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# Design Strategy of Interior Permanent Magnet Synchronous Motor for Electrical Power Steering Considering Cogging Torque and Torque Ripple using Current Harmonics

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**This paper presents the design strategy of interior permanent magnet synchronous motor for electrical power steering considering cogging torque and torque ripple reduction using geometrical optimal design and current harmonics. Cogging torque and torque ripple reduction are important design factors of electrical power steering due to driving comforts. In order to reduce cogging torque and torque ripple, optimization of motor geometry is generally adopted with the design parameters of pole angle, slot opening, notch, etc. However, it is shown that optimal geometry design for both of minimum cogging torque and torque ripple does not exist in the presented design. In order to minimize both cogging torque and torque ripple, design parameters minimizing cogging torque is firstly determined. Then, torque ripple is reduced by harmonic current. Therefore, minimization of both cogging torque and torque ripple are achieved.**

***Index Terms*— Permanent magnet motors, torque ripple, cogging torque**

## I. INTRODUCTION

Interior permanent magnet synchronous motors have higher torque density per volume than induction motor and reluctance motor with wide operating speed range with the help of field weakening control. Therefore, it is widely applied from small power to large power such as traction motor for electrical vehicles. In addition, manufacturing can be simplified comparing to surface mounted permanent magnet motor due to non-existence of sleeve.

For the application of electrical power steering (EPS), high power density, low torque ripple, and low cogging torque are required [1]. In order to reduce cogging torque and torque ripple, various design topologies can be chosen. Adoption of fractional pole/slot combination or optimal geometry design can be regarded. Fractional pole/slot combination provides low cogging torque and torque ripple, meanwhile unbalanced radial forces in air gap leads to high vibration and noise. For optimal shape design of magnetic circuit, large computation time and efforts are still required even with high performance computer system. Because many motor geometry parameters closely related to torque ripple and cogging torque [2]~[5].

In addition, reduction of cogging torque and torque ripple simultaneously with shape optimization is difficult because minimum cogging torque design does not guarantee minimum torque ripple and vice versa. Therefore, there should be compromise between cogging torque reduction and torque ripple reduction design. In addition, sometimes other motor characteristics should be sacrificed to satisfy cogging torque and torque ripple since both are the main constraints for comfortable driving.

On the other hand, output torque ripple can be reduced by control strategy using voltage or harmonic current [6]~[8]. There are many researches dealing with torque ripple reduction of permanent magnet brushless DC motor [5]~[8]. However few researches conducted for the permanent magnet synchronous motor(PMSM) [9], this is because PMSM generally gives smooth torque due to sinusoidal back emf and input current. However, recent development of electrical machine requires higher performances. In this paper, current harmonics are used for reduction of torque ripple, and design strategy for both cogging torque and torque ripple minimization using geometrical optimization to reduce cogging torque and current harmonic injection is presented.

Pervious research on the torque ripple reduction using harmonic current injection [9] adopts flux linkages for harmonic current calculation and iteration processes is required. Therefore, improvement of torque ripple reduction is not significant. On the other hand, torque waveforms are used for harmonic current calculation in this paper. Therefore, almost 0% of torque ripple can be achieved if enough harmonics are injected. In addition design strategy for EPS motor considering cogging torque and torque ripple minimization.

## II. HARMONIC CURRENT FOR TORQUE RIPPLE REDUCTION

### *A. Harmonic current estimation*

General input current of synchronous motor is assumed to be sinusoidal and corresponding output torque is produced by interaction between magnetic field by permanent magnet and armature current. Due to non-linear characteristics of magnetic material, output torque and torque ripple are not proportional to input current. Therefore, output torque waveforms for various input current are estimated by finite element analysis (FEA) and instantaneous current which provides constant torque are calculated. Calculated current waveforms are composed of various harmonic components, represented by a set of function of input current and harmonic order. Therefore, in ideal case of high response speed of microprocessors, nearly 0% of torque ripple can be achieved. The results of harmonic current are firstly examined by FEA. The main process of estimation of harmonic currents is summarized as follow;

1. Calculation of output torque wave form by FEA for various sinusoidal input currents
2. Instantaneous current for required constant torque are calculated.
3. Harmonic analysis for instantaneous input current
4. Development of function of harmonic current

Fig. 1 shows the torque waveforms respect to input currents. The results are estimated by 2D FEA. In order to calculate current waveform for constant torque, intersections between constant torque line and torque waveforms are identified then corresponding currents are calculated by,

$$i(\theta) = \sqrt{2} \cdot i_{\theta} \cos(\theta) \quad (1)$$

where $i_\theta$ is current value at intersection between constant torque line and input current.

Then, overall current waves for three phase is expressed as,

$$i_a(\theta) = \sum_{n=1}^{\infty} (I_n \cdot \cos(n\theta))$$

$$i_b(\theta) = \sum_{n=1}^{\infty} (I_n \cdot \cos(n\theta - 120^\circ)) \quad (2)$$

$$i_c(\theta) = \sum_{n=1}^{\infty} (I_n \cdot \cos(n\theta - 240^\circ))$$

Practical limitations for consideration of harmonic components exist in equation (2).

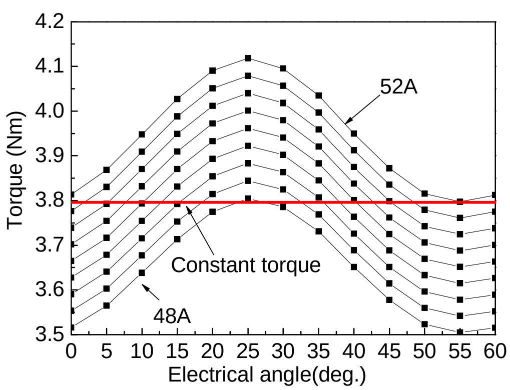


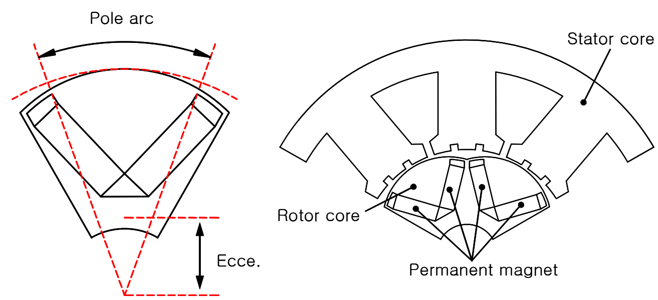

Fig. 1 Current estimation for constant torque

## III. Optimal Design for Cogging Torque Reduction

Table I shows the main specification of analysis model. The model has 6pole and 9slots with concentrated windings. Fig. 2 shows the design variables for optimal design, and motor structure. The IPMSM is chosen and two design variables of pole angle and rotor eccentricity are chosen. Like general IPMSM, permanent magnets are buried in the rotor core. To reduce cogging torque and torque ripple, notch and eccentricity are applied to stator teeth and rotor respectively. In addition, rotor eccentricity provides sinusoidal air gap flux density and back emf. The model is optimized for cogging torque only satisfying output power. Unlike general EPS motor, the developed motor has no skew for research purpose.

TABLE I
Design Specifications of Motor

| Item | Description |
|---|---|
| Motor type | IPMSM |
| Phase number | 3 |
| Pole/slot number | 8/9 |
| Stator OD/rotor OD (mm) | 90/41 |
| Stack length (mm) | 5 |
| Remanent flux density of PM (T) | 1.1 |

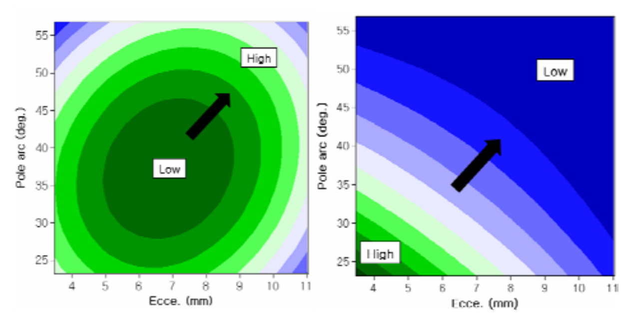



(a) (b)

Fig. 2 (a) design variables, (b) model construction

Fig. 3 shows the effect of design variables on cogging torque and torque ripple. As shown in the figure, it is impossible to find pole arc and eccentricity minimizing both cogging torque and torque ripple.

For minimum cogging torque, pole angle and eccentricity are chosen 37̊ and 7mm respectively, and shown in Fig. 4.




(a) (b)

Fig. 3 Equi-plot of (a) cogging torque and (b) torque ripple.

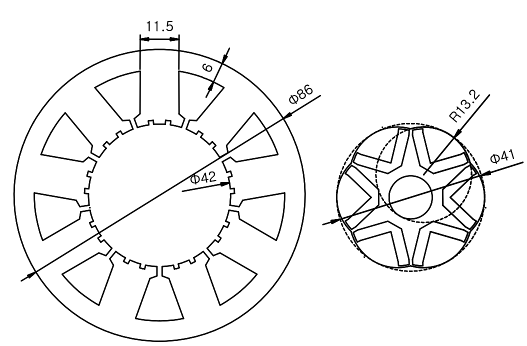



Fig. 4 Stator and rotor

## IV. Design results and motor charcateristics

Fig. 5 shows the flux density distribution at no load condition. 2 dimension FEA is conducted in the magneto-static field. Instead of full modeling, 1/3 model is used for FEA. Fig. 6 shows the cogging torque. Cogging torque is minimized, and torque ripple is not considered significantly in the design.

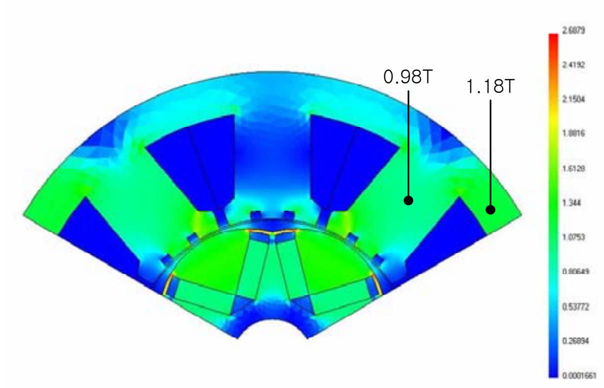



Fig. 5. Flux density distribution at no-loads

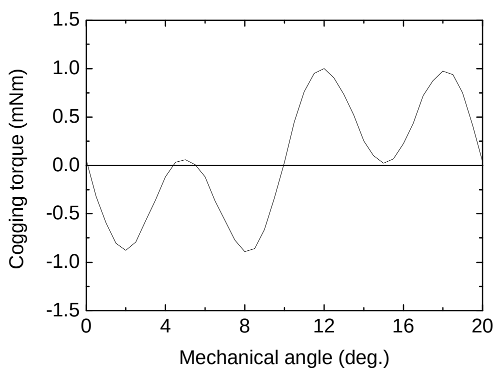



Fig. 6 Cogging torque (FEA)

### B. Harmonic current calculations and torque ripple

In order to calculate current waveform for constant torque, torque waveforms according to input currents are estimated with FEA, and currents for constant torque line respect to angular position is calculated.

Current waveform for constant torque is compared with sinusoidal wave in Fig. 7 and its harmonic components are shown in Fig. 8. Unlike general current controlled synchronous motors, input current is distorted and contains harmonic components are and phase current can be expressed,

$$i(\theta) = 10.4\cos(\theta) + 0.15\cos(5\theta) + 0.14\cos(7\theta) \quad (3)$$

where, only 1$^{st}$ , 5$^{th}$, and 7$^{th}$ harmonics are used for practical reason.

In Fig.9, comparison of output torque waveforms between sinusoidal current drive and harmonic current injection. In the figure, 5% of torque ripple is obtained with sinusoidal current and 0.7 % of torque ripple is obtained with harmonic current injection. The average torque is slightly reduced but the ratio is not significant and it is caused by calculation error of input current. It is expected that if the current step in Fig. 1 is smaller, 0% of torque ripple can be achieved without decrease of average torque.

## V. Verification

Measured line-line back emf at 600rpm and FEA results are shown in Fig. 10. Control block diagram for harmonic current injection is shown in Fig. 11. Harmonic currents are injected at the current sensors with position sensing.

Fig. 12 shows the experimental setup for torque ripple. Torque transducer and powder brake are connected to the motor. Fig. 13 shows the comparison of torque ripple between sinusoidal current input and harmonic current injection. With sinusoidal current input, 3% of torque ripple is obtained and 0.9% of torque ripple is obtained with harmonic current injection. It is interesting that small harmonic components reduce significantly torque ripples. Comparing to FEA results, torque ripples are reduced in the experiments, since FEA is conducted in the magneto-static field, therefore inertia of rotor is not considered which reduces torque ripples when rotating.

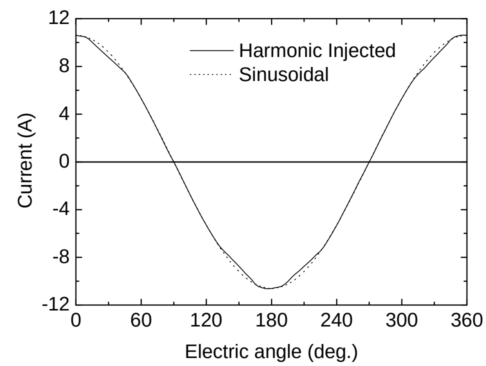



Fig. 7 Current waveform for constant torque

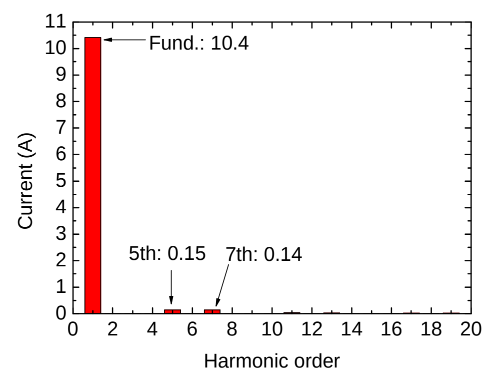



Fig. 8 Harmonic components for constant torque

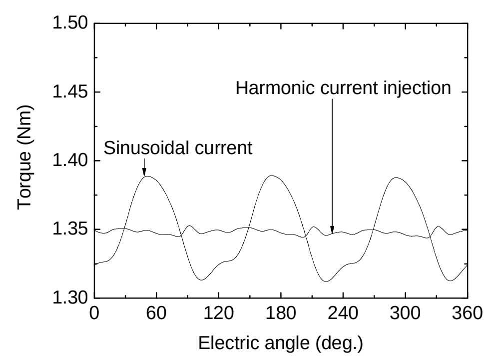



Fig. 9 Comparison of torque ripple

## VI. CONCLUSION

This paper presented the design strategy of IPMSM for EPS to minimize both cogging torque and torque ripple. Cogging torque is minimized by optimal design of motor geometry and torque ripple is minimized by harmonic current and verified by experiments.

It seems that there is practical limitation in injecting high order of current harmonics, however small amplitude of 5th and 7th harmonic gives significant reduction of torque ripple in the studied model. If enough harmonic currents are injected, 0% of torque ripple can be obtained. Obviously practical limitation of high carrier frequency exists. But small harmonic current injection is very effective for torque ripple reduction and can be usefully applied for high torque density with low torque ripple.

In addition, getting torque waveforms according to input currents using 2D FEA is time consuming tasks, however presented method is clearly effective and useful for torque ripple reduction.

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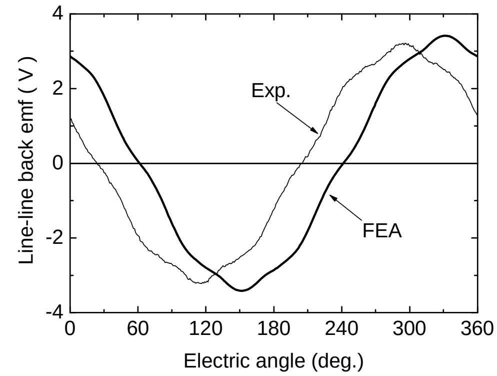

Fig.10 Line-line back emf

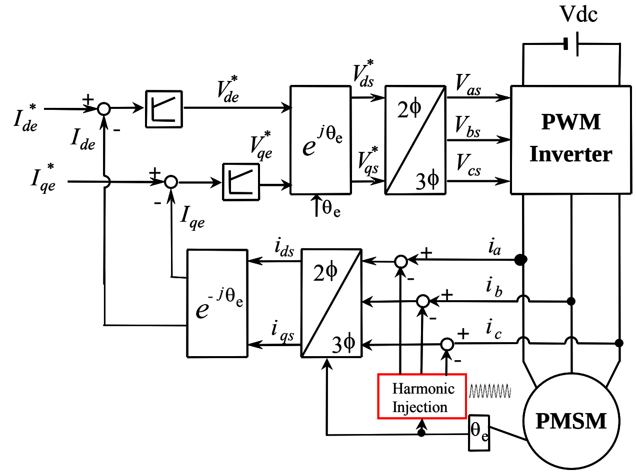

Fig. 11. Control block diagram

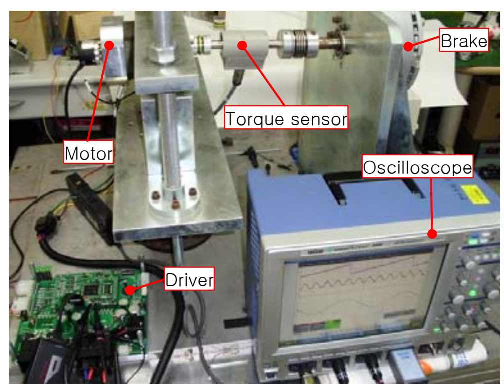

Fig. 12 Test setup

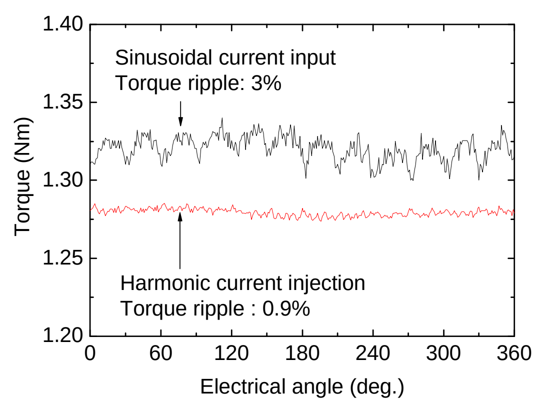

Fig. 13 Comparison of torque ripple