A Study on Torque Ripple Calculation for Permanent Magnet Motor according to Load Angle

Ki-Chan Kim, Min-Gyu Kim, and Dong-Seok Ryu
Dept. of Electrical Engineering, Hanbat National University
Email : kckim@hanbat.ac.kr

***Abstract* — The paper presents a torque ripple calculation method of interior permanent magnet synchronous motor (IPMSM) considering torque characteristics according to load angle by using FEM analysis. On an assumption that the current of stator windings is controlled with sinusoidal waveform by vector inverter, torque ripple can be calculated by superposing load angle curves which are derived by inputting each instantaneous value of three phase currents. Therefore, the load angle range having minimum torque ripple as well as the maximum average torque according to the load angle can be induced easily by the proposed method. Finally, torque ripple reduction study of IPMSM is represented in the paper by using proposed method.**

I. INTRODUCTION

Although IPMSM generates high torque from an aspect of utilizing reluctance torque as well as magnetic torque, demerit of IPMSM is the generation of large d-axis current at a high speed region which corresponds to field weakening control [1]. Therefore, IPMSM has large torque ripple due to its complex barrier structure in addition to large d-axis current. So, several papers for decreasing method of torque ripple have been presented [2]. The target of this paper is not only the study on the reduction of torque ripple but also the study on the analytical calculation method for torque ripple. In this paper, we present an efficient calculation method of torque ripple for IPMSM without using general torque ripple calculation method which uses transient solver in FEM including motion equation and voltage equation.

The paper presents torque ripple calculation method by superposing the load angle curves from magneto-static solver by inputting each instantaneous value of three phase windings. We also perform the experiment for the verification of proposed method. We can find the load angle for minimum torque ripple with ease by proposed method. Moreover, we can analyze the torque ripple characteristics according to rotor types.

TABLE I
SPECIFICATIONS OF ANALYSIS MODEL

	Item	Unit	Specification
Rated	Voltage / Current	V / A	12 / 10.5
	Speed	rpm	1000
	Power	W	130
Stator	Stack width / Outer diameter	mm	40 / 86
	Parallel Circuit		4
	Series turns / phase		44
Rotor	Number of poles		4
	Outer diameter	mm	46.2
	Remanence of Magnet	T	1.2 @ 20℃

II. ANALYSIS MODEL

For the best use of reluctance torque in IPMSM, the barriers in the rotor and stator slots are designed to have the maximum saliency ratio and maximum gap of d-axis and q-axis inductance [3]. Three pieces of permanent magnets per pole are inserted in the middle of each barrier. Fig. 1 shows the picture of analysis model, and Table I shows the specification of size and rated operation point of the motor.

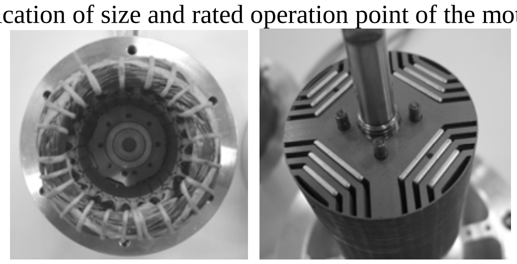


Fig. 1. Stator and permanent magnet rotor structure of IPMSM.

III. TORQUE RIPPLE ANALYSIS BY LOAD ANGLE CURVES

The general method for calculating load angle curve by using magneto-static solver in FEM is as follows. We input $\sqrt{2}$ times of rated current into the region of winding A, and then we input the half times of rated current with minus sign into the regions of winding B and winding C. Secondly, we calculate the output torque according to rotating angle while rotating the rotor. This is somewhat adequate analytical method for load angle curve with small reluctance torque or no reluctance torque such as SPMSM. Fig. 2 shows the load angle curve of IPMSM. There is so much fluctuation in it. In this figure, we cannot calculate the average torque according to load angle.

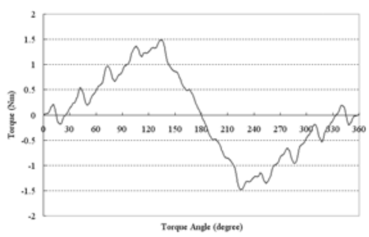


Fig. 2. The analysis results of load angle curve by using static FEM.

This paper presents the effective calculation for torque ripple as well as average torque without transient solver in FEM of time domain. Fig. 3 shows the balanced sinusoidal current waveform of three phase winding. The load angle curve in Fig. 2 is analyzed under the condition of dc current set at 1st state in Fig. 3. In case the motor is operated with sinusoidal current controller, we can calculate another load angle curve with the dc current set at 2nd state. The remaining dc current set from 3rd to 7th state also can calculate load angle curves in the same way. The dc current conditions are repeated again with interval of 30°. We can make synthetic load angle curve by superposition of seven kinds of load angle curves as shown in Fig. 4.

In Fig. 4, average torque curve is calculated by averaging seven torque values at each load angle, and torque ripple curve is calculated by subtracting minimum torque from maximum torque at each load angle. We can find that torque ripple in the vicinity of 90° load angle is smaller than that of 130° load angle. That is, the IPMSM is usually expected to be controlled with 130° load angle for the maximum torque production. However, torque ripple is also increased at this load angle.

In order to verify the proposed method, we perform the dynamic analysis by FEM with sinusoidal rated current 10.5A and load angles of 90° and 130°, respectively. Fig. 5 shows the results of torque ripple waveform and it gives good agreement with torque ripples by the proposed method.

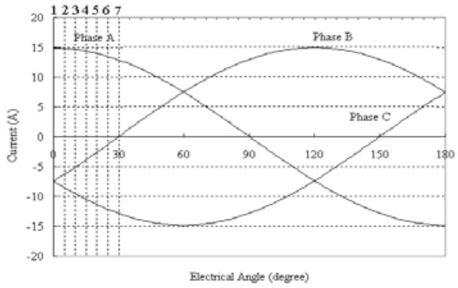


Fig. 3. Condition of input currents for load angle curve analysis

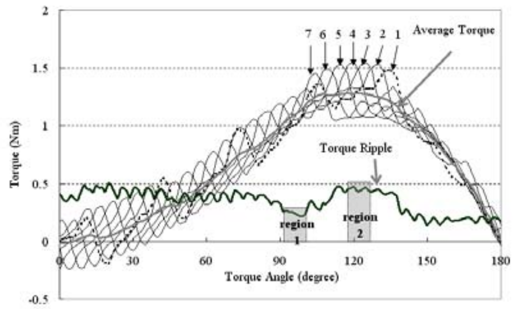


Fig. 4. Torque ripple and average torque according to load angle

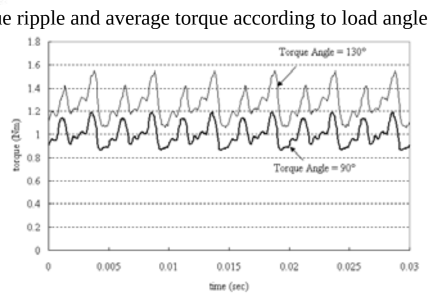


Fig. 5 Torque waveform according to load angles by time transient solver in FEM.

IV. EXPERIMENT AND DISCUSSION

Fig. 6 shows the experimental set for load angle test of IPMSM. The test result of load angle curve is shown in Fig. 7(a) when dc current set of 1st state is inputted in each winding and the rotor is rotated by dynamometer, we can see the fluctuation of torque according to the load angle is similar to Fig. 4. Fig. 7(b) shows the experimental results of torque at two kinds of load angle 90° and 130°. Vector inverter is used and the rated current is distributed to d-axis and q-axis current relevantly according to the load angle. The comparison results between analysis and experimental result of load angle curve is shown in Fig. 8 for the verification of validity of the proposed method.

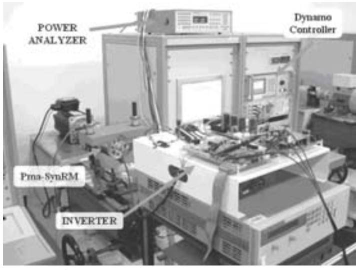
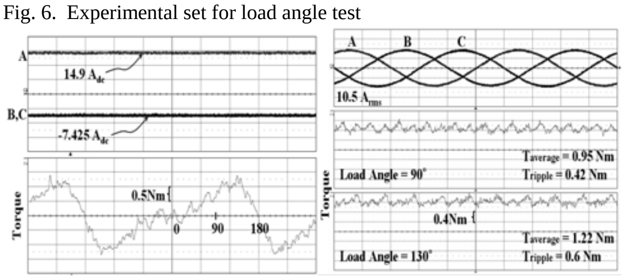


Fig. 6. Experimental set for load angle test



(a) Load angle curve test by dc current source

(b) Test results on the average torque and torque ripple at 90° and 130° load angle by vector inverter

Fig. 7. Experimental results.

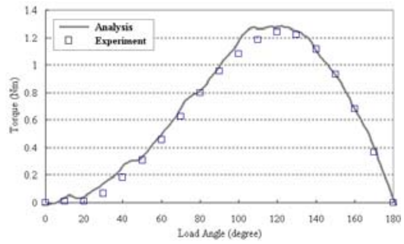


Fig. 8. Load angle curve by analysis and experiment. (average torque)

V. CONCLUSION

In this paper, we proposed a calculation method for torque ripple of IPMSM by superposing load angle curves calculated by FEM. Moreover, we calculate an exact load angle curve which represents the average torque at each load angle in case of a motor with large torque ripples.

VI. REFERENCES

[1] Niazi, P. and Toliyat, H.A., “Design of a low-cost concentric winding permanent magnet assisted synchronous reluctance motor drive”, Industry Applications Conference, Fortieth IAS Annual Meeting. Vol. 3, pp. 1744–1748, 2-6 Oct. 2005.

[2] Ohnishi, T. and Takahashi, N, “Optimal design of efficient IPM motor using finite element method”, IEEE Transactions on Magnetics, Vol. 36, Issue 5, Part 1, pp. 3537-3539, Sep. 2000.

[3] I. Boldea, T. Fukao, T.A. Lipo, L. Malesani, T.J.E. Miller and A. Vagati, Synchronous Reluctance Motors and Drives A New Alternative, IEEE IAS 29th Annual Meeting, Oct. 1994.