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Torque Ripple Reduction Control of Permanent Magnet Synchronous Motor for Electric Power Steering Using Harmonic Current at Loaded Conditions

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Abstract

This paper deals with the torque ripple reduction of permanent magnet synchronous motor using harmonic current injection. Torque ripple of electric motor reduces system stability and performances, therefore efforts to reduce torque ripple is exerted in the design process. Torque ripple can be reduced by appropriate pole/slot combination, skew of rotor or stator, design of magnetic circuit, etc [1],[2]. In addition, torque ripple can be also by input voltage and current, and many researches have been conducted to reduce torque ripple for six-step drive [3]. Torque ripple reduction controls for sine wave also have been conducted and verified by investigating back emf wave form [4]. Torque ripple reduction in this paper started from getting torque profile according to input current and electrical angle calculated by FEA, then instantaneous current of each electrical angle for constant torque is calculated and applied to experiments. Therefore 0% of torque ripple can be obtained with harmonic current injection. In order to maximize the effect of torque ripple reduction, a brushless dc motor having high harmonic component of back emf is chosen. With sinusoidal current drive, over 100% of torque ripple is obtained initially, then 0.5 % of torque ripple is obtained by FEA. The effect is verified by experiment and the presented method can be effectively applicable to Electric Power Steering (EPS).

Keywords: Electric power steering, permanent magnet synchronous motor (IPMSM), cogging torque, torque ripple

1 Introduction

Permanent magnet synchronous motors (PMSMs) have higher power than other type electric motor such as induction or reluctance motor with wide operating speed range due to flux weakening control. Therefore its application becomes wider. Torque ripple of PMSMs is the source and vibration and noise, and should be reduced in the design stage. Especially, for the EPS system, torque ripple becomes significant.

In the aspect of magnetic circuit design, for the reduction of torque ripple, sinusoidal air gap flux density distribution, fractional pole/slot number, increase of pole and slot number, etc. can be considered. Fractional pole/slot combination provides low torque ripple and cogging torque without optimal design. However, unbalanced flux distribution in the air gap leads to the increased vibration and noise. The increase of pole/slot number has the disadvantage of high manufacturing cost and increase of switching frequency of electronic devices.

In this paper, torque ripple is reduced by harmonic current, and the harmonic current is calculated by FEA. Presented method is verified by experiments. The calculation of harmonic current is shown in Fig. 1.

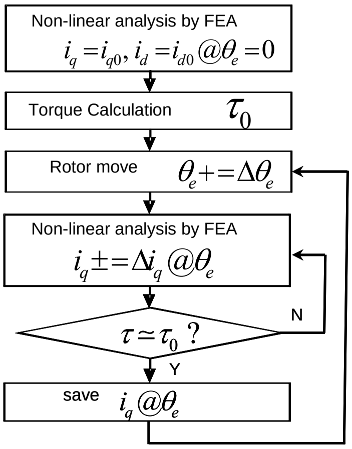

Fig. 1 Harmonic current calculation

2 Model and specification

Table 1 shows the brief information of analysis model for torque ripple reduction. The motor initially designed as brushless dc motor having 120^o flat back emf with high harmonic components.

The Fig. 2 shows the structure of analysis model in this paper. Fig. 3 shows the comparison of the phase back emf at 1500rpm, the FEA result is almost identical to measurements and precise analysis results could be achieved. The motor is general BLDC motor having 120 ^{o} flat top back emf.

Table 1 Specification of analysis motor

Output power (W)	420
Rated torque(Nm)	2.74
Rated current(Arms)	5
Stack length(mm)	40
Series turns per phase	108
Coil diameter (mm)	0.75
Br (T)	1.21
Core material	35PN230

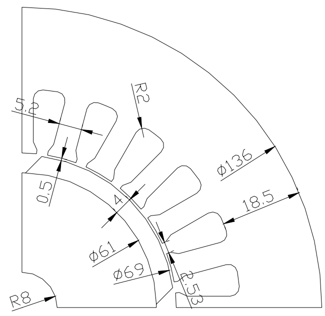

Fig. 2 Analysis model(1/4)

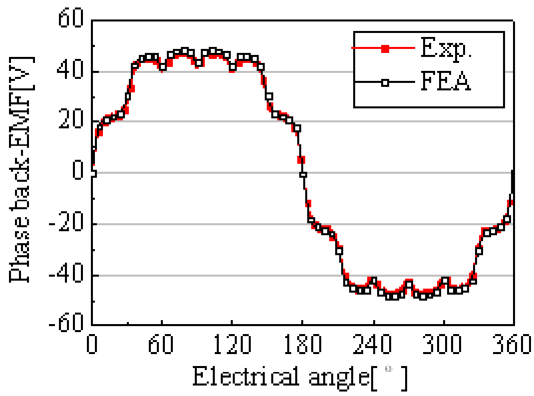

Fig. 3 Phase back emf at 1500rpm,

3 Calculation of harmonic current

Fig. 4. shows the torque wave form according to the rotation angle with various input current. The current vector is maintained to 0 degree with back emf. As the current increased, output torque increased and torque ripple is maintained in this model. When ideal sinusoidal current is applied output torque ripple is about100%. The target is the constant torque line in the figure.

Phase current in for the constant torque line in the Fig. 4 can be calculated as follow.

$$\textit{Harmonic current of a phse} = A(\theta)\cdot\sqrt{2}\cdot\cos(\theta) \quad (1)$$

where, A(θ) is the current identified at theta crossing to constant torque line.

Fig. 5 shows the waveform of input current to get the constant torque in Fig. 4. As shown in the figure, current wave has large harmonic components unlike to general sinusoidal current drive. Fig. 6 shows the harmonic components of current wave form in Fig. 5.

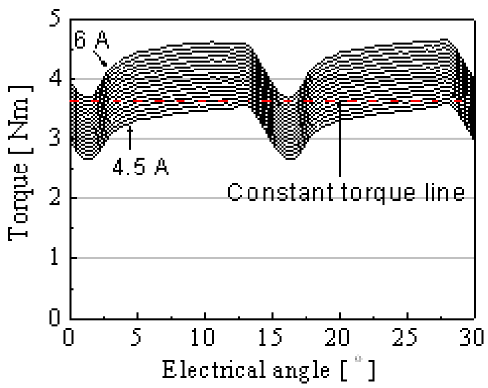

Fig. 4 Torque waveform according to input current and rotor position

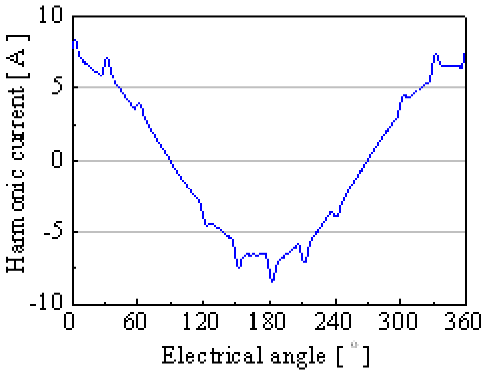

Fig. 5 Input current wave for constant torque in Fig. 3

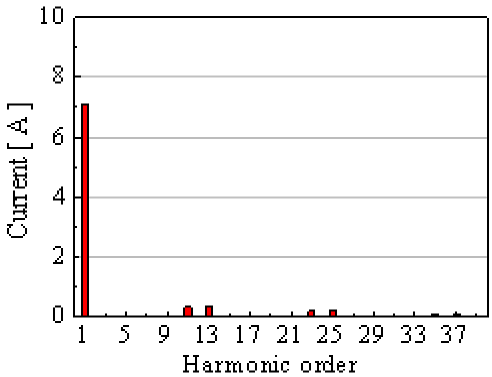

Fig. 6 Harmonic component of input current

4 Experimental verification

4.1 Fixed rotor test

Fig. 5 shows the test setup for torque ripple measurements. Sine torque ripple is identified by FEA in magneto-static field, torque ripple is measured with fixed rotor. By fixing the rotor, corresponding dc current to rotor position is applied. Multiple dc power source is used 3 phase input. Input current for each rotor position is shown Fig. 5(b). The position of rotor is sensed by rotary encoder.

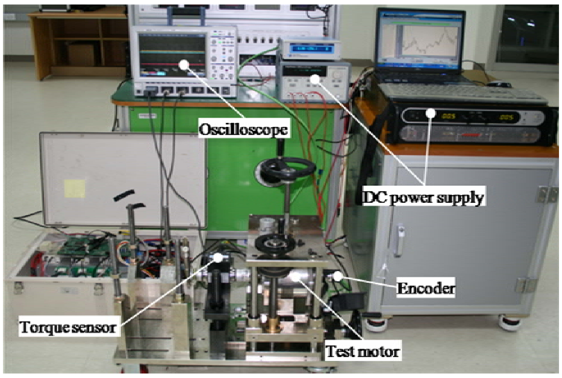

Fig. 7 Test setup for fixed rotor test

Fig. 8 shows the comparison of measured torque and calculated torque by FEA according to the rotor position when sinusoidal current is supplied. Measured torque is close to expected.

Fig. 9 shows the comparison when the harmonic current is injected. Comparing to Fig.8, torque ripple is dramatically reduced and analysis result is close to measurements.

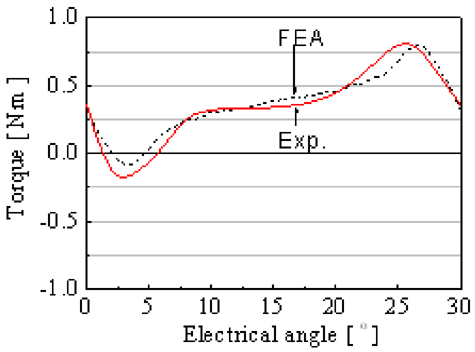

Fig. 8 Torque comparison with sinusoidal current drive

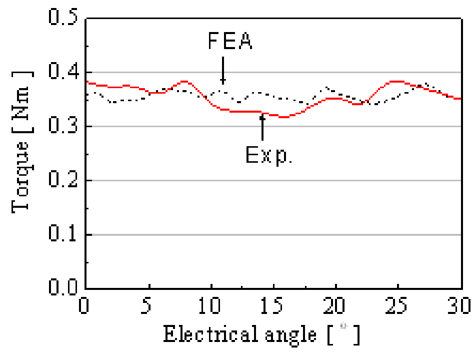

Fig. 9 Torque comparison with harmonic current injection

4.2 Load test

Load test is conducted at500rpm. The test setup is shown in Fig. 10. Constant load torque is provided by controlled DC motor. Fig. 11 shows the control block diagrams.

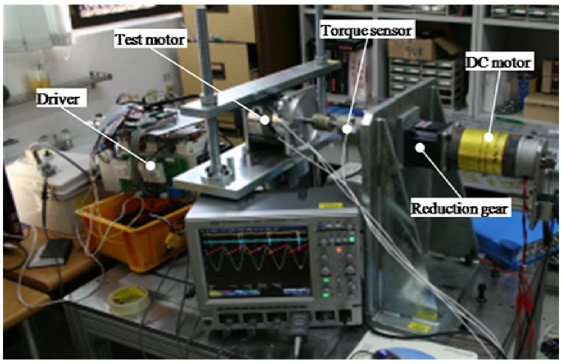

Fig. 10 Test setup for load test

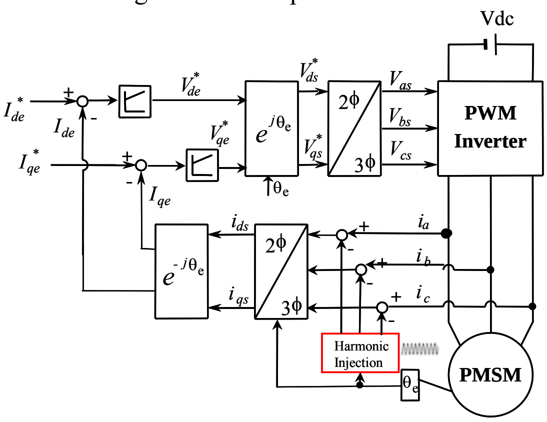

Fig. 11 Block diagram of harmonic current control

Fig. 12 shows the measured output torque wave and FEA result by sinusoidal current and harmonic current injection. In the measurements, torque ripple reduced comparing FEA result due to mechanical inertia.

In Fig. 13 torque wave with harmonic current injection are shown. Comparing to Fig. 12, output torque is slightly reduced by the control method, and torque ripple is effectively reduced.

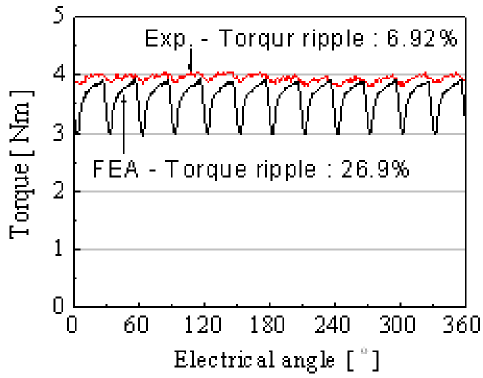

Fig. 12 FEA and test results with sinusoidal current drive

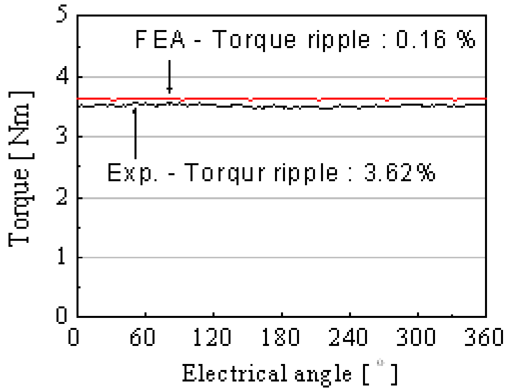

Fig. 13 FEA and test results with harmonic current injection

4.3 Effect of harmonic current

It is proved that appropriate current harmonics can effectively reduce torqur ripple by experiments. Meanwhile harmonic current effects to the required input voltage and losses should be identified. Therefore, the effect of harmonic currents is estimated by FEA. The results are shown in Table 2. As shown in Table 2, by adding harmonic currents, voltage, current, core loss are increased, however, the increase is not significant.

Table 2 Motor characteristics comparison (1500rpm)

	Sine wave drive	Harmonic current injection
Input voltage (Vrms)	103.47	104.45
Input current (Arms)	5.00	5.06
Core loss(W)	5.73	5.87
Copper loss(W)	48.49	49.66

5 Conclusion

In this paper, the torque ripple reduction using harmonic current is presented, and torque ripple close to 0% can be obtained in theory. The presented method is verified by experiments. By applying torque ripple reduction control, other motor characteristics of voltage, current, and loss are increased, however, torque ripple can be effectively reduced and effectively applied to EPS application.

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