Reduction of Torque Ripple Using Harmonic Current Injection in Interior Permanent Magnet Synchronous Motor

Ji-Hyung Bahn*, Sung-Il Kim*, Jung-Pyo Hong* and Geun-Ho Lee**

*Dept of Electrical Eng., Changwon Nat'l Univ, Changwon, Gyeongnam

** Gyeongnam Provincial Namhae Collage, Namhae, Gyeonanam

***Abstract*— Interior Permanent Magnet Synchronous Motor(IPMSM) is now widely used for many industry applications such as hybrid electric vehicle traction motor, air-conditioner compressor motor and home appliances due to its high power density and wide speed range.**

This paper proposes a method to reduce torque ripple for IPMSM. In case of IPMSM d-axis current should be fed to use reluctance torque and the more d-axis current is needed as the motor speed goes up.

In this paper, firstly, dominant harmonic order of back EMF is investigated. Then under the consideration of harmonic order, torque ripple using harmonic current injection will be compared with that of sinusoidal current by Finite Element Analysis(FEA).

***Index Terms*—IPMSM, torque ripple, harmonic current injection, FEA**

I. Introduction

Interior Permanent Magnet Synchronous Motor (IPMSM) has advantage of using not only magnetic torque but reluctance torque which is generated by difference of inductances between d-axis and q-axis. IPMSM is now widely used for many industrial applications such as power train for the hybrid electric vehicle, compressor and home appliances due to its high power density and wide speed range in comparison with Surface Permanent Magnet Synchronous Motor (SPMSM). Especially, there is growing interest in applying concentrated winding IPMSM to industrial application to minimize the production cost and increase the productivity.

However, torque ripple in IPMSM is often a major concern in applications where speed and position accuracy is of great importance. In case of IPMSM, d-axis current should be fed to use reluctance torque and the more d-axis current is needed as the motor speed increase. Therefore, back EMF of IPMSM contains much harmonics; hence, a ripple occurs in the output torque when driven by a sinusoidal current.

In order to minimize cogging torque and harmonics in the induced electromotiveforce (EMF), [1]-[4] introduce structures such as distributed winding and skewed rotor, which result in increased production cost and loss in productivity and power density.

This work was supported by grant no.RTI04-01-03 from the regional technology innovation program of ministry of commerce, Industry and energy (MOCIE).

The solution to the torque ripple is being examined in terms of the control current waveform. With such an approach, torque ripple is compensated by means of specific current waveforms using Fourier series or torque observers [5-6].

On the other hand, some current control methods are introduced to reduce torque ripple using modified current such as deadbeat current control [7], and repetitive control technique [8].

The aim of this paper is to reduce torque ripple with harmonic injection current. Firstly dominant harmonic order of back EMF is investigated, then under the consideration of distorted back EMF, torque ripple using harmonic current injection is compared with that of sinusoidal current by Finite Element Analysis (FEA).

II. Analysis Model and Theory

A. Basic equation

Fig.1 shows the vector diagram the IPMSM and the voltage equation in the steady state is expressed in d-q coordinates as follow [9];

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_a + pL_d & -\omega L_q \\ \omega L_d & R_a + pL_q \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \omega \begin{bmatrix} 0 \\ \psi_a \end{bmatrix} \quad (1)$$

and torque equation is given by

$$\begin{aligned} T &= P_n \left\{ \psi_a i_q + \left(L_d - L_q\right) i_d i_q \right\} \\ &= P_n \left\{ \psi_a i_a \cos\beta + \frac{1}{2}\left(L_q - L_d\right) i_a^2 \sin 2\beta \right\} \\ &= T_m + T_r \end{aligned} \quad (2)$$

where id, iq: d, q components of armature current; vd, vq: d, q component of armature voltage; Ψa: linkage flux due to permanent magnet; Ld, Lq: inductance along d, q axes: p=d/dt; Pn: number of pole pairs; ρ =Lq/Ld: saliency ratio β: lead angle of current vector from q axis; Ia: armature current in d-q coordinates.

The first term of right side in torque equation is the magnetic torque which is generated by armature current and permanent magnet and second term is reluctance torque component which is generated by the difference of inductances between d-q axes.

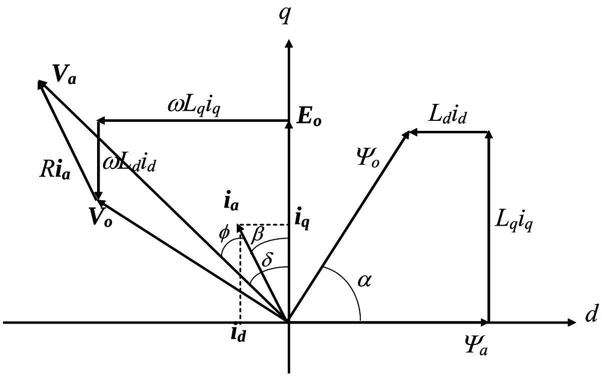


Fig. 1. Vector diagram of IPMSM

B. Analysis model

Fig. 2 shows the configuration of the IPMSM with concentrated winding. The maximum output torque of the model is 280 N·m at 680rpm. Base speed is 680rpm and Constant Power Speed Range (CPSR) is from 680rpm to 3400rpm. The detailed specification of the analysis model is listed in Table I.

C. Torque ripple

Fig.3 (a) and (b) indicate generated torque of the analysis model by a sinusoidal current at the base speed and the maximum speed, respectively. At the base speed, the torque is obtained when current is 68Arms and β is 48°. And maximum speed torque is calculated by 65 Arms when β is 81°. Each result is obtained by 2D-FEA.

As shown in Fig. 3, average torque is 272.6 N·m and torque ripple is 7.8 % at the base speed but at the same time average torque at the maximum speed is 61.6 N·m and torque ripple is 84.6 %. Torque ripple at base speed is not a significant concern. However, torque ripple at the maximum speed can be a problem in a system which needs accurate position and speed control. Fig.4 is the variation of torque ripple according to the speed

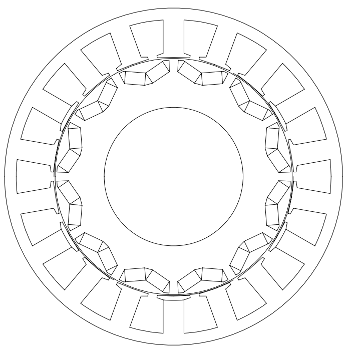
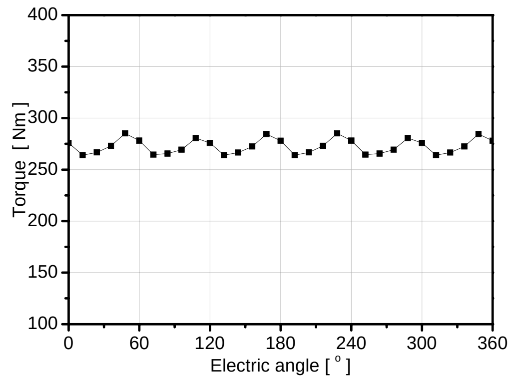


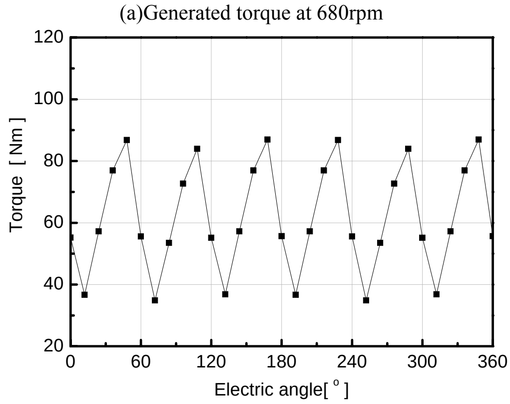
Fig. 2. Analysis model

TABLE I SPECIFICATION OF ANNALYSIS MODEL

Parameter		Value	Unit
Pole/Slot		12/18	
Stator diameter		292	mm
Rotor diameter		204.8	mm
Stack lenght		85	mm
No.of turn per phase		144	turn
Permanent magnet	Remanent flux-density *Br*	1.24	T
	Relative permeability μ_r	1.05	
Core material		RM14	
Phase resistance		103.8	mΩ



(a)Generated torque at 680rpm



(b)Generated torque at 3400rpm

Fig. 3. Torque profile at the base speed and the maximum speed

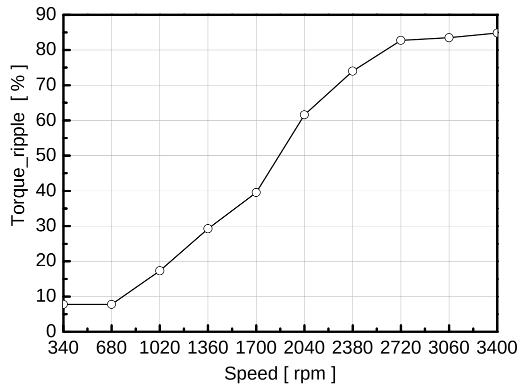


Fig. 4 Variation of torque ripple according to speed

D. Harmonic analysis of flux linkage

Fig.5 shows flux linkage at no-load and the maximum speed obtained by 2D-FEA. Fig.6 (a) and (b) show the harmonic analysis results of each flux linkage using Discrete Fourier Transform (DFT), respectively. As it can be seen, no load flux linkage has little harmonics and its Total Harmonic Distortion (THD) is 0.5%. However, as shown in Fig. 6, flux linkage at the maximum speed contains much more harmonics than that of no load flux linkage. Even though the analysis model is designed to minimize the THD of no-load flux linkage, as the d-axis current is increased, THD of flux linkage at the maximum speed is increased to 18.2%.

In the harmonic analysis result, $6n \pm 1^{th}$ harmonics are dominant harmonic. In this paper consideration of 5^{th} and 7^{th} harmonics, phasor diagram of flux linkage is indicated in Fig.7. Since the phasor diagram of flux linkage is not an ideal circle, output power has fluctuation by a sinusoidal current.

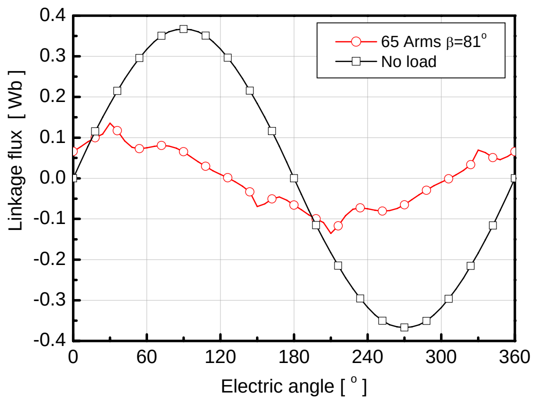
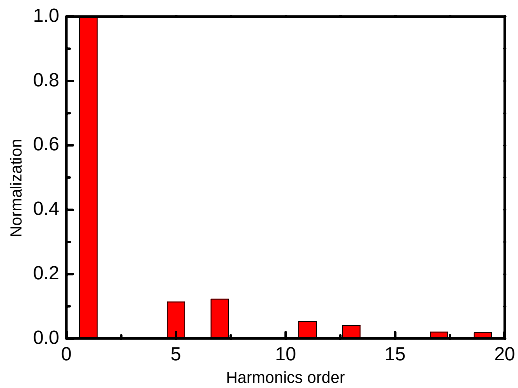


Fig. 5. Linkage flux at no-load and maximum speed

(a) Harmonic analysis of no load flux linkage



(b)Harmonic analysis of flux linkage at maximum speed

Fig. 6. Harmonic analysis of flux linkage

E. Harmonic injected current

Since the torque ripple occurs when sinusoidal current interacts with the distorted back-EMF V_o, supposing that rotational speed is constant, torque ripple can be constant by using harmonic current injection. Considering the phasor diagram of the linkage flux, following current will ensure a constant torque

$$V_o \cdot I_{inst} = 1 = const \tag{3}$$

where V_0 and I_{inst} are the instantaneous values of EMF and stator current, respectively.

Fig. 8 shows the harmonic injected current to achieve minimization of the torque ripple. The current is obtained by considering phasor diagram and harmonic component of the linkage flux on the assumption that the rotational speed is constant.

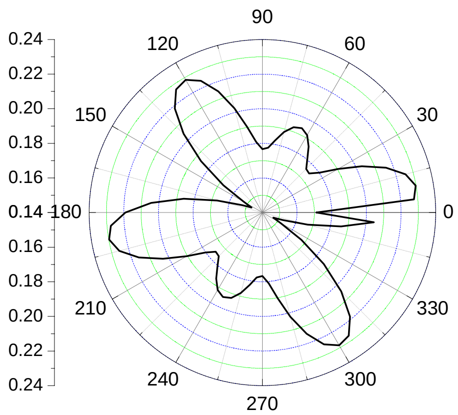


Fig. 7. Phasor diagram of flux linkage at max speed

III. Result

Harmonic analysis result of the harmonic injected current is indicated in Fig.9. The result shows 5^{th} and 7^{th} harmonics are also dominant harmonic. As it can be seen, the rate of 5^{th} and 7^{th} harmonics to the fundamental is almost same with that of flux linkage.

Comparison of generated torque by sinusoidal current and harmonic injected current is shown in Fig.10. In case of using a sinusoidal current, input current is 65 Arms. On the other, harmonic injected current is 69 Arms. Lead angle of current vector from q-axis is 81° for each model. As shown in Fig.10, generated average torque by a sinusoidal current is 61.6 N·m and torque ripple is 84.6%. At the same time, by using harmonic injected current, average torque is increased to 74.1 N·m and torque ripple is fallen to 48.1%. By using harmonic current injection, average torque increased by 20% and torque is decreased from 84.6% to 48.1%.

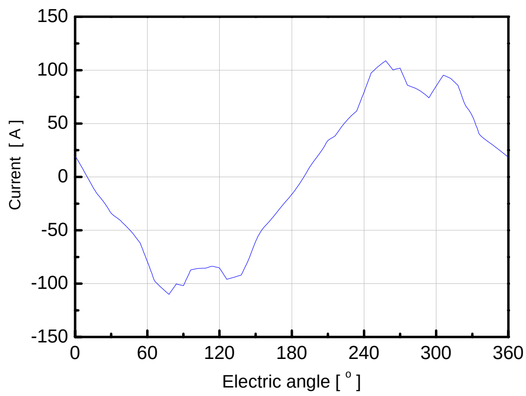


Fig. 8. Harmonic injected current

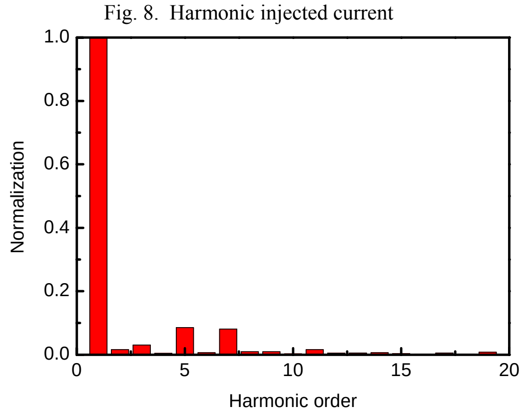


Fig. 9. Harmonic analysis of harmonic injected current

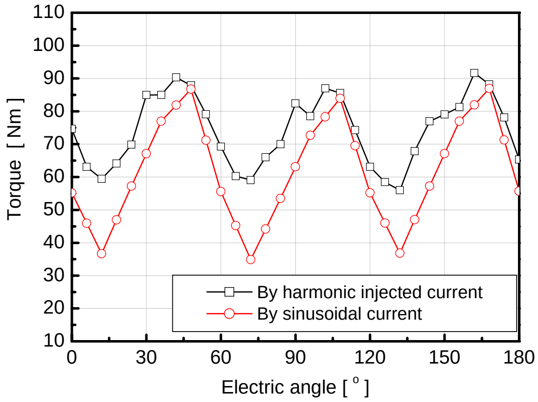


Fig. 10. Comparison of torque ripple

IV. Conclusion

This paper has proposed a method to find harmonic injected current to achieve minimization of torque ripple. Using proposed method average torque is increased by 20% and torque ripple is decreased from 81.4% to 48.1%. This method can be used to improve the accuracy of speed and position.

The method introduced in this paper will be verified by comparing simulation result with experimental result.

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