2008 IEEE Industry Applications Society Annual Meeting - Adobe Acrobat Pro

파일(F) 편집(E) 보기(V) 문서(D) 주석(C) 양식(R) 도구(T) 고급(A) 창(W) 도움말(H)

작성 결합 공동 작업 보안 서명 양식 멀티미디어 주석

1 / 439 58% 찾기

책갈피

2008 IEEE Industry Applications Society Annual Meeting

5-9 October 2008 Edmonton, Alberta, Canada

GETTING STARTED

WELCOME

CONFERENCE INFORMATION

COMMITTEES

SESSIONS

AUTHORS

SEARCH

Papers by Author

Lee, Kyo-Beum

- Direct Power Control of a Doudly Fed Induction Generator with a Fixed Switching Frequency

Lee, S. T.

- 16,000-RPM Interior Permanent Magnet Reluctance Machine with Brushless Field Excitation

Lee, Sang Bin

- A Stator Core Quality Assessment Technique for Inverter-Fed Induction Machines
- Automated Monitoring of High-Resistance Connections in the Electrical Distribution System of Industrial Facilities

Lee, Sang-Ho

- A Study on the Acoustic Noise Reduction of Interior Permanent Magnet Motor with Concentrated Winding

Main Menu
Authors

A Study on the Acoustic Noise Reduction of Interior Permanent Magnet Motor with Concentrated Winding

Sang-Ho Lee, Jung-Pyo Hong
School of Mechanical Engineering, 17 Haengdang-dong, Seongdong-gu, 133-791, Seoul, Korea
sh80@hanyang.ac.kr, hongjp@hanyang.ac.kr

***Abstract*—This paper deals with a study on the acoustic noise reduction according to the change of the pole angle in interior permanent magnet (IPM) motor with concentrated winding. This research is divided into 3 steps. Firstly, noise sources, such as resonant frequencies of stator and harmonic component of magnetic forces, are analyzed by the simulation and experimental results, respectively. Secondly, design of experiment (DOE) and optimal design using response surface methodology (RSM) are utilized to reduce the harmonic component of magnetic forces at a stator tooth compared with prototype. Objective function in the DOE and the optimal design is that the reduction of the summation of harmonic magnitude of normal force at a stator tooth. Finally, the reduction degree of the acoustic noise is compared by experimental results under the rated operating condition.**

Keywords-Acousitc noise, EMC, Harmonics, IPM, Magnetic force, Objective function, Optimal design

I. INTRODUCTION

Resonance of stator mostly occupies mechanical noise source in electric machines due to stator vibration generated by the resonance of stator [1]. Especially, harmonic component, which corresponds to the resonant frequencies of stator, boosts the resonance of stator. [2]. As the excitation force vibrating stator in electric machines, it is divided into tangential and normal force. In order to reduce the acoustic noise in electric machines, many papers dealt with focus on the reduction in cogging torque and torque fluctuation, which are the results of tangential force [3] - [4]. However, the harmonic magnitude of normal force is so bigger than tangential force.

As one of the method of magnetic force calculation, equivalent magnetizing current (EMC) method uses magnetizing current which exists on element boundary and it can directly calculate the electromagnetic force which affects the surface of structure [5]. EMC only distributes on the element surface of different material because the interior magnetizing current in core is cancelled. The tangential and normal force at a stator tooth are expressed as

$$f_t = H_{t1}B_{n1} - H_{t2}B_{n2} \tag{1}$$

$$f_n = \frac{1}{2}\left(H_{n1}B_{n1} - H_{t1}B_{t1}\right) - \frac{1}{2}\left(H_{n2}B_{n2} - H_{t2}B_{t2}\right) \tag{2}$$

where B_{n1}, B_{t1}, H_{n1}, and H_{t1} are the components in the air, B_{n2}, B_{t2}, H_{n2}, and H_{t2} are the components in the core.

This paper deals with a study on the acoustic noise reduction according to the change of pole angle in IPM motor with concentrated windings. This research consists of the analysis of mechanical and magnetic noise sources, optimal design using response surface methodology (RSM) which is to reduce the harmonic component of magnetic forces at the stator tooth, and the comparison with cogging torque, torque fluctuation, the harmonic components which affect the stator tooth, and acoustic noise between prototype and optimal model under the rated operating condition. The objective function in DOE and optimal design is the reduction of the summation of the harmonic magnitude of normal force at the stator tooth. And then, optimal model, which is changed the pole angle compared with prototype, is designed. Finally, the relationship between the acoustic noise and the magnetic forces is compared by the simulation and experimental results.

II. CHARITERSITICS OF PROTOTYPE

Table I shows specifications of prototype and material property of stator in the prototype. The prototype, which consists of 4 poles and 6 slots with concentrated winding, is driven by 6-step operation, and then PWM frequency is 4.0 kHz. In order to know the noise sources of the prototype, the resonant frequencies of the stator and the harmonic component of magnetic force are analyzed.

Fig. 1 shows noise spectra when mechanical operating frequency of the prototype is 50 Hz and measured 1m away from the motor by microphone under the rated operating condition. Total noise is 74.2 dBA and the frequency aspects (f_a) of noise at the rated operating frequency (f_{ro}) is expressed as

$$f_a = 2n \times f_{ro},\ n = 1, 2, 3, \cdots \tag{3}$$

, and then the maximum noise is usually generated at the 2.2 kHz.

TABLE I. SPECIFICATIONS OF PROTOTYPE AND MATERIAL PROPERTY OF THE STATOR

Contents		Values
Specifications	Rated speed	3000 rpm
	Rated torque	8.0 Nm
	Rated current	15 A_{rms}
Material property	Mass density	7680 kg/m^3
	Poisson's ratio	0.3
	Elastic moudlus	200 GPa

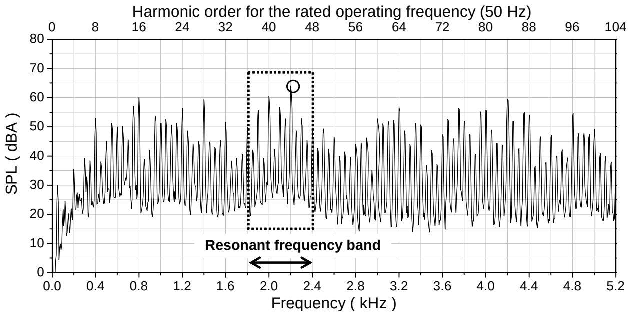


Fig. 1. Noise spectra of the prototype under the rated operating condition.

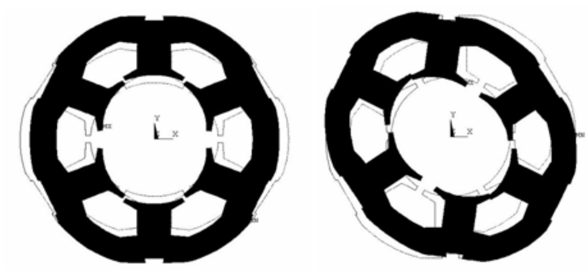
A. Mechanical noise source

The resonance of stator broadly occupies the mechanical noise source of electric machines because it boosts the stator vibration. In order to analyze the resonant frequencies of the stator in prototype, modal analysis considering the material property is performed by 2D finite element analysis (FEA) ANSYS. Fig. 2 shows the resonance mode shape of the stator, which is expressed by deformed. Previous work successfully showed [6] that intensity of the acoustic noise is the highest when the resonance mode shape of stator is an oval such as Fig. 2 (a). And then, the frequency of first mode of the stator is 1.9 kHz. Moreover, the resonant frequencies of the stator in assembled status compared with only stator status are increased because the stiffness of the stator is increased by the boundary condition according to the change of assembly condition. In order to reduce the harmonic magnitude continuous with the resonant frequencies of the stator, the frequencies between 1.8 kHz and 2.4 kHz are designated by the resonant frequency band.

B. Magnetic noise source

Table II shows the fundamental frequency and harmonic order of magnetic forces when the mechanical operating frequency of the prototype is 50 Hz under the rated operating condition. The fundamental frequency of cogging torque and torque ripple, it so-called results of global forces, is decided by combination of pole and slot number. In addition, the fundamental frequency of tangential and normal force which affect the stator tooth, it so-called results of local forces, is determined by pole number. Although the harmonic components of magnetic forces do not conform to the resonant frequencies of the stator, it around the resonant frequencies of the stator boosts the resonance of stator.

Fig. 3 shows the distribution of the local forces, which affect the stator tooth, according to the change of rotor position and its harmonic components. The harmonic magnitude of normal force should be reduced because it is so bigger than that of tangential force. Therefore, the reduction of the summation of harmonic magnitude of normal force which affects the stator tooth is designed by the objective function.

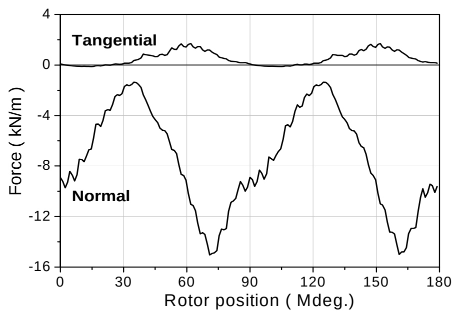


(a) First mode (b) Second mode

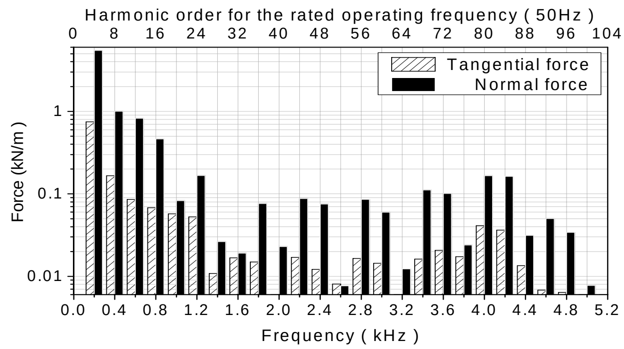
Fig. 2. Resonance mode shape of stator in the prototype

TABLE II. FUNDAMENTAL FREQUENCY AND HARMONIC ORDER FOR MAGNETIC FORCES UNDER THE RATED SPEED

	Fundamental frequency	Harmonic order	
Cogging torque	600 Hz	$f_{ct} = 12n \times f_{ro}$	n = 1, 2, 3, …
Torque ripple	600 Hz	$f_{tf} = 12n \times f_{ro}$	
Tangential and normal force at a stator tooth	200 Hz	$f_{tn} = 4n \times f_{ro}$	



(a) Distribution



(b) Harmonic components

Fig. 3. Characteristics of local forces which affect the stator tooth

III. DESIGN PROCEDURES

A. Calculation process of magnetic forces

Fig. 4 shows the calculation process of the magnetic forces. In order to get the current according to the change of the stator and rotor shape, dynamic simulation, which reflects not only inductance but also PWM frequency, is performed. Although the commutation section is important factor for the distribution of normal force at the stator tooth, starting point of the commutation section, which is lagged behind 10^{o} in electrical degree for the zero-crossing of back-EMF under the no-load, is identical.

B. Objective function

The normal force at the stator tooth in the prototype has many harmonic components because the main flux concentrates on the stator tooth. Therefore, objective function in DOE and optimal design using RSM is the reduction of the summation of the harmonic magnitude of normal force which affects the stator tooth. The objective function and the constraint condition are defined as follows:

Objective function:

$$K = 10\log \sum 10^{\frac{(F_{normal} + F_A + F_W)}{10}} \tag{4}$$

Constraint condition:

$$\textit{Average torque} \geq 8.0Nm$$

where F_{normal} is the harmonic component of normal force at the stator tooth, F_A is the value of A-weighting in weighting frequency curves [7], F_W is the weighting factor for 1.8~2.4 kHz which is the main resonant frequency band.

C. Design of experiment (DOE)

In order to select significant factor for the objective function, DOE is performed. Fig. 5 shows the design variables, which consist of bridge width (BW), pole angle (PA), slot open (SO), and tooth height (TH). Full factorial design (FFD) is utilized to select significant factor, and then advantages of FFD are written as follows [8], [9]

The effect of design variables is shown in Fig. 6. The main and interaction effect are significantly expressed by pole angle slot open when the level of significance is 0.5. Therefore, two design variables, which are pole angle and slot open, are selected to reduce the values of objective function in the optimal design. The design area of pole angle and slot open in optimal design using RSM is newly designated based on the high design area point in DOE because the values of objective function at the high design area point are lower than other design areas. However, design value both bridge width and tooth height is fixed by 2.5mm in the optimal design using RSM since the response values of bridge width and tooth height have the lowest at the central point.

D. Optimal design using RSM

In this paper, central composite design (CCD) is used to response of design variables [8]. Table III shows the design area of PA and SO based on the results of DOE, and then CCD is required to conduct 9 experiments.

The predicted response surface is drawn as shown in Fig. 7. As the optimal point, optimal model is found at the point, which slot open and pole angle are 4.2 mm and 72^{o}, respectively.

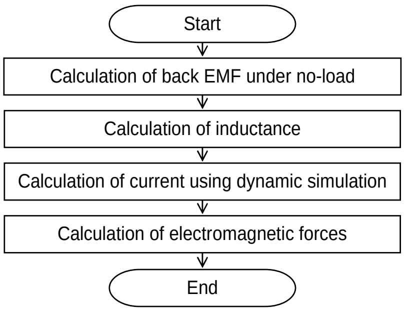


Fig. 4. Calulation process of magnetic forces

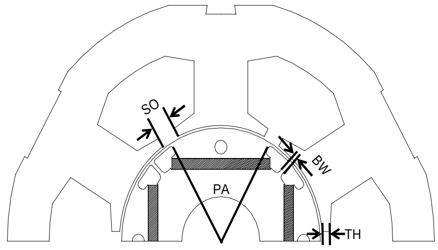


Fig. 5. Design variables

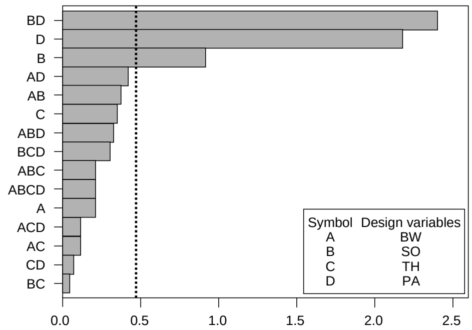


Fig. 6. The effect of design variables for the objective function

TABLE III. DESIGN AREA IN RSM

Design variables	Unit	Coded values				
		-1.682	-1.0	0	1.0	1.682
Slot open (SO)	mm	3.8	4.2	5.4	6.6	7.00
Pole angle (PA)	o	51.4	56.0	62.0	69.5	72.6

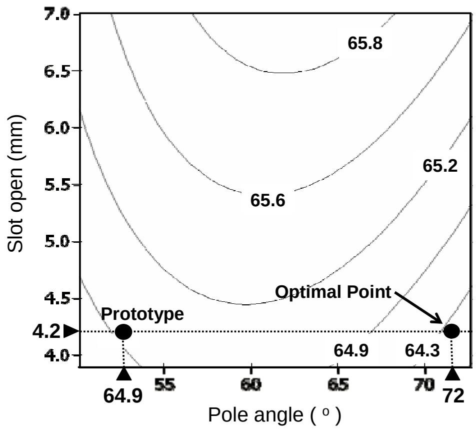


Fig. 7. Response surface for the objective function

IV. DESIGN RESULTS AND DISCUSSION

A. Simulation results

Fig. 8 shows the comparison with cogging torque between prototype and optimal model. The measured peak values of prototype and optimal model are 0.36 Nm and 0.76 Nm, respectively. The waveform of cogging torque according to the change of the pole angle behaves differently. The phase and peak values of cogging torque of optimal model compared with prototype model are reversed and increased, respectively.

Torque fluctuation under the rated torque is shown in Fig. 9. Torque ripple of prototype and optimal model are 36.0% and 59.0%, respectively.

Fig. 10 shows the comparison with local forces at the stator tooth between prototype and optimal model. The distribution of normal force according to the change of rotor position is shown in Fig. 10 (a). Although commutation section is identical, the distribution aspect of optimal model is more sinusoidal than prototype model due to the extension of pole angle. Therefore, the harmonic magnitude of normal force is reduced. As the objective function to reduce the acoustic noise in IPM motor with concentrated winding, the harmonic analysis for normal force at the stator tooth is shown in Fig. 10 (b). The harmonic magnitude of optimal model entirely is lower than prototype model. The values of predicted by RSM and calculated by FEM are 64.2 and 63.2, respectively.

The comparison with design results between prototype and optimal model is shown in Fig. 11. Although the values of objective function for optimal model is lower than prototype, cogging torque and torque fluctuation of optimal model are higher than prototype. From this result, in order to reduce the acoustic noise in IPM motor with concentrated, significant factor among the harmonic magnitude of normal force which is related with the resonant frequency band of stator, cogging torque, and torque fluctuation is clearly compared by experimental results under the rated operating condition.

B. Experimental results

Fig. 12 shows the noise spectra, which are measured by one of third octave band under the rated operating condition. Total noise of prototype and optimal model is 74.2 dBA and 71.4 dBA, respectively. The noise of prototype is generated from the resonant frequency band of stator and PWM frequency band. The noise of optimal model only is generated from the resonant frequency band of stator but its overall noise value is lower than that of prototype. The reason is that inductance of prototype is lower than optimal model due to the increase in magnetic saturation by the reduction in pole angle. Therefore, current waveform of prototype more exactly reflects the PWM characteristics and the noise around PWM frequency is more highly measured than optimal model.

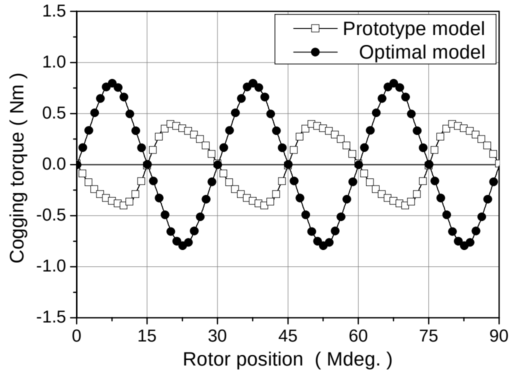


Fig. 8. Cogging torque

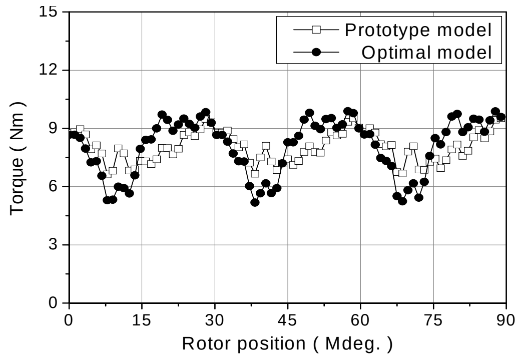
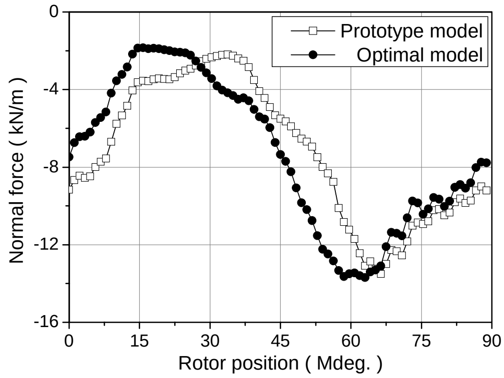
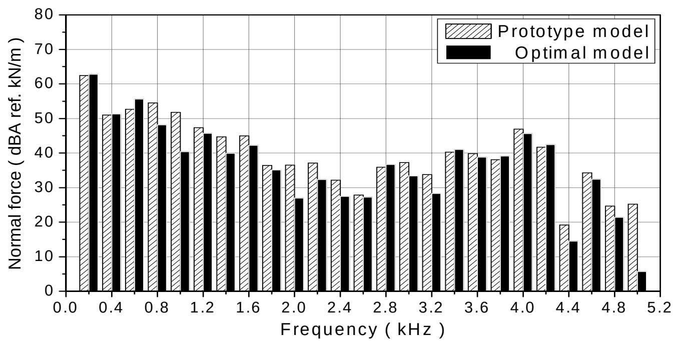


Fig. 9. Torque fluctuation



(a) Distribution



(b) Harmonic components

Fig. 10. The comparison with local forces between prototype and optimal model

V. Conclusions

In order to reduce the acoustic noise in IPM motor with concentrated winding, the analysis of noise sources, DOE, and optimal design using RSM are presented in this paper. The acoustic noise of optimal model reduced the harmonic magnitude of normal force which affects the stator tooth is reduced about 3 dBA compared with prototype model.

The acoustic noise in electric machines has close correlation between the resonant frequencies of stator and the harmonics of normal force. Accordingly, design procedures pay more attention to the reduction of the harmonic magnitude of normal force which affects the stator tooth, which corresponds to the resonant frequency band of the stator.

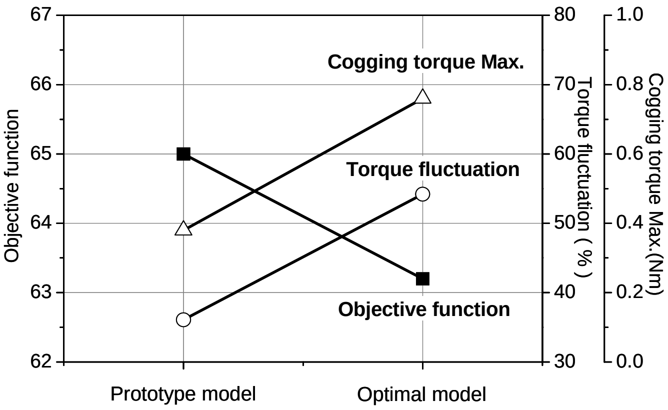


Fig. 11. The comparison with desgin results between prototype and optimal model

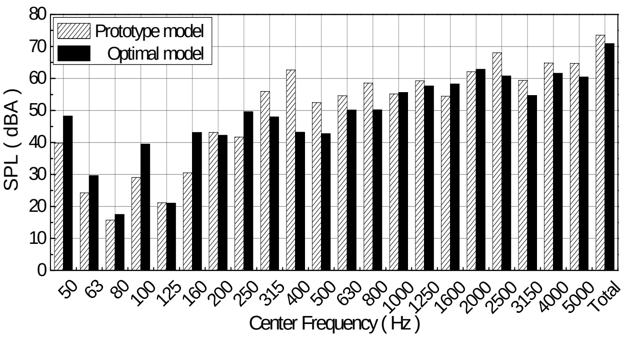


Fig. 12. The comparison with noise spectra between prototype and optimal model

References

[1] Kyung-Ho Ha, Young-Kyoun Kim, Geun-Ho Lee, and Jung-Pyo Hong, "Influence of Stator Structure on Vibration of Switched Reluctance Motor," *KIEE Int. Trans. on EMECS*, vol.2-B, no. 3, pp.95-99, 2002.

[2] G. h. Jang, D. K. Lieu, "The Effect of Magnet Geometry on Electric Motor vibration," *IEEE Trans. Magn*., vol. 27, no. 6, pp. 5202-5204, Nov. 1991.

[3] S. Sakabe, Y. Shinoda and H. Yokoyama, "Effect of Inter-Pole on Cogging Torque of Two Phase Permanent Magnet Motor," *Trans. of JIEE*, vol.110, no.2, pp131-137.

[4] S. M. Hwang, D. K. Lieu, "Reduction of Torque ripple in Brushless DC Motors," IEEE Trans. Magn., vol. 31, no. 6, pp. 3737-3739, Nov. 1995.

[5] G. Henneberger, P. K. Sattler, D. shen, "Nature of the equivalent magnetizing current for the force calculation," *IEEE Trans., Magn.*, Vol. 28, No. 2, pp. 1068-1072, Mar. 1992.

[6] R. S. Colby, F. M. Mottier, and T. J. E. Miller, "Vibration modes and acoustic noise in a four-phase reluctance motor," *IEEE Trans., Ind., Applicant*., vol. 32, pp. 1357-1364, Nov./Dec. 1996.

[7] Nau, S.L., Mello, H.G.G., "Acoustic noise in induction motors: causes and solutions," Petroleum and Chemical Industry Conference, 2000. Industry Applications Society 47th Annual Conference Paper, pp. 253-263,11-13, Sept. 2000.

[8] Sung-Il Kim, Jung-Pyo Hong, Young-Kyoun Kim, Hyuk Nam, Han-Il Cho, "Optimal design of Slotless-Type PMLSM Considering Multiple Response by Response Surface Methodology," *IEEE Trans., Magn.*, vol. 42, no. 5, pp. 1219-1222, Apr. 2006.

[9] Raymond H. Myers, and Douglas C. Montgomery, "Response Surface Methodology Process and Product Optmization using Designed Experiments," *John Wiley & Sons*, Inc., 1995.