Numerical Analysis and Experimental Evaluation of IPMSM Considering Time Harmonics of Switching Frequency

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***Abstract*— In this paper, the electromagnetic characteristics analysis in Interior Permanent Magnet Synchronous Motor with concentrated winding has been conducted by using 2D non-linear finite element method (FEM) in case of both ideal sinusoidal current and experimental current of pulse width modulation data from inverter. Time-harmonic component containing switching frequency through PWM largely affects to torque ripple which can generate noise and vibration. In addition, the time-harmonic component of PWM carrier frequency can increase iron loss in the core. As a result, The PWM carrier frequency should be considered in the IPMSM design was verified by comparing Numerical analysis with experimental current data.**

***Index Terms*— Interior Permanent Magnet Synchronous Motor(IPMSM), Pulsation Width Modulation(PWM), torque ripple, Iron loss, time harmonics.**

I. Introduction

With interest in eco-friendly green technology recently, developments on hybrid and fuel cell vehicles are accelerated. Especially, hybrid vehicle uses an internal combustion engine and electric motor at the same time. Therefore, it has a good efficiency (i.e. gas mileage) and also can use the previous oil refining infrastructure with its system. That is why hybrid vehicle is considered as the most practical vehicle.

Accordingly, for a large output power and minimization of size of electric machines, such as driving motor and generator which are the origin of electricity, water or oil cooling system (or both) is increasingly used. Especially, because of high power density and high torque density, Interior Permanent Magnet Synchronous Motor (IPMSM) is mostly used for vehicles driving motors and generator [1]-[3].

IPMSM with concentrated winding has been used for applications and industrial system which requires high torque and extended operational speed range capability[4]. In order to drive IPMSM, the inverter must conduct vector control according to the magnetic pole position in the rotor. Moreover, Pulsation Width Modulation (PWM) carrier frequency has drawback of iron loss at the injecting circumstance of flow time-harmonic, especially, its effect to the eddy current into the magnet and the core are not able to ignore[5]. In addition to that IPMSM can become temperature rise enough to be damaged and the high current ripple will cause to increase losses[6],[7]. Also, torque ripple should be minimized for better performance by reducing the harmonic noise and vibration of IPMSM. Furthermore, torque ripple is increased by that time-harmonic is coupled with space harmonic[8],[9]. In this paper, the iron loss and torque ripple in IPMSM at each current wave form are investigated considering the PWM carrier frequency. Finally, it is proved by calculated and measured results.

II. Numerical Analysis of Torque Ripple

The electromagnetic torque can be expressed by the machine of the rotor flux and the stator current. In other words, non-sinusoidal air gap flux of IPMSM due to the magnetic saturation of the leakage flux paths gives rise to alignment torque ripple, which can be explained with space harmonics of back-EMF. Likewise, the current of the PWM frequency carrier have mainly influence on the torque ripple and torque harmonics.

$$T_e = \frac{3}{2\omega_m}[E_m I_m \cos\theta - E_{m5} I_m \cos(6\omega_e t - \theta_5) + E_{m7} I_m \cos(6\omega_e t - \theta_7)\cdots] \qquad (2)$$

Torque ripple is dominantly occupied by 6 times of harmonic component (cycle- per-pole-pair).

III. Design and Experiment Setup of IPMSM

IPMSM has the one-layered cavities configuration with segmented 2-pieces of Permanent Magnet embedded in rotor. Experimental set-up is shown in Fig. 1.

Table II shows the analysis of motor specification of IPMSM with concentrated winding, and experimental set-up is shown in Fig. 2. The control part in the inverter is equipped with a 32-bit power architecture micro-controller with parallel operation of power module employing switching frequency of 8k Hz.

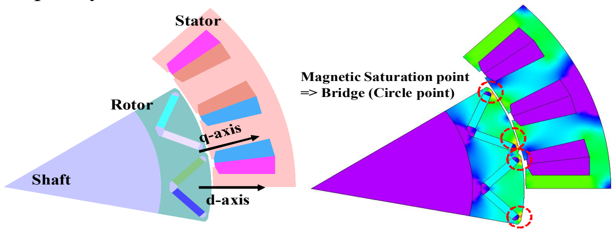

Fig. 1 modeling of IPMSM and magnetic saturation point

TABLE II
Specification of Interior Permanent Magnet Synchronous Motor

	Design Parameters	Specification	Unit
Performance	Torque	330	[Nm]
	Speed	2500	[r/min]
General	No. of Pole and Slot	16 / 24	
	No. of Phase	3	
	Air-Gap	1	[mm]
Stator	Outer Diameter	360	[mm]
	Core Material	Silicon Steel	
Rotor	Permanent Magnet Property	NdFeB (Br=1.16~1.19)	[T]

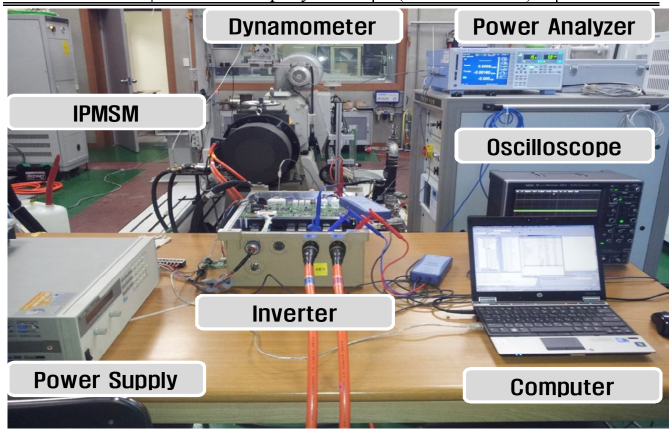

Fig. 2. Experimental setup for validation

IV. Numerical and Experimental Analysis of IPMSM

Sinusoidal and experimental current are shown in Fig. 3. Measured real current include time-harmonic component (compared with sinusoidal current) because of input current's switching effect. In this paper, torque ripple according to change on input current wave form were compared and the result is shown in Fig. 4 as follows. As a result of analysis, the 6-th harmonic dominantly affects to torque ripple and over the other 20-th harmonic components are generated as shown in Fig. 5. And Fig. 6 shows iron loss density distribution.

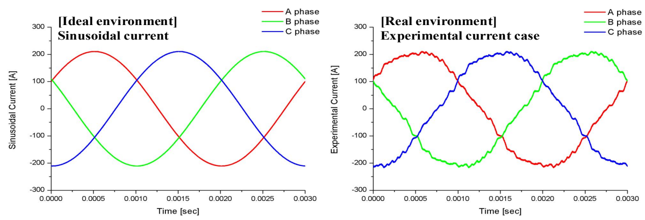

Fig. 3. Comparison of current waveform

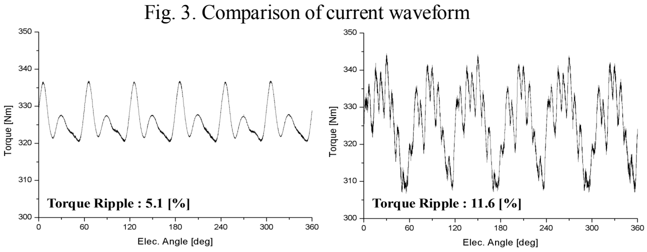

Fig. 4. Result of torque ripple

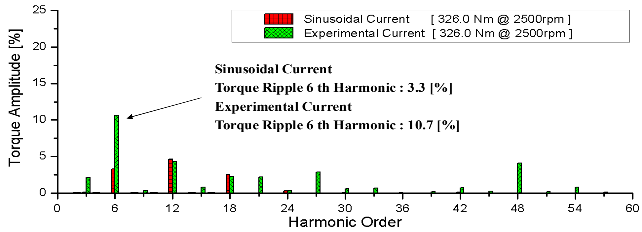

Fig. 5. Result of torque ripple harmonics

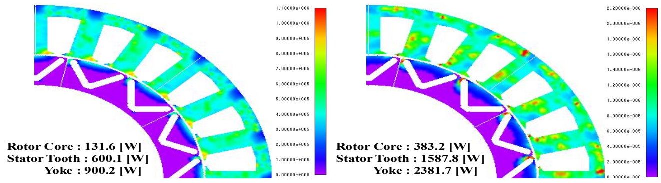

Fig. 6. Iron loss density

V. Conclusion

In this paper, The current waveform is dominant to decide the iron loss. IPMSM design must consider the PWM carrier frequency. Moreover, with current data considering time harmonic components, iron loss analysis has been conducted. As a result in this study, time harmonic components were confirmed as the main reason for increase of iron loss. In further studies, noise and vibration reduced and heat resistive IPMSM design technique considering time-harmonic is necessary.

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