REDUCTION OF COGGING TORQUE IN IPM MOTORS BY USING THE TAGUCHI AND FINITE ELEMENT METHOD

S. RASHIDAEE and S. Asghar GHOLAMIAN

Babol, University of Technology, Faculty of Electrical and Computer Engineering **(Iran)**

ABSTRACT

This paper proposes a method for shape optimization for reduction of cogging torque in Interior Permanent Magnet (IPM) motor. In the process of optimization, use the Taguchi Experiment Design and The optimization is realized by analyses and simulations with Finite Element Analysis (FEA). The design optimization process is described and results are presented in this paper. Results from simulations, indicate reduction of cogging torque and torque ripple and doesn't considerable 1.16% decrease of the average of motor's output torque.

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KEYWORDS

Interior Permanent Magnet motor; Finite Element Method; Taguchi Experiment Design Method

1. INTRODUCTION

BLDC motors are being widely used in speed and position control systems for its characteristics of high efficiency and easy speed control [1]-[4]. However, cogging torque caused by the interaction between permanent magnets and stator teeth is usually an inherent problem in BLDC motors. Cogging torque, showing itself as tending to make the rotor remain at certain positions or preventing the motor to rotate smoothly, is a major factor of torque ripple which results in undesirable vibration and noise. To a large extent, this problem restricts such motors to be applied in some accurate motion control systems. The interior permanent magnet (IPM) motor is one of the most attractive motors applied in a compact system. Because the motor generates both magnetic torque and reluctance torque, it can have high power density per motor volume. In an IPM motor, however, torque ripple increased by reluctance torque causes noise and vibration, and the amplitude of torque ripple generally depends on permanent magnet arrangement in the rotor of IPM motor. Since permanent magnet arrangement in the rotor has a great effect on reluctance torque, optimization of the rotor shape is required to improve performance of IPM motor [5]. various techniques can be adopted to reduce cogging torque such as design of fractional ratio of slots per phase, no uniformed teeth structure, skew stator stack or magnet [5]–[10].

In this paper carries out optimization of four design variables, of the V-type IPM motor. The Taguchi method is chosen as one of the many optimization methods. Compared to other optimization methods, such as genetic algorithms-based optimization techniques [20], [21], rosenbrock□s method [23], [24], and response surface method [22], the taguchi method has been proven its useful in industrial process to improve quality. In comparing with experimental frequency of optimization methods, if there are four variables each at three levels, full factorial approach needs 3^4=81 experiments. On the other hand, the Taguchi method can obtain satisfactory results by only nine times [7]. Thus, with changing the rotor shape, this paper describes the rotor design to reduce cogging torque by the robust design. The torque and cogging torque waveform with variations in stator and magnet shapes have been computed using 2-D finite element analysis (FEA).

2. MODEL OF MOTOR

The schematic diagram of the V-type IPM motor under study shown in Figure 1 and the main parameters are shown in Table 1.

Table1. Main parameters of the IPM motor

Stator outer diameter	270 mm
Stator inner diameter	162 mm
Rotor outer diameter	161.5 mm
Shaft outer diameter	110.5 mm
Number of slots	48
Number of poles	8
Air gap length	0.5 mm
Stator and rotor core material	DW360-50
PM material	NdfeB 30SH

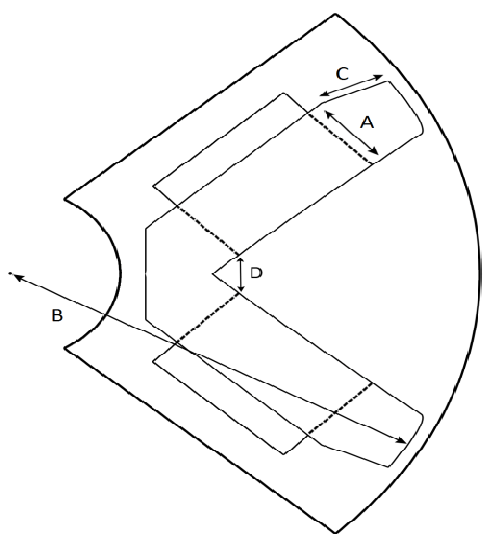

Figure1. Rotor configuration of v-type IPM motor.

3. DESIGN OF EXPERIMENT

The Taguchi Method by Using Orthogonal Array Tables extremely reduced the number of experiments. These arrays of special features among the total number of experiments are selected. It is noteworthy that the answer does not necessarily optimal in there and selected experiments using the Taguchi method of calculation of the array experiments can be answered in optimal conditions and to determine the optimal conditions and at the end by Confirming test, confirming its accuracy can be obtained comes [12],[13].

3.1. Design Factors

The design factors and their respective levels are given in Table 2, where A is the width of duct in millimeters, B is the distance from duct edge from shaft in millimeters, C is the duct height in millimeters, D is minimum distance of two magnets in millimeters.

Table2. Level of design factors

Factors	Level 1	Level 2	Level 3
A [mm]	4.2	4.7	5.2
B [mm]	78.22	78.72	79.22
C [mm]	2.5	3	3.5
D [mm]	3.5	4.5	5.5

3.2. Conduct the Experiment

A standard taguchi's orthogonal array L-9 used for the matrix numerical experiments is shown in Table 3. There are only 9 experiments required for us to determine the optimum combination of the levels of these factors as shown in Table 3 and to know the contribution of each to produce the values of average torque and cogging torque. On the other hand, the taguchi method can obtain satisfactory results by only nine times that saves considerable time of simulation to reach the optimal point. To obtain the values of average torque and cogging torque for each case, 2-D FEM analysis is conducted. Table 4 shows the results of simulation results.

4. ANALYSIS OF SIMULATION RESULT

After conducting the matrix experiment and obtaining all the simulation results, analysis of means (ANOM) and analysis of variance (ANOVA) are carried out to estimate the effects of the four design parameters and determine the relative importance of each design variable, respectively [24].

Table3. L-9 orthogonal array

Experiment	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table4. Simulation results

Experiment	T_c (N.m)	T_{avg} (N.m)
1	2.5851	212.8295
2	1.3727	216.821
3	2.1563	219.521
4	2.985	215.097
5	2.3393	225.1016
6	4.969	236.9437
7	3.2042	222.7802
8	4.9355	234.1338
9	5.2520	245.03

4.1. Analysis of means (ANOM)

The means of all simulation results can be calculated as

$$m = \frac{1}{9}\sum_{i=1}^{9} T_i \qquad (1)$$

Table 5 tabulates the results.

Table5. Analysis of means

	T_c (N.m)	T_{avg} (N.m)
m	3.3110	225.362

4.2. Calculate Average Effect

The value of average torque of setting variable A at level 3 is calculated by

$$mA_2(T_{avg}) = \frac{1}{3}(T_{avg}(4) + T_{avg}(5) + T_{avg}(6)) \qquad \textbf{(2)}$$

Where the factor A is set to level 2 only in experiments 4, 5, 6 as shown in Table 3. average torque of all variables can be obtained by a similar way. Table 6 shows the results. A plot of main factors effects is illustrated in fig 2. It is seen that the factor-level combination (A3, B3, C1, D1) contributes to maximization of average torque.

Table6. Average torque for all levels of factors

	Ai	Bi	Ci	Di
i=1	216.3905	216.9022	227.969	227.6537
i=2	225.7141	225.3521	225.6494	225.515
i=3	233.9814	233.8316	222.4676	222.9173

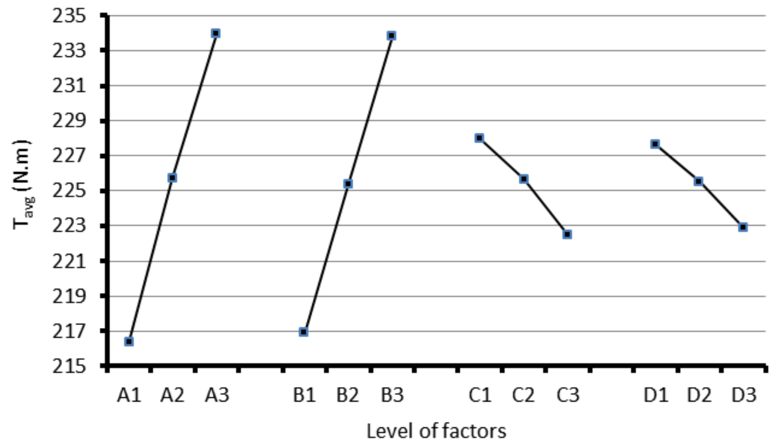

Figure2. Main factor effects on average torque

In a similar way, the peak to peak value of cogging torque can be obtained for all levels of factors . the results are shown in Table 7. Fig 3 illustrates the main factor effect on the peak to peak value of cogging torque. It is seen that the factor-level combination (A1, B2, C3, D2) contributes to minimum peak to peak value of cogging torque.

Table7. Peak to peak value of cogging torque for all levels of all factors

	Ai	Bi	Ci	Di
i=1	2.0380	2.9947	4.1632	3.3921
i=2	3.4310	2.8825	3.2032	3.182
i=3	4.464	4.1258	2.5666	3.359

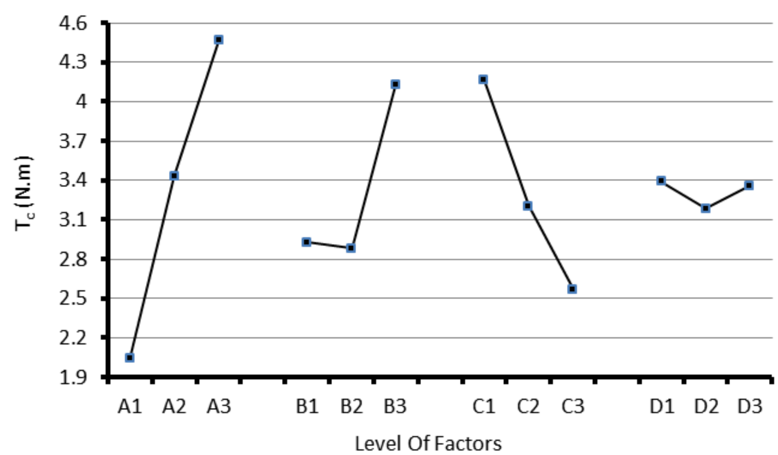

Figure3. Main factor effects on peak to peak value of cogging torque

4.3. Analysis Of Variance (ANOVA)

An important purpose of ANOVA is to determine the relative importance of the various design variables. to conduct ANOVA, the sum of squares (SS) is calculated first. It is measure of the deviation of simulation data from the mean value of the data. The sum of squares (SSF_c) due to various factors can be calculated as

$$SSF_C = 3\sum_{i=1}^{3}(m_{C_i} - m)^2 \tag{3}$$

SSF_A, SSF_B and SSF_D can be obtained in the same way. These results show in Table 8.

Table8. Effects of all factors on characteristic analysis

	T_{avg} (N.m)		T_c (N.m)	
	SSF	Factor effect (%)	SSF	Factor effect (%)
A	464.713	47.7047	8.892	56.1563
B	429.906	44.1316	2.990	18.8830
C	45.770	4.6984	3.876	24.477
D	33.7555	3.4651	0.076	0.4836
Total	974.144	100	15.834	100

5. MAGNETIC FIELD ANALYSIS

After the motor has been properly modeled, a 2D FEM magnetic field calculation is performed. The distribution of the magnetic field is presented in Fig. 4.

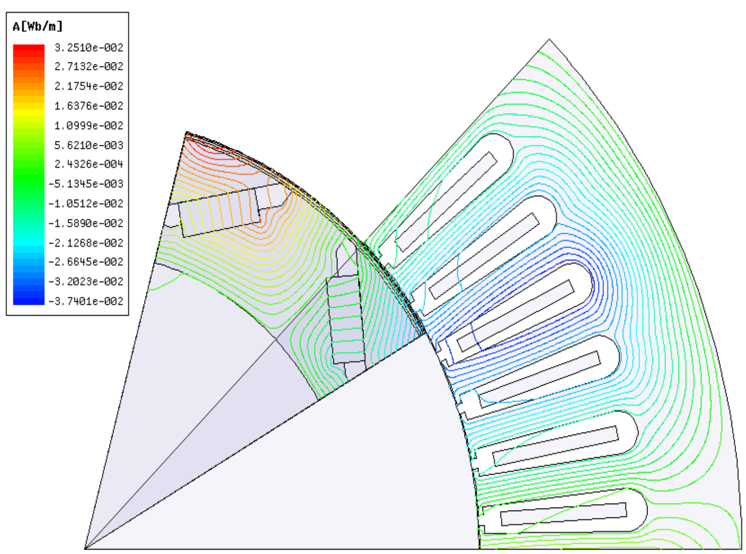

Figure4. Magnetic field distribution for IPM motor

6. DESIGN OPTIMIZATION

According to Table 6 and Fig. 2 that the best combination of design parameters for maximum average torque is determined to be (A3,B3,C1,D1). It is also noted in Table 7 and Fig. 3 that the best combination of design parameters for minimum the peak to peak value of cogging torque is determined to be (A1,B2,C3,D2). None of levels don't selected to constitute the elements of the optimum design for maximum average torque and minimum the peak to peak value of cogging torque. It is seen that in Table 8 factor A, has larger effect on Tc (56.156%) to Ta (47.713%), factor B, larger effect on Ta (44.132%) to Tc (18.883%), Factor C, has larger effect on Tc (24.477%) to Ta (4.6984%) and factor D, also has larger effect on Ta (3.4651%) to Tc (0.4836%). Therefore, the best combination of design parameters for minimum the peak to peak value of cogging torque and for maximum average torque is determined to be (A1,B3,C3,D1). The performance of the optimized machine was obtained using FEM analysis again and compared with the initial one. Table 9 compares the data of the machine between the initial, Taguchi parameter designs and simulation results. It can be seen that The peak to peak value of cogging torque decreases from the initial design of 3.5290 Nm to Taguchi parameter design of 2.1896 Nm, and to simulation result of 2.1463 Nm, that represent 39.18% decreases in cogging torque. . However the average torque only decreases from the initial design of 225.9689 N.m to Taguchi parameter design of 224.2574 N.m, and to simulation result of 223.3301 N.m, that represent only 1.16% decreases in average output torque.

Table9. Comparison Results

	T_{avg} (N.m)	T_c (N.m)
Initial	225.9689	3.5290
Taguchi results	224.2574	2.1896
Result after optimization	223.3301	2.1463

Graphic performance comparison the average torque between initial and optimized desighn is given in fig 5.

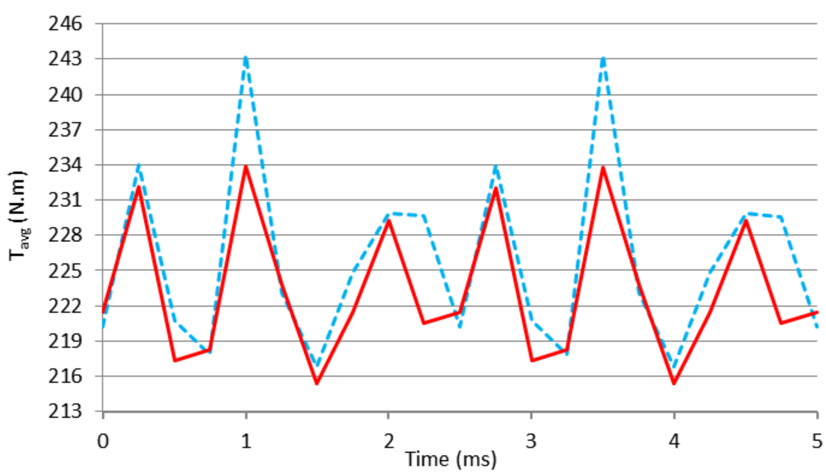

Figure5. Output torque of initial design (blue line) and optimized design (red line)

Fig .6, Compares the cogging torque between initial and optimized design.

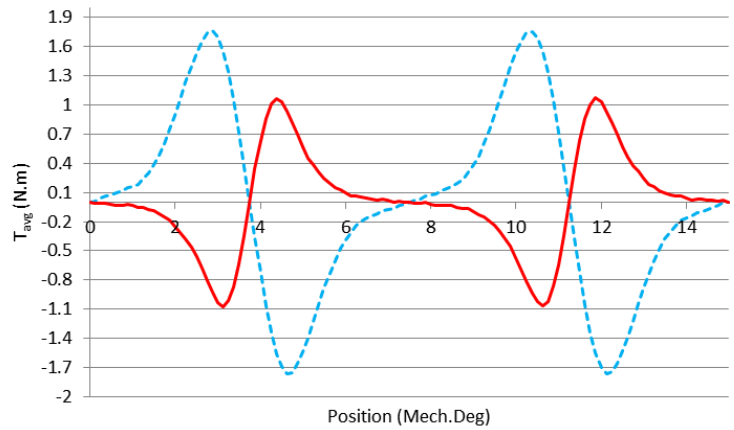

Figure6. Cogging torque of initial design (blue line) and optimized design (red line)

For better comparison result, output torque ripple has been calculated before and after optimization. Output torque ripple calculated from division of the AC rms value to average output torque. Also Value of output torque ripple has been compared in Table 10. The output torque ripple after optimization has 22.73% considerable decrease.

Table10. The comparison of output torque ripples before and after optimization.

	AC rms value (N.m)	Output ripple torque (%)
Initial	7.8314	3.4657
Result after optimization	5.9801	2.6777

7. CONCLUSION

This paper applied the Taguchi methods to design optimization of IPM motor for the minimization the cogging torque and without considerable decrease of the output average torque. Because of using taguchi method, we have least of simulations for optimal design. Comparison of result before and after optimization shows 39.18% decreases in cogging torque, doesn't considerable 1.16% decrease of output average torque and considerable 22.73% decrease ripple of output torque curve.

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Sayyed Asghar Gholamian was born in Babolsar, Iran, in 1976. He received a B.Sc. degree in electrical engineering from K.N.Toosi University of Technology, Tehran, Iran in 1999 and a M.Sc. degree in electric power engineering (electrical machines) from university of Mazandaran, Babol, Iran in 2001. He also received the Ph.D degree in electrical engineering from K.N.Toosi University of Technology, Tehran, Iran in 2008. He is currently an assistant professor in the department of Electrical Engineering at the Babol University of Technology, Iran. His research interests include power electronic and design, simulation, modeling and control of electrical machines (motor, generator and transformer).