IJE TRANSACTIONS C: Aspects Vol. 34, No. 9, (September 2021) 2097-2106

International Journal of Engineering

Journal Homepage: www.ije.ir

Multi-objective Optimization Design and Verification of Interior Permanent Magnet Synchronous Generator Based on Finite Element Analysis and Taguchi Method

S. R. Karimpour[a], M. R. Besmi*[a], S. M. Mirimani[b]

[a] *Faculty of Electrical and Computer Engineering, Shahed University, Tehran, Iran*
[b] *Faculty of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Iran*

PAPER INFO

Paper history:
Received 15 Jan 2020
Received in revised form 11 July 2021
Accepted 23 July 2021

Keywords:
Interior Permanent Magnet Machine
Finite Element Method
Multi-objective Optimization Design
Orthogonal Matrix
Taguchi Method

ABSTRACT

This paper proposes the optimal design process of an interior permanent magnet synchronous generator (IPMSG) for wind power systems using the finite-element analysis (FEA). A multi-objective optimization design of PM generator based on Taguchi method is proposed. This paper takes into consideration as a design parameters the influence of the pole arc angle, magnet inset, magnet thickness, magnet width, stator tooth width and slot depth. The main characteristics of generator efficiency, torque ripple and output power are taken as optimization objectives. The orthogonal matrix is established according to the number of selected parameters and the level factor of each parameter. Also, FEM is used to solve the experimental matrix. As a result, an improved generator was designed and selected, which had higher maximum output power and efficiency and lower torque ripple. Finally, a prototype IPMSG was manufactured based and tested on results analysis and Taguchi method. The experimental tests were conducted to verify the validity of the proposed design process and the effectiveness of the generator and as a result, perfectly cleared the optimization design.

***doi**: 10.5829/ije.2021.34.09c.07*

NOMENCLATURE

n_n	Rated speed of the generator	Q	The number of levels
I_n	Rated current of the generator	D_{os}	The outer diameter of stator
P_n	Rated power of the generator	D_{or}	The outer diameter of rotor
η	The efficiency of the generator	g	The air-gap length between rotor and stator
NF	The Noise Factor of the Taguchi Test	l	The stack length of generator
m	The overall mean of the experimental results	A	The stator tooth width
m_η	The overall mean of the efficiency (η)	B	The stator slot depth
m_{Tr}	The overall mean of the torque ripple	C	The rotor magnet thickness
m_P	The overall mean of the output power	D	The rotor magnet width
$m_{\eta A}$	The mean of the efficiency (η) under each level of factor A	E	The rotor magnet inset
S_A	The variance of definite objective function under factor A	F	The rotor magnet spread angle
$S_{\eta A}$	The variance of the efficiency under factor A	M470-50A	The stator and rotor core material
S_{Tr}	The variance of the torque ripple under factor A	NdFeB	The permanent magnet material
S_P	The variance of the output power under factor A		

1. INTRODUCTION

Permanent magnet (PM) machines are popular and attractive for many Applications with high-efficiency, such as wind turbine systems and have more advantages than traditional machines due to their high efficiency, high power density, noticeable torque-to-current ratio, and low maintenance cost. The design of generator in wind turbine systems depends on ease of maintenance, efficiency and generator performance [1, 2]. Therefore, their design optimization process becomes more

---

*Corresponding Author Institutional Email: besmi@shahed.ac.ir (M. R. Besmi)

Please cite this article as: S. R. Karimpour, M. R. Besmi, S. M. Mirimani, Multi-objective Optimization Design and Verification of Interior PMSG Based on Finite Element Analysis and Taguchi Method, International Journal of Engineering, Transactions C: Aspects Vol. 34, No. 9, (2021)...2097-2106

complex as more engineering domains and constraints are involved. Design optimization of PM generators is always one of the most important topics; which has been discussed intensively in literature [3-12]. Considering the manufacturing quality of the electrical machines in practical production, robust optimization model can be developed to replace the conventional deterministic model [13, 14].

Minimization of the torque ripple is an issue for design of IPMSG. To reduce the ripple, some investigations have already been through on the rotor structure with different geometries in different poles and structures [15, 16].

Presently, many experts and researchers have presented several optimization algorithms into the multi-objective optimization design of the generator such as genetic algorithm. That may be complex, according to design structure of electrical machines [17]. To decrease the rejection rates and increase the manufacturing reliability of electrical machines, robust design optimization is always a necessity. Multi-objective optimization has become popular in this field nowadays, as design optimization, such as maximizing the torque, efficiency, power density, output power and minimizing the torque ripple, active material cost, machine weight. To achieve the multi-objective optimization of generator design and solve the different parameters, this paper pursues Taguchi method to optimal design of interior PM generator.

Taguchi method is an optimal design method that can recognize the multi-independent optimization Parameters, and it is initiated by Doctor Taguchi in the 1970s. This method is developed from quality engineering with different specific focuses on probabilistic analysis and optimization. The best alternative concerning the chosen objective metrics is selected as the solution. The Taguchi method can support the engineers to speedily discovery the optimal combination of the design variables by the minimum amount of investigates. Taguchi has the advantages of fast convergence and high efficiency. Presently, the Taguchi method has been extensively used in the optimization of interior and surface-mounted permanent magnet machines, such as being used for improvement of efficiency and some other electromagnetic performances of the machine [18-23]. The purpose of this paper is to design and optimize IPMSG for wind power generation.

In this paper, we will deal with the efficiency and output power improvement and torque ripple reduction of a 8-pole, 27-slot, three-Phase interior permanent magnet synchronous generator (IPMSG). This aim can be effectively achieved by optimal design of the stator and rotor structure using the Taguchi and finite element methods. To get the multi-objective optimisation of generator design and solve the contrasts among different parameters, this paper adopts Taguchi method to design multi-objective optimisation of IPM generator. The Taguchi method was applied in order to evaluate and determine the geometric variables.

The optimization variables are selected such as the pole arc angle, magnet inset, magnet thickness, magnet width, stator tooth width and slot depth affect the performance of the generator. The orthogonal table of the Taguchi method was designed based on the number of geometry variables and its value levels. Multi-objective optimization was done for the main characteristics of the generator efficiency, output power and torque ripple. Finally, optimized prototype has been constructed. The finite element simulation results and the prototype experiments verify the effectiveness of the optimization method.

2. MODEL AND SPECIFICATION OF IPMSG

A three-phase Interior permanent magnet synchronous generator (IPMSG) is the object of the paper, which the geometry of the machine before improving the stator and rotor parameter is shown in Figure 1. It has buried permanent magnets. The initial values and basic parameters of the machine parameters are shown in Table 1 The stator and rotor core are composed of 0.5mm laminations of low-loss steel (M470-50A steel). The arrangement of magnets in the rotor is chosen in V shape. The stator winding adopts the fractional slot, over lapping type of double layer windings that is chosen, as it’s widely used in PM machines. The machine is a small-scale prototype to be used in wind turbine application the combination of poles and slots used is 8 poles and 27 slots.

Some comparisons are made to select the best solution to meet the requirements. Efficiency, output power and torque ripple is precisely calculated by FEM and then used in Taguchi method to select the best combination as final design.

3. MULTI-OBJECTIVE OPTIMISATION DESIGN OF IPMSG

Optimisation is a systematic approach in the design of generator to make a decision about the optimum design with the appropriate goal to determine the best results such as efficiency, torque ripple, output power and all the design requirements. In this paper, Taguchi method is used to optimize the generator. This technique is an experimental design method and aims to improve product quality.

This method dramatically reduces the number of tests by using orthogonal arrays and minimizes the effects of factors that cannot be controlled, considering

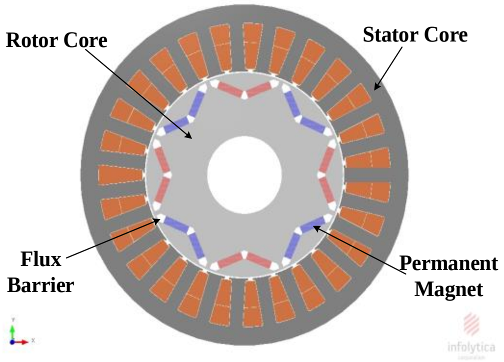


Figure 1. The geometry of the IPMSG

TABLE 1. Specifications of the IPMSG

Parameter	Symbol	Value	Unit
Rated speed	n_n	1000	r/min
Rated current	I_n	2	A
Rated Power	P_n	600	W
Pole number	p	8	– –
Slot number	Q	27	--
Outer diameter of rotor	D_{or}	66	mm
Air-gap length	g	0.4	mm
Outer diameter of stator	D_{os}	109.6	mm
Stack length	l	70	mm
Tooth width	A	4.3	mm
Slot depth	B	16.5	mm
Magnet thickness	C	2.5	mm
Magnet width	D	9	mm
Magnet inset	E	5	mm
Pole arc angle	F	42	°
Stator and rotor core material	M470-50A	--	--
Permanent magnet	NdFeB	--	--

the noise factor according to the environmental conditions in the IPMSG. Furthermore, it provides a simple, efficient and systematic approach to specifying the optimum design manufacturing process.

3. 1. Optimization Variables and Objective Function

The selected optimization variables are shown in Figure 2 and the optimization variables are represented as *A*, *B*, *C*, *D*, *E* and *F*, respectively. As shown in Figure 2, *A* represents the stator tooth width; *B* represents the stator slot depth; C represents the magnet thickness; D represents the magnet width; E represents the magnet inset and the angle F represents the magnet spread angle. For each parameter, five levels of influence factors are selected, and the Design Variables, Noise Factors and level values are shown in Table 2. The selected optimization objectives include the generator efficiency, torque ripple and output power. Among them, the generator efficiency and output power are expected to be better and the torque ripple is expected to be as small as possible.

3. 2. Experimental Results and Results Processing

According to the six variables optimization parameters selected above and the five-level factor ranges determined by each parameter, an experimental matrix is established according to the orthogonal experiment principle of Taguchi method. The traditional single variable optimization method requires 5^6 (15625) experiments. While Taguchi method only needs 25 experiments, which can be achieved through multi-objective optimization design. The experimental $L_{25}(5^6)$ orthogonal table is established according to the number of design variables and the number of levels corresponding to each factor. The generator efficiency (η), torque ripple (Tr) and output power (P) of each experiment listed in Table 3, are calculated respectively at the 25°C and 75°C ambient temperature by applying a common finite element software-motor solve 4.1.1. The transient state solution was used to analyze and optimize the optimization objectives of each group of experiments, and the experimental matrix and solution results are shown in Table 3.

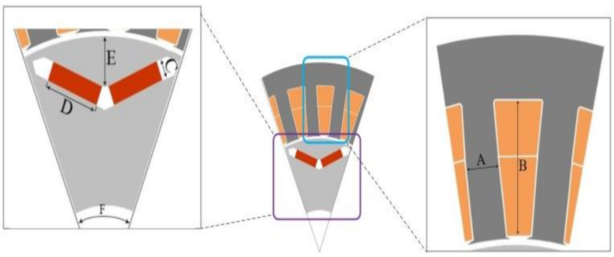


Figure 2. Design variables for Taguchi design of experiment

TABLE 2. Design Variables, Noise Factors and level values

Parameters	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)	F (°)
level factor 1	4.1	15.9	2	8	4	38
level factor 2	4.2	16.1	2.1	8.5	4.5	39
level factor 3	4.3	16.3	2.2	9	5	40
level factor 4	4.4	16.5	2.35	9.5	5.5	41
level factor 5	4.5	16.7	2.5	10	6	42
Noise Factor				array pattern		
Ambient Temperature			25° C		75° C	

3. 3. Analysis of Experimental Results

To analyze the influences on generator performances produced by different factors at different levels, Taguchi optimization method uses the statistical mean made by orthogonal arrays and analysis results of FEM. In the statistical analysis of the experimental results, the average is analyzed first.

3. 3. 1. Analysis of Overall Mean

The overall mean of the experimental results in each column listed in 3 is analyzed, respectively, and the calculation formula is shown in Equation (1):

$$m = \frac{\sum_{i=1}^{n} m_i}{n} \tag{1}$$

where *m* is the overall mean of the experimental results in certain column listed in Table 3 and *n* is the number of experiments and m_i is the experimental result of the *i* experiment in certain column listed in Table 3.

The overall mean of the efficiency (η) at 25°C in Table 3 is calculated using Equation (1), and is shown as follows:

$$m_\eta = \frac{\eta_1+\eta_2+\cdots+\eta_{25}}{25} = 89.5776 \tag{2}$$

In the same approach, the overall mean of other experimental results listed in Table 3 at 2 noise factors is achieved respectively as listed in Table 4.

TABLE 3. The experimental matrix and the analysis results

Experimental number	Experimental matrix						Efficiency (%)		Torque ripple (%)		Output power (W)	
							NF1	NF2	NF1	NF2	NF1	NF2
	A	B	C	D	E	F	25° C	75° C	25° C	75° C	25° C	75° C
1	1	1	1	1	1	1	89.03	87.30	3.100	3.661	474.3	451
2	1	2	2	2	2	2	89.31	87.25	3.240	3.761	496.8	467
3	1	3	3	3	3	3	89.61	87.70	3.408	3.567	517.4	487
4	1	4	4	4	4	4	89.83	87.75	4.632	4.200	535.0	504
5	1	5	5	5	5	5	89.95	88.10	5.482	5.165	545.2	514
6	2	1	2	3	4	5	89.21	87.45	3.462	3.842	487.5	462
7	2	2	3	4	5	1	90.37	88.50	3.340	3.448	564.3	532
8	2	3	4	5	1	2	90.71	89.10	4.593	4.230	593.7	561
9	2	4	5	1	2	3	88.79	86.60	2.896	3.430	468.4	440
10	2	5	1	2	3	4	88.71	86.50	3.212	3.110	466.9	439
11	3	1	3	5	2	4	90.49	88.90	4.165	3.962	572.0	544
12	3	2	4	1	3	5	88.22	85.90	3.530	4.200	437.8	410
13	3	3	5	2	4	1	89.61	87.50	2.654	2.930	514.4	484
14	3	4	1	3	5	2	89.56	87.60	3.231	3.155	514.3	484
15	3	5	2	4	1	3	90.03	88.30	4.174	3.770	546.4	516
16	4	1	4	2	5	3	89.23	87.55	3.705	4.397	489.2	464
17	4	2	5	3	1	4	89.87	88.00	3.472	4.152	528.9	497
18	4	3	1	4	2	5	89.70	87.70	3.987	3.915	521.4	490
19	4	4	2	5	3	1	90.58	88.80	4.499	4.182	587.5	556
20	4	5	3	1	4	2	88.57	86.20	3.075	3.858	460.1	432
21	5	1	5	4	3	2	90.56	89.00	3.518	3.711	576.1	548
22	5	2	1	5	4	3	90.43	88.70	4.357	3.972	569.6	549
23	5	3	2	1	5	4	88.09	85.70	4.341	5.140	434.1	406
24	5	4	3	2	1	5	88.98	86.90	3.122	3.841	476.5	447
25	5	5	4	3	2	1	90	88.10	2.859	2.680	543.8	513

TABLE 4. Overall mean of experimental results

Operating point	m_η (%)	m_{Tr} (%)	m_P (W)
At 25° C temperature	89.5776	3.68216	516.864
At 75° C temperature	87.644	3.85116	487.88

3. 3. 2. Analysis of Mean under Each Level of Each Factor

The mean of the efficiency (η) under each level of factor *A* at 25°C is set as an example to be calculated, and are shown as Equations (3)-(7).

$$m_{\eta A(1)} = \frac{\eta_1+\eta_2+\eta_3+\eta_4+\eta_5}{5} = 89.546 \tag{3}$$

$$m_{\eta A(2)} = \frac{\eta_6+\eta_7+\eta_8+\eta_9+\eta_{10}}{5} =89.558 \tag{4}$$

$$m_{\eta A(3)} = \frac{\eta_{11}+\eta_{12}+\eta_{13}+\eta_{14}+\eta_{15}}{5} =89.582 \tag{5}$$

$$m_{\eta A(4)} = \frac{\eta_{16}+\eta_{17}+\eta_{18}+\eta_{19}+\eta_{20}}{5} = 89.59 \tag{6}$$

$$m_{\eta A(5)} = \frac{\eta_{21}+\eta_{22}+\eta_{23}+\eta_{24}+\eta_{25}}{5} = 89.612 \tag{7}$$

In the same way, the mean of the generator efficiency, torque ripple and output power under each level of each factor at each operating point can be achieved, respectively; and the results are shown in Tables 5 and 6.

The changes of the efficiency, torque ripple and output power with the changes of the levels of each factor can be seen from Tables 5 and 6, as shown in Figure 3.

When the value taken by factor A (the stator tooth width) is larger, the efficiency of the machine is larger. The smaller the value taken by factor B (the stator slot depth), or the larger the value taken by factor *C* (the magnet thickness), the larger the increment of the efficiency and output power will be. At the same time, when the value taken by factor *D* (magnet width) is larger, the efficiency and output power will be larger. Moreover, when the value taken by factor *E* (the magnet inset), and the value taken by factor *F* (the magnet spread angle), is larger, the efficiency and output power will be less.

Further, the combinations of the level taken by each factor with the largest efficiency and output power and decrement of the torque ripple can be achieved from Tables 5 and 6, for example, at the 25°C temperature point, the combination of the level taken by each factor making the efficiency largest is *A*(5)*B*(1)*C*(5)*D*(5)*E*(1)F(1).

The combination that makes the torque ripple smallest is *A*(2)*B*(2)*C*(3)*D*(2)*E*(2)*F*(1); the combination that makes the output power largest is *A*(5)*B*(1)*C*(5)*D*(5)*E*(1)*F*(1). In the same way, the combinations of the level taken by each factor that make the efficiency and output power largest and the torque ripple smallest can be achieved at the 25°C temperature point. It can be seen from the above analysis that the combinations of the level taken by each factor that make the largest efficiency and output power, and decrement of the torque ripple are different. Consequently, it is necessary to investigate the relative importance of the effects of each design variable on the efficiency, output power and the torque ripple by the analysis of variance, and then an optimization scheme can be reached. Analysis of variance is used to evaluate the response magnitude in each parameter in the orthogonal experiment. It is used to quantify the causes of different experimental results from different parameters.

3. 4. Analysis of Variance (ANOVA)

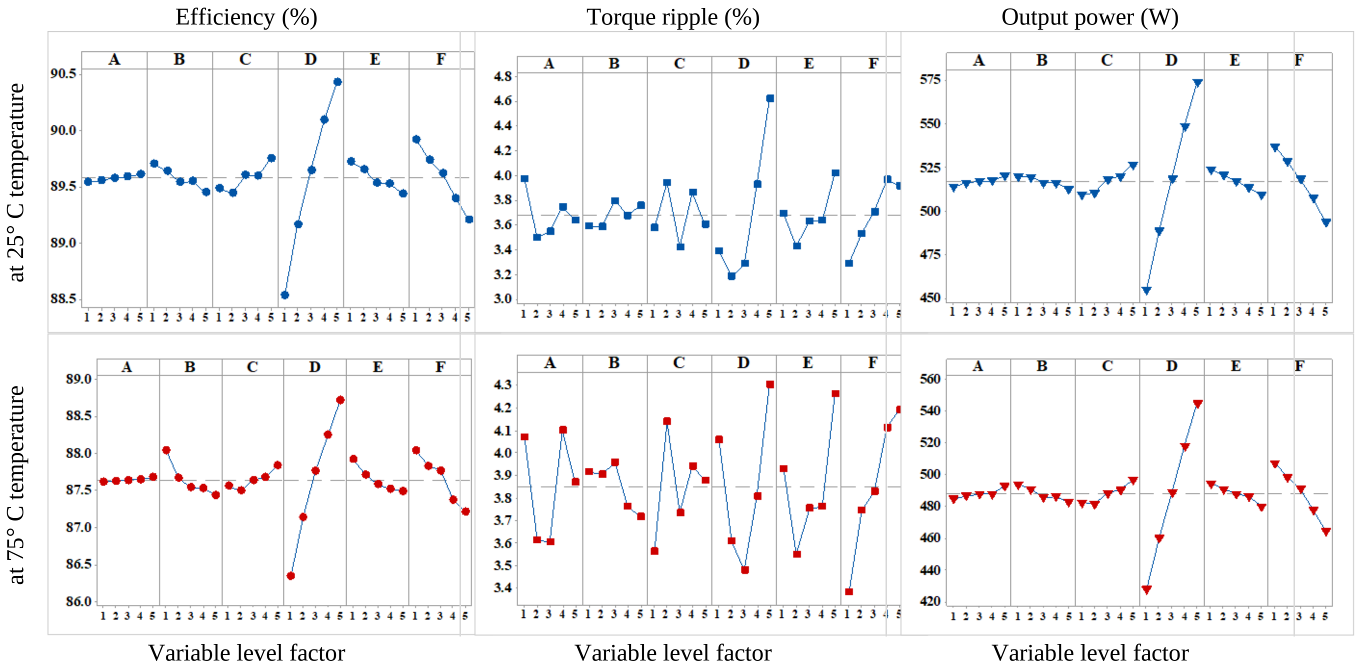
To analyze the proportions of influences on generator

TABLE 5. Mean of efficiency, torque ripple and output power under each level of each factor at 25°C temperature point

Factor	Level	m_η (%)	m_{Tr} (%)	m_P (W)
A	1	89.546	3.9724	513.74
	2	89.558	3.5006	516.16
	3	89.582	3.5508	516.98
	4	89.59	3.7476	517.42
	5	89.612	3.6394	520.02
B	1	89.704	3.59	519.82
	2	89.64	3.5878	519.48
	3	89.544	3.7966	516.2
	4	89.548	3.676	516.34
	5	89.452	3.7604	512.48
C	1	89.486	3.5774	509.3
	2	89.444	3.9432	510.46
	3	89.604	3.422	518.06
	4	89.598	3.8638	519.9
	5	89.756	3.6044	526.6
D	1	88.54	3.3884	454.94
	2	89.168	3.1866	488.76
	3	89.65	3.2864	518.38
	4	90.098	3.9302	548.64
	5	90.432	4.6192	573.6
E	1	89.724	3.6922	523.96
	2	89.658	3.4294	520.48
	3	89.536	3.6334	517.14
	4	89.53	3.636	513.32
	5	89.44	4.0198	509.42
F	1	89.918	3.2904	536.86
	2	89.742	3.5314	528.2
	3	89.618	3.708	518.2
	4	89.398	3.9644	507.38
	5	89.212	3.9166	493.68

TABLE 6. Mean of efficiency, torque ripple and output power under each level of each factor at 75°C temperature point

Factor	Level	m_η (%)	m_{Tr} (%)	m_P (W)
A	1	87.62	4.0708	484.6
	2	87.63	3.612	486.8
	3	87.64	3.6034	487.6
	4	87.65	4.1008	487.8
	5	87.68	3.8688	492.6
B	1	88.04	3.9146	493.8
	2	87.67	3.9066	491
	3	87.54	3.9564	485.6
	4	87.53	3.7616	486.2
	5	87.44	3.7166	482.8
C	1	87.56	3.5626	482.6
	2	87.5	4.139	481.4
	3	87.64	3.7352	488.4
	4	87.68	3.9414	490.4
	5	87.84	3.8776	496.6
D	1	86.34	4.0578	427.8
	2	87.14	3.6078	460.2
	3	87.77	3.4792	488.6
	4	88.25	3.8088	518
	5	88.72	4.3022	544.8
E	1	87.92	3.9308	494.4
	2	87.71	3.5496	490.8
	3	87.58	3.754	488
	4	87.52	3.7604	486.2
	5	87.49	4.261	480
F	1	88.04	3.3802	507.2
	2	87.83	3.743	498.4
	3	87.77	3.8272	491.2
	4	87.37	4.1128	478
	5	87.21	4.1926	464.6



(a) Influence of parameter level factor on the efficiency

(b) Influence of parameter level factor on the Torque ripple

(c) Influence of parameter level factor on the output power

Figure 3. Influence of parameter level factor on target performance

performances that are produced by each factor's different levels, analysis of variance that provides a measure of confidence is conducted. The sum of squares is a measure of the deviation of the experimental data from the average value of data. ANOVA is a statistical method which is used to determine the individual interactions of all of the control factors in the experimental design. S_A generated by various factors and different levels can be calculated as Equation (8):

$$S_A = \frac{\sum_{i=1}^{Q}(m_{A(i)} - m)^2}{Q} \tag{8}$$

where S_A is the variance of definite objective function under factor *A*; $m_{A(i)}$ is the mean of certain objective function under level *i* of factor *A*; *m* is the overall mean of definite objective function; *Q* is the number of levels taken by each factor, and *Q*=5 in this paper.

Calculation for the variance of the efficiency under factor *A* at the 25° C temperature point is set as an example to explain the calculation of the variance, and the expression is shown as follows:

$$S_{\eta A} = \frac{\sum_{i=1}^{5}(m_{\eta A(i)} - m_{\eta})^2}{5} = 0.000548 \tag{9}$$

In the same approach, the variances of the efficiency, torque ripple and the output power under each factor at each operating point are calculated using Equation (8), and the results are listed in Table 7.

It can be observed from Table 7 that factor *D* has the largest impact on the efficiency, output power and the torque ripple at both of the operating points, as shown in Table 7, the efficiency is sensitive to *D, F, C, E, B* and *A*, respectively at the 25° C temperature point; *D* is the most sensitive factor; *A* has a relatively weak effect on it. Similarly, the sensitivity and proportion percent of each factor on objectives at each operating points is achievable.

3. 5. Optimization Scheme of the Improved IPMSG

It can be observed from Table 5 that the combination of the level taken by each factor to make the efficiency largest is *A*(5)*B*(1)*C*(5)*D*(5)*E*(1)*F*(1), and the combination of the level taken by each factor to make the torque ripple smallest is *A(2)B(2)C(3)D(2)E(2)F(1)*, and the combination that makes the output power largest is *A(5)B(1)C(5)D(5)E(1)F(1)*, at the 25°C temperature point. in the three combinations, the level taken by factor *F* is the same and it is *F(1)*, and in the two combinations, the levels taken by factors *A, B, C, D* and *E* are the same and they are *A(5)B(1)C(5)D(5)E(1)*. It can be seen from Table 7 that the relative importance of the effects of each factor on the efficiency is DFCEBA from the largest to smallest, and the relative importance of the effects of each factor on the torque ripple is DFCEAB from the largest to smallest, and the relative importance of the effects of each factor on the output power is DFCEBA from the largest to smallest. In the same way, the combinations of the level taken by each factor to make the efficiency and output power largest and the torque ripple smallest at the 75°C temperature point are achieved respectively according to the Tables 5 and 6. Then the relative importance of the effects of each factor is achieved according to Table 7.

Finally, optimization schemes of the improved IPMSG at the 25° C and 75° C temperature point are achieved, respectively as shown in Table 8.

As a result, the best combination of factors for maximum efficiency and output power and minimum torque ripple, by the six optimization variables in the

TABLE 7. Calculation results of the variance

Factor	S_η **(%)**				S_{Tr} **(%)**				S_P**(W)**			
	25° C	**Proportion (%)**	**75° C**	**Proportion (%)**	**25° C**	**Proportion (%)**	**75° C**	**Proportion (%)**	**25° C**	**Proportion (%)**	**75° C**	**Proportion (%)**
A	0.000548	0.101	0.00042	0.049	0.028114	6.152	0.045891	14.255	4.107584	0.197	6.8576	0.341
B	0.00753	1.389	0.04458	5.087	0.007330	1.604	0.008860	2.752	7.103264	0.341	15.7216	0.783
C	0.011836	2.183	0.01350	1.541	0.037168	8.133	0.037681	11.704	40.73254	1.958	30.5056	1.519
D	0.450089	83.002	0.69906	79.759	0.285614	62.494	0.089102	27.676	1771.0805	85.114	1704.6816	84.902
E	0.010165	1.875	0.02474	2.823	0.036499	7.986	0.056585	17.576	26.295584	1.264	23.1936	1.155
F	0.06209	11.45	0.09414	10.741	0.062298	13.631	0.083822	26.037	231.51478	11.126	226.9056	11.3

TABLE 8. Optimization schemes of the improved IPMSG

	Combination (η)	**Combination (Tr)**	**Combination (P)**	**Effect (η)**	**Effect (Tr)**	**Effect (P)**	**Final optimization scheme**
Results at 25° C temperature point	A(5)B(1)C(5)D(5)E(1)F(1)	A(2)B(2)C(3)D(2)E(2)F(1)	A(5)B(1)C(5)D(5)E(1)F(1)	DFCEBA	DFCEAB	DFCEBA	A(5)B(1)C(5)D(5)E(1)F(1)
Results at 75° C temperature point	A(5)B(1)C(5)D(5)E(1)F(1)	A(3)B(5)C(1)D(3)E(2)F(1)	A(5)B(1)C(5)D(5)E(1)F(1)	DFBECA	DFEACB	DFCEBA	A(5)B(1)C(5)D(5)E(1)F(1)
Final optimization scheme	-	-	-	-	-	-	A(5)B(1)C(5)D(5)E(1)F(1)

final optimization scheme are *A(5)B(1)C(5)D(5)E(1)F(1)*. The specific values taken by each factor are listed in Table 9.

4. RESULT COMPARISONS AND OPTIMISED PROTOTYPE AND EXPERIMENTAL VERIFICATION

The design parameters of the IPMSG are optimized to satisfy the generator efficiency and output power and reduce the torque ripple through the proposed design process. Generator efficiency, output power and torque ripple are analyzed using FEM for the optimization model via the Taguchi method. According to the above optimization results, an Interior permanent magnet synchronous generator is designed and the prototype of the IPMSG was manufactured to validate the performances of optimized machine. Figures 4 and 5 show the components and test set of the IPMSG.

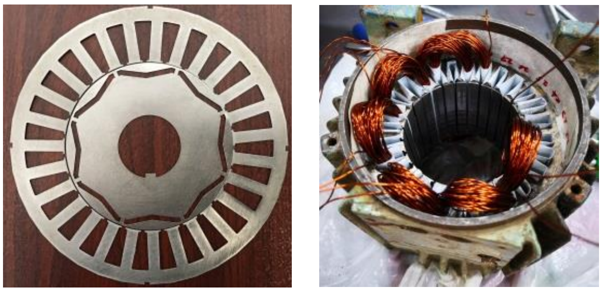
Figure 6 shows the waveform of back Emf at rated speed before and after optimization at initial and optimized model. It can be seen that after optimization, the amplitude of back EMF increased from 130.7 to 149.5 V, which increase about 14.38%.

The generator is dragged to the rated speed using the prime mover, and the phase voltage is measured. The comparison between the phase voltage and the FEM are shown in Figure 7. It can be seen that the measured waveform corresponds to the analytical one.

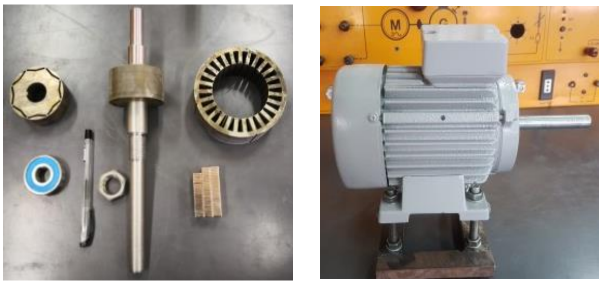
Table 10 compares the structure parameters and output performances of the IPMSG between the initial, optimized and manufactured machine and we can see that the results improved. It can be seen that the generator efficiency and output power improves as optimization progresses, and the FEA and the test results are in good agreement. As well as, it can be seen that the torque ripple is reduced as the optimization design progresses. According to the proposed optimization design method, the optimized IPMSG compared to initial one improved the generator efficiency and output power about 1.797% and 15.38%, respectively, and the torque ripple is reduced by 11.72% at the rated speed and 25°C temperature point.

TABLE 9. Values taken by each factor in the final optimization scheme of the improved IPMSG

Factor	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)	F (°)
Value	4.5	15.9	2.5	10	4	38



(a) (b)



(c) (d)

Figure 4. Generator components. (a) Rotor and stator steel sheet, (b) stator winding, (c) components, and (d) housing

Figure 5. Test set for experiment

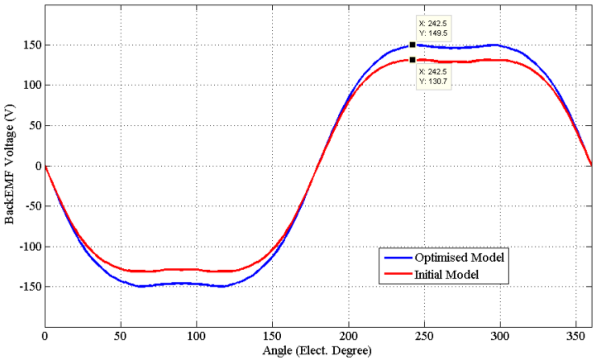
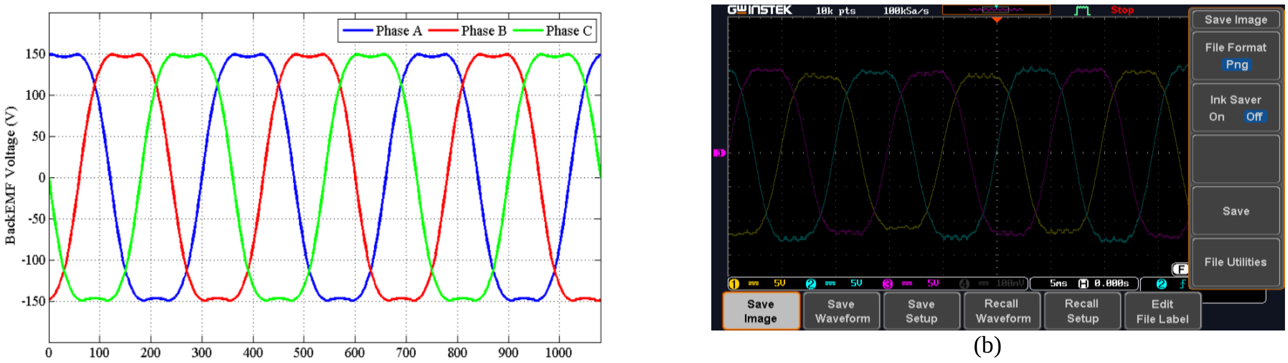


Figure 6. Comparison of results before and after optimisation at initial and optimized model



(a)

(b)

Figure 7. Back EMF waveform of (a) the analyzed result and (b) the experimental result

TABLE 10. Comparison of Parameters and results

Model	Parameter value						Response value		
	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)	F (°)	Efficiency (%)	Torque ripple (%)	output power (W)
Initial	4.3	16.5	2.5	9	5	42	89.4	4.35	533
Optimized	4.5	15.9	2.5	10	4	38	91	3.84	615
manufactured	4.5	15.9	2	10	4	38	90.8	3.89	594

5. CONCLUSION

This paper presents a multi-objective optimization design based on the Taguchi–FEA. The main performance characteristics such as generator efficiency, torque ripple and output power are taken as the optimization objectives, and the range of parameters that have a great influence on the generator optimization objective, which is reasonably selected as optimization variables. Taguchi method is utilized to optimize the improved IPMSG at the 25° C and 75° C temperature point. The effects of each optimization variable of the improved IPMSG on the generator efficiency, torque ripple and output power is analyzed, and then the optimization schemes at each operating point are achieved.

Finally, the final optimization scheme of the improved IPMSG is achieved. The improved machine effectively increases efficiency and output power; on the other hand, it also effectively reduces the torque ripple.

Finally, a prototype 0.6 KW, 8-pole/27-slot IPMSG was manufactured based on analysis results and Taguchi method, and was tested. The experimental tests were conducted to verify the validity of the proposed design process and the effectiveness of the generator.

6. REFERENCES

1. J. H. J. Potgieter and M. J. Kamper, “Design optimization of directly grid-connected pm machines for wind energy applications”, IEEE Transactions on Industry Applications, Vol. 51, No. 4, (2015), 2949-2958. DOI: 10.1109/TIA.2015.2394506
2. Y. Duan and R. G. Harley, “Present and future trends in wind turbine generator designs”, ***IEEE Power Electronics and Machines in Wind Applications***, (2009), 1-6. DOI: 10.1109/PEMWA.2009.5208401.
3. A. Di Gerlando, G. Foglia, M. F. Iacchetti, and R. Perini, “Axial flux pm machines with concentrated armature windings: Design analysis and test validation of wind energy generators”, ***IEEE Transactions on Industrial Electronics***, Vol. 58, No. 9, (2011), 3795-3805. DOI: 10.1109/TIE.2010.2081956.
4. D. Fodorean, A. Djerdir, I.-A. Viorel, and A. Miraoui, “A double excited synchronous machine for direct drive application - design and prototype tests”, ***IEEE Transactions on Energy Conversion***, Vol. 22, No. 3, (2007), 656-665. DOI: 10.1109/TEC.2007.896279.
5. F. B. Chaaban, “Determination of the optimum rotor/stator diameter ratio of permanent magnet machines”, ***Electric Machines and Power Systems***, Vol. 22, No. 4 (1994), 521-531. DOI: 10.1080/07313569408955584.
6. L. J. Wu, Z. Q. Zhu, J. T. Chen, Z. P. Xia, and G. W. ewell, “Optimal split ratio in fractional-slot interior permanent-magnet machines with non-overlapping windings”, ***IEEE Transactions on Magnetics***, Vol. 46, No. 5, (2009), 1235-1242. DOI: 10.1109/IEMDC.2009.5075435.
7. A. Di Gerlando, G. Foglia, M. F. Iacchetti, and R. Perini, "Axial flux PM machines with concentrated armature windings: design analysis and test validation of wind energy generators", ***IEEE Transactions on Industrial Electronics***, Vol. 58, No. 9, (2011), 3795-3805. DOI: 10.1109/TIE.2010.2081956.
8. J. Tapia, J. Pyrhonen, J. Puranen, S. Nyman, and P. Lindh, "Optimal design of large permanent magnet synchronous generators", ***IEEE Transactions on Magnetics***, Vol. 49, No. 1, (2013), 642-650. DOI: 10.1109/TMAG.2012.2207907.
9. M. Moallem, A. Kiyoumarsi and M. R. Hassanzadeh, "A Novel technique on the analytical calculation of open circuit flux

density distribution in brushless permanent magnet motor", ***International Journal of Engineering, Transactions B: Applications***, Vol. 17, No. 1, (2004), 51-59. DOI: 10.5829/ije.2004.17.01b.06.

10. H. Moradi Cheshmeh Beigi, "Design, Optimization and FEM Analysis of a Surface-Mounted Permanent-magnet Brushless DC Motor", ***International Journal of Engineering, Transactions B: Applications***, Vol. 31, No. 2, (2018), 339-345. DOI: 10.5829/ije.2018.31.02b.19.
11. 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, Transactions B: Applications***, Vol. 32, No. 2, (2019), 286-295. DOI: 10.5829/ije.2019.32.02b.14.
12. A. N. Patel, B. N. Suthar, "Cogging Torque Reduction of Sandwiched Stator Axial Flux Permanent Magnet Brushless DC Motor using Magnet Notching Technique", ***International Journal of Engineering, Transactions A: Basics***, Vol. 32, No. 7, (2019), 940-946. DOI: 10.5829/ije.2019.32.07a.06.
13. Lei, G.; Zhu, J.G.; Guo, Y.G, "Multidisciplinary Design Optimization Methods for Electrical Machines and Drive Systems", Springer-Verlag: Berlin/Heidelberg, Germany, (2016), 1-6. DOI: 10.1007/978-3-662-49271-0.
14. Yao, D.; Ionel, D.M, "A review of recent developments in electrical machine design optimization methods with a permanent magnet synchronous motor benchmark study", ***IEEE Transactions on Industry Applications***, Vol. 49, No. 3 (2013), 1268-1275. DOI: 10.1109/TIA.2013.2252597.
15. N. Bianchi, S. Bolognani, D. Bon, M. D. Pre, “Rotor flux-barrier design for torque ripple reduction in synchronous reluctance and PM-assisted synchronous reluctance motors”, ***IEEE Transactions on Industry Applications***, Vol. 45, (2009), 921-928. DOI: 10.1109/TIA.2009.2018960.
16. M. Sanada, K. Hiramoto, S. Morimoto, Y. Takeda, “Torque ripple improvement for synchronous reluctance motor using asymmetric flux barrier arrangement”, 38th IAS Annual Meeting, Conference Record of the IEEE, (2003), 250-255. DOI: 10.1109/IAS.2003.1257510.
17. G. V. Cvetkovski, L. B. Petkovska, “Weight reduction of permanent magnet disc motor for electric vehicle using genetic algorithm optimal design procedure”, ***IEEE EUROCON*** (2009). DOI: 10.1109/EURCON.2009.5167738.
18. Chang-Chou Hwang, Li-Yang Lyu, Cheng-Tsung Liu, Ping-Lun Li, “Optimal Design of an SPM Motor Using Genetic Algorithms and Taguchi Method”, ***IEEE Transactions on Magnetics***, Vol. 44, No. 11, (2008), 4325-4328. DOI: 10.1109/TMAG.2008.2001526.
19. Ki-Chan Kim, Ju Lee, Hee Jun Kim, Dae-Hyun Koo, “Multiobjective Optimal Design for Interior Permanent Magnet Synchronous Motor”, ***IEEE Transactions on Magnetics***, Vol. 45, No. 3, (2009), 1780-1783. DOI: 10.1109/TMAG.2009.2012820.
20. Mahdi Ashabani, Yasser Abdel-Rady I. Mohamed, Jafar Milimonfared, “Optimum Design of Tubular Permanent-Magnet Motors for Thrust Characteristics Improvement by Combined Taguchi–Neural Network Approach”, ***IEEE Transactions on Magnetics,*** Vol. 46, No. 12, (2010), 4092-4100. DOI: 10.1109/TMAG.2010.2067450.
21. Chang-Chou Hwang, Chia-Ming Chang, Cheng-Tsung Liu, “A Fuzzy- Based Taguchi Method for Multiobjective Design of PM Motors”, ***IEEE Transactions on Magnetics***, Vol. 49, No. 5, (2013), 2153-2156. DOI: 10.1109/TMAG.2013.2242854.
22. Kim, S.-I.; Lee, J.-Y.; Kim, Y.-K.; Hong, J.-P.; Hur, Y.; Jung, Y. H., "Optimization for reduction of torque ripple in interior permanent magnet motor by using the Taguchi method", ***IEEE Transactions on Magnetics***, Vol. 41, (2005), 1-5. DOI: 10.1109/TMAG.2005.846478.
23. J. Zhu, S. Li, D. Song, Q. Han, J. Wang, G. Li, “Multi-objective optimization design of air-cored axial flux PM generator”, ***IET Electric Power Applications,*** (2018), 1390-1395. DOI: 10.1049/iet-epa.2018.5092.
24. S. R. Karimpour, M. R. Besmi, S. M. Mirimani, “Optimal design and verification of interior permanent magnet synchronous generator based on FEA and Taguchi method”, ***International Transactions on Electrical Energy Systems,*** (2020), e12597, 1-15. DOI: 10.1002/2050-7038.12597.

Persian Abstract

چکیده

در این مقاله فرآیند طراحی بهینه یک ژنراتور سنکرون مغناطیس دائم با آهنربای داخلی (IPMSG) برای کاربرد در سیستم‌های بادی به کمک روش تجزیه و تحلیل اجزای محدود (FEA) ارائه شده است. روش طراحی بهینه‌سازی چند هدفه ژنراتور مغناطیس دائم بر اساس روش تاگوچی پیشنهاد گردیده است. این مقاله تأثیر زاویه گام قطب آهنربا، فاصله قرارگیری آهنربا تا فاصله هوایی، ضخامت آهنربا، عرض آهنربا، عرض دندانه استاتور و عمق شیار را به عنوان پارامترهای طراحی در نظر گرفته است. مشخصه‌های اصلی بازدهی ژنراتور، انحراف گشتاور و توان خروجی به عنوان اهداف بهینه‌سازی در نظر گرفته شده است. ماتریس متعامد تاگوچی با توجه به تعداد پارامترهای انتخاب شده و ضریب سطح هر پارامتر و روش اجزای محدود، به منظور حل ماتریس آزمایش‌های تاگوچی به کار گرفته شده است. در نتیجه، یک ژنراتور بهینه شده، طراحی و انتخاب گردید، که دارای ویژگی‌های حداکثر توان و بازدهی و انحراف گشتاور پایین‌تر می‌باشد. در پایان، یک ژنراتور نمونه آزمایشگاهی بر اساس نتایج آنالیز و روش تاگوچی ساخته شد و مورد آزمایش قرار گرفت. تست‌های آزمایشگاهی به منظور تأیید صحت فرآیند طراحی پیشنهادی و کارایی ژنراتور مزبور انجام شد و در نتیجه تائیدی بر طراحی بهینه ژنراتور مزبور می‌باشد.