 °, 149 °, 151 °
θ2	38 °, 41 °, 44 °
θ3	17 °, 17.5 °, 18 °



(a) Asymmetric Barrier 1 (b) Asymmetry Barrier 2

Fig.4. Design parameters for the optimal design

The ratio of torque ripple to average torque is 16.26% in case of base model as shown in Fig. 1 without magnet skew. However, it can be decreased around 5% by adopting proposed asymmetric barrier. Table II shows the analysis results for the minimization of torque ripple by Taguchi method. Among the result, model_8 has the lowest torque ripple as 4.51%.

TABLE II

ANALYSIS OF TORQUE RIPPLE ACCORDING TO EACH PARAMETER

Model	Theta1	Theta2	Theta3	Ripple [%]
Model_1	147 °	38 °	17 °	5.88
Model_2	147 °	41 °	17.5 °	4.58
Model_3	147 °	44 °	18 °	5.79
Model_4	149 °	38 °	17.5 °	5.20
Model_5	149 °	41 °	18 °	6.88
Model_6	149 °	44 °	17 °	5.11
Model_7	151 °	38 °	18 °	7.60
Model_8	151 °	41 °	17 °	4.51
Model_9	151 °	44 °	17.5 °	5.62

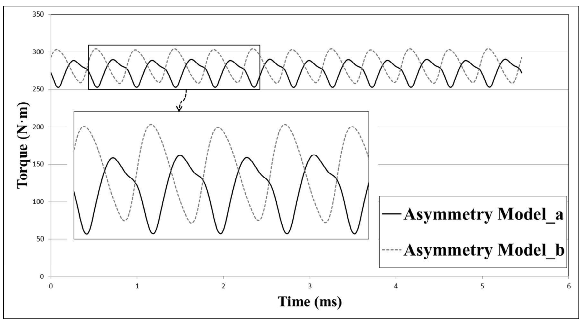


Fig. 4 Torque of each Asymmetry Barrier Model_8

In case of model_8, two kinds of torque waveforms of asymmetric barrier 1 and asymmetric barrier 2 can be calculated by using FEM as shown in Fig. 4. Because two waveforms have phase difference, torque ripple can be minimized effectively when superposing two waveforms. Fig. 5 shows the comparison results of torque characteristic between base model and optimized model.

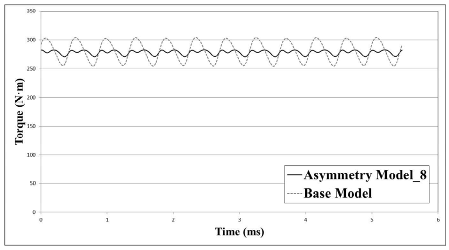


Fig.5. Comparison Result for Torque Ripple

IV. TORQUE RIPPLE CHARACTERISTIC AT FIELD WEAKENING CONTROL REGION

The field weakening control is generally used to increase operation region of IPMSM. It controls current amplitude and current angle which can change armature reaction. If motor speed is increased, torque ripple is also increased due to intensive armature reaction. In this paper, in case of proposed model of asymmetry barrier in a rotor, torque ripple can be decreased by optimal design of asymmetry barrier structure. Fig. 6 shows comparison result of torque ripple characteristic in a field weakening area according to current angle

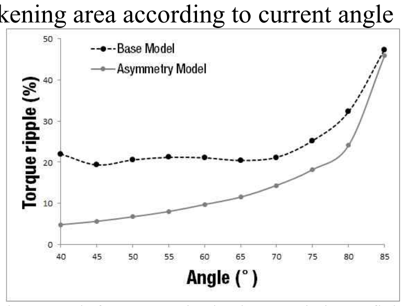


Fig.6. Comparison result for torque ripple characteristics at field weakening area.

V. CONCLUSION

In this paper, a novel method for torque ripple minimization is proposed without magnet skew. By using Taguchi method for the optimal design with shape parameters related to barriers, torque ripple can be decreased three times effectively. Moreover, it can decrease torque ripple in a field weakening area.

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