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Finite Element Based Design Optimization of FSPM Motor using Taguchi Method

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***Abstract*—In recent years permanent magnet has a lot of applications in industries due to the high power and torque density, high reliability, and high efficiency. The key part of the design of the electrical motor is geometry optimization. In this paper, the Taguchi method based on finite element analysis is implemented to sensitivity analysis and multi-objective design optimization of flux switching permanent magnet motors. In the design process, the electromagnetic torque, torque ripple, and PM volume are considered for objectives. The results indicate that the Taguchi optimization method can provide an optimal design of FSPM motor with a small number of simulations. Through comparison, it is found that the optimization method can provide an optimal design with better motor performance, about a 44 percent increase in the average of the electromagnetic torque.**

Keywords—FSPM Motor, DOE, Taguchi Method, FEM, and Optimization

I. Introduction

The need for reducing the cost of used material in the manufacturing of the electrical machines and also improve the performance of machines has led to considerable attempts in optimizing the structure of Permanent Magnet (PM) motors. There is a different approach to optimizing electrical machines. The Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are the most popular methods for researchers [1]– [4]. To increase the accuracy of the optimization the base requirement data for optimization must be obtained by Finite Element Method (FEM). These optimization algorithms need a huge of FEM runs so the time consumption and memory required are too high. So the need for a new optimizing algorithm that has enough accuracy and also low FE runs are obvious.

The method proposed in this paper is one of the Designs of Experiment (DOE), which is commonly known as the Taguchi optimization method. This method is one of those that use orthogonal array to screen the experimental conditions and means, the advantage of this method is that it uses the least experimental data based on the number of factors and levels in factor parameter space to achieve the best combination of parameter design and optimal results [5], [6]. Permanent-magnet (PM) motors with both magnets and armature windings on the stator (stator PM motors) have attracted considerable attention due to their simple structure, robust configuration, high power density, easy heat dissipation, and suitability for high-speed operations [7], [8]. One of these PM motors is Flux Switching Permanent Magnet (FSPM) motor. In this paper, the Taguchi method based on FEM results is applied to multi-objective optimize the motor structure. The objectives considered in this paper are the average of electromagnetic torque, torque ripple, and PM volume.

This paper consists of five sections. In section II the characteristics of the FSPM motor, design variables, and objective functions are presented. In section III, the establishment of the orthogonal array and obtained results to determine the effects of different factors on objectives are presented. In section IV, the procedure for the optimization of FSPM motor by the Taguchi method is introduced. Finally, the conclusions are given in section V.

TABLE I. Main Initial Design Dimensions and Variables

Par.	Description	Unit	Value
P	Number of Phases	--	3
I	Nominal current	A	12
N	Number of winding turns	--	46
N_r	Number of Rotor Poles	--	14
N_s	Number of stator poles	--	12
L	Axial length	m	2
R_{ir}	Inner rotor radius	mm	12
R_{or}	Outer rotor radius	mm	24.05
L_g	Air gap length	mm	0.65
R_{is}	Inner stator radius	mm	24.7
R_{os}	Outer stator radius	mm	45
R_{wtr}	Ratio width of rotor tooth	--	0.36
H_{rt}	Rotor tooth height	mm	3.602
R_{wpm}	Ratio width of PM	--	0.0958
R_{wsw}	Ratio width of the stator tooth	--	0.261
H_{st}	Stator tooth height	mm	3.264

II. Design Variables and Objective Functions

In this section the motor under study and the objective functions are introduced as follows:

A. Motor under Study

The motor under study in this paper is FSPM. In an FSPM motor, the stator windings and magnets are all located on the stator, leading to sinusoidal flux, roughness, and high speed and torque [9]. FSPM motors are suitable for high-speed applications and electric vehicles. The initial design dimensions and variables are stated in TABLE I. The motor under study is used for application as the electrical submersible pump (ESP) which aids raising oil and gas to the surface in oil wells [10].

Using Altair Flux 2018 software the FE model of FSPM motor is simulated. The FEM results are the base of the Taguchi method. The distribution of magnetic flux density and the magnetic flux path of the FSPM motor is shown in figure 1.

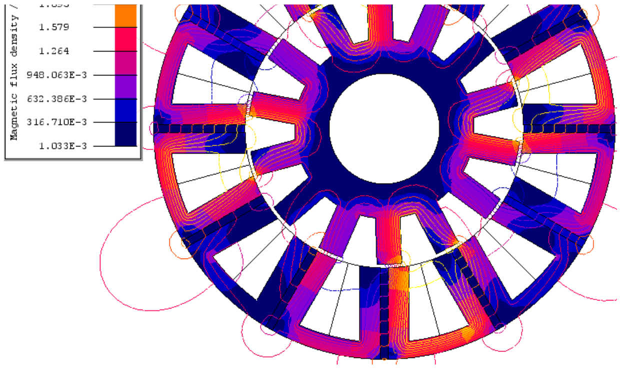

Figure 1. Distribution of magnetic flux density on the surface of the FSPM motor

B. Objective Functions and Design Variables

In this paper, three objectives are considered to be optimized. The considered objectives are the average of electromagnetic torque, torque ripple, and PM volume. As we know to improve in one objective probably leads to weakness in the other objective. So in the design optimization of electrical machines, multi-objective optimization must be carried out to all design requirements are achieved. With a tradeoff between the feasible solutions, the best design is achieved.

There are different factors that can influence the performance of the FSPM motor. In this paper, optimization is carried out in the condition that the volume of the motor is constant i.e. the outer radius and the axial length of the motor are fixed. So, eight parameters remain for sensitivity analysis (H_{st} , R_{wsw}, R_{wpm}, H_{rt}, R_{wtr}, R_{ir}, R_{is}, and L_g). For sensitivity analysis, the DOE method is applied. The details of the DOE method are presented in section III.

III. Sensitivity Analysis

In design optimization of electrical motor different parameters are influenced. In the optimization procedure, some parameters have a significant influence on the objective related to others. Ignoring this fact and optimizing all parameters leads to huge consumption time, memory required, and test samples. So, it's necessary to perform a sensitivity analysis on the motor parameters and determine the important parameters [11], [12]. The procedure of sensitivity analysis based on DOE are as follow

A. Establishment of Orthogonal Array

To implement the orthogonal design, three-level is considered for each parameter, for example, the three-level for first parameters are {(1-10%)X_1, X_1, and (1+10%)X_1}. With considering 8 parameters and 3 levels, The Taguchi array is L27 (3^8), so 27 FEM run is needed which is much lesser the required FEM run in direct optimization methods. The traditional motor design method needs to calculate every time as each factor level changes, and it needs to calculate at least 3^8 = 6561 times for experimental analysis, whereas the orthogonal array established by the Taguchi method using FEA software only needs to calculate for 27 times. The L27 array is a matrix where the rows present the combination of control factor levels for each simulation, and the columns present the control factors and the target values, the columns of the arrays are balanced and orthogonal. This means that in each pair of columns, all factor combinations occur the same number of times. Orthogonal designs let you estimate the effect of each factor on the response independently of all other factors. The orthogonal array of the Taguchi method is a simulation table layout, which uses a minimized set of simulations to learn the effects of all control factors on the target value [13], [14]. The orthogonal array by the Taguchi method is shown in TABLE II. By running the 2D FE model the results of 27 different conditions in case of electromagnetic torque, torque ripple, and PM volume are obtained.

TABLE II. Orthogonal Array and Experimental Results

Run	Factors								Torque	T_{rip}	V_{PM}
	A	B	C	D	E	F	G	H	N.m.	%	m^3
1	1	1	1	1	1	1	1	1	143.99	3.42	0.000548
2	1	1	1	1	2	2	2	2	170.101	4.84	0.000609
3	1	1	1	1	3	3	3	3	193.86	1.61	0.000670
4	1	2	2	2	1	1	1	2	161.98	3.28	0.000543
5	1	2	2	2	2	2	2	3	191.12	2.88	0.000603
6	1	2	2	2	3	3	3	1	214.64	1.73	0.000670
7	1	3	3	3	1	1	1	3	173.26	3.30	0.000524
8	1	3	3	3	2	2	2	1	203.70	2.11	0.0005838
9	1	3	3	3	3	3	3	2	231.08	2.40	0.0006418
10	2	1	2	3	1	2	3	1	217.79	2.09	0.000603
11	2	1	2	3	2	3	1	2	206.93	2.0	0.000663
12	2	1	2	3	3	1	2	3	192.59	2.40	0.000543
13	2	2	3	1	1	2	3	2	240.14	1.71	0.000583
14	2	2	3	1	2	3	1	3	227.02	2.71	0.000641
15	2	2	3	1	3	1	2	1	226.79	1.30	0.000524
16	2	3	1	2	1	2	3	3	147.10	2.81	0.000609
17	2	3	1	2	2	3	1	1	138.04	2.64	0.000670
18	2	3	1	2	3	1	2	2	123.49	4.10	0.000548
19	3	1	3	2	1	3	2	1	264.82	1.28	0.000641
20	3	1	3	2	2	1	3	2	242.87	1.51	0.000524
21	3	1	3	2	3	2	1	3	230.61	4.34	0.000583
22	3	2	1	3	1	3	2	2	160.73	6.01	0.000670
23	3	2	1	3	2	1	3	3	142.56	4.33	0.000548
24	3	2	1	3	3	2	1	1	125.25	3.41	0.000609
25	3	3	2	1	1	3	2	3	187.34	2.74	0.000670
26	3	3	2	1	2	1	3	1	165.19	1.88	0.000543
27	3	3	2	1	3	2	1	2	159.92	3.32	0.000603

B. Determining the Signal to Noise Ratio

Signal-to-Noise (S/N) ratio determines the deviation between the experimental value and the desired value and it is used to transform the performance characteristics in the optimization process. Normally, three categories of performance characteristics in the analysis of the S/N ratio are introduced: the smaller is better, the higher is better, and the nominal is better [15]. In this paper for electromagnetic torque the larger is better is considered and for torque ripple and PM volume the smaller is better is considered because we want to minimize the PM volume and torque ripple on the other side maximize the average of the electromagnetic torque.

TABLE III. Response Table for Signal to Noise Ratio for Torque

Level	A	B	C	D	E	F	G	H
1	45.36	46.19	43.41	45.47	45.32	44.66	44.63	45.27
2	45.40	45.27	45.46	45.32	45.31	45.27	45.45	45.31
3	45.16	44.46	47.06	45.13	45.29	45.99	45.84	45.35
Delta	0.24	1.74	3.65	0.35	0.03	1.34	1.21	0.08
Rank	6	2	1	5	8	3	4	7

TABLE IV. Response Table for Signal to Noise Ratio for Torque Ripple

Level	A	B	C	D	E	F	G	H
1	-8.59	-7.46	-10.8	-7.66	-8.67	-8.39	-9.82	-6.39
2	-7.27	-8.78	-7.67	-8.06	-8.27	-9.26	-8.68	-9.36
3	-9.13	-8.76	-6.53	-9.28	-8.06	-7.35	-6.50	-9.25
Delta	1.858	1.317	4.272	1.616	0.606	1.905	3.326	2.969
Rank	5	7	1	6	8	4	2	3

C. *Analysis of Mean Value*

To analyze the influences on motor performances produced by different factors at different levels, the Taguchi optimization method uses the statistical mean made by orthogonal arrays and analysis results of FEM, as shown in Figure 4 and Figure 5. The trend of main effects plot for means for electromagnetic torque is the same as the S/N ratio. But for torque ripple, the trend of the two plot is opposite which is normal and the trend is according to what we have expected.

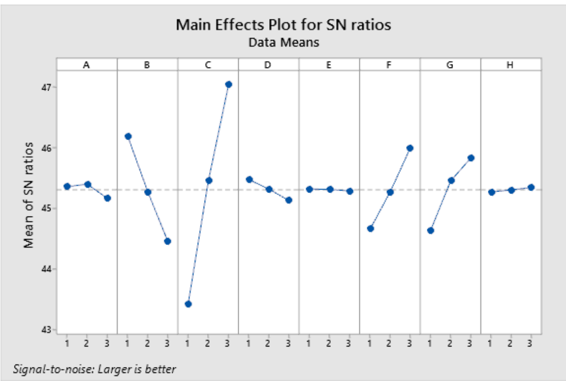

Figure 2. Main effects plot for S/N ratio of the torque

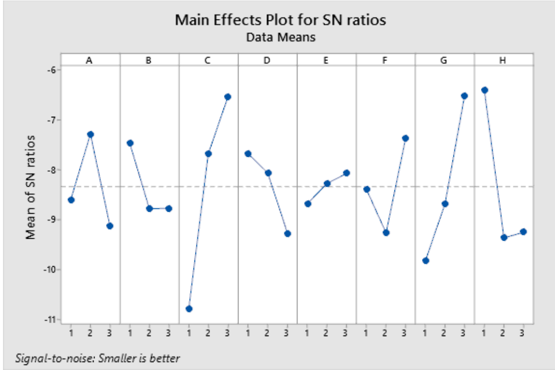

Figure 3. Main effects plot for S/N ratio of the torque ripple

Figure 4. Main effects plot for the mean value of the torque

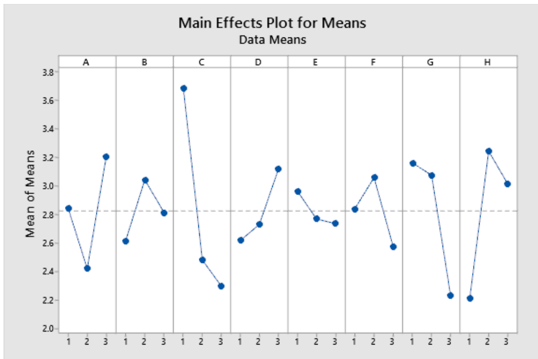

Figure 5. Main effects plot for the mean value of the torque ripple

D. *Discussion*

In the case of torque ripple and PM volume the S/N ratio determining by equation (1).

$$SN_i = 10\log(\frac{\overline{y_i}^2}{s_i^2}) \quad (1)$$

For the case of maximizing the objective function (electromagnetic torque), the S/N ratio is calculated by (2)

$$SN_i = -10\log[\frac{1}{N_i}\sum_{u=1}^{N_i}\frac{1}{y_u^2}) \quad (2)$$

Where n is the No. of measurements and y is the measured value.

The S/N ratios for torque and torque ripple are shown in TABLE III. and TABLE IV. respectively. The results have shown that factor C has a significant effect on both of the objectives. The rank of other factors on response is shown in the mentioned tables. The results showed that the optimal solution in the case of electromagnetic torque is (A2, B1, C3, D1, E1, F3, G3, and H3). In the case of torque ripple, the optimal solution is (A3, B3, C1, D3, E1, F2, G1, and H2).

IV. Optimization Using Taguchi Method

In the Taguchi method, without considering all possible combinations of design parameters, the effect of each parameter on the output response is determined. Also, is capable of extracting the appropriate combination of design parameters to achieve the optimal performance characteristic. The procedure for multi-objective design optimization of FSPM motor using the Taguchi method is shown in Figure 6.

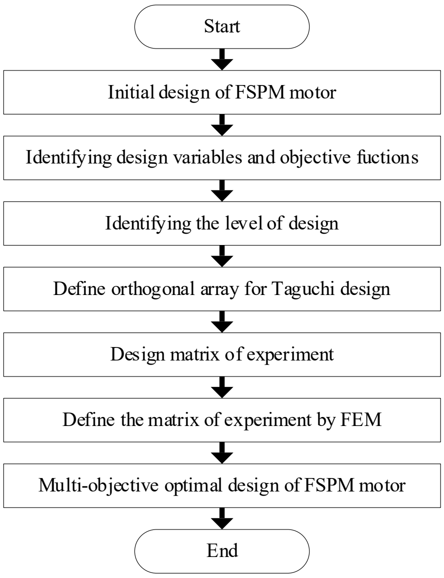

Figure 6. Taguchi optimal design procedure

In order to perform multi-objective optimal design, there are three objectives, maximizing the average torque and minimizing the torque ripple and PM volume. Based on them, an objective function is defined as follows to determine the best combination of control factor values.

$$f(x)=\frac{T_{ave}(initial)}{T_{ave}(i)}+\frac{T_{rip}(i)}{T_{rip}(initial)}+\frac{V_{PM}(i)}{V_{PM}(initial)} \quad (3)$$

The calculation method can be briefly summarized as follows [16]:

compute the f(x) of all 27 samples listed in TABLE II.

calculate the S/N ratio for each row in the table (with a target as the smaller is better)

compute the average S/N ratio for each level of all control factors

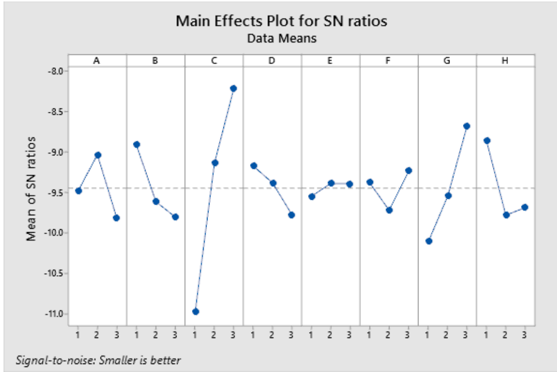

Figure 7. S/N ratios for each level of all factors.

To identify the best combination of the control factor values, figure 7 illustrates the average S/N ratios for all eight factors. The best level of each factor can be obtained by selecting a level with the highest S/N ratio. As shown, levels 2, 1, 3, 1, 3, 3, 3, and 1 should be chosen for these eight control factors, respectively.

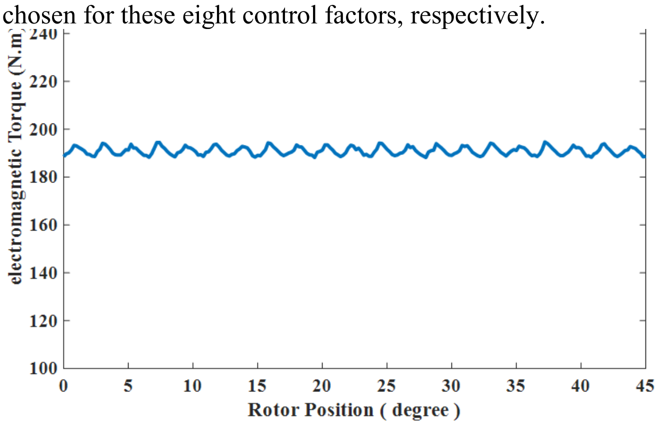

Figure 8. Electromagnetic torque of initial and modified

For the optimal design obtained from the Taguchi parameter design, the motor average torque is torque 274.78 Nm and torque ripple is 2.765 %. They are better than those of the initial design (190.91 Nm and 2.93 %). However, the PM volume is increased by about 2 %. The main reason is that only 27 samples and 3 levels have been considered for the control factors in the optimization process. There are big step sizes for different levels. Despite the slight increase in the volume of the magnet, we see a significant increase in the mean of the electromagnetic torque (about 44 %). Finally, the ratio of torque/PM volume increased by about 35%. The results shown in Figure 8 indicate that the Taguchi optimization method can provide an optimal design of FSPM motor with a small number of runs and a very high saving in computing time. The important point is that this method can determine the region of the optimal answer by the small number of simulations. Then the evolutionary algorithms like GA or PSO can obtain the global optimum design of the motor.

V. Conclusion

In this paper, a parametric analysis is carried out to investigate the impact of design parameters on the characteristic of the FSPM motor. The Taguchi design of the experimental method is used to determine the contribution of each design parameter on the desired objective function (electromagnetic torque, torque ripple, and PM volume). Several transient 2D finite element calculations are conducted to perform a sensitivity analysis and construct orthogonal array for Taguchi optimization. An optimal combination of the design parameters is determined based on the S/N ratio. The results indicate that the Taguchi optimization method can provide a multi-objective design optimization of FSPM motor with a small number of simulations. Finally, the FEM simulation results confirmed that the proposed optimization procedure effectively increases the performance of the FSPM motor in comparison with the initial design.

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