Proceedings of the 7th World Congress on Mechanical, Chemical, and Material Engineering (MCM'21)
~~Prague, Czech Republic~~ Virtual Conference – August, 2021
Paper No. ICMIE 105
DOI: 10.11159/icmie21.105

Magnetic Flux Density Distribution of 1.5 kW Permanent Magnet Synchronous Generator by using Response Surface Methodology

Deniz Perin[1], Mehmet Baki Dogru[1], Demet Gonen Ocaktan[2], Ali Oral[3], Aslan Deniz Karaoglan[2]
[1]ISBIR Electric Co.
Department of R&D, 10150, Balikesir, Turkey
tsr16@isbirelektrik.com.tr; tsr03@isbirelektrik.com.tr
[2]Balikesir University
Department of Industrial Engineering, 10145, Balikesir, Turkey
dgonen@balikesir.edu.tr; deniz@balikesir.edu.tr
[3]Balikesir University
Department of Mechanical Engineering, 10145, Balikesir, Turkey
alioral@balikesir.edu.tr

Abstract - In this paper, design optimization of 1.5 kW permanent magnet synchronous generator (PMSG) is performed. The aim is to obtain the target magnetic flux density distributions for the responses namely stator-teeth flux density (Tesla), stator-yoke flux density (Tesla), and air-gap flux density (Tesla). For this purpose response surface methodology (RSM) – which is a well-known design of experiments technique – is used for mathematically modelling the relations between the mentioned responses and the design parameters (embrace, outer diameter, and thickness). Maxwell simulation results are used for experimental calculations. Optimization results are also confirmed by using Maxwell program. The results indicate that the RSM is an effective method for design optimization of this type of magnetic devices.

***Keywords*:** magnetic flux density distribution (MFDD), permanent magnet synchronous generator (PMSG), response surface methodology (RSM), design optimization.

1. Introduction

It is important for the generators to keep the magnetic flux density distribution in a particular range to provide the high efficiency for the electric machine. Magnetic device design optimization by the aid of RSM was investigated by many researchers in the last decades. Gillon and Brochet [1] researched electric motor design optimization using RSM. Jolly et al. [2] studied permanent magnet motor (PMM) design optimization using RSM and genetic algorithm (GA). For numerical experiments, they used finite element analysis (FEA). Fang et al. [3] optimized the design of an interior PM synchronous motor (PMSM) by using RSM. Hasanien et al [4] used RSM and GA together to optimize the design of PM transverse flux linear motor (TFLM). FEA computations are used for numerical experiments. Hasanien, and Muyeen [5] studied on the design optimization of frequency converter of a variable speed wind turbine (VSWT) driven PM synchronous generator (PMSG) by using GA and RSM. Wen et al. [6] used RSM and particle swarm optimization (PSO) together for optimizing the coil design of wind turbine generator. They considered air gap magnetic flux density (AGMFD) as response. Zhang et al. [7] used PSO and RSM for optimization of transverse flux PMM (TFPMM) design. Asef et al. [8] used RSM and Booth's algorithm using simulated annealing (BA-SA) together to optimize the design of PMSG. Soleimani et al. [9] proposed RSM for optimizing high power TFPMG design. Fekri et al. [10] presented optimal design of surface mounted 3-phase axial flux switching PMG (SMAFSPM) by using RSM and FEA together. Semon et al. [11] studied on rotor design optimization of a V-type interior PMSM. They used RSM to optimize the air-gap magnetic flux density. Karaoglan et al. [12] studied on stator slot design optimization of PMG. They used RSM for multi-objective optimization of the magnetic flux for air-gap, stator teeth, and stator yoke, and also maximizing the efficiency.

In this study design optimization of 1.5 kW 16-poled PMSG is performed. The responses are selected as the magnetic flux density distributions at the stator-teeth, stator-yoke, and air-gap. The factors those will be optimized are the embrace, outer diameter, and thickness. The selected performance criterions (responses) and the factors did not investigate together previously and this is the novelty aspect of this research. Next section describes the materials and methods of this study.

2. Response Surface Methodology

Optimization by using design of experiment techniques has three main steps. These are: (*i*) constructing the experimental design and performing the experiments, (*ii*) mathematical modelling by using these experimental data, (iii) performing the optimization by using the mathematical models. RSM is one of the widely used design of experiment technique. It is used for modelling the mathematical relations between the factors (input variables) and the response (output variable) by using the experimental results (which are obtained from an orthogonal design). Central composite design, face centered design, and Box-Behnken design are the well-known RSM experimental design. In this study we used face centered design [13, 14].

Mathematical models in RSM can be linear or second order polynomials. These polynomials are called regression equation. In this study, full quadratic regression model is used. This model includes linear, square, and interaction terms. General representation of full quadratic model is given in Eq. (1) [13, 14]:

$$Y_u = \beta_0 + \sum_{i=1}^{n} \beta_i X_{iu} + \sum_{i=1}^{n} \beta_{ii} X_{iu}^2 + \sum_{i<j}^{n} \beta_{ij} X_{iu} X_{ju} + e_u \tag{1}$$

Following the calculation of mathematical models, coefficient of determination (R^2) is calculated. R^2 is desired to be closer to 1 (in other words: 100%). Then this means the factors (X terms) used in the mathematical model is sufficient and the model has the ability of explaining the response (Y). Then significance for the regression equation is tested by using analysis of variance (ANOVA). In this study we used Minitab statistical package for designing, modelling and optimizing the problem. To perform ANOVA, using P-value approach is a common way. According to this approach if the P-value calculated by the aid of Minitab is less than 0.05 (5%) (Type-I error is 5% for 95% confidence level), then this means the mathematical model represented in Eq. (1) is significant and can be used for optimization [13, 14].

In the third phase, optimization is performed to determine the optimum factor levels those provide us to obtain the desired response values. RSM uses gradient search algorithm for this purpose. In this study we used gradient search algorithm by the aid of 'Minitab Response Optimizer Module'.

3. Experimental Results

The aim of this research is to calculate the optimum design values for embrace, outer diameter, and thickness to obtain the desired magnetic flux distributions for the 1.5 kW 16-poled PMSG. The performance criteria are determined as 1.8 Tesla, 1.1 Tesla, and 0.9 Tesla values for stator-teeth, stator-yoke, and air-gap flux density values, respectively. The structure of the PMSG that is used for the experiments are presented in Figure 1. Embrace is a ratio that shows how much of the rotor surface the magnet is enveloping. So it has no unit. The measurements for the other two factors are expressed in millimetres (mm).

RSM face centered design is used for designing the experiment. The factor levels are determined (as [min, max] values) as [0.45, 0.95], [210, 250], and [3, 10] for the embrace, outer diameter, and thickness respectively. The center points are 0.7, 230, and 6.5 respectively. The experimental design is given in Table 1. In Table 1, the factor level of thickness in the RSM experiment design (run numbers: 9, 10, 13, 14, 15) was 6.5 mm in the original experimental design. However, this value was taken as 7 mm as it does not comply with mass production conditions.

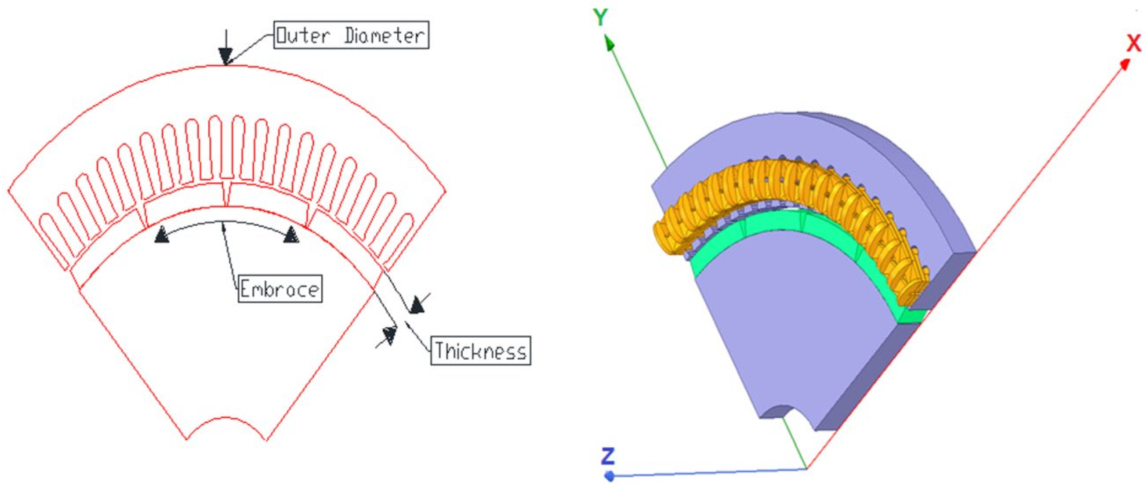

Fig.1: Design of the PMSG that will be optimized.

Table 1: Simulation results of Maxwell for the RSM face centered design.

Run	Factors			Responses		
	Embrace (X_1)	Outer Diameter (X_2) (mm)	Thickness (X_3) (mm)	Stator -Teeth Flux Density (Y_1) (Tesla)	Stator -Yoke Flux Density (Y_2) (Tesla)	Air-Gap Flux Density (Y_3) (Tesla)
1	0.45	210	3	1.54	0.73	0.78
2	0.95	210	3	1.56	1.47	0.79
3	0.45	210	10	1.87	0.92	0.94
4	0.95	210	10	1.96	1.73	0.99
5	0.45	250	3	1.54	0.22	0.78
6	0.95	250	3	1.56	0.44	0.79
7	0.45	250	10	1.87	0.27	0.94
8	0.95	250	10	1.96	0.52	0.99
9	0.45	230	7	1.8	0.4	0.91
10	0.95	230	7	1.86	0.79	0.94
11	0.7	230	3	1.55	0.52	0.78
12	0.7	230	10	1.92	0.66	0.97
13	0.7	210	7	1.83	1.35	0.92
14	0.7	250	7	1.83	0.41	0.92
15	0.7	230	7	1.83	0.63	0.92

The mathematical models those represents the relations between the responses and the factors are calculated by using Minitab statistical package and given in Eqs. (2) - (4) below:

$$\mathrm{Y1\ (Stator - Teeth\ Flux\ Density\ )} = 1.0783444444444 + 0.004888888889\mathrm{X}_1 + 0.001277777778\mathrm{X}_2 + 0.114084656085\mathrm{X}_3 - 0.017777777778X_1^2 - 0.00000277777777777768X_2^2 - 0.005830687831X_3^2 - 0.0000000000000000755\mathrm{X}_1\mathrm{X}_2 + 0.02\mathrm{X}_1\mathrm{X}_3 + 0.000000000000000000040\mathrm{X}_2\mathrm{X}_3 \quad (2)$$

$$\mathrm{Y2\ (Stator - Yoke\ Flux\ Density)} = 31.19413306 + 8.05066125\mathrm{X}_1 - 0.27747873\mathrm{X}_2 + 0.18763905\mathrm{X}_3 - 0.68444444X_1^2 + 0.00060556X_2^2 - 0.00312434X_3^2 - 0.027\mathrm{X}_1\mathrm{X}_2 + 0.01235772\mathrm{X}_1\mathrm{X}_3 - 0.0005874\mathrm{X}_2\mathrm{X}_3 \quad (3)$$

$$\text{Y3 (Air} - \text{Gap Flux Density)} = 0.358474255 - 0.077344173\text{X}_1 + 0.002555556\text{X}_2 + 0.055106594\text{X}_3 + 0.044444444X_1^2 - 0.00000556X_2^2 - 0.002851852X_3^2 - 0.000000000000000000382\text{X}_1\text{X}_2 + 0.011382114\text{X}_1\text{X}_3 + 0.000000000000000000041\text{X}_2\text{X}_3 \tag{4}$$

The statistical analysis results obtained from Minitab are presented in Table 2. According to these results the R^2 values are very good (close to 100%) which means these three factors are sufficient to explain the responses. Also the P-values are lover then the 5% which means these models are significant and can be used for optimization.

Table 2: Statistical analysis results for the mathematical models.

Response	R2 Results			ANOVA Results	
	R^2 (%)	R^2 (Prediction) (%)	R^2 (Adjusted) (%)	P-Value	Result
Stator Teeth Flux Density	100	99.98	99.99	0.000<0.05	Significant
Stator Yoke Flux Density	99.71	97.31	99.18	0.000<0.05	Significant
Air Gap Flux Density	99.95	99.58	99.86	0.000<0.05	Significant

Table 3 presents the prediction performances of the models. In Table 3, Y_i values represents the observed values (Maxwell results), and the $\hat{Y}_i$ values are the expected values (Minitab predictions for the mathematical models). PE is the prediction error ($PE_i(\%) = \left(\left|Y_i - \hat{Y}_i\right|/\hat{Y}_i\right)100$):

Table 3: Prediction performances.

Run	Stator Teeth Flux Density			Stator Yoke Flux Density			Air Gap Flux Density		
(i)	Y_{i1}	$\hat{Y}_{i1}$	PE_{i1} (%)	Y_{i2}	$\hat{Y}_{i2}$	PE_{i2} (%)	Y_{i3}	$\hat{Y}_{i3}$	PE_{i3} (%)
1	1.54	1.5396	0.03	0.73	0.7427	1.71	0.78	0.7794	0.08
2	1.56	1.5596	0.03	1.47	1.4725	0.17	0.79	0.7889	0.14
3	1.87	1.8706	0.03	0.92	0.9473	2.88	0.94	0.9414	0.15
4	1.96	1.9606	0.03	1.73	1.7203	0.56	0.99	0.9908	0.08
5	1.54	1.5396	0.03	0.22	0.2293	4.06	0.78	0.7794	0.08
6	1.56	1.5596	0.03	0.44	0.4191	5.00	0.79	0.7889	0.14
7	1.87	1.8706	0.03	0.27	0.2694	0.21	0.94	0.9414	0.15
8	1.96	1.9606	0.03	0.52	0.5024	3.49	0.99	0.9908	0.08
9	1.8	1.7998	0.01	0.4	0.3512	13.89	0.91	0.9084	0.17
10	1.86	1.8598	0.01	0.79	0.8357	5.47	0.94	0.9407	0.07
11	1.55	1.5518	0.11	0.52	0.5164	0.69	0.78	0.7836	0.45
12	1.92	1.9178	0.12	0.66	0.6604	0.07	0.97	0.9656	0.46
13	1.83	1.8298	0.01	1.35	1.3171	2.49	0.92	0.9196	0.05
14	1.83	1.8298	0.01	0.41	0.4397	6.76	0.92	0.9196	0.05
15	1.83	1.8309	0.05	0.63	0.6362	0.98	0.92	0.9218	0.19

The results given in Table 3 show that the mathematical models good-fit the observations. The optimization is performed by using 'Minitab Response Optimizer Module' by using the Eqs. (2) – (4). The Optimization graph obtained from Minitab is presented in Figure (2). According to this figure optimum factor levels are calculated as 0.9, 220 mm, and 6 mm for the embrace, outer diameter, and thickness respectively. The responses are predicted as 1.7976 Tesla (Target: 1.80), 1.1076 Tesla (Target: 1.1), and 0.9076 Tesla (Target: 0.9) for the stator-teeth flux density, stator-yoke flux density, and air-gap flux density.

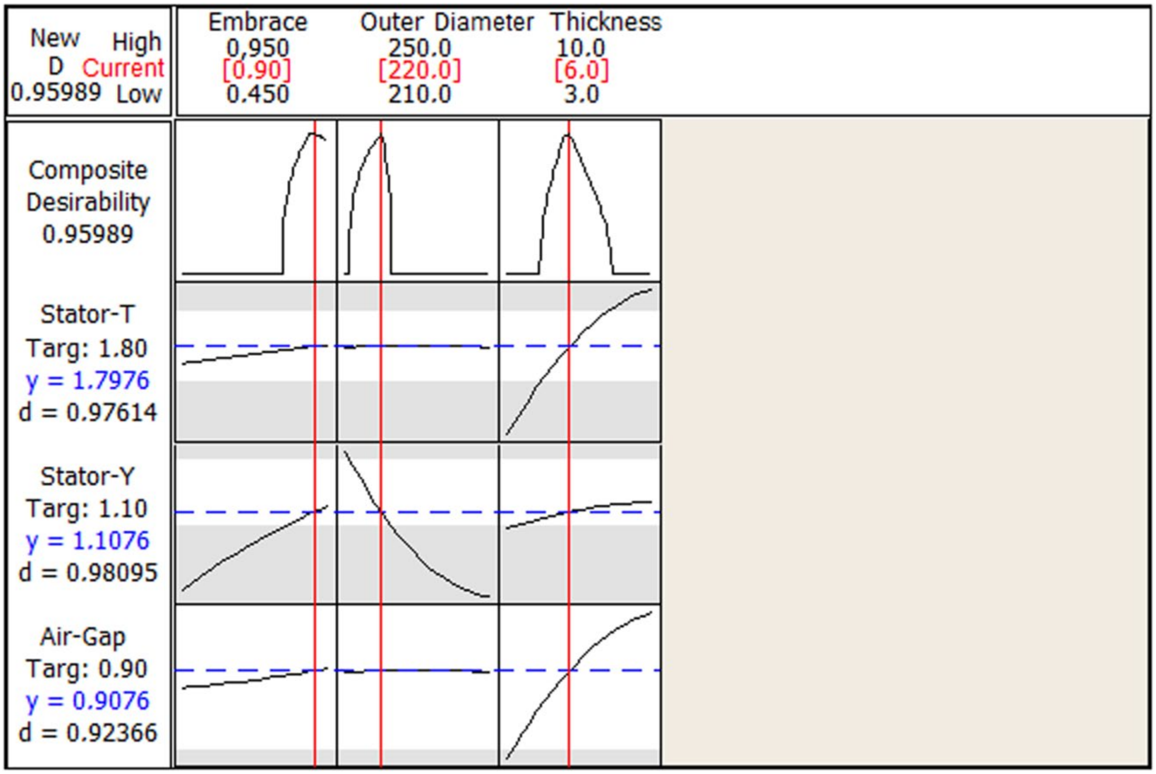

Fig.2: Optimization result calculated by 'Minitab Response Optimizer'.

The optimum design is confirmed by Maxwell simulation. The confirmations and comparisons are given in Table 4.

Table 4: Confirmations and comparisons concerning the optimization results.

Responses	Maxwell (Y_i)	Minitab ($\hat{Y}_i$)	PE (%)
Stator-teeth flux density	1.81	1.7976	0.69
Stator-yoke flux density	1.04	1.1076	6.10
Air-gap flux density	0.91	0.9076	0.26

According to the results presented in Table 4, it can be clearly indicated that the predicted results are very close to the Maxwell results and the overall prediction error is less than 6.1%. This means the design optimization is completed and this design can be used in mass production. The magnetic flux density distribution graph obtained from Maxwell simulation is presented in Figure 3.

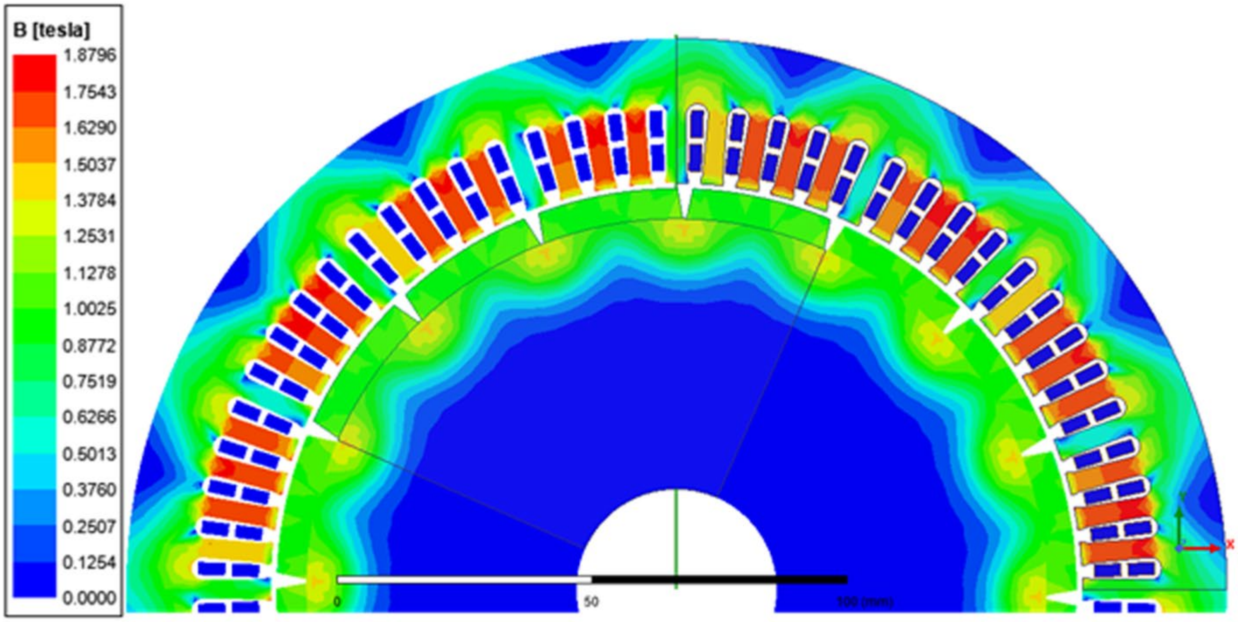

Fig.3: Maxwell simulation result for magnetic flux density distribution of the optimized PMSG.

4. Conclusion

In this study design optimization of 1.5 kW 16-poledPMSG is performed. For this purpose RSM is used to design the experiments, mathematical modelling and optimization. The observations for the experimental design are calculated from Maxwell simulations. Optimum factor levels are calculated by using 'Minitab Response Optimizer module'. Optimum factor levels are calculated as 0.9, 220 mm, and 6 mm for the embrace, outer diameter, and thickness respectively. According to the confirmations performed by using Maxwell simulations, the target magnetic flux density distributions are reached for the responses. These results indicate that the RSM can be used effectively for this type of problems. In the future research this study can be extended for additional performance criterions. Also the accuracy of the results will be confirmed by producing prototype PMSG.

Acknowledgements

We would like to thank Isbir Electric Co. for providing us with the ability to use its facilities and softwares.

References

[1] F. Gillon and P. Brochet, "Screening and response surface method applied to the numerical optimization of electromagnetic devices," *IEEE Transactions on Magnetics,* vol. 36, no. 4, pp. 1163-1167, 2000.

[2] L. Jolly, M. A. Jabbar and L. Qinghua, "Design optimization of permanent magnet motors using response surface methodology and genetic algorithms," *IEEE Transactions on Magnetics,* vol. 41, no. 10, pp. 3928-3930, 2005.

[3] L. Fang, J. W. Jung, J. P. Hong and J. H. Lee, "Study on high-efficiency performance in interior permanent-magnet synchronous motor with double-layer PM design", *IEEE Transactions on Magnetics,* vol. 44, no. 11, pp. 4393-4396, 2008.

[4] H. M. Hasanien, A. S. Abd-Rabou and S. M. Sakr, "Design optimization of transverse flux linear motor for weight reduction and performance improvement using response surface methodology and genetic algorithms," *IEEE Transactions on Energy Conversion*, vol. 25, no. 3, pp. 598-605, 2010.

[5] H. M. Hasanien and S. M. Muyeen, "Design optimization of controller parameters used in variable speed wind energy conversion system by genetic algorithms," *IEEE Transactions on Sustainable Energy*, vol. 3, no. 2, pp. 200-208, 2012.
[6] C. Wen, H. T. Yu, T. Q. Hong, M. Q. Hu, L. Huang, Z. X. Chen and G. J. Meng, "Coil shape optimization for superconducting wind turbine generator using response surface methodology and particle swarm optimization," *IEEE Transactions on Applied Superconductivity*, vol. 24, no. 3, Article Number: 5202404, 2014.
[7] C. J. Zhang, Z. H. Chen, Q. X. Mei and J. J. Duan, "Application of particle swarm optimization combined with response surface methodology to transverse flux permanent magnet motor optimization", *IEEE Transaction on Magnetics*, vol. 53, no. 12, Article Number: 8113107, 2017.
[8] P. Asef, R. B. Perpina, M. R. Barzegaran, A. Lapthorn, D. Mewes, "Multiobjective design optimization using dual-level response surface methodology and booth's algorithm for permanent magnet synchronous generators," *IEEE Transactions on Energy Conversion*, vol. 33, no. 2, pp. 652-659, 2018.
[9] J. Soleimani, A. Ejlali and M. Moradkhani, "Transverse flux permanent magnet generator design and optimization using response surface methodology applied in direct drive variable speed wind turbine system," *Periodicals of Engineering and Natural Sciences*, vol. 7, no. 1, pp. 36-53, 2019.
[10] H. Fekri, M. A. Shamsi-Nejad and S. M. Hasheminejad, "Performance analysis of a novel three-phase axial flux switching permanent magnet generator with overlapping concentrated winding," *International Journal of Engineering*, vol. 32, no. 2, pp. 286-295, 2019.
[11] A. Semon, L. Melcescu, O. Craiu, A. Craciunescu, "Design optimization of the rotor of a v-type interior permanent magnet synchronous motor using response surface methodology," in *11th International Symposium on Advanced Topics in Electrical Engineering (ATEE)*, Bucharest, Romania, Mar 28-30, 2019.
[12] A. D. Karaoglan, D. G. Ocaktan, A. Oral and D. Perin, "Design optimization of magnetic flux distribution for PMG by using response surface methodology," *IEEE Transactions on Magnetics*, vol. 56, no. 6, pp. 1-9, 2020.
[13] D. C. Montgomery, *Design and analysis of experiments,* NJ: John Wiley & Sons, 2003.
[14] R. L. Mason, R. F. Gunst and J. L. Hess, *Statistical Design and Analysis of Experiments* (2nd ed.), NJ: John Wiley & Sons, 2003.