Optimization for Reduction of Torque Ripple in an Axial Flux Permanent Magnet Machine

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This paper presents an axial-flux permanent magnet (AFPM) machine with an internal coreless stator and twin external permanent magnet (PM) rotors, based on the finite-element method (FEM) by robust design, call Taguchi method to the optimum design for minimum the torque ripple and maximum the ratio between torque ripple and average torque. The optimization is realized by analyses and simulations with finite-element analysis (FEA). The design optimization process is described and the results are presented in this paper.

***Index Terms*—Axial flux permanent magnet (AFPM), finite-element analysis (FEA), Taguchi method, torque ripple.**

I. Introduction

IN recent years, axial-flux permanent magnet (AFPM) machines have been used increasingly in industrial drives for various applications due to the benefits of high efficiency and simplicity of construction [1]–[3]. However, similar to the conventional radial flux permanent magnet (RFPM) machines, AFPM machines also produce undesirable torque ripples in the developed electromagnetic torque that affect their output performance. Normally, the main sources of torque ripple can be classified into four categories: cogging torque, nonideal back EMF waveforms, saturation of the machine magnetic circuit, and electronic controller induced.

Ideally, an AFPM machine with coreless stator design may eliminate the cogging torque completely. Nevertheless, parasitic torque ripples still exist due to limitations in machine design even if ideal controller implementation.

A lot of techniques have been proposed to reduce the torque ripple in RFPM machines by many researchers [4]–[8] including the slots or magnets skewing, magnet shaping and sizing, adding dummy slots, and control strategies. Recent attention has been given in the literature to reduce cogging torque in AFPM machines [9], [10]. In this paper, the design of an AFPM machine with an internal coreless stator and twin external permanent magnet (PM) rotor is based on the well established design procedures [3], [11], [12], and the Taguchi method [13], [14] for reducing the torque ripple and improving the ratio between torque ripple and average torque is described using the techniques presented in [4]–[10].

Compared to the other optimization methods, such as genetic algorithms-based optimization techniques [15], [16], response surface method [17], and Rosenbrock's method [18], [19], the Taguchi method has been proven its useful in industrial process to improve quality. And it does not require to use sophisticated algorithms and additional programming aside from the finite-element analysis (FEA) of electromagnetic field. It also allows many settings of as many as necessary design parameters in optimization computation. Hence, effects of several factors on machine performance can be investigated simultaneously. The effectiveness of the technique is confirmed by measurements.

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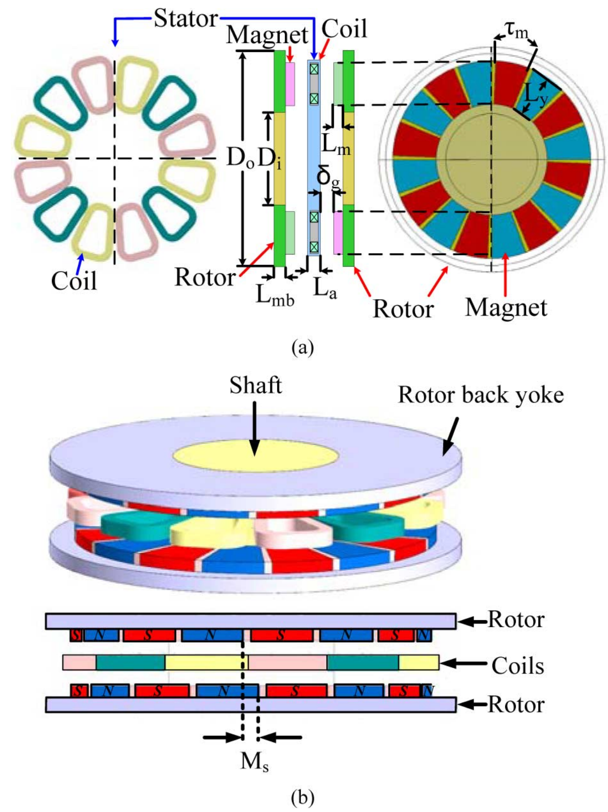

Fig. 1. AFPM machine topology showing geometrical definitions.

II. Model of the Motor

Fig. 1 shows a three-phase, 36-V, 400-W, 3600-rpm, Y-connected AFPM machine. It consists of a coreless stator with 12 single layer trapezoidally shaped coils sandwiched between two 16-pole rotors. Each rotor disc consists of 16 magnets of alternating polarity. The initial design of the machine parameters are given in Table I.

TABLE I
MACHINE PARAMETERS

Parameters	Values
Rotor outer diameter, D_o [mm]	120
Rotor inner diameter, D_i [mm]	65
Axial thickness of rotor yoke, L_{mb} [mm]	5
Axial length of air gap, δ_g [mm]	0.5
Radial thickness of Magnet, L_y [mm]	26.5
Axial thickness of magnet, L_m [mm]	2.5
Axial thickness of stator, L_a [mm]	5
Magnet pole-arc/pole-pitch ratio, α	0.889
Circumferentially changing the relative position of the two rotors, M_s [°M]	0

TABLE II
LEVELS OF DESIGN VARIABLE

Design variable	Level 1	Level 2	Level 3	Level 4
A: δ_g [mm]	0.5	0.75	1	1.25
B: α	0.8	0.844	0.889	0.933
C: L_y [mm]	25.5	26.5	27.5	28.5
D: L_m [mm]	1.75	2	2.25	2.5
E: M_s [°M]	0	0.5	1	1.5

III. DESIGN OF EXPERIMENT

Taguchi's parameter design method provides the designers with a systematic and efficient approach for conducting the numerical experiments to determine near optimum settings of design parameters. In this technique, an orthogonal array that depends on the number of factors and levels included is used to study the parameter space [13], [14]. The performance of the motor in the matrix experiments are computed using the 3-D FEA software FLUX3D [20].

A. Establish Orthogonal Array

In this AFPM machine, the axial thickness of the air gap and magnets are the most important part that affects the machine performance [3]–[10]. Accordingly, five design variables related to these parts are chosen in the study as shown in Fig. 1. The factors and their respective levels are given in Table II, where A is the axial length of the air gap in millimeters (levels 0.5, 0.75, 1, and 1.25), B is the ratio of magnet pole-arc (τ_m) to pole pitch (levels 0.8, 0.844, 0.889, and 0.933), C is the radial thickness of magnet in mm (levels 25.5, 26.5, 27.5, and 28.5), D is the axial thickness of magnet in mm (levels 1.75, 2, 2.25, and 2.5), and E is the circumferentially changing the relative position of the two rotors in mechanical degrees (°M) (levels 0, 0.5, 1, 1.5) as shown in Fig. 1(b). A standard Taguchi's orthogonal array L-16 used for the matrix numerical experiments is shown in Table III, [13], [14].

B. Conduct the Experiment

There are 16 experiments required for us to determine the optimum combination of the levels of these factors as shown in Table III and to know the contribution of each to produce the values of torque ripple and average torque. To obtain the values of torque ripple and average torque for each case, 3-D FEM analysis is conducted. Table IV tabulates the motor performance indexes.

TABLE III
L-16 ORTHOGONAL ARRAY AND RESULTS

Experiment	A	B	C	D	E
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

TABLE IV
MOTOR PERFORMANCE

Experiment	T_a (N.m)	T_r (N.m)	T_r/T_a (%)
1	1.2307	0.2122	17.24
2	1.3940	0.2274	16.31
3	1.5620	0.3212	20.56
4	1.6986	0.4982	29.33
5	1.4309	0.2256	15.77
6	1.4607	0.1882	12.88
7	1.3488	0.2839	21.05
8	1.4402	0.3158	21.92
9	1.4412	0.2118	14.69
10	1.4841	0.2170	14.62
11	1.2010	0.3285	27.35
12	1.1593	0.3469	29.92
13	1.2337	0.1845	14.95
14	1.1079	0.2277	20.55
15	1.3828	0.2569	18.58
16	1.2032	0.3035	25.22

T_a = average torque, T_r = peak-to-peak value of torque ripple

TABLE V
ANALYSIS OF MEANS

	T_a (N.m)	T_r (N.m)	T_r/T_a (%)
m	1.3612	0.2718	20.06

IV. ANALYSIS OF RESULTS

After conducting the matrix experiments and obtaining all the experimental data, analysis of means and analysis of variance are carried out for estimating the effect of design parameters and for determining the relative importance of each design parameter.

A. Analysis of Means

The means of all results can be calculated as

$$m = \frac{1}{16}\sum_{i=1}^{16} T(i). \tag{1}$$

Table V tabulates the results.

B. Calculate Average Effect

The value of average torque of setting factor D at level 2 is calculated as

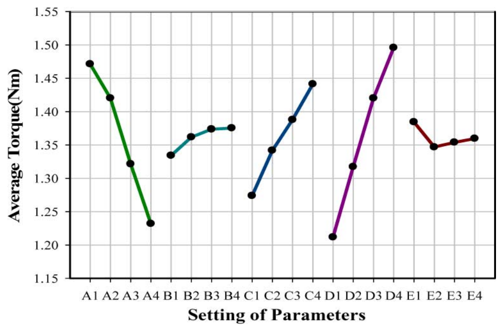

Fig. 2. Main factor effects on average torque.

TABLE VI
AVERAGE TORQUE FOR ALL LEVELS OF ALL FACTORS

Settings/ Factors	A_i (Nm)	B_i (Nm)	C_i (Nm)	D_i (Nm)	E_i (Nm)
i = 1	1.4713	1.3341	1.2739	1.2117	1.3844
i = 2	1.4202	1.3617	1.3418	1.3172	1.3468
i = 3	1.3214	1.3736	1.3879	1.4201	1.3539
i = 4	1.2319	1.3753	1.4413	1.4958	1.3596

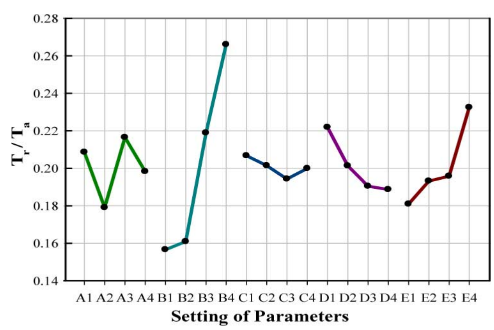

Fig. 3. Main factor effects on the ratio between torque ripple and average torque.

$$m_{D_2}(T_a) = \frac{1}{4}(T_a(2) + T_a(8) + T_a(11) + T_a(13)) \quad (2)$$

where the factor D is set to level 2 only in experiments 2, 8, 11, and 13 as shown in Table III. The values of average torque for all levels of factors can be obtained in a similar way. Table VI shows the results. Fig. 2 illustrates the main factor effects on average torque. It is seen that the factor-level combination (A1, B4, C4, D4, E1) contributes to maximization of average torque.

The ratio between torque ripple and average torque for all levels of factors can be obtained in the same way. The results are shown in Table VII. Fig. 3 illustrates the main factor effects on the ratio between torque ripple and average operational torque. The level combinations (A2, B1, C3, D4, E1) contributes to minimization of average torque and ratio between torque ripple and average operational torque, respectively.

C. Analysis of Variance

Analysis of variance (ANOVA) provides a measure of confidence. The technique does not directly analyze the data, but rather determines the variance of the data. To conduct ANOVA, the sum of squares (SS) is calculated first. It is a measure of the deviation of the experimental data from the mean value of the data. The sum of squares (SSF_A) due to various factors can be calculated as

TABLE VII
TORQUE RIPPLE/AVERAGE TORQUE FOR ALL LEVELS OF ALL FACTORS

Settings/ Factors	A_i (%)	B_i (%)	C_i (%)	D_i (%)	E_i (%)
i = 1	20.86	15.66	20.67	22.19	18.09
i = 2	17.91	16.09	20.15	20.14	19.32
i = 3	21.65	21.89	19.43	19.04	19.58
i = 4	19.83	26.60	19.99	18.87	23.25

TABLE VIII
EFFECTS OF ALL FACTORS ON MOTOR PERFORMANCE INDEXES

Factors	T_a		T_r/T_a	
	SSF	Factor effect (%)	SSF	Factor effect (%)
A	0.1356	35.02	31.415	7.040
B	0.0044	1.120	324.71	72.72
C	0.0605	15.62	3.1329	0.700
D	0.1836	47.41	27.977	6.270
E	0.0032	0.830	59.309	13.28
Total	0.3872	100	446.55	100

$$\mathrm{SSF}_A = 4\sum_{i=1}^{4}(m_{A_i} - m)^2. \quad (3)$$

$\mathrm{SSF}_B, \mathrm{SSF}_C, \mathrm{SSF}_D$, and SSF_E can be obtained in the same way. These results are summarized in Table VIII.

V. DESIGN OPTIMIZATION

It is noted in Table VI and Fig. 2 that the best combination of design parameters for maximum average torque is determined to be (A1, B4, C4, D4, E1). It is also noted in Table VII and Fig. 3 that the best combination of design parameters for minimum the ratio between torque ripple and average torque is determined to be (A2, B1, C3, D4, E1). Therefore, the elements D4 and E1 are immediately selected to constitute the elements of the optimum design for maximum average torque and minimum the ratio between torque ripple and average torque. On the other side, factors A, B and C are used to regulate the values of average torque and minimum the ratio between torque ripple and average torque. It is seen that in Table VIII factor A, the axial length of the air gap has larger effect on T_a (35.02%) to T_r/Ta (7.04%), and factor C, the radial thickness of magnet has also larger effect on T_a (15.62%) to T_r/Ta (0.74%). Factor B, the magnet pole-arc/pole pitch ratio has larger effect on T_r/Ta (72.7202%) to T_a (1.12%). Therefore, the best combination of design parameters for minimum torque ripple and maximum the ratio between torque ripple and average torque is determined to be (A1, B1, C4, D4, E1). The performance of the optimized machine was obtained using 3-D FEM analysis again and compared with the initial one. Table IX compares the data of the machine between the initial, Taguchi parameter designs and measurement. Fig. 4 compares the average torques. It is seen that the values of predicted and measured average torque of the optimized machine are good agreement with each other. Also, it can be seen that average torque increases from the initial design of 1.2254 Nm to Taguchi parameter design of 1.6994 Nm,

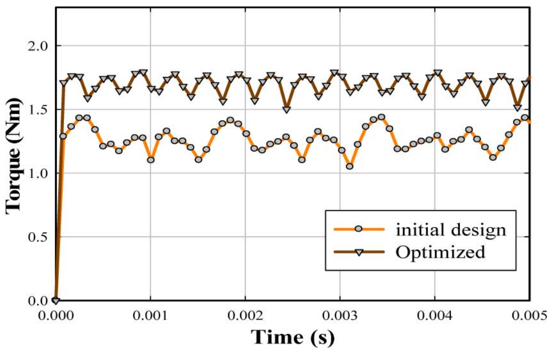

Fig. 4. Comparison of average torque.

TABLE IX
COMPARISON RESULTS

Parameters	Initial	Taguchi	Test
Rotor outer diameter, D_o [mm]	120	121	-
Rotor inner diameter, D_i [mm]	65	64	-
Axial length of air gap, δ_g [mm]	0.5	0.5	-
Magnet pole-arc/pole-pitch ratio, α	0.889	0.8	-
Radial thickness of magnet, L_y [mm]	26.5	28.5	
Axial thickness of magnet, L_m [mm]	2.5	2.5	-
Circumferentially changing the relative position of the two rotors, M_s [°M]	0	0	-
Average torque, T_a [Nm]	1.2254	1.6694	1.5800

and the ratio between torque ripple and average torque reduces from the initial design of 33.23% to Taguchi parameter design of 18.28%.

VI. CONCLUSION

This paper applied the Taguchi methods to design optimization for the minimization the torque ripple and maximization of the ratio between torque ripple and average torque. The optimal design can be obtained through the least experiments by using Taguchi method. It has been shown that, similar to RFPM machines, an optimal ratio of magnet pole arc to pole pitch and radial length of magnet exists for AFPM machines for minimum torque ripple. It has also been shown that in an AFPM machine with an internal coreless stator and twin external PM rotor, circumferentially changing the relative position of the two rotors, or changing the axial length of air gap, or changing the radial thickness of magnet is ineffective in minimizing torque ripple.

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