Proposal of Motor Improvement Design Method under Limited Conditions Using Taguchi Method

Hong-Rae Noh [1], Cheol-Min Kim [1], Ki-Chan Kim [2*]
[1] Department of Electrical Engineering, Hanbat National University, Daejeon, 34158 Korea

Article Info
Page Number: 548 – 554
Publication Issue:
Vol. 71 No. 3 (2022)

Article History
Article Received: *12 January 2022*
Revised: *25 February 2022*
Accepted: *20 April 2022*
Publication: *09 June 2022*

Abstract
In this paper, we present a optimal design method that reduces torque ripple, a cause of noise and vibration, when there is a limited condition that the shape of the rotor cannot be changed during the process of planning the improvement design of the motor in the general industrial group. To proceed with such an optimal design, the optimal design is carried out by using the Taguchi method among experimental design methods suitable for carrying out the optimal design under limited experimental conditions. To use the Taguchi technique, each characteristic is simulated by FEM analysis because the characteristic changes whenever an influencing factor is changed.

Keywords: Finite Element Method (FEM), Taguchi Method, Brushless AC Motor, Optimal Design

1. Introduction

BLAC motors have characteristics of high output and high efficiency. Also, have the advantage of being small size and weight compared to other types of motors based on the same output and efficiency. It is for the same reason that BLAC is mainly adopted in places where low weight and quiet motors are required, such as home appliances, automobiles, and air conditioning systems. In the case of a system that has a large effect on the EQ index felt by humans, such as a car system, it is inevitable to reduce noise and vibration. Sources of noise and vibration are cogging torque and torque ripple. In BLAC, the cogging torque has a large structural influence on the rotor including permanent magnets, and the torque ripple has a large structural influence on the stator where the field flux is generated.

In this paper, we present a shape-optimal design method that reduces torque ripple, a cause of noise and vibration, when there is a limited condition that the shape of the rotor cannot be changed during the process of planning the improvement design of the motor in the general industrial group. Assuming that the motor characteristics are divided into performance and emotional factors, the area for noise and vibration will be included in the emotional factor area. Since there may be a loss in the most important performance area while optimizing the emotional factor, it is necessary to design a model that optimizes the emotional factor while maintaining or improving the performance. To proceed with such an optimal design, the optimal design is carried out by using the Taguchi method among experimental design methods suitable for carrying out the optimal design under limited experimental conditions.

To use the Taguchi technique, each characteristic is simulated by FEM analysis because the characteristic changes whenever an influencing factor is changed.

2. Taguchi Method

The Taguchi method is the most suitable experimental method when designing an optimal design with minimal changes to the main influencing factors within limited experimental conditions. In this paper, under the constraint that the shape of the rotor including the permanent magnet cannot be changed in the situation to improve the noise and vibration of the BLAC motor, the sensibility factor is optimally designed while maintaining or improving the performance of the motor using only the shape change of the stator. Efficiency was selected as the most intuitive characteristic to judge the performance of the motor. Efficiency is a characteristic that is better maintained or increased, so it is classified as a Larger-the-better characteristic of the quality characteristic.

Fig. 1: Main Effect Diagram According to the Interaction of Design Parameters

The noise and vibration characteristics belonging to the area of the emotional factor are classified as the Smaller-the-better characteristics of the quality characteristics, the less the noise and vibration characteristics in the current design goal.

If the Taguchi analysis is carried out with these two characteristics as the Larger-the-better characteristic and the Smaller-the-better characteristic, the efficiency indicating the performance may decrease. So, efficiency is selected as the Larger-the-better characteristic, and torque ripple, the source of noise and vibration, is selected as the noise factor.

To select the stator shape parameters for the reduction of torque ripple, we analyze the <Main effect diagram according to the interaction of design parameters>, which examines how the factors affect the response by plotting the average of the data for each level of one or more factors.

In Fig 1, slot opening and tooth width with a large slope are the factors that have the greatest influence on the quality characteristics. These two factors are divided into 3 levels and a total of 9 experiments are conducted.

Table 1 shows the number of experiments by showing two factors divided into three levels in a table. Efficiency and torque ripple are derived by FEM analysis of all 9 cases.

No.	Slot Opening	Teeth Width
1	2.6	3.8
2	2.6	4.0
3	2.6	4.2
4	3.0	3.8
5	3.0	4.0
6	3.0	4.2
7	3.4	3.8
8	3.4	4.0
9	3.4	4.2

Table 1: Taguchi Experiments Worksheets

3. FEM Analysis

Fig 2 shows the FEM cross-section of the base model. The base model is an outer rotor type 10-pole 12-slot BLAC, and some specifications are shown in Table 2.

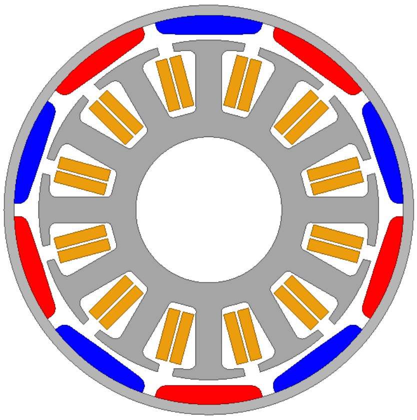

Fig. 2: Base Model FEM Analysis 2D Cross-Section

Parameter	Specification	Unit
Num. of Pole	10	-
Num. of Slot	12	-
Turns	17	-
Slot Opening	3.0	mm
Stator Length	15	mm
Rotor Length	19	mm
Torque Ripple	0.45	%
Efficiency	81.98	%

Table 2: Base Model's Specification

Figures 3 and 4 are the FEM result efficiency graph and torque ripple graph of the base model.

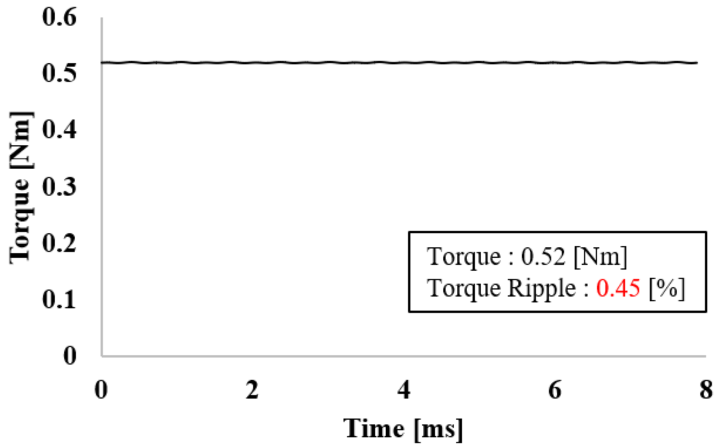

Fig. 3: Base Model's Torque Graph

Efficiency was 82.08% and torque ripple was 0.45%. The number of turns of the winding, applied current, and voltage are all set to be the same, and FEM analysis of 9 comparative models is performed.

No.	Slot Opening	Teeth Width	Efficiency	Torque Ripple
1	2.6	3.8	81.18	0.94
2	2.6	4.0	81.47	0.75
3	2.6	4.2	81.64	0.64
4	3.0	3.8	81.51	0.71
5	3.0	4.0	81.75	0.60
6	3.0	4.2	81.88	0.54
7	3.4	3.8	81.78	0.51
8	3.4	4.0	81.96	0.49
9	3.4	4.2	82.06	0.41

Table 3: Taguchi Experiments Worksheet Results

Table 3 shows the design change factors of the nine models subjected to the FEM analysis, and the resulting efficiency and torque ripple. The contents of Table 3 are analyzed using the Taguchi technique.

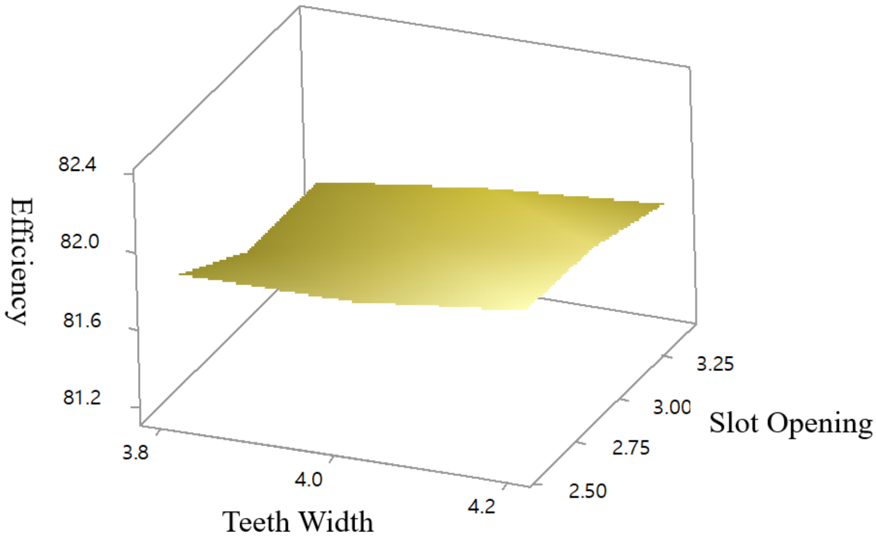

Fig. 4: Taguchi Analysis Result Efficiency 3D Graph

Among the 9 models tested, the models with no decrease in efficiency and reduced torque ripple were models 3, 6, and 9. Among them, the model that most effectively showed optimal efficiency and torque ripple is model number 9. Repeating the same process several times is a good way to ensure the reliability of the results, but the difference is not significant.

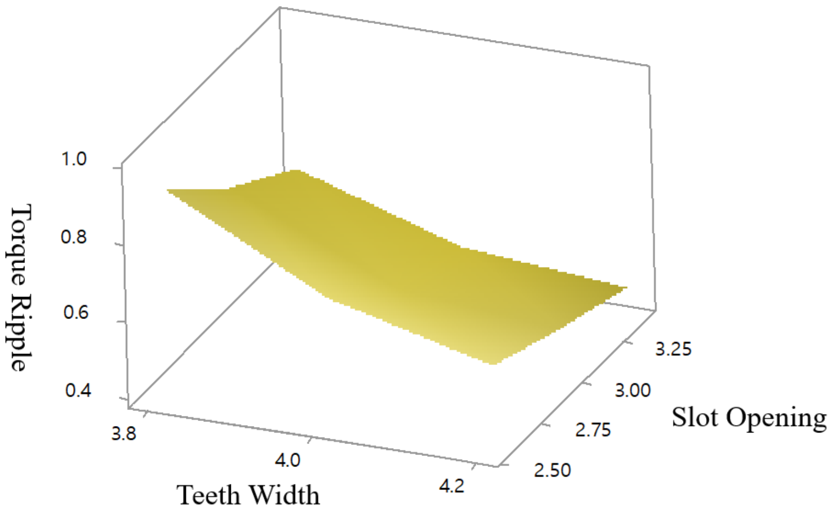

Fig. 5: Taguchi Analysis Result Torque Ripple 3D Graph

Fig 4 and Fig 5 show the analysis results using a 3D plan view. Now that the optimal design conditions are obtained, the final model is designed. Figures 6 shows the torque ripple of the optimal model, respectively. Numerically, the efficiency increased by 0.08% and the torque ripple decreased by 0.04%.

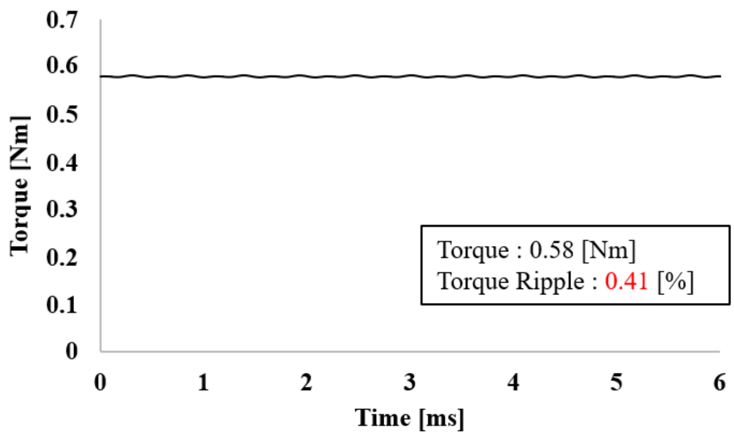

Fig. 6: Optimal Model's Torque Graph

4. Conclusion

When designing improved motors in the general industry, it is often the case that an existing motor is benchmarked, and improved design is carried out. In addition, the performance of the motor should be improved with the minimum number of cases within the limited change conditions during the improvement design. In this paper, we propose a method for improving design by changing only sensitive parameters effectively and quickly using the Taguchi technique in the above-mentioned situation. To reduce noise, only the shape parameters that have the most influence on torque ripple were adjusted, and the existing performance was analyzed in the direction of maintaining or further improving.

5. Acknowledgments

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea (No. 20204030200080).

6. References

1. Barbarosoglu, G. & Pinhas, D. (1995). Capital rationing in the public sector using the analytic hierarchy process. *The Engineering Economist*, 40, 315-341. DOI:
2. Bianchi, N., & Canova, A. (2002). FEM analysis and optimisation design of an IPM synchronous motor.
3. Chung, S. U., Moon, S. H., Kim, D. J., & Kim, J. M. (2015). Development of a 20-pole–24-slot SPMSM with consequent pole rotor for in-wheel direct drive. IEEE Transactions on Industrial Electronics, 63(1), 302-309.
4. Fang, J., Li, H., & Han, B. (2011). Torque ripple reduction in BLDC torque motor with nonideal back EMF. IEEE transactions on power electronics, 27(11), 4630-4637.
5. Hur, J., Reu, J. W., Kim, B. W., & Kang, G. H. (2011). Vibration reduction of IPM-type BLDC motor using negative third harmonic elimination method of air-gap flux density. IEEE Transactions on Industry Applications, 47(3), 1300-1309.

6. Jang, S. M., Cho, H. W., & Choi, S. K. (2007). Design and analysis of a high-speed brushless DC motor for centrifugal compressor. IEEE Transactions on Magnetics, 43(6), 2573-2575.
7. Jeon, Y. S., Mok, H. S., Choe, G. H., Kim, D. K., & Ryu, J. S. (2000, July). A new simulation model of BLDC motor with real back EMF waveform. In COMPEL 2000. 7th Workshop on Computers in Power Electronics. Proceedings (Cat. No. 00TH8535) (pp. 217-220). IEEE.
8. Jeyapaul, R., Shahabudeen, P., & Krishnaiah, K. (2005). Quality management research by considering multi-response problems in the Taguchi method–a review. The International Journal of Advanced Manufacturing Technology, 26(11), 1331-1337.
9. Kim, D. K., Lee, K. W., & Kwon, B. I. (2006). Commutation torque ripple reduction in a position sensorless brushless DC motor drive. IEEE Transactions on Power Electronics, 21(6), 1762-1768.
10. Ko, H. S., & Kim, K. J. (2004). Characterization of noise and vibration sources in interior permanent-magnet brushless DC motors. IEEE Transactions on Magnetics, 40(6), 3482-3489.
11. Lascu, C., Boldea, I., & Blaabjerg, F. (2000). A modified direct torque control for induction motor sensorless drive. IEEE Transactions on industry applications, 36(1), 122-130.
12. Lee, T. Y., Seo, M. K., Kim, Y. J., & Jung, S. Y. (2016). Motor design and characteristics comparison of outer-rotor-type BLDC motor and BLAC motor based on numerical analysis. IEEE Transactions on Applied Superconductivity, 26(4), 1-6.
13. Miller, T. J. E., Hutton, A., Cossar, C., & Staton, D. A. (1991). Design of a synchronous reluctance motor drive. IEEE Transactions on industry applications, 27(4), 741-749.
14. Miyamasu, M., & Akatsu, K. (2013). Efficiency comparison between Brushless dc motor and Brushless AC motor considering driving method and machine design. IEEJ Journal of Industry Applications, 2(1), 79-86.
15. Ta, C. M., & Hori, Y. (2001). Convergence improvement of efficiency-optimization control of induction motor drives. IEEE Transactions on Industry Applications, 37(6), 1746-1753.
16. Wang, H. T., Liu, Z. J., Chen, S. X., & Yang, J. P. (1999). Application of Taguchi method to robust design of BLDC motor performance. IEEE Transactions on Magnetics, 35(5), 3700-3702.