Research on Shape Design to reduce Torque Ripple in IPMSM for High-voltage Electric Oil Pump based on Numerical Analysis

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***Abstract*— In this paper, the shape design of IPMSM (Interior Permanent Magnet Synchronous Motor) for high-voltage EOP (Electro Oil Pump), considering reduction of torque ripple, has been accomplished through numerical analysis of the non-linear EMF (Electric and Magnetic Field) based on FEA (Finite Element Analysis). In the prototype model of 6-pole motor with 9-slots, concentrated winding, it has been conducted a study on performance advancement depending on various combinations among the shapes of teeth, slitting-off the q-axis of rotor core and barrier. From this result, both improvement on design and characteristics analysis have been researched about IPMSM for reduction of torque ripple and back-EMF THD.**

***Index Terms*— IPMSM, Shape Design, Torque Ripple, EOP.**

I. INTRODUCTION

The development of green-car globally comes to the force as the increase of awareness about environment, reinforcement of fuel efficiency regulation and the high oil prices in automobile industry. For this reason, they accelerate the related technology development in response to growing demand of green-car such as hybrid vehicle. The engine of hybrid vehicle stops at *'idle stop'* mode, so additional electric-driven pumps are required for replacement of mechanical pump driven by the engine [1]. EOP is an integral part for hybrid and the research is being carried out. Especially, development of the motor, essential to operation, is required. Since the motor for EOP is loaded on the vehicle, IPMSM has to be considered to satisfy the performance for miniaturization, weight lightening and structural robustness of vehicles.

By mounting magnets inside of rotor, IPMSM has merit on structural stability and can produce high torque and output power density, because not only magnetic torque but also reluctance torque affect as well [2]. Also, it can be used in wide operational speed region by excellent characteristic of field weakening control [3-4].

This paper presents a research on shape design of IPMSM to reduce torque ripple for high-voltage EOP. Especially, design proceeds in the light of reduction of back-EMF THD and torque ripple causing vibration and noisy [5-7]. Finally, through performance characteristic analysis based on FEA, the result of design has been confirmed. Also, by comparing prototype and developed model, validity and reliability are verified.

II. NUMERICAL ANALYSIS OF IPMSM

The output power of motor is generally limited by maximum current (I_{max}) and maximum voltage (V_{max}). These can be represented as follows,

$$v_{ds}^2 + v_{qs}^2 \le V_{max}^2 \quad (1)$$

$$i_{ds}^2 + i_{qs}^2 \le I_{max}^2 \quad (2)$$

where i_{ds}, i_{qs} are currents of d-axis and q-axis, and V_{ds}, V_{qs} are terminal voltages of d-axis and q-axis. The d-q voltage equation of IPMSM, described in synchronous frame that is based on the rotor rotating at synchronous speed, are formulated as follows,

$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_r \lambda_{qs} \quad (3)$$

$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega_r \lambda_{ds} \quad (4)$$

where ω_r is synchronous electrical angular speed, R_s is phase resistance of stator and λ_{ds}, λ_{qs} are referred as d-q flux linkage of stator.

Furthermore, the mechanical output power equation can be explained as follows.

$$P_m = \frac{3}{2}\omega_r(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (5)$$

The electrical torque equation calculated from mechanical output power is

$$T_e = \frac{3}{2}\frac{P}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (6)$$

where P is the number of pole.

III. RESEARCH ON SHAPE DESIGN TO REDUCE TORQUE RIPPLE

The objective output of IPMSM for high-voltage EOP is 700W. The torque is 2.1Nm at rated speed(3200rpm) and DC link voltage is $240V_{dc}$. Fig. 1 presents a shape of prototype model and flux density distribution of it.

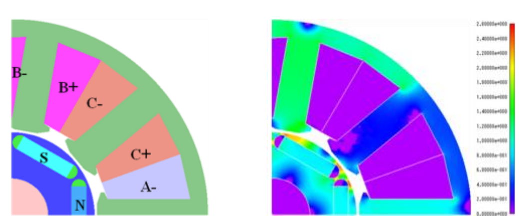

Fig. 1. Shape of Prototype Model and Flux Density Distribution

TABLE I
Design specifications of IPMSM

classification	Design Parameters	Specification	Unit
Performance	Torque	2.1	Nm
	Speed	3200	rpm
General	No. of Pole and slots	6 / 9	
	No. of Phase	3	
	Air-gap	0.5	mm
Stator	Outer Diameter	85	mm
Rotor	PM Property	Nd-FE-B	

Table I shows a design specifications of IPMSM. In Fig. 2, the shapes of teeth, slitting-off the q-axis of rotor core and barrier have four different shapes respectively. It has been conducted a study on performance change about Back-EMF THD and Torque ripple according to the shapes respectively and combinations among them.

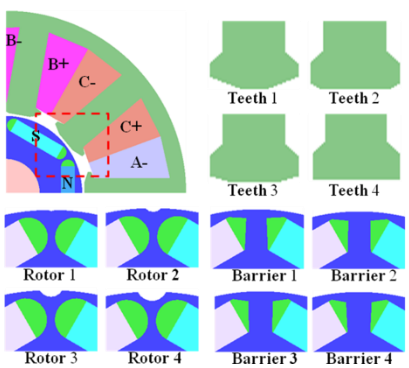

Fig. 2 Shapes of Teeth, Slitting-off the q-axis of Rotor Core, and Barrier

TABLE II
Result of back-EMF THD and torque ripple of shape combinations

Teeth	Rotor	Barrier	Back-EMF THD	Torque Ripple
4	2	1	2.9%	1.9%
		2	2.8%	2.5%
		3	2.7%	3.1%
	3	1	3.3%	1.2%
		2	2.9%	1.1%
		3	**2.7%**	**1.6%**
	4	1	4.0%	2.4%
		2	3.6%	1.5%
		3	3.2%	0.8%

Table II presents 9 best-performed results out of 64 combinations showing the results of Back-EMF THD and Torque ripple according to the shape combinations. The shape combination of Teeth 4, Rotor 3 and Barrier 3 has been adopted on the developed model considering both back-EMF THD and torque ripple. Fig 3. presents a shape of developed model and flux density distribution.

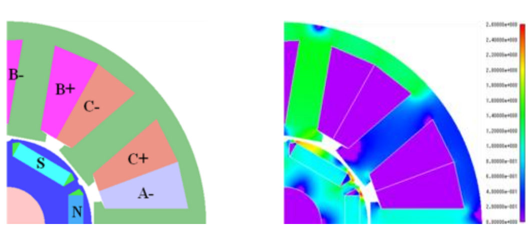

Fig. 3. Shape of Developed Model and Flux Density Distribution

IV. Analysis Result

As shown in Table III, the developed model compared with prototype model decrease 6% of back-EMF THD and 14.1% of torque ripple even maintaining the same average torque level. Comparison result of torque and back-EMF wave form is presented in Fig. 4.

TABLE III
Comparison of performance between prototype and developed model

	Prototype Model	Developed Model
Back-EMF THD	8.7%	2.7%
Average Torque	2.1Nm	2.1Nm
Torque pk-pk	0.33Nm	0.03Nm
Torque Ripple	15.7%	1.6%

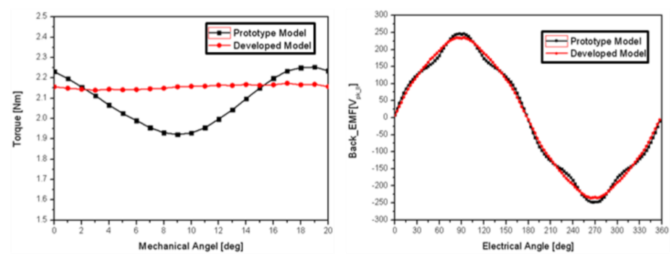

Fig. 4. Comparison results of Torque and Back-EMF wave form.

V. Conclusion

In this paper, design methods for reduction torque ripple are proposed such as shapes of teeth, slitting-off the q-axis of rotor core and barrier. Its effectiveness is clarified with the numerical results obtained by nonlinear FEA. In addition, the developed model is under manufacturing. So, as soon as it is completed, the result of manufactured model will be compared with that of simulation model to verify validity and reliability of this paper.

References

[1] Yeonho Kim; Jaesang Lee; Chihoon Jo; Yongha Kim; Minseok Song; Jonghyun Kim; Hyunsoo Kim, “Development and Control of an Electric Oil Pump for Automatic Transmission-Based Hybrid Electric Vehicle,” *IEEE Trans. on Veh.*, vol.60, no.5, pp.1981-1990, 2011.

[2] Seungho Lee; Yong-Jae Kim; Sang-Yong Jung, “Numerical Investigation on Torque Harmonics Reduction of Interior PM Synchronous Motor With Concentrated Winding,” *IEEE Trans. Magn.*, vol.48, no.2, pp. 927-930, 2012.

[3] C. Mademlis and V. G. Agelidis, “A high-performance vector controlled interior PM synchronous motor drive with extended speed range capability,” in Proc. IECON’01, Nov. 2001, vol. 2, pp. 1475–1482..

[4] W. L. Soong and M. Ertugrul, “Field-weakening performance of interior permanent-magnet motor,” *IEEE Trans. Ind. Appl.*, vol. 38, no. 5, pp. 1251–1258, Sep. 2005.

[5] M. Lukaniszyn, M. JagieLa, and R. Wrobel, “Optimization of permanent magnet shape for minimum cogging torque using a genetic algorithm,” *IEEE Trans. Magn.*, vol. 40, no. 2, pp. 1228–1231, Mar. 2004.

[6] Liang Fang; Sung-Il Kim; Soon-O Kwon; Jung-Pyo Hong, “Novel Double-Barrier Rotor Designs in Interior-PM Motor for Reducing Torque Pulsation,” *IEEE Trans. Magn.*, vol. 46, no. 6, pp. 2183-2186, June, 2010.

[7] Stumberger, B.; Stumberger, G.; Hadziselimovic, M.; Marcic, T.; Virtic, P.; Trlep, M.; Gorican, V. “Design and Finite-Element Analysis of Interior Permanent Magnet Synchronous Motor With Flux Barriers,” *IEEE Trans. Magn.*, vol. 44, no. 11, pp. 4389-4392, Nov, 2008.