DESIGN AND OPTIMIZATION OF AXIAL FLUX PERMANENT MAGNET SYNCHRONOUS MACHINES USING TAGUCHI APPROACH

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ABSTRACT

In this study, an axial flux permanent magnet synchronous machine has been optimized for design using the Taguchi method. Five factors have been selected for optimizing , each of which has four levels. A total of sixteen experiments have been conducted according to Taguchi's L-16 orthogonal arrays. The variable to be optimized has been selected to be the air gap flux. Results from the 16 experiments have been analyzed with ANOVA. Finally, from ANOVA analysis, the best level for each of the factors and the regression equation have been determined.

I. INTRODUCTION

Axial flux machines (AFMs) offer an alternative to the conventional machines (Radial Flux Machines-RFMs). In the axial flux machine the air gap flux is axial in direction and coils that carry current are radially positioned.

The history of electrical machines shows that the earliest machines were AFMs though they were replaced by RFM after a relatively short period of time.

One objection to the AFM is the strong magnetic pull between its stator and rotor discs. However, this problem can be overcome by using a sandwich configuration with a rotor sandwiched between two stators or a stator sandwiched between two rotors[1].

Axial flux machines can be constructed in one of the fallowing ways [1]:

(i) Single stator and single rotor (one air gap)
(ii) Single stator sandwiched between two rotors (double air gaps)
(iii)single rotor sandwiched between two stators (double air gap)
(iv)a variety of multiple stators or rotors (multiple air gaps- multi modules).

Design criteria for AFMs are inner and outer stator core diameter, axial length of core and magnets, the material of the stator core, number of the poles, length of the air gap, etc. One of the most important factors is the diameter ratio k= Do/Di. Its value will influence the ratio of active to overhang length of armature winding [1].

In this study, the selected factors for optimization have been listed in table 1.

Table 1. Design factors and their levels

	levels			
Factors	1	2	3	4
Ri	50	60	70	80
hm	4	6	8	10
P	6	8	10	12
hs	35s	40s	35i	40i
g	1	2	3	4

In Table.1; Ri: inner radius of core in mm, hm: magnet's height in mm, p: number of the poles, hs: core height in mm and finally g : air gap in mm.

The quality engineering methods of Genichi Taguchi, employing statistically designed experiments, is an important tool for designing high quality system at reduced cost. These methods provide an efficient and systematic approach to optimize designs for performance, quality and cost. The objective is to identify the settings of design factors that optimize the performance characteristic and reduce the sensitivity of engineering designs to source of variation.

Using the Taguchi method, information on variable trends and interactions can be identified efficiently leading to optimum solutions and considerable resource saving. Taguchi methods have been used successfully in Japan and the United States in designing reliable, high quality products at low cost in such areas as automobiles and consumer electronics [2].

These methods are also increasingly being used in the designing of electrical machines [3]

To determine the optimum conditions a full factorial approach where all possible combination of parameter values are tried, may be necessary. Unfortunately, the time and cost involved in conducting such a detailed study during advanced design is prohibitive. As an example, if the designer is studying 8 design parameters at 3 levels, a full factorial approach would require studying 3^8= 6561 experimental configurations.

Taguchi's approach to parameter design provides the designer with a systematic and efficient method for conducting experimentation to determine near optimum settings design parameters. The Taguchi method uses orthogonal arrays from design of experiments theory to study the parameter space with a small number of experiments. The design of experiment methods were originally formalized by the British statistician R. A. Fisher in the 1920's,using arrays called fractional factorial designs. Constructions of fractional factorial designs were generally thought to be too complex and difficult to use. Taguchi simplified their use by providing tabulated sets of standard orthogonal arrays to fit a specific project.[2].

This paper briefly describes the Taguchi method and illustrates its application for a permanent magnet axial flux machine optimization.

II. APPLICATION

The axial flux permanent magnet synchronous machine has been selected for optimization. Its factors for the optimization process are listed in Table.1. The wide availability and reduction cost of high remanence, Neodymium-Iron-Boron (NdFeB) permanent magnets have made axial flux machines a cost effective alternative for low and medium power motor and generator applications. The very sort axial length required to accommodate the magnetic and electric components can lead to designs that do not require separate bearings and the high moment of inertia of the rotor can serve a useful flywheel function. Particular examples of the use of axial flux machines are for direct drive wind turbine generators.

Concntration will be placed on iron cored slotless stator and toroidal coils forming the air gap stator windings. The NdFeB magnets have been arranged circumferentially around the rotor plates in a N-S-N-S arrangement. A north magnet on one disc faces a north magnet on the other disc so that magnetic flux travels axially across the air gap and then turns circumferentially into the iron stator core before returning to the rotors one pole pitch further on. Each armature coil is wound toroidally round the stator. The number of armature coils are the same as the number of poles poles at each experiment.

The flux inside the machine arises from the permanent magnets and from the current passing through the stator coils[4]. This arrangement has been shown in Fig 1.

Determination of the magnetic flux density in an axial flux machine can be carried out by a finite element solution. To determine the air gap flux density, a 3-D finite element method has been used.

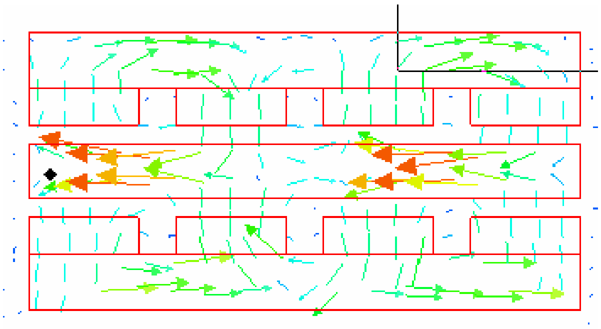

Fig. 1. Arrangement of the magnets on the rotor disks.

To optimize with factors which are listed at Table 1, Taguchi L-16 orthogonally array has been selected. The set of the factors in L-16 arrays has been shown in Table 2.

Table 2. The factors levels at Taguchi L-16 array.

experi ments	Factors				
	Ri	hm	P	hs	g
1	50	4	6	35s	1
2	50	6	8	40s	2
3	50	8	10	35i	3
4	50	10	12	40i	4
5	60	4	8	35i	4
6	60	6	6	40i	3
7	60	8	12	35s	2
8	60	10	10	40s	1
9	70	4	10	40i	2
10	70	6	12	35i	1
11	70	8	6	40s	4
12	70	10	8	35s	3
13	80	4	12	40s	3
14	80	6	10	35s	4
15	80	8	8	40i	1
16	80	10	6	35i	2

III. RESULTS

As an objective function air gap flux magnitude has been selected. The quality characteristic has been chosen as the **bigger is the best**. After all the experiments were examined, the values of air gap flux have been analyzed with MINITAB R-14 and Qualitek-4 statistical software's limited release. The whole body of the model for finite element analysis is shown in Fig. 2.

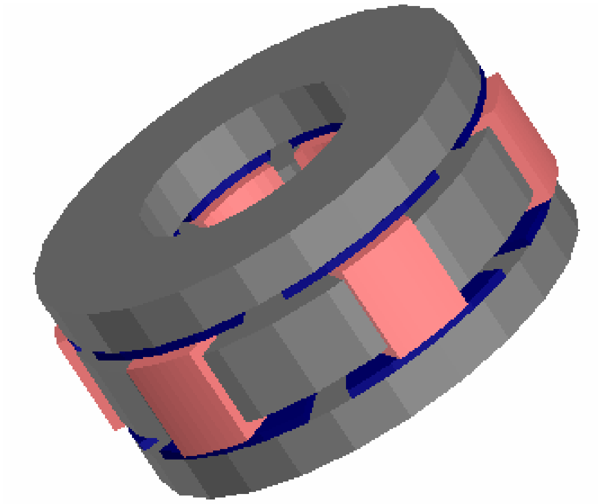

Fig.2. The whole body of the AFM's

All parts of the machine for which the FEM analysis was carried out could have been shown here if it weren't for the space limitation . Only stator surface flux vector has been shown in Fig.3.

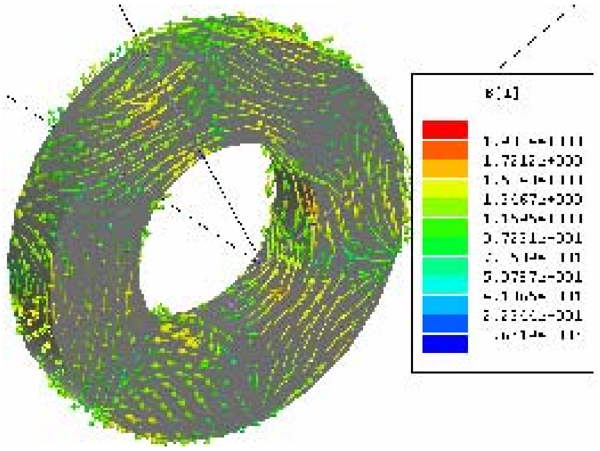

Fig. 3. The flux on stator surfaces

After all FEM analyses have been carried out, the results have been analyzed with the MINITAB software. The best level conditions of the each factor have been determined as shown in Table 3.

Table 3. The optimum levels of the factors

Column # / Factor	Level Description	Level	Contribution
1 Ri	60	2	.007
2 hm	10	4	.104
3 p	8	2	.002
4 hs	35s	1	.002
5 g	1	1	.062

There is no row which includes all optimum factor levels in Taguchi orthogonal arrays. So we must carry out a new experiment for optimum factor levels. This experiment has been conducted for two cases; without stator current and with 500 Ampere-turn stator current. In the second one, the effect of the stator current has been observed. Figs. 4 and 5 show the air-gap flux with no stator current and with 500 AT stator current respectively.

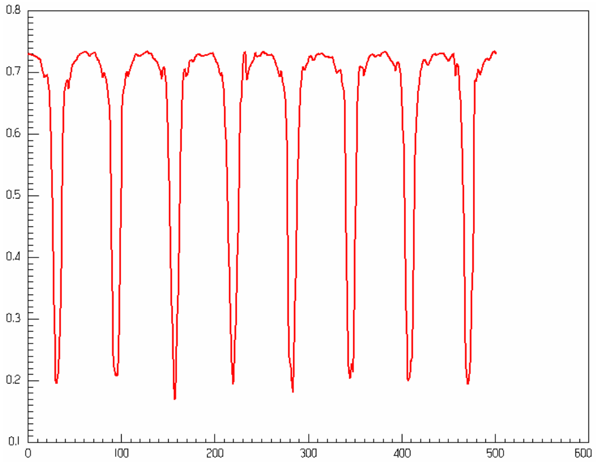

Fig. 4. The air gap flux with no stator current

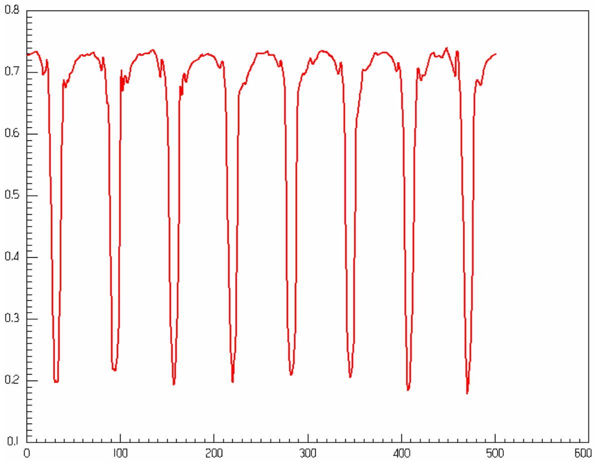

Fig. 5. The air gap flux with 500AT stator current

The air gap flux under one pole pitch has been shown in Fig. 6.

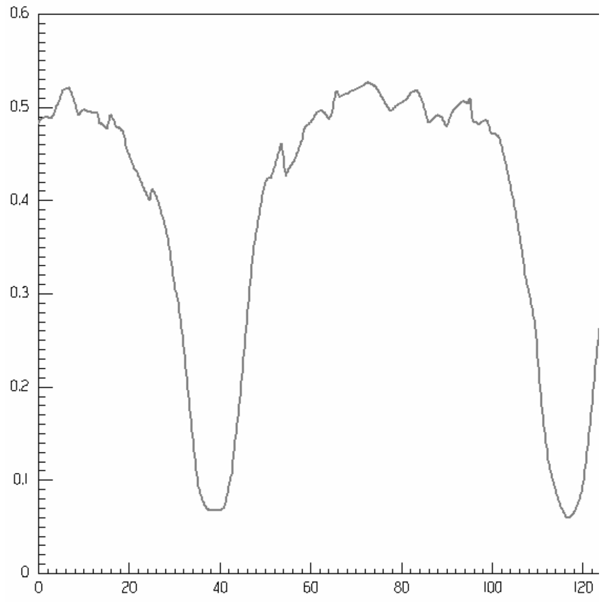

Fig. 6. The air gap flux under one pole pitch

Using Qualitk-4 software the regression equation for a best model of the AFM's has been evaluated as follows.

Regression Analysis: Bg versus Ri, hm, p, hs, g

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The regression equation is
Bg = 0.420 - 0.000390 Ri + 0.0390 hm + 0.00005 p -
0.00064 hs - 0.0399 g

Predictor        Coef    SE Coef       T      P
Constant      0.42038    0.06646    6.33  0.000
Ri         -0.0003904  0.0003851   -1.01  0.335
hm           0.039048   0.001925   20.28  0.000
p            0.000048   0.001925    0.02  0.981
hs          -0.000642   0.001623   -0.40  0.701
g           -0.039904   0.003851  -10.36  0.000

S = 0.0171866   R-Sq = 98.1%   R-Sq(adj) = 97.2%

Analysis of Variance

Source          DF        SS        MS       F      P
Regression       5  0.154046  0.030809  104.30  0.000
Residual Error  10  0.002954  0.000295
Total           15  0.157000
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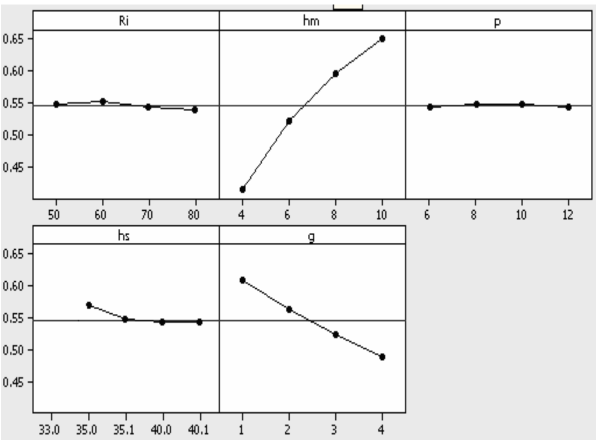

Fig. 7. Multi plot of each factor which contributes to design

IV. CONCLUSION

All these studies have demonstrated that Taguchi method can be used in the design of electrical machines. The use of Taguchi method ,along with FEM analysis, in the design of electrical machines contributes to saving remarkable time and costs in the design process of the electrical machines.

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