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Optimization of axial flux permanent magnet generator by Taguchi experimental method

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Abstract. In this study, the optimization of air gap magnetic flux density of open slotted axial flux permanent magnet (AFPM) machine which was developed for wind turbine has been obtained using the Taguchi experimental method. For this, magnetic analyzes were performed by ANSYS Maxwell program according to Taguchi table. Then the optimum values have been determined and the average magnetic flux density values have been calculated for air gap and iron core under load and no-load conditions with ANSYS Maxwell. Traditionally, 15625 analyzes are required for 6 independent variables and 5 levels when experimental method is used. In this study, optimum values are determined by 25 magnetic analyzes, which use L25 orthogonal array. For this purpose, both factor effect graph and signal to noise ratios are used, according to the factors and levels which are obtained from the factor effect graph and the signal to noise ratio. Parameters are re-analyzed by Maxwell. The optimum factors and levels are determined. For optimized values, the air gap magnetic flux density is improved by 65.7% and 173.26%, respectively, according to the average value and the initial design. Therefore, the variables are optimized in a shorter time with Taguchi experimental design method instead of the traditional design method for open slotted AFPM generator. In addition, the results were analyzed statistically using ANOVA and Regression model. The variables were found to be significant by ANOVA. The degree of influence of the variables on the air gap magnetic flux density was also determined by the Regression model.

Key words: axial flux generator, permanent magnet, taguchi experimental method, finite element method.

1. Introduction

Increasing energy demand in recent years has led all countries to invest in renewable energy sources. One of the renewable energy sources is wind energy. Permanent magnet generators (PMG) are used to convert wind energy to electrical energy. The absence of field windings in the PMG increases efficiency. Therefore, studies on PMG have gained interest in literature. One type of PMG is axial flux. Axial flux permanent magnet (AFPM) generators have high power density and efficiency [1]. It is one of the most important candidates for wind turbines in the last ten years [2].

The magnetic flux generated by the windings in axial flux permanent magnet machines (AFPM) is parallel to the machine shaft. AFPM generators have a high number of poles, hence the direct drive machine in the wind turbine. The wind turbine total efficiency will increase as it does not require gear system in direct driven wind turbines [3]. However, the disadvantage is the cogging torque – the torque fluctuation due to the interaction between the magnet and slot edges [4–5]. There are different techniques in the literature to reduce cogging torque, such as different magnet shapes, magnet skew techniques, magnet placement angle in the self axis (for rectangular magnets) and magnet grouping techniques [6–9].

The programs used in the analysis of radial and axial flux machines compute with finite element method (FEM) [10–12]. One of these programs is ANSYS Maxwell [1, 13, 14]. Maxwell can perform magnetostatic and transient analyzes as 3d and 2d. The main disadvantage of Maxwell 3d is that the analysis time depends on the computer characteristics.

In the conventional optimization process of the AFPM generator, it is necessary to conduct separate analyses for many parameters and levels. In this study, a total of 15.625 magnetostatic analyses should be performed at Maxwell 3d for specified parameters. In this case, analysis time is too long and analyses cannot be performed with a desktop computer.

Different optimization methods are needed since the traditional way takes a long time. Taguchi is an optimization method used in many different fields in the literature [15–16]. Taguchi is an experimental design method. According to the classical optimization, Taguchi method is performed with much less experiments. In Taguchi experiment design method it is possible to determine the optimum levels of all parameters. Although Taguchi experimental design method is used in many different fields [17], there are many studies in the design of electrical machines. Demir and Aküner line-start permanent magnet synchronous motor rotor pole structure depending on the power factor and efficiency is optimized using the Taguchi method. In their study, L8 orthogonal array was used for 8 variables and 2 levels. For each level, parameters with high impact rates were selected according to the difference from the average [18]. Demir and Aküner designed and optimized asynchronous motor for electric vehicles using taguchi experimental design method. In this study, they used L16 orthogonal array for 14 variables and 2 levels [19]. Kurt and Önbilgin used the Taguchi experimental method for the design and optimization of the axial flux permanent magnet synchronous machine. In their study, they

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used L16 orthogonal array for 5 variables and 4 levels. In the experimental results of the AFPM synchronous machine, air gap magnetic flux values were obtained for load and unload cases. In Taguchi method, optimization was performed by using regression analysis with the graph of the effect rates of the variables (factors) [20]. Tsai used the Taguchi experimental method for the design of radial flux permanent magnet synchronous generator. For optimization with Taguchi method, L18 orthogonal array consisting of 8 factors and 3 levels was used. With obtained values, the points where the output power and efficiency are maximum were found. In order to find maximum values, the signal to noise ratios and factor effects graph and statistical analysis of variables (ANOVA) were used to determine the significance of factors and levels [21]. Özoğlu proposed a genetic and fuzzy logic based on Taguchi optimization method for mean torque, cogging torque and total harmonic distortion (THd) of induced EMF (electro motor force) in a permanent magnet machine with external stator. In the optimization with Taguchi, they used L18 orthogonal array for 7 factors and 3 levels [22]. Shirazi et al. used the Taguchi experimental design method to minimize the cogging torque of permanent magnet machines. The most effective parameters were determined using the analysis of means and effect rates graph for the L16 orthogonal array for 4 factor and 4 levels in an electric machine model with internal rotor [23].

In literature, there are many studies on optimization of parameters with Taguchi in permanent magnet electrical machines. In the studies, orthogonal array were analyzed according to the factor and levels. However, the effect rates of the variables were determined on the regression, mean values, variance, standard deviation and effect graphs.

In this study, the parameters selected for the maximum value of the magnetic flux density in the air gap and the core for the loaded and unloaded states of the open slotted axial flux permanent magnet synchronous generator with trapezoidal winding were optimized using the Taguchi experimental design method. L-25 orthogonal array with 6 factor 5 level was selected for Taguchi experimental design method. In the conventional experimental method, a total of 15625 experiments are required for 6 factor and 5 levels. 25 magnetic analyzes were performed by Taguchi experimental method. With the analysis, mean magnetic flux value of the air gap and stator core and signal to noise ratio values were obtained for stator loaded and unloaded states and the parameters with high effect values were determined using the graphical effect values of the factors. However, the results obtained were examined statistically in terms of significance and effect rates.

2. AFPM synchronous generator with trapezodial windings

AFPM machines are disc-shaped and compact. AFPM machines have higher power and efficiency values than radial flux permanent magnet (RFPM) machines [24, 25]. The biggest disadvantage of AFPM machines is the cogging torque. Cogging torque is the torque fluctuation caused by the interaction between the magnet poles and the slot edges. AFPM machines have 3 basic structures, rhomboidal, toroidal and trapezoidal winding according to winding structure. In this study, trapezoidal winding AFPM machine was used.

2.1. 3d magnetic analyses of AFPM synchronous generator.

ANSYS Maxwell software was used for magnetic analysis of AFPM synchronous generator. Maxwell is a program that performs 2d and 3d analysis using finite element method (FEM). In this study, 3d design was created and magnetic analyzes were obtained by Maxwell. In the designed AFPM synchronous generator model, slot width (Sw), slot height (Sh), core height (Ch), air gap (Airg), magnet height (Mh) and magnet width (Mw) parameters are assigned as variables. 5 different values are defined for each variable. When the analysis table is created from the optimetrics module for the defined variables, a total of 15625 calculations occur. The computer used in the analysis is the Intel core i7-4790 CPU 3.60 GHz processor, 32 GB RAM and the graphics card Zotac gtx 770 4gb ddr5. Therefore, it is not possible to perform 15625 analyses with Maxwell in terms of both memory and processing capacity in the computer where analyses are performed.

The ANSYS 3d Maxwell model of the designed AFPM synchronous generator with trapezoidal winding is given in Fig. 1. Figure 1a shows the stator structure of the AFPM synchronous generator. AFPM machine has 3 phase trapezoidal winding.

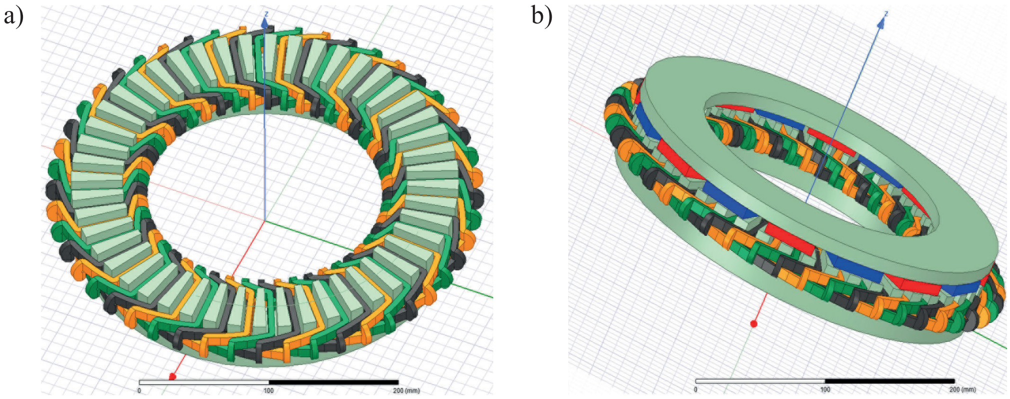

Fig. 1. AFPM Synchronous generator with trapezodial winding a) Stator b) Full model

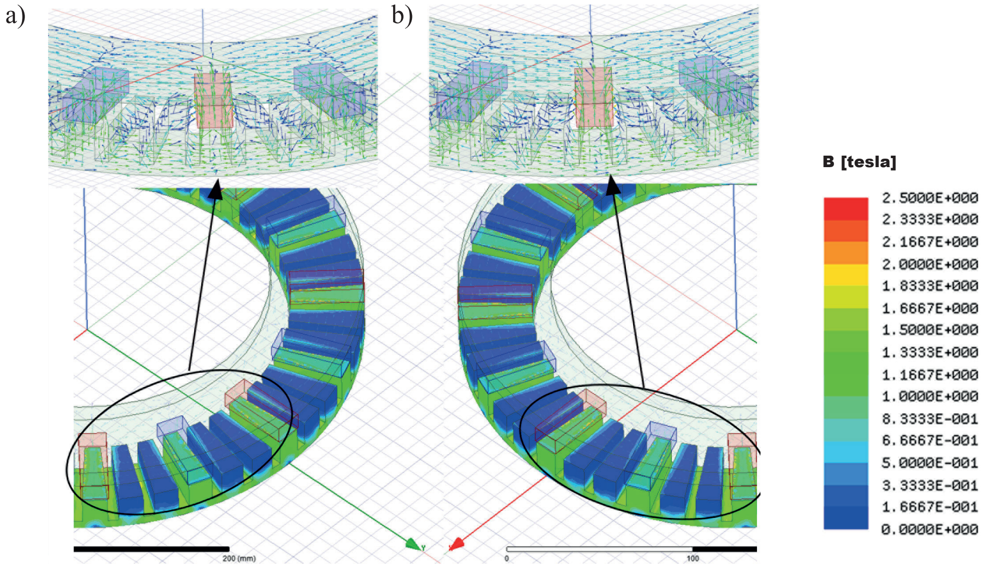

Fig. 2. Analysis result of designed AFPM synchronous generator a) Noload stator b) Load stator

Open slot structure is used in the design. Figure 1b shows the exact model of the design.

Design parameters are given in Table 1. The stator of the AFPM synchronous generator has an open slot structure and the number of slot is 48. The stator core inner diameter, outer diameter, phase number and winding structure of the design are 220 mm, 300 mm, 3, trapezoidal winding, respectively. The rotor consists of 16-pole surface-mounted magnets. The magnet type was selected from the program library as N35 (Neodymium magnet).

In the ANSYS Maxwell model given in Fig. 1, Sw, Sh, Ch, Airg, Mh and Mw were taken as 6 mm, 16 mm, 5 mm, 1 mm, 4 mm, 15 mm respectively and analyzes were performed. The values obtained as a result of magnetostatic analysis made in ANSYS Maxwell are given in Fig. 2 and Fig. 3. In magnetic analyses, the analysis results were obtained for the windings unloaded and loaded states (50 ampere turns). In Fig. 2, the magnetic flux density distribution on the core surface is obtained. The mean value of the magnetic flux density in the core was obtained as 0.65711614 and 0.64366949 Tesla for unloaded and loaded state, respectively. In Fig. 2, it is seen that the magnetic flux density value is approximately 1.33 Tesla at the slot edges. Therefore, there is no magnetic saturation in the slot edges of the core.

Table 1
Parameters of AFPM synchronous generator

Pole number (2P)	16	**Stator outer diameter (Do)**	300 mm
Magnet type	N35	**Phase number**	3
Rotor back iron	10 mm	**Winding type**	Trapezoidal
Slot type	Open slot	**Lambda (λ)**	0.733
Slot number	48	**Slot width (Sw)**	6 mm
Stator inner diameter (Di)	220 mm	**Core yoke height (Ch)**	5 mm
Slot height (Sh)	16 mm	**Magnet height (Mh)**	4 mm
Airgap (Airg)	1 mm		
Magnet width (Mw)	15 mm		

Figure 3 shows the variation of the magnetic flux density along a contour in the air gap for unloaded and loaded. The magnetic flux density along the contour in the air gap is 0.274036 and 0.280864 Tesla for unloaded and loaded, respectively.

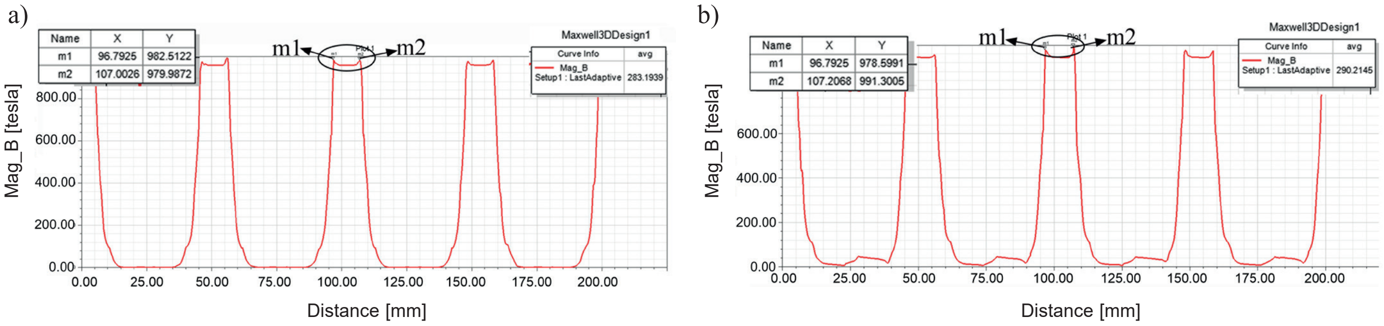

Fig. 3. The change of magnetic flux density throughout the contour a) No-load stator b) Load stator

3. Optimization of AFPM synchronous generator parameters with Taguchi

In this study, Taguchi experimental design method was used for optimization of AFPM synchronous generator stator and rotor design parameters. The Taguchi experimental design method was invented by Sir Ronald Fisher in the 1920s to increase the productivity of agriculture. This method was used to determine the effects of different factors such as fertilizer, irrigation and climatic conditions on agricultural production. For the last decades, this method has been used effectively in electrical machine design.

The Taguchi experimental design method consist in determining the factors and levels, obtaining the experimental results, determining the data and analysis technique and interpreting the experimental results. Thanks to Taguchi experimental design method, it is possible to obtain results with very few experimental studies by using orthogonal array table instead of multiple combinations of different factors and levels [26–28]. The flow chart that we have created considering these section is given in Fig. 4.

In Taguchi experimental design method, factors and levels for AFPM synchronous generator were first determined in Table 2. For this study, 6 factor (A, B, C, D, E, F) and 5 levels were determined in Taguchi method. In conventional experimental method, the number of all combinations is 15625. From the Taguchi orthogonal array selection table, the L25 orthogonal array was selected for 6 factors and 5 levels.

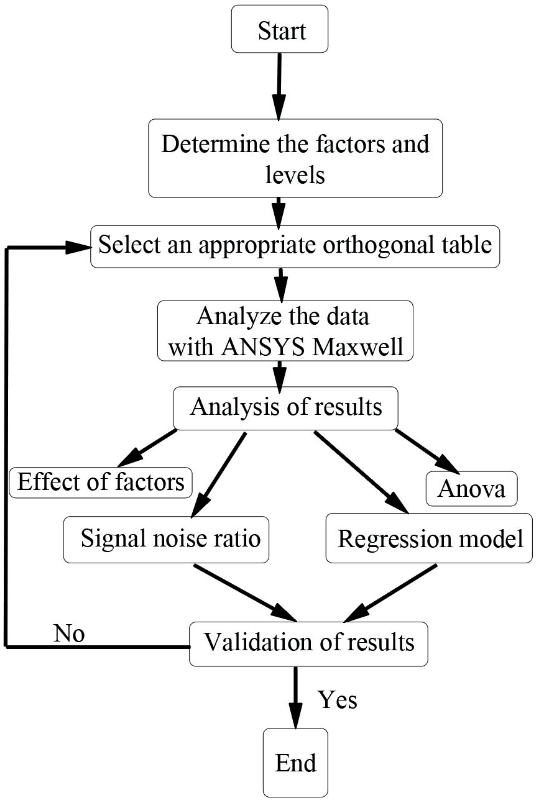

Fig. 4. The flowchart

Table 2
Factors and levels of AFPM synchronous generator

Parameters		Levels of parameters				
		1	2	3	4	5
Sw (Slot width)	A	6	7.5	9	10.5	12
Sh (Slot height)	B	16	22	28	34	40
Ch (Core height)	C	5	8.75	12.5	16.25	20
Airg (Air gap)	D	1	1.5	2	2.5	3
Mh (Magnet height)	E	4	6	8	10	12
Mw (Magnet width)	F	15	21.25	27.5	33.75	40

Table 3 shows the magnetic flux densities in the unloaded and loaded together with the Taguchi L25 array. The average magnetic flux density in the unloaded airgap, in the unloaded core, in the loaded airgap and in the loaded core are given in Table 3 as S1, S2, S3 and S4, respectively.

Table 3
Taguchi L25 sequence and magnetic flux density values

No	Parameters						Results			
	Sw	Sh	Ch	Airg	Mh	Mw	B_{air} no-load	B_{core} no-load	B_{air} loaded	B_{core} loaded
	A	B	C	D	E	F	S1	S2	S3	S4
1	1	1	1	1	1	1	0.274036	0.657116	0.280864	0.643669
2	1	2	2	2	2	2	0.382028	0.677468	0.381228	0.656469
3	1	3	3	3	3	3	0.480026	0.717914	0.476441	0.693529
4	1	4	4	4	4	4	0.580916	0.780137	0.575960	0.751938
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
24	5	4	3	2	1	5	0.528617	1.500092	0.524092	1.171396
25	5	5	4	3	2	1	0.244299	0.460728	0.244948	0.432281

Mean value, signal to noise ratio, variance analysis, standard deviation and factor effects graph can be used when interpreting the values taken in Table 3. In this study, the effect level of each factor was determined by using mean values and factor effects graph. However, the effect values were determined with the help of signal to noise ratios and results were found to be similar. Finally, the effects of independent variables on dependent variables were examined statistically.

3.1. Average effect. In order to obtain the factor graphs of the values given in Table 3, the variable levels shown in (1–6) were summed and averaged.

$$A_1 = \frac{1}{5}\big(A(1) + A(2) + A(3) + A(4) + A(5)\big) \tag{1}$$

$$B_1 = \frac{1}{5}\big(B(1) + B(2) + B(3) + B(4) + B(5)\big) \tag{2}$$

$$C_1 = \frac{1}{5}\big(C(1) + C(2) + C(3) + C(4) + C(5)\big) \tag{3}$$

$$D_1 = \frac{1}{5}\big(D(1) + D(2) + D(3) + D(4) + D(5)\big) \tag{4}$$

$$E_1 = \frac{1}{5}\big(E(1) + E(2) + E(3) + E(4) + E(5)\big) \tag{5}$$

$$F_1 = \frac{1}{5}\big(F(1) + F(2) + F(3) + F(4) + F(5)\big) \tag{6}$$

Table 4 shows the values of the design variables. Design variables are calculated using (6–11). Thus, the effect of each variable level is determined for factor graphs.

Table 4
Taguchi experimental design variables

	Ai	**Bi**	**Ci**	**Di**	**Ei**	**Fi**
1	A1	B1	C1	D1	E1	F1
2	A2	B2	C2	D2	E2	F2
3	A3	B3	C3	D3	E3	F3
4	A4	B4	C4	D4	E4	F4
5	A5	B5	C5	D5	E5	F5

The results in Table 3 with the placement of the values obtained using formulas 1–6 according to Table 4 are given in Table 5. Table 5 shows the design variables in the airgap and iron core for no-load and loaded states.

Figure 5 gives a graphical representation of factor effects for loaded and unloaded conditions. In Fig. 5a, the factor and levels of A1B1C2D2E5F5 in the no-load maximizes the magnetic flux density of the airgap. In Fig. 5b, the factor and levels of A5B2C1D2E3F5 in the no-load maximizes the magnetic flux density of the iron core. In Fig. 5c and Fig. 5d, the factor and

Table 5
Design variables for no-load and loaded cases

No-load B_{air} (Tesla)

	Ai	**Bi**	**Ci**	**Di**	**Ei**	**Fi**
1	0.4758	0.4587	0.4465	0.4109	0.3696	0.2677
2	0.4687	0.4554	0.4576	0.4641	0.4273	0.3611
3	0.4523	0.4004	0.4353	0.4527	0.4823	0.4534
4	0.4320	0.4510	0.3551	0.4168	0.4854	0.5397
5	0.4304	0.4542	0.4487	0.4109	0.4946	0.6375
Δ	0.0454	0.0187	0.1024	0.0531	0.1249	0.3697
R	5	6	3	4	2	1

Loaded B_{air} (Tesla)

	Ai	**Bi**	**Ci**	**Di**	**Ei**	**Fi**
1	0.4747	0.4577	0.4467	0.4080	0.3682	0.2685
2	0.4669	0.4522	0.4552	0.4620	0.4255	0.3593
3	0.4491	0.4377	0.4317	0.4501	0.4796	0.4505
4	0.4289	0.4482	0.3532	0.4142	0.4824	0.5358
5	0.4282	0.4520	0.4457	0.4087	0.4921	0.6336
Δ	0.0464	0.0200	0.1019	0.0532	0.1239	0.3650
R	5	6	3	4	2	1

No-load B_{core} (Tesla)

	Ai	**Bi**	**Ci**	**Di**	**Ei**	**Fi**
1	0.7324	0.7415	0.9759	0.7363	0.7632	0.5199
2	0.7341	0.8993	0.8850	0.8642	0.7437	0.6339
3	0.8644	0.8160	0.8414	0.7602	0.8562	0.7928
4	0.7645	0.8794	0.6314	0.7151	0.8596	0.8872
5	0.9857	0.7448	0.5914	0.7363	0.8584	1.2472
Δ	0.2533	0.1578	0.3845	0.1491	0.1159	0.7272
R	3	4	2	5	6	1

Loaded B_{core} (Tesla)

	Ai	**Bi**	**Ci**	**Di**	**Ei**	**Fi**
1	0.7081	0.7293	0.9607	0.7124	0.6784	0.5000
2	0.7163	0.8372	0.8594	0.7873	0.7236	0.6118
3	0.7984	0.7973	0.7579	0.7388	0.7937	0.7687
4	0.7441	0.7920	0.5711	0.6944	0.8391	0.8678
5	0.9040	0.7153	0.5715	0.7124	0.8362	1.1226
Δ	0.1959	0.1219	0.3896	0.0929	0.1606	0.6225
R	3	5	2	6	4	1

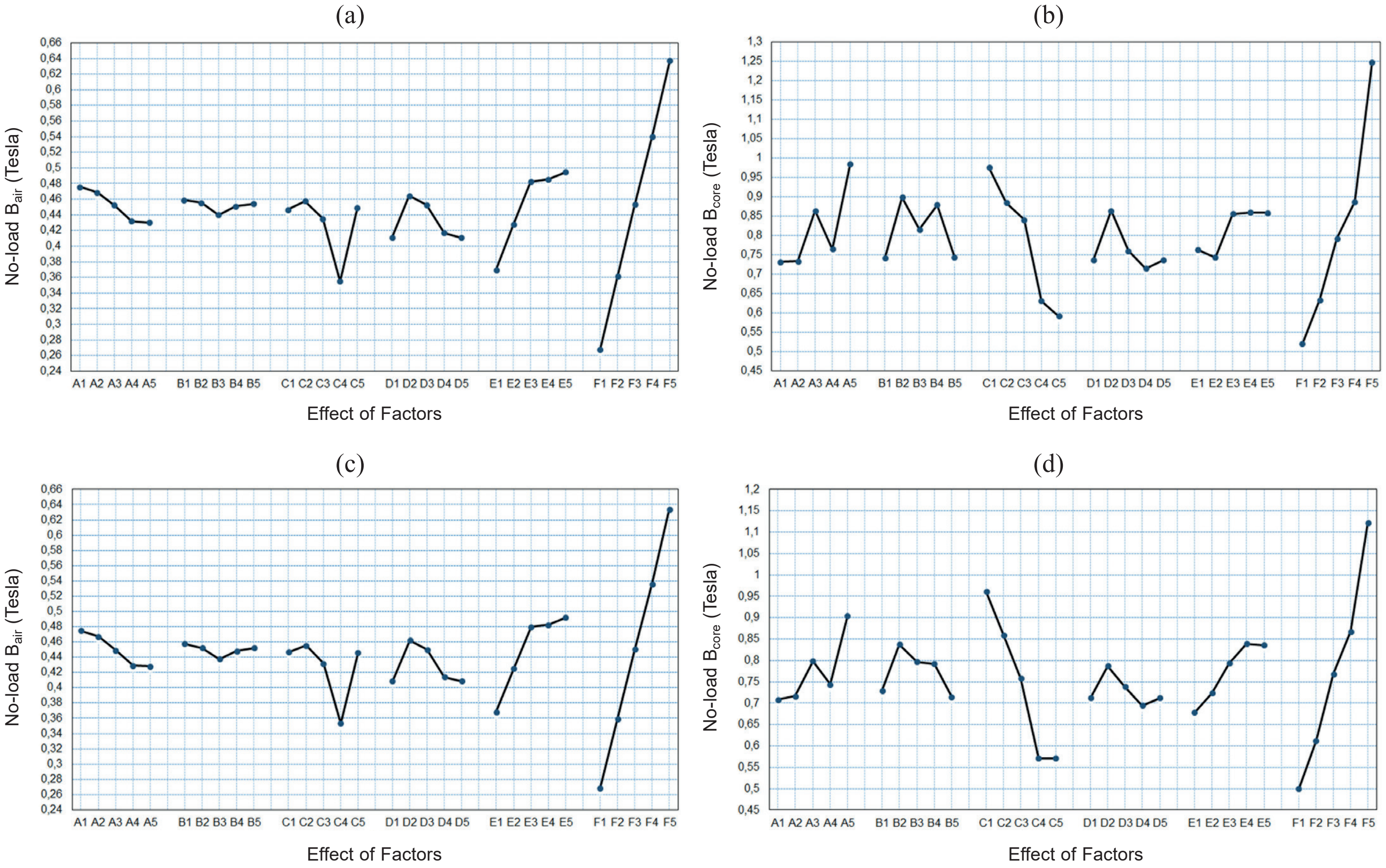

Fig. 5. Effect of factors a) No-load magnetic flux density in airgap b) No-load magnetic flux density on core c) Loaded magnetic flux density in airgap d) Loaded magnetic flux density on core

levels of A1B1C2D2E5F5 and A5B2C1D2E4F5 are effective values for the airgap and iron core.

In Table 6, the result of the analysis were obtained with ANSYS Maxwell using the effective factors and levels obtained from Taguchi experimental design method. The average of the air gap and iron core magnetic flux density values in the loaded and unloaded conditions were found as a result of the analysis. In addition, the average magnetic flux density values obtained by the initial design results are also given. The results obtained by using the factor graphs in Taguchi experimental design method were also given the rates of change according to the first design parameter and average. Accordingly, the average magnetic flux density of the air gap in no-load condition is 65.7%, 37.42%, 44.06% improvement in 1st, 2nd and 3rd improvements, respectively. When the average magnetic flux density in the iron core is examined, the 1st, 2nd, and 3rd improvements were developed by 37.43%, 79.73% and 83.55% respectively.

According to Table 6, the effective factors and levels found with Taguchi experimental design method are A1B1C2D2E5F5, A5B2C1D2E3F5 and A5B2C1D2E4F5. For these values, magnetostatic analyzes were performed in ANSYS Maxwell. The results of the magnetic flux density in the no-load state are given in Figs. 6, 7 and 8 respectively.

Table 6
ANSYS analysis results of Taguchi experimental design method

No	Taguchi design	No-load B_{air}	No-load B_{core}	Loaded B_{air}	Loaded B_{core}
1	Initial design	0.2740	0.6571	0.2809	0.6437
2	Average of design	0.4519	0.8163	0.4496	0.7742
3	A1B1C2D2E5F5	0.7488	1.1218	0.7460	1.1129
4	A5B2C1D2E3F5	0.6211	1.4671	0.6196	1.4572
5	A5B2C1D2E4F5	0.6510	1.4983	0.6499	1.4902
	Comparison of 1 and 3	173.2%	70.71%	165.5%	72.9%
	Comparison of 1 and 4	126.6%	123.2%	120.6%	126.3%
	Comparison of 1 and 5	137.5%	128.0%	131.3%	131.5%
	Comparison of 2 and 3	65.7%	37.43%	65.91%	43.74%
	Comparison of 2 and 4	37.42%	79.73%	37.81%	88.21%
	Comparison of 2 and 5	44.06%	83.55%	44.54%	92.47%

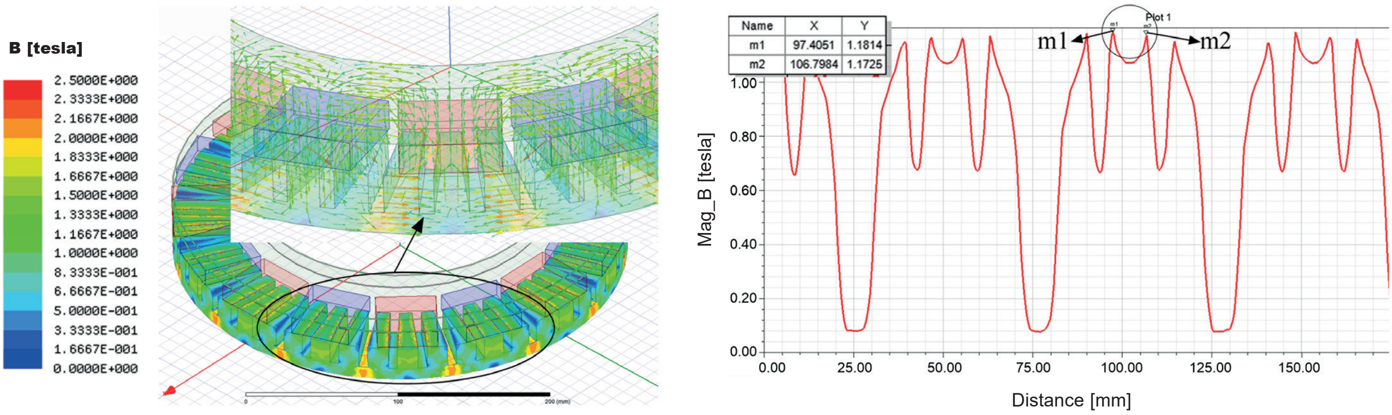
(a) (b)

Fig. 6. No-load magnetic flux density for A1B1C2D2E5F5 a) On the core surface b) In the air gap

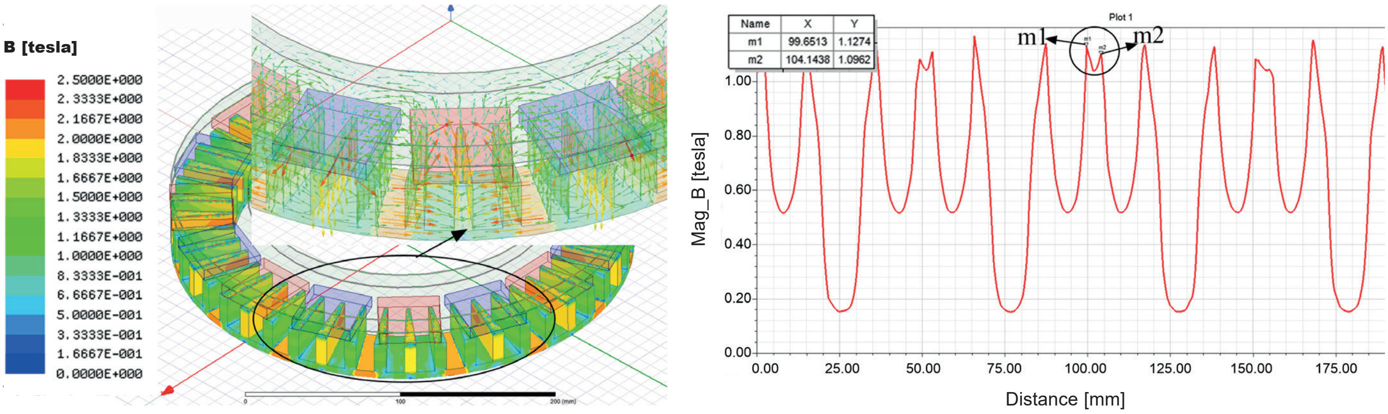
(a) (b)

Fig. 7. No-load magnetic flux density for A5B2C1D2E3F5 a) On the core surface b) In the air gap

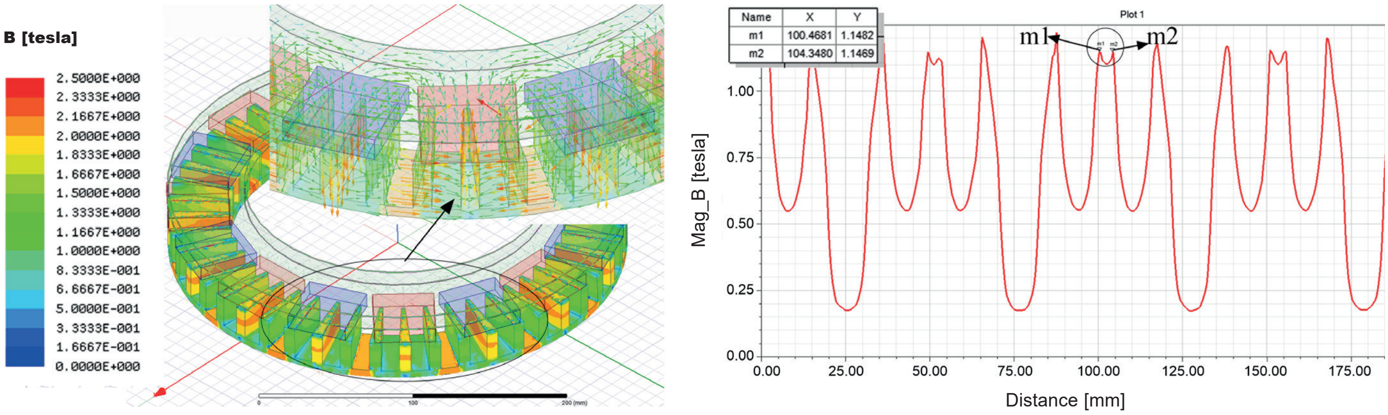
(a) (b)

Fig. 8. No-load magnetic flux density for A5B2C1D2E4F5 a) On the core surface b) In the air gap

3.2. Taguchi experimental design method according to signal noise ratio. In the literature, Taguchi experimental design methods are optimized by using factor graphs [20, 25, 29] and signal to noise ratio [22, 30] methods. In some studies, impact rates are determined according to both methods [21]. In Taguchi experimental design method, there are 3 function which are mentioned as signal to noise ratio (S/N) function. These function are given in (7–9). The S/N ratios given in (7–9) give the biggest best case, the smallest best case and the nominal value best case respectively. Equation (7) was used in this study since it is proportional to the power to maximize the magnetic flux density in the air gap and iron core. Therefore, for maximum power, both air gap and iron core magnetic flux density should be maximum. However, it is necessary to check that the magnetic flux density does not exceed the saturation of the iron core.

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=n}^{n}\frac{1}{y_i^2}\right) \tag{7}$$

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=n}^{n}y_i^2\right) \tag{8}$$

$$S/N = -10\log\left(\frac{\bar{y}^2}{S^2}\right) \tag{9}$$

In (7–9), y_i, n, y, S^2 and S/N respectively represent the ith observation value, number of test, average of values, variance of data and signal to noise ratio. The larger the S/N ratio, the smaller the variance near the value. In (10, 11), y value and S^2 value are given respectively.

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n}y_i \tag{10}$$

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n}(y_i-\bar{y})^2 \tag{11}$$

When the factor graphs are drawn according to the effect values of the averages in Table 5, it is seen that the factors and levels in the loaded and unloaded state have the same effect rate. Therefore, design variables according to signal to noise ratios are created in Table 7 only for no-load condition.

Figure 9 shows the signal to noise (S/N) ratios of the mean magnetic flux density in the airgap and iron core for no-load condition.

Table 7
S/N Ratio of design variables for no-load

No-load B_{air} (Tesla)						
	Ai	**Bi**	**Ci**	**Di**	**Ei**	**Fi**
1	–9.3030	–8.5777	–8.7284	–8.2063	–8.8290	–8.7931
2	–8.1224	–8.4263	–8.3699	–8.4802	–8.5552	–8.6639
3	–8.0325	–8.3820	–8.3056	–8.1517	–8.3342	–8.4074
4	–8.0837	–8.2446	–6.5720	–8.1492	–8.0354	–8.1523
5	–8.2205	–8.1315	–8.1127	–8.2063	–8.0084	–7.7454
Δ	1.2705	0.4463	2.1564	0.3310	0.8206	1.0476
R	2	5	1	6	4	3
No-load B_{core} (Tesla)						
	Ai	**Bi**	**Ci**	**Di**	**Ei**	**Fi**
1	–3.2665	–3.4544	–3.7053	–3.6273	–3.7423	–3.5931
2	–3.5451	–3.5150	–3.3568	–3.6721	–3.7181	–3.7813
3	–3.7225	–3.7076	–3.4500	–3.3476	–3.6277	–3.7079
4	–3.6402	–3.5992	–2.9876	–3.4673	–3.3182	–3.5963
5	–3.6188	–3.5169	–3.6830	–3.6273	–3.3868	–3.1146
Δ	0.4560	0.2532	0.7176	0.3244	0.4241	0.1881
R	2	5	1	4	3	6

From Fig. 9a it is seen that the most effective parameters and levels are A3B5C4D3E5F5, and from Fig. 9b, the most effective parameters and levels are A1B1C4D3E4F5.

In Fig. 9, the analyses were repeated according to the most effective parameters and levels obtained according to the S/N ratio. The analysis results obtained with ANSYS Maxwell are given in Table 8.

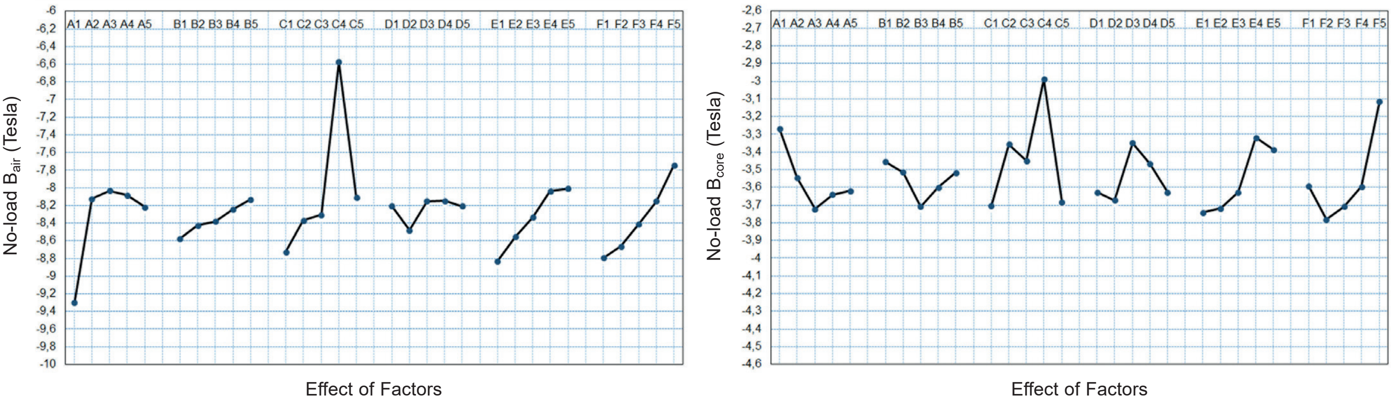
(a) (b)

Fig. 9. Effect of factors S/N ratio a) No-load magnetic flux density in airgap b) No-load magnetic flux density on iron core

Table 8
Result of ANSYS with S/N ratio

No	Taguchi design	No-load B_{air}	Loaded B_{core}
1	Initial design	0.2740	0.6571
2	Average of design	0.4519	0.8163
3	A3B5C4D3E5F5	0.7139	1.1084
4	A1B1C4D3E4F5	0.7218	0.8736
	Comparison of 1 and 3	160.50%	68.67%
	Comparison of 1 and 4	163.38%	32.95%
	Comparison of 2 and 3	57.96%	35.79%
	Comparison of 2 and 4	59.71%	7.03%

3.3. Anova and regression analysis. In this study, air gap magnetic flux density of AFPM synchronous generator was optimized with Taguchi experimental design method. The results were also examined statistically. Firstly, the significance levels of effects of the independent variables Sw, Sh, Ch, Airg, Mh and Mw on the airgap magnetic flux density were obtained by the ANOVA table. The results of ANOVA obtained from SPSS analysis are given in Table 9. ANOVA table shows that the statistical value of "F" is 94.071. The level of significance associated with this value is 0.000. Hence, it can be said that the model created by SPSS is meaningful and regression analysis which gives effect levels of independent variable values can be performed.

Table 9
Anova table

Model	Sum of Squares	df (degree of freedom)	Mean Square	F	Sig.
Regression	0.510	6	0.085	94.071	0.000
Residual	0.016	18	0.001		
Total	0526	24			
a. Dependent Variable: B_{airgap} (airgap magnetic flux density)					
b. Predictors: (Constant), Mw, Mh, Airg, Ch, Sh, Sw					

Regression analysis was performed for the effect rate of the independent variables on the magnetic flux density of air gap which is the dependent variables. Table 10 shows the values obtained as a result of regression analysis.

In the regression model in Table 10, the "sig" value show the significance of the variables. Significance increases as the "sig" value approaches zero. In cases where "sig" value is greater than 0.05, variables are meaningless. Therefore, it can be said that the model in Table 10 is statistically insignificant for the variables "Sh" and "Ch" (considering the sig value). Other variables (Sg, Airg, Mh, Mw) were statistically significant. Because "sig" values are less than 0.05. In Table 10, the coefficient "B" shows the weight of each independent variable. Using the coefficient "B", the effects of the variables on the air gap magnetic flux density are given in (12). As can be seen in (12), we can say that the independent variables "Sh" and "Ch" have no effect. However, "Mh" and "Mw" effect rates are equally positive. Independent variable "Airg" has the largest negative effect on the dependent variable "B_{airgap}". However, the effect of "Sw" is negatively minimized to other independent variables.

Table 10
Regression model

Model	Unstandardized coefficients		Standardized coefficients		Sig.
	B	Std. Error	Beta	t	
(Constant)	0.101	0.047		2.148	0.046
Sw	−0.008	0.003	−0.123	−2.968	0.008
Sh	0.000	0.001	−0.012	−0.301	0.767
Ch	0.001	0.001	0.018	0.446	0.661
Airg	−0.051	0.009	−0.248	−5.985	0.000
Mh	0.015	0.002	0.301	7.265	0.000
Mw	0.015	0.001	0.895	21.600	0.000
a. Dependent Variable: B_{airgap} (airgap magnetic flux density)					

$$B_{air\,gap} = 0.101 - 0.008\,Sw + 0.000\,Sh + 0.001\,Ch - \\ - 0.051\,Airg + 0.015\,Mh + 0.015\,Mw \tag{12}$$

4. Result and discussion

In this study, air gap magnetic flux density of AFPM trapezoidal winding generator with open slotted has been optimized by Taguchi experimental design method. Firstly, magneto static analysis of the designed AFPM generator was performed by ANSYS Maxwell program. Then, slot width (Sw), slot height (Sh), iron core height (Ch), air gap (Airg), magnet height (Mh) and magnet width (Mw) parameters were determined as independent variables. It was calculated that a total of 15625 analyzes should be performed in the classical experimental method for 6 independent variables and 5 levels. In Taguchi experimental design method, it is possible to find the best parameters and levels by performing a total of 25 analyzes.

According to Taguchi experimental design method, the factors and levels of A1B1C2D2E5F5, A5B2C1D2E3F5, A5B2C1D2E4F5 were found to be effective in unloaded and loaded from Fig. 3. In the unloaded state, magnetic analyzes were performed for these factor and levels.

According to the results in the air gap, the magnetic flux density improved by 65.7% (for A1B1C2D2E5F5), 37.42% (for A5B2C1D2E3F5) and 44.06% (for A5B2C1D2E4F5) respectively, when compared with the average values. Considering the first design parameter instead of average values, 173.26% (for A1B1C2D2E5F5), 126.63% (for A5B2C1D2E3F5), and 137.57% (for A5B2C1D2E4F5) improvements were calculated, respectively. According to the results in the iron core, the magnetic flux density improved by 37.43% (for A1B1C2D2E5F5), 79.73%

(for A5B2C1D2E3F5) and 83.55% (for A5B2C1D2E4F5) respectively, when compared with the average values. Considering the first design parameter instead of average values, 70.71% (for A1B1C2D2E5F5), 123.26% (for A5B2C1D2E3F5), and 128.01% (for A5B2C1D2E4F5) improvements were calculated, respectively. The values in the loaded state are close to the unloaded values.

In the factor effect graph given in Fig. 4a, 4c, the factor and levels of A1B1C2D2E5F5 in the air gap have taken the maximum value of magnetic flux density in the analysis results. However, in the factor effect graph given in Fig. 4b, 4d, the factor and levels of A5B2C1D2E3F5, A5B2C1D2E4F5 in the iron core have taken the maximum value of magnetic flux density in the analysis results. Factor and levels of A5B2C1D2E4F5 have a higher effect on both air gap and iron core magnetic flux density than A5B2C1D2E3F5. However, the factor and level of A1B1C2D2E5F5 provided the highest rate of improvement for the air gap magnetic flux density. For the value of iron core magnetic flux density, the factor and levels of A5B2C1D2E4F5 provide the best improvement.

Therefore in this study, A1B1C2D2E5F5 factors and levels are taken as the optimum value with the improvement rate of 65.7% compared to the average value for air gap magnetic flux density. Accordingly, for A1B1C2D2E5F5 factor and levels Sw, Sh, Ch, Airg, Mh, Mw, are 6 mm, 16 mm, 8.75 mm, 1.5 mm, 12 mm and 40 mm, respectively.

Factor and levels of A3B5C4D3E5F5, A1B1C4D3E4F5 were obtained as optimum values considering signal to noise ratios. The factor and levels of A3B5C4D3E5F5, A1B1C4D3E4F5 improved 57.96% and 59.71%, respectively, for the air gap magnetic flux density compared to the average value in no–load condition.

The dependent variable is the air flux magnetic density and the effect of independent variables on dependent variable was also examined statistically. ANOVA table and regression model were obtained statistically with SPSS program. The results of the experimental analysis were confirmed by the ANOVA table. According to the regression model, the most effective parameter is the air gap length “Airg”. However, it is seen that the magnet height (Mh) and magnet width (Mw) parameters have the same degree of effect. The slot width (Sw) was found to have the minimum effect in the reducing direction and slot height and iron core height were found to be statistically insignificant according to the “sig” value.

In this study, 6 parameters of open slotted AFPM generator were optimized by using factor effect graph and signal to noise ratio in Taguchi experimental method. According to the average magnetic flux of air gap, the most effective values are A1B1C2D2E5F5 factors and levels with 65.7% improvement over average value.

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