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A NEW IMPLEMENTATION OF TAGUCHI'S METHOD

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ABSTRACT

Taguchi's method is an efficient and important optimization method based on orthogonal array concept which offers systematic and efficient process. it causes a balance in experiments design as well. In this paper, a new implementation of Taguchi's method for shape optimization of electromagnetic devices is presented and applied to torque profile optimization of Double Stator Switched Reluctance Motor (DSSRM). Due to nonlinearity of DSSRM Torque characteristic, Finite Element Analysis is implemented. Previous implementation of Taguchi's method does not use the output of optimization process efficiently, so the convergence to the optimum parameters levels is prolonged. Our presented method uses the same bases to the ordinary implementation, but, finally determines parameters which are dependent or have nonlinear effect on the system operation, and uses this information in the optimization process. This article uses the response table efficiently to obtain the optimum parameters levels. Simulation results show the efficiency and accuracy of the new method.

Keywords: ***Taguchi's Method, Optimization, Double Stator Switched Reluctance Motor, Torque Ripple, Design of Experiments, Shape Optimization***

1. INTRODUCTION

One simple and well known method for optimization is trial and error approach. This method has a simple concept but is not practical for the complex systems with many parameters. In order to solve the problem, Taguchi's method was developed based on the concept of the orthogonal arrays(OA), which can significantly reduce the number of trials required in an optimization procedure [1].

It offers a practical method for selection of the optimum levels of design parameters in an optimization problem. Although Taguchi's method has been efficiently applied in many fields such as integrated chip manufacturing, chemical engineering, mechanical engineering, and power electronics [2]–[5], it is not well known to the electromagnetic community, and only a few number of applications have been done for the design of absorbers [6], [7], electrically conductive adhesives [8], diplexers [9],and statistical characterization of microwave circuit parameters[10], antenna array synthesis[11]-[12], phase array synthesis [13]-[14]-[15], .

Torque enhancement based on optimal design of electrical machines has always been interesting for power engineers. In this field, genetic algorithm and neural networks are used mostly to obtain the best design parameters. In this paper, a new electromagnetic optimization method based on Taguchi's method is used to reduce the torque ripple of double stator switched reluctance motor (DSSRM).A detailed implementation of the procedure is presented, and each step is illustrated by the array example.

This paper shows that the proposed method is simple and efficient to find the optimum design parameters levels. In section II, we describe the orthogonal arrays. In section III, the conventional implementation of Taguchi's method is explained. In section IV our new technique in using Taguchi's method is introduced. In section V the previous approach and new implementation are compared and finally in section VI the proposed method is

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used to obtain the optimum parameter levels of a DSSRM.

2. ORTHOGONAL ARRAYS

This section briefly reviews the basic concepts of orthogonal arrays.

2.1 Definition Of Orthogonal Arrays

Consider S as a set of levels or symbols. A matrix A, called an array of N rows and K columns with entries from S, is said to be an orthogonal array with s levels and strength t($0 \leq t \leq k$) if in every $N \times t$ sub-array of A, each t-tuple based on S appears exactly the same times as a row [11, ch1]. This causes a kind of balance in experiments. OA(N,k,s,t) presents an orthogonal array.

Orthogonal Arrays (OAs) which have been used in statistics [16] play an important role in Taguchi's method. Orthogonal arrays were introduced in the 1940s and have been used in design of experiment. They present an effective and systematic way to select the parameters values so that the optimal result can be obtained with only a few experiments.

In table 1, the OA(12,11,2,2) which has 12 rows, 11 columns, 2 levels. Each entry of the array is selected from a set S={1,2}, thus, this is a 2 levels orthogonal array. There are four combinations as a row: (1,1), (1,2), (2,2), (2,1). It is openly seen that each combination exists exactly 3 times in each two selected columns. This OA has eleven parameters to be optimized. The entry levels 1 and 2 can be chosen for each parameter during design of experiments. For example, the sixth row says the parameters 1,5,8,10,11 have the level 1 and parameters 2, 3, 4,6,7,9 have the level 2. Each row shows one combination of selected parameters levels and one can conduct an experiment and save the output to be used for comparison and selection of the best combination.

Table 1.OA(12,11,2,2)

Experiment Number	Columns										
	1	2	3	4	5	6	7	8	9	10	11
1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	2	2	2	2	2	2
3	1	1	2	2	2	1	1	1	2	2	2
4	1	2	1	2	2	1	2	2	1	1	2
5	1	2	2	1	2	2	1	2	1	2	1
6	1	2	2	2	1	2	2	1	2	1	1
7	2	1	2	2	1	1	2	2	1	2	1
8	2	1	2	1	2	2	2	1	1	1	2
9	2	1	1	2	2	2	1	2	2	1	1
10	2	2	2	1	1	1	1	2	2	1	2
11	2	2	1	2	1	2	1	1	1	2	2
12	2	2	1	1	2	1	2	1	2	2	1

2.2 Some Characteristics Of Orthogonal Arrays

The OA in table 1 shows just twelve experiments are needed to achieve the optimum levels. In contrast, a full factorial method needs $2^{11} = 2048$ experiments and it is the most precise method, but it is not practical to study all possible combinations. After conducting the experiments by analysis of the output results, all the optimum levels of parameters are obtained. It is demonstrated in statistics that although the number of experiments is dramatically reduced, the optimum result obtained from using the orthogonal array is close to that obtained from the full factorial strategy. In design of experiments, a balance in the selected levels needs to receive special attention. For example, in table 1 and column 4, parameter 4 has level 1 and level 2 six times. Also, when a parameter has a level other parameters have all possible levels. For example, when parameter 7 has level 2, parameter 9 has level 1 in rows 4, 7, 8, and level 2 in rows 2,6,12. Also, all possible combinations of up to *t* parameters levels occur equally, which guarantees a balanced and fair comparison during experiments. Therefore, the orthogonal array investigates not only the effects of the individual parameters on the experiment outcome, but also the interactions of any two parameters. Another property of orthogonal array is that any selected $N \times t'$ sub-array is an OA(N,k',s,t') where $t'=min\{k',t\}$. This means that if some columns are deleted from an orthogonal array, it is still an orthogonal array, which has less parameter. This property is very useful while some parameters should be deleted during optimization.

Parameters of OA(N,k,s,t) must satisfy the following inequalities:

$$N \geq \sum_{i=0}^{u} \binom{k}{i} (s-1)^i, \; if \; t = 2u, \quad u \rangle 0 \qquad (1)$$

$$N \geq \sum_{i=0}^{u} \binom{k}{i} (s-1)^i + \binom{k-1}{u} (s-1)^{u+1} \;\; if \;\; t = 2u+1, \quad u \geq 0 \qquad (2)$$

Different methods are used to construct orthogonal arrays. Nowadays, many orthogonal arrays with different number of parameters, levels and strengths have been developed and archived in libraries [17] which can be seen in the texts connected to Taguchi's method or orthogonal arrays.

3. NEW IMPLEMENTATION OF TAGUCHI'S METHOD

This paper presents a new implementation of Taguchi's method as shown in Fig.1

In the new implementation of Taguchi's method, steps 1 to 5 of the previous section are repeated exactly. So, the process is continued from step 5.

By comparison between two groups optimum set 1 and optimum set 2, it is probable that some levels are in common. Parameters owning the same levels in two groups are labeled "definite parameters". Definite parameters are fixed and excluded from the other optimization process because both the experiments and response table introduce them as the optimum parameters. In the next section, the substitution process (step 6) is elucidated.

3.1 Substituting The Indefinite Parameters Levels In The Best Experiment

The experiment which shows the best result is one of the full factorial experiments. So, another experiment may have a better output, and one of these better experiments may be the best experiment in step three substituted by one indefinite parameter level belonged to set 2. If this indefinite parameter level is the optimal level, substituting this level in the best experiment individually should be investigated. This process should be performed individually. If the substituted parameter level is independent, the order of substitution is unimportant and all replaced levels enhancing the objective function are fixed and considered as definite parameters. If any substituted level does not improve the objective function, it should be excluded again and the other indefinite parameter level should be replaced and examined.

3.2 Selection Of Appropriate New Orthogonal Array With Indefinite Parameters

In this section, indefinite parameters are optimized using another Taguchi's process. According to number of indefinite parameters and their levels, suitable Taguchi's table is selected again and the steps are repeated from step 3 forward. It is noted that for few indefinite parameters, full factorial experiment can be designed. The optimization process is stopped after the termination criterion is met.

In this section the conventional implementation of Taguchi's method shown in Fig.1 is described.

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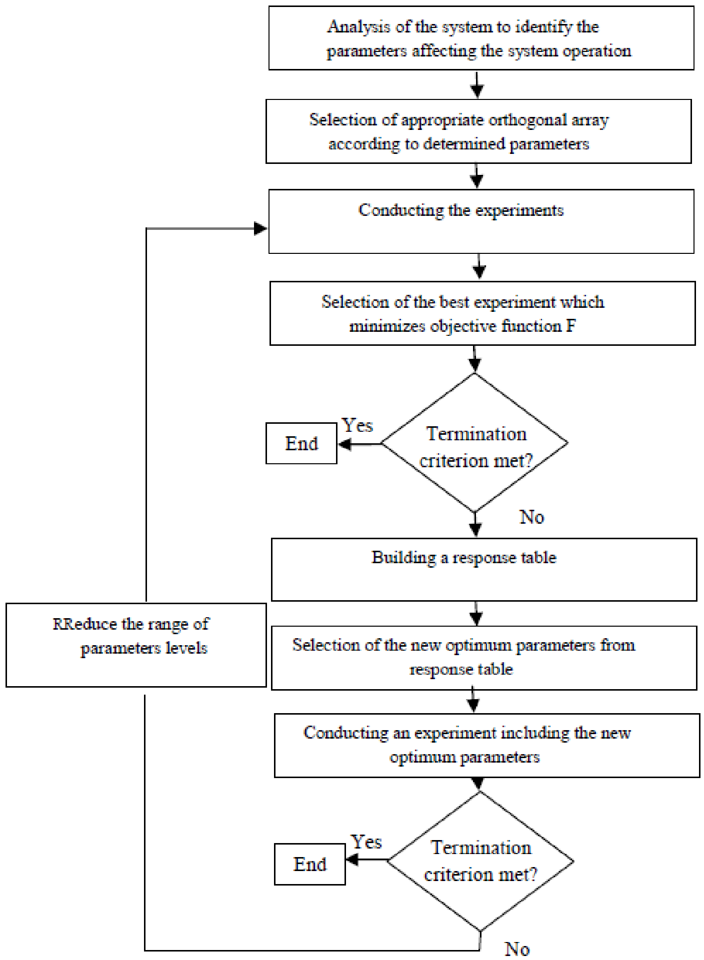

Fig. 1.Flow chart of conventional Taguchi's method

3.3 System Precise Analysis To Identify The Parameters And Their Levels Affecting Its Operation

The first step in all optimization methods is system analysis to identify the parameters influencing the system operation. These parameters and their levels usually are selected based on the previous knowledge of the system operation. The selected parameters are used in the optimization process. These parameters can change the objective function on which the final selection of the optimum parameters is done based.

3.4 Selection Of The Appropriate Orthogonal Array With Determined Parameters

According to number of parameters and their selected levels, a suitable Taguchi's table is selected. Sometimes, the number of selected parameters and their levels don't match a Taguchi's table. For using the Taguchi's table it is necessary to define some dummy parameters which do not have noticeable effect on the system characteristics. Taguchi's tables are available online.

3.5 Conduction Of The Experiments

After selection of proper Taguchi's table, experiments should be conducted. Conducting the experiments is performed either by an analytical method or by using a simulation software. In this article Finite Element Method is used. The

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objective function uses these experiments' output in its formula.

3.6 Selection Of The Best Experiment Which Maximizes The Objective Function F

After conducting the experiments, it is possible to evaluate the objective function F and selecting the best experiment. In this section, the only data necessary for evaluation are objective function values associated with different experiments. The levels related to the best experiment are named the optimum set 1.

3.7 Build A Response Table

After step 4, if the termination criterion is not met, step 5 is considered. Each entry of the response table is allocated to one parameter and one level. For example, one problem with x parameters, each owning y levels, has a response table with a number of $x \times y$ entries. All entries are made by averaging the experiments F values. For example, for parameter one and level two, the average of experiments in which the parameter 1 has level 2 is calculated. Finally, the levels which cause the minimum entry for each parameter are considered as the best levels and named optimum set 2. On the other hand, another group of parameters levels are presenting the best combination in experiments (optimum set 1). So, two groups of levels are candidate for being considered as the optimum levels. Conducting a new experiment including the optimum levels of set 2 enables us to select between optimum set 1 and optimum set 2.

4. DIFFERENCES BETWEEN THE CONVENTIONAL AND NOVEL IMPLEMENTATION OF TAGUCHI'S METHOD

In the conventional implementation of Taguchi's method, the optimum set 1 and 2 are compared finally and the optimum levels are determined. In the new implementation of Taguchi's method, the parameters are divided into definite and indefinite parameters. As mentioned, definite parameters are determined and temporarily excluded from the next optimization process. But, indefinite parameters are investigated more precisely and this is the remarkable difference between the conventional and new implementation of Taguchi's method. In the new implementation, the bases of Taguchi's method is used, therefore, there is no need to present the verification process for the new approach. For preventing the interaction between indefinite parameters, our new implementation doesn't use them simultaneously in an experiment and tries to find more definite parameters. Finally, indefinite parameters left at the end are investigated by another Taguchi's process. In our method, response table is used which plays a similar roll to SNR (Signal to Noise Ratio). In the next section, for evaluating the new approach, an example is investigated by the conventional and new implementation of Taguchi's method.

5. Optimization Of Double Stator Switched Reluctance Motor (DSSRM) Based On The Improved Taguchi's Method

DSSRM is a newly invented motor [18]. The cross section of motor is shown in
Fig. 3. It is shown in [19] that appropriate rotor pole shaping can be effective for enhancement of the produced torque. In [14], the structure shown in Fig.4 is considered for optimization. In this section, this motor will be optimized using the proposed new optimization method for evaluating the new implementation of Taguchi's Method.

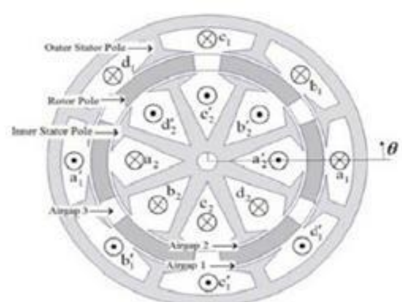

Fig.3.Cross section of 4-phase DSSRM

In Fig. 4, P_i is the radius of i_{th} circle and θ_i is the angle between center of the circle i and the horizontal dashed line.

In this article, torque ripple is defined as:

$$T_{ropple} = \frac{T_{\max} - T_{\min}}{T_{av}} \quad (3)$$

And the objective function is as follows:

$$F = \left(\frac{T_{av}}{T_{\max} - T_{\min}}\right) p \quad (4)$$

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$$p(\,penalty\ \ factor) = \begin{Bmatrix} 0 & T_{av} < 17.7 \\ 1 & T_{av} \geq 17.7 \end{Bmatrix} \qquad (5)$$

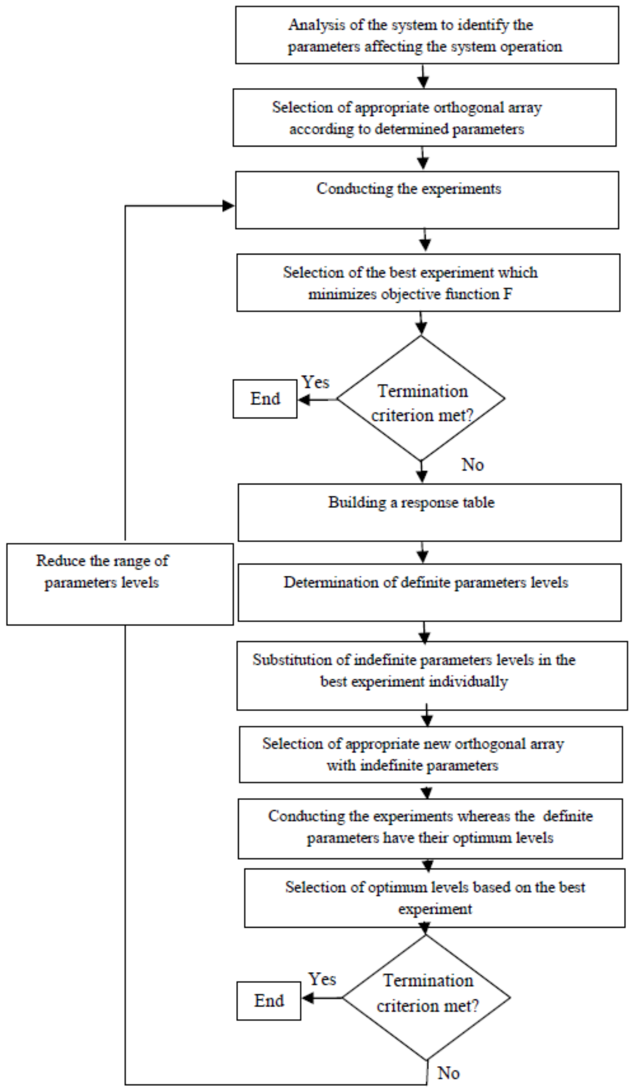

Fig. 2.Flow chart of improved Taguchi's method

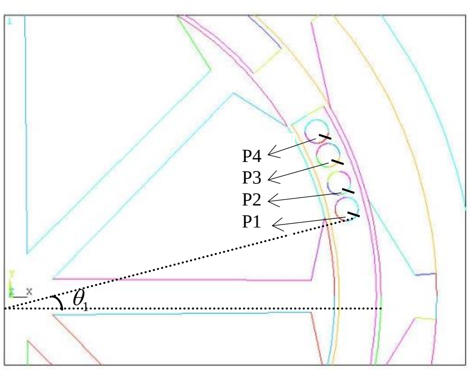

Fig. 4.Use of the circular holes for practical rotor shaping

Termination criterion is selected based on the designer requirements. In this article we consider the termination criteria arbitrary as:

$$F>2 \qquad (6)$$

The average Torque of DSSRM before changing the rotor structure is 18.06N.m and torque ripple is 101%. In this optimization process, the maximum permissible decrease of the average

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torque during the optimization process is chosen to be 2%; that is why 17.7N.m is selected as the critical value for changing the penalty factor (p) from one to zero.

Torque ripple before changing the rotor structure is 101%. In the next step, we use the proposed optimization method to optimize the holes attributes for minimum torque ripple. In continue, the optimization process is conducted.

5.1 Step One

Analysis of DSSRM and selection of important parameters is done in [19]. Authors in [19] decided to change the rotor structure; therefore they optimized the rotor pole shown in Fig. 4

5.2 Step Two

Because there are 8 parameters, it seems to be proper to use the Taguchi's table2 for optimization.

Table 2.Taguchi's table with 8 parameters

Experiment number	P1	P2	P3	P4	θ_1	θ_2	θ_3	θ_4
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

In table 2, other than parameter P1 which has two levels, other parameters have 3 levels. The number of levels and their values are selected by experience or knowledge of designers. For parameter P1 just two levels are considered because the parameter P1 shown in Fig.4 is not effective noticeably; so, just two levels for this parameter are allocated.

In table3, selected levels for parameters of Fig.4 are given as follows:

5.3 Step Three

In this section, the experiments shown in table2 are conducted by Finite Elements analysis. Obtained results are shown in table 4.

Table 3.Selected levels for 8 parameters

Variables	Level1	Level2	Level3
P1	1.2(mm)	.8(mm)	
P2	1.6(mm)	1.2(mm)	.8(mm)
P3	2.1(mm)	1.8(mm)	1.5(mm)
P4	3.3(mm)	3.2(mm)	3.1(mm)
θ1	0.255(rad)	0.253(rad)	0.25(rad)
θ2	0.315(rad)	0.31(rad)	0.305(rad)

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θ3	0.395(rad)	0.39(rad)	0.385(rad)
θ4	0.49(rad)	0.485(rad)	0.48(rad)

Table 4.Objective function calculated from Finite Element Analysis

Experiment number	Average torque [N.m.]	Torque ripple [%]	F
1	17.93	44.4	2.25
2	17.87	50.2	1.99
3	17.85	59.2	1.69
4	17.75	55.25	1.81
5	17.55	68.5	0
6	17.56	36	0
7	17.68	43.67	0
8	17.6	55.5	0
9	17.45	71.94	0
10	17.86	67.56	1.48
11	17.98	40.48	2.47
12	17.7	59.5	1.68
13	17.95	69	1.45
14	17.8	41.2	2.43
15	17.82	44.6	2.24
16	17.79	54.05	1.85
17	17.84	62.9	1.59
18	17.86	35.7	2.8

Table 4, shows the experiment 18 offers the largest F value in the row 18. Therefore, the levels allocated to experiment 18 (table 5) are selected as the first candidates for optimum parameters levels.
Since the termination criterion is not met, it is necessary to continue the process to step four.

5.4 Step Four

In this step, response table based on table 4 is built and shown in table 6.

Table 5.Selected levels as the first candidate of optimum levels

Variables	Levels
P1	0.8 mm
P2	0.8 mm
P3	2.1 mm
P4	3.1 mm
θ_1	0.25 rad
θ_2	0.31 rad
θ_3	0.39 rad
θ_4	0.49 rad

Table 6.Response table based on table 4

	P1	P2	P3	P4	θ1	θ2	θ3	θ4
Level1	1.94	1.93	1.86	1.96	2.7	1.93	1.84	2.2
Level2	2.13	2.03	1.96	2.14	1.9	2.18	2.06	1.99
Level3	-	2.15	2.3	2	1.51	2	2.2	1.91

Table 6, suggests the levels presented in table 7, as the optimum parameters levels.

5.5 Step Five

Parameters with identical levels in tables 5 and 7 are labeled as definite parameters and are shown in table 8.

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Table 7.Optimum levels offered by response table

Variables	Levels	values
P1	2	0.8 mm
P2	3	0.8 mm
P3	3	1.5 mm
P4	2	3.2 mm
θ_1	1	0.255 rad
θ_2	2	0.31 rad
θ_3	2	0.385 rad
θ_4	1	0.49 rad

Table 8.Definite parameters in iteration 1

P1	0.8 mm
P2	0.8 mm
θ_2	0.31 rad
θ_4	0.49 rad

5.6 Step Six

In this step, optimal levels of indefinite parameters are searched while definite parameters are constant in the experiment 18(of table 4) and indefinite parameters shown in table 9, are substituted individually. Each parameter which increases F becomes constant and is considered as a definite parameter. If all parameters are substituted simultaneously, the interaction between them may cause improper consequences. The results are shown in table 10.

Table 9.Indefinite parameters in Iteration.1

P3
P4
θ_1
θ_3

Table 10.Results of parameters substitution in iteration1

Substituted parameters	F
Just P3 is substituted in experiment 18	1.6
Just P4 is substituted in experiment 18	2.92
P4 and θ_1 are substituted in experiment 18	**2.93**
P4, θ_1 and θ_3 are substituted in experiment 18	2.74

As seen in table 10, first, parameter P3 is replaced in the experiment 18 with its optimal level obtained from response table. With this combination, F value becomes 1.6 which is much less than 2.8 associated with previous experiment 18; therefore, P3 is not considered as a definite parameter and its value is set to the previous level. In the next step, P4 is substituted in the experiment 18 by its optimum level obtained from response table. With this combination, F value is 2.92,which is more than 2.8 associated with experiment 18; therefore, P4 is considered as a new definite parameter and this level is fixed in the experiment 18. Now, θ_1 is replaced in the experiment 18 by its optimal level obtained from response table. With this combination, F value is 2.93 being identical to previous F value (2.92). Because this level does not change F value substantially, it is possible both setting and not setting the parameter θ_1 as definite one. The fewer indefinite parameters, the simpler is optimization process, so, this parameter is considered as a definite one.

Up to now, P4 and θ_1 are selected as definite parameters. In the next stage, parameter θ_3 is replaced in the experiment 18 by its optimal level obtained from response table. With this combination, F value is 2.74 which is less than 2.93 associated with previous F value. So, θ_3 is not considered as a definite parameter and its value is set to the previous level.

5.7 Step Seven

In this step, all remained indefinite parameters should be investigated in experiment 18 which its parameters P4 and θ_1 have the levels of table 7. Because the number of remained parameters is two and each has 2 levels, as shown in table 11, instead of Taguchi's table a full factorial experiment is preferred. The results are shown in table 12.

Table 11.Indefinite parameters needing extra investigation

Indefinite Parameters	Level 1	Level 2
P3	1.5 mm	2.1 mm
θ_3	0.385 rad	0.39 rad

Table 12.Experiments results obtained by Finite Element Analysis

Experiment number	P3	θ_3	F
1	1	1	1.57
2	1	2	1.51
3	2	1	2.74
4	2	2	2.93

Table 12, shows the best combination of parameters P3 and θ_3 in the last row in which the parameters P3 and θ_3 have level 2. In this section, the termination criterion (F>2.85) is met and the optimization is terminated. If the termination criteria is not met, a new iteration is necessary to be carried out. By substituting all optimal parameters levels obtained by response table simultaneously as offered in [20], the F value becomes 1.57 which is much less than 2.93 obtained by our improved method. Therefore, replacement of all parameters at the same time does not always offer the best result. In table 13 torque ripple obtained by conventional and new implementation of Taguchi's method are compared.

Table 13.Torque ripples obtained by conventional and new implementation of Taguchi's method

	Torque ripple%
Conventional Taguchi's method	35.7
New Implementation	34.1

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6. Conclusion

A new implementation of Taguchi's method for design optimization of electromagnetic devices was presented. To show the efficiency of our proposed method, it was used for minimization of torque ripple of Double Stator Switched Reluctance motor using Finite Element Method. Our method determines parameters which are dependent or have nonlinear effect on the system operation by using the response table. Contrary to conventional implementation of Taguchi's method, the new approach uses this information in the optimization process to reach a more precise design. Simulation results show the new implementation of Taguchi's method is effective to solve optimization problems.

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