A New Approach for Magnetic Arc Optimization to Reduce Cogging Torque in Surface Mounted Permanent Magnet Motors

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***Abstract* — This paper presents a new algorithm to optimize the pole arc width in surface mounted permanent magnet (SPM) motors in order to minimize its cogging torque. The cogging torque of SPM is derived from its single-slot torque waveform as a function of its rotor position using finite element analysis (FEA) and the initial design of its pole arc width. The resultant torque due to two adjacent slots is obtained by synthesizing the torque waveforms of two shifted single slots. With this approach, the synthesized cogging torque can be minimized by changing the inter-pole angle. Consequently, it is unnecessary to run the time-consuming FEA in each step of the optimization process, and the computation time can thus be reduced significantly. Two examples are presented to illustrate the application of the proposed approach.**

I. INTRODUCTION

Cogging torque is produced by the interaction of the ends of the magnetic poles with the stator or rotor slots in surface mounted permanent magnet (SPM) motors [1]-[2]. It causes vibration and noise, and hence should be minimized as early as in the design stage. Numerous methods to reduce the cogging torque have been proposed [2]-[6]. Skewing either the slots or the magnets generally yields good results [2]-[5]. The use of a fractional number of slots per pole [6], optimizing the pole arc [2]-[4], and using pole shifting [2] may also reduce the cogging torque significantly.

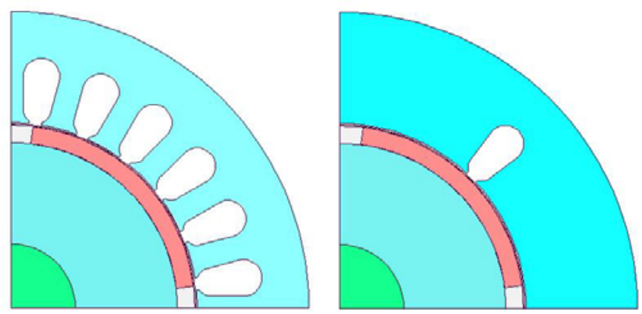
This paper presents a novel method to optimize the pole arc width in order to minimize the cogging torque, which is synthesized from the single-slot torque waveform in SPM motors. Based on the initial, i.e. pre-optimal, design of the pole arc width, the cogging torque waveform of a single-slot of the SPM motor is computed as a function of rotor position using finite element analysis (FEA). The torque due to two adjacent slots can be obtained by synthesizing the torque waveforms of two shifted single slots. The resultant cogging torque due to two slots can be minimized by changing the inter-pole angle. With this new approach, it is unnecessary to run FEA in each step of the optimization process, and the computation time can be reduced significantly.

II. SINGLE-SLOT TORQUE WAVEFORM

The cogging torque contributed by all slots inside a SPM motor can be synthesized from the torque waveforms of individual single slot [7]. A 4-pole, 24-slot synchronous PM motor is taken as the illustrating example in this paper. The main design parameters of the motor are listed in Table I. Fig. 1 shows the one-pole geometry of the motor.

TABLE I
MAIN PARAMETERS OF THE 4-POLE, 24-SLOT SYNCHRONOUS PM MOTOR

Parameters	Values	Units
Pole number (p)	4	-
Slot number (n_s)	24	-
Slot opening width (w_{so})	2.5	mm
Stator inner diameter (d_s)	37.5	mm
Rotor PM outer diameter (d_m)	37	mm
Rotor core outer diameter (d_r)	33.5	mm
Stack length (l_s)	65	mm
Magnetic coercivity	727	kA/m
Relative recoil permeability	1.0	-



(a) (b)

Fig. 1. One-pole geometry of the 4-pole, 24-slot synchronous PM motor: (a) with all slots; (b) with one slot per pole.

The initial design of the rotor pole arc is to assume the inter-pole angle θ_{inp}, that is the angle of the space between two adjacent permanent magnets, to be the same as the slot-pitch angle θ_s = 360°/24 = 15°. For the single-slot geometry as shown in Fig. 1(b), the FEA computed cogging torque waveform is shown in Fig. 2, where the angle between the positive peak and the negative peak, or the peak-to-peak angle θ_{pp}, is 16.5°.

The FEA results in Fig. 3 show that when the inter-pole angle is greater than half of the slot-opening angle, which is

$$\theta_o = \arcsin(w_{so} / d_s) = 1.9° \quad (1)$$

the peak-to-peak angle is a linear function of the rotor inter-pole angle, and can be expressed as

$$\theta_{pp} = \theta_{inp} + \theta_d \quad (2)$$

where the angular difference θ_d = 1.5° is a constant and can be determined from the results in Fig. 2.

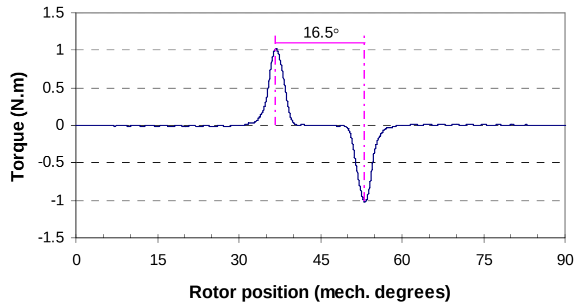


Fig. 2. Cogging torque waveform with single-slot effects computed from FEA (the peak-to-peak angle is 16.5° at the inter-pole angle of 15°).

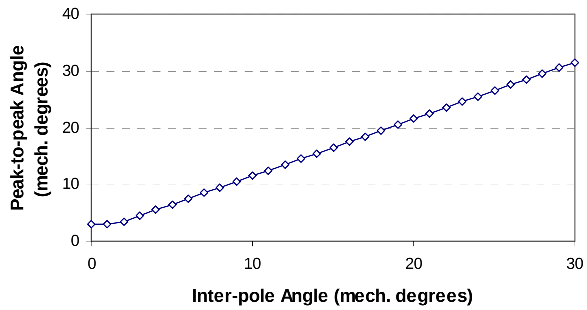


Fig. 3. Peak-to-peak angle of the single-slot cogging torque waveform which is computed from FEA and expressed as a function of rotor inter-pole angle.

III. COGGING TORQUE SYNTHESIS AND MINIMIZATION

It can be seen from Fig. 2 that when the slot-pitch angle is equal to the peak-to-peak angle, that is $\theta_{pp} = \theta_s$, the negative torque peak of a slot will cancel out the positive torque peak of the adjacent slot. Fig. 4 shows the synthesized torque peak due to two adjacent slots can indeed be reduced significantly if the adjacent slots are shifted intelligently. An estimated optimal design of the inter-pole angle is found from

$$\theta_{inp} = \theta_s - \theta_d = 13.5° . \quad (3)$$

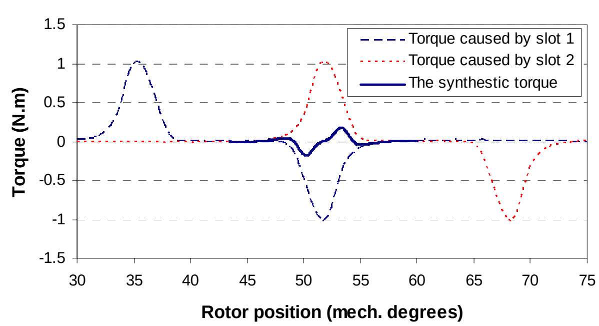


Fig. 4. Cogging torque synthesized from two adjacent single-slot torque waveforms when the slot-pitch angle is 16.5° and inter-pole angle is 15°.

Since the single-slot torque curve is not evenly symmetrical about the axis at a peak, the two adjacent single-slot torque curves will not be completely cancelled within the region of one slot-pitch. Small adjustment of the inter-pole angle may reduce the peak value of the synthesized cogging torque further. Therefore, an accurate optimal design of the inter-pole angle must be searched in order to minimize the synthesized cogging torque, as shown in Fig. 5, where the synthesized torque peak is compared with the FEA results. For both curves in Fig. 5, the optimal design of the inter-pole angle is 13.75°.

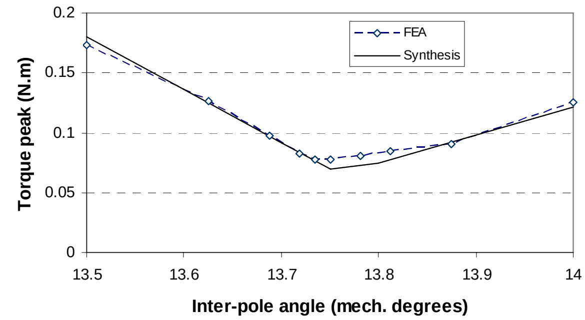


Fig. 5. Cogging torque peak as a function of inter-pole angle at the desired slot-pitch angle, compared with the FEA results at the Pattern Search points.

TABLE II
FEA COMPUTED COGGING TORQUES OF DIFFERENT DESIGNS

Designs	Inter-pole angle (°)	Pole arc to pole pitch ratio	Cogging torque peak (N.m)
Searched optimal design	13.75	0.847	0.077
Estimated optimal design by (3)	13.5	0.85	0.175
Analytical optimal design in [4]	15	0.833	0.375

The FEA computed cogging torque of the searched optimal design is 0.077 Nm, and that of the estimated optimal design by (3) is 0.175 Nm. This is compared to the analytical optimal design of 0.375 Nm presented in [4] and given in Table II.

In the full paper, more application examples will be provided, and the optimal designs obtained from the proposed approach will be compared with those obtained by the Pattern Search algorithm.

IV. REFERENCES

[1] T. M. Jahns and W. L. Soong, "Pulsating torque minimization techniques for permanent magnet ac motor drives – a review," *IEEE Trans. Ind. Electron.*, vol. 43, no. 2, pp. 321–330, Apr. 1996.

[2] T. Li and G. Slemon, "Reduction of cogging torque in permanent magnet motors," *IEEE Trans. Magn.*, vol. 24, no. 6, pp. 2901-2903, Nov. 1988.

[3] Z. Q. Zhu and D. Howe, "Influence of design parameters on cogging torque in permanent magnet machines," *IEEE Trans. Energy Convers.*, vol. 15, no. 4, pp. 407–412, Dec. 2000.

[4] Li Zhu, S. Z. Jiang, Z. Q. Zhu, and C. C. Chan, "Analytical method for minimizing cogging torque in permanent magnet machines," *IEEE Trans. Magn.*, vol. 45, no. 4, pp. 2023-2031, Apr. 2009.

[5] R. Islam, A. Fardoun, and K. McLaughlin, "Permanent-magnet synchronous motor magnet designs with skewing for torque ripple and cogging torque reduction," *IEEE Trans. Ind. Appl.*, vol. 45, no. 1, pp. 152–160, Jan./Feb. 2009.

[6] C. C. Hwang, S. B. John, and S. S. Wu, "Reduction of cogging torque in spindle motors for CD-ROM drive," *IEEE Trans. Magn.*, vol. 34, no. 2, pp. 468–470, Mar. 1998.

[7] Z. Q. Zhu, S. Ruangsinchaiwanich, and D. Howe, "Synthesis of cogging-torque waveform from analysis of a single stator slot," *IEEE Trans. Ind. Appl.*, vol. 42, no. 3, pp. 650–657, May/Jun. 2006.