ICEMG 2023-XXXXX

Performance evaluation of the optimal structure of the stator in the outer rotor vernier generator with spoke magnet and multi-objective optimization based on finite element analysis and Taguchi method

Mahdi Roshandel bana [1], Mohammad reza Besmi [2]

[1] Department of Electrical and Electronic Engineering, Shahed University, Tehran; mahdi.roshandel@shahed.ac.ir
[2] Department of Electrical and Electronic Engineering, Shahed University, Tehran; besmi@shahed.ac.ir

Abstract
In this research, a simulation study of the design of the optimal structure for the spoke external rotor vernier generator stator, to improve the performance of various applications such as some household electrical appliances and most new energy equipment such as wind turbines has been investigated and compared. In this article, stator tooth length, stator gap depth, distance between two stator grooves, groove opening height are considered as optimization variables, and optimal parameters are selected with the help of Taguchi analysis method. The main characteristics of generator efficiency, effective voltage and output power are considered as optimization goals. Also, finite element method is used to solve the experimental matrix. As a result, an improved generator is designed and selected, which will have maximum output power, effective voltage and higher efficiency.

Keywords: vernier generator, permanent magnet, finite element method, Taguchi method.

1. Introduction

In many high-efficiency applications use permanent magnet machines. Generator operation, efficiency, and maintenance affect wind turbine system design [1-2]. In 1963, Lee invented the reluctance vernier machine. Ishizaki and colleagues introduced the vernier permanent magnet machine in 1995 to deliver high torque at low speed. To maximize torque, Toba and Lipo proposed a vernier permanent magnet machine with magnets on the rotor [3].

Using permanent magnet structures has been attempted in recent years. The high torque permanent magnet machine's unique design and construction is its best feature. Many magnetic poles allow permanent magnet vernier machines to generate high torque at low speed. Researchers found that even the slightest rotor movement changes the air gap flux in the vernier structure. The permanent magnet vernier machine operates on the magnetic gear, and its leakage current is higher than that of the permanent magnet machine, resulting in a low power factor. Rotary vernier machines can be radial, axial, or intersecting flow. [4,5]. Electric machines that can match load with low-speed and have high torque and efficiency are required for applications like wind energy generation. Low-speed machine designs or mechanical speed-increasing gears are the two solutions currently used to solve this problem. The first causes high noise levels, low efficiency, and mechanical wear and tear, whereas the second raises the generator's size and weight as well as the cost of raw materials [6]. The external rotor single-drive vernier machine can place more magnets on it than the internal rotor single-drive vernier machine because it has a larger radius. Because of this, the external rotor vernier machine has a much higher flux density and torque than the internal rotor vernier machine[3]. One of the structures made for electric machines and wind turbines is the vernier structure. This structure makes use of the Vernier concept. Pierre Vernier put forth the Vernier concept in 1631 [7]. In [8], a wind direct drive machine with an outer rotor. According to the authors, vernier machines are especially helpful for adjusting for low wind speeds and high generator operating speeds because of the magnetic gearing effect. This naturally solves the issue that wind turbines have with speed matching. The design of a vernier permanent magnet motor for direct drive applications is looked at and optimized in the study [9]. To quickly determine electromagnetic functions like power factor, ripple torque, and air gap flux, an analytical model is developed. A thorough overview of recent developments in permanent magnet vernier machines can be found in [10]. With the help of different coil configurations, modulation poles, and rotor structures, this review aims to better understand new topologies of permanent magnet vernier machines as well as the function and makeup of the magnetic gears used in these devices.

in this article, the length of the stator teeth (A), the depth of the stator gap (B), the distance between two stator slots (C), and the height of the slot opening (D) are considered as optimization variables. The three main factors of output power, effective voltage, and generator efficiency are taken into account as optimization objectives. Also, the finite element method is used to solve the experimental matrix. As a result, a better generator is produced and selected.

2. Machine analysis with the finite element method

From the 1950s, the finite element method was crucial. Boeing company modeled and analyzed an airplane wing using triangular elements in 1950, the first industrial application of finite elements. Professor Kello coined the term finite element method in 1960, and Zinkevich wrote his famous book in 1967. The finite element method and Ansys software began design evolution in 1970 [11]. Most non-numerical analysis methods cannot accurately analyze the behavior of electric machines due to their complexity and non-linear behavior. Numerical methods for electric machine analysis, especially design, have increased due to computer science's hardware and software advances. The finite element method is crucial to electric machine analysis. Finite element analysis software is best for electric machine analysis.

3. Taguchi method

When Japan began its reconstruction work after World War II, it faced a severe shortage of raw materials, quality equipment, and skilled engineers, and began to compete to produce high-quality products and continuously improve quality under those conditions. Dr. Genichi Taguchi, the electrical communication laboratories' special telecommunication product engineer, was tasked with solving the competition problem [12]. Dr. Taguchi introduced the Taguchi Method for quality improvement based on his definition of quality as the amount of harm done to society by the production of defective products. Taguchi's orthogonal array method greatly reduced testing. From the total number of experiments in the full factorial method, these arrays with particular properties are chosen. Of course, Taguchi's method does not imply that the best solution must exist in the chosen experiments, but by using array experiment calculations, it is possible to identify the best conditions and the best solution. Finally, by repeating the test and verifying that the answer is reproducible, its accuracy is established. Taguchi method is widely used to optimize permanent magnet machines. in [13,14] describes Taguchi experiment design. In [15], Taguchi method permanent magnet machine design is examined. The current article follows Taguchi's method for the optimal design of the spoke external rotor vernier generator.

4. Topology of designed vernier machine

Figure 1 shows the topology of the external rotor permanent magnet vernier generator with spoke arrangement in two-dimensional space. This machine has 12 slots in the stator and 44 poles in the rotor.

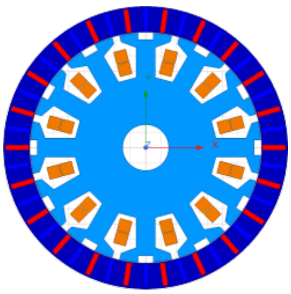


Figure 1. Topology of external rotor permanent magnet vernier generator with spoke arrangement

4.1. Basic design of external rotor vernier generator

In this section, The electromagnetic relations governing permanent magnet machines are used to extract the analytical model of the vernier machine, and the Taguchi algorithm is then used to determine the machine's optimal operating parameters. The purpose of optimization is to raise the machine's effective voltage, output power, and generator efficiency. The basic vernier machine's parameters are listed in the table 1. For the best design, the machine's parameters should be carefully chosen. Parameters form the basis of the design. Table 1 displays the parameters required to depict the stator and rotor structures of the vernier machine, and Table 2 lists the details of the three-phase vernier machine. The designed external rotor permanent magnet vernier machine's dimensional parameters are both shown in Figure 2.

Table 1. Definition of parameters

characteristic	symbol
The outer radius of the stator	$D_{so}/2$
air gap	Lg
Magnet thickness	$Y\text{-}Mag$
The length of the magnet	$X\text{-}Mag$
outer diameter of the rotor	$D_{ro}+Lg$
Inner diameter of the rotor	$D_{ri}+Lg$
The length of the generator	L
Number of coil turns	Nm
The length of the cross section of the conductor	X_Coil
The width of the cross section of the conductor	Y_Coil

Table 2. Basic specifications of the three-phase vernier machine before optimization

row	characteristic	information
1	Machine type (vernier, three-phase)	3 phases
2	The speed of the machine	1000 rpm
3	The number of poles of the machine	44
4	The number of stator slots	12
5	Number of coil turns	100
6	The length of the machine	50 mm
7	Stator outer diameter	150 mm
8	Outer diameter of the rotor	184 mm
9	Inner diameter of the rotor	150 mm
10	The length of the air gap	0.5 mm
11	shaft diameter	20 mm
12	The area of the magnet	48 mm^2
13	The type of permanent magnets	NdFeB35

Figure 2 shows the slot structure of the designed vernier generator and its related parameters. The stator is made of iron (M19_29G).

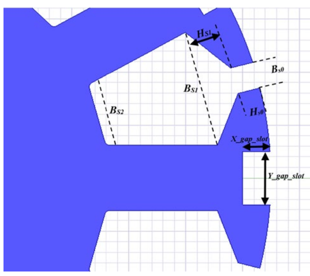


Figure 2. Tooth and slot structure and related parameters

Table 3 shows the basic values of design variables and the results of effective voltage and output power and efficiency. Also, Figure 3 shows the voltage of the basic model in the spoke vernier generator.

Table 3. Table of basic values of design variables and its results

	Specifications	results
mm	*Y_gap_slot*	8
	X_gap_slot	5
	Bs0	5
	Hs0	4.2
Voltage (V)	V_{max}	264
	V_{rms}	186.68
Torque ripple (nm)	T_{rip_max}	-6
	T_{rip_min}	-10.33
	T_{rip_dif}	4.33
Output power (W)	P_{out}	870
efficiency(%)	η	95

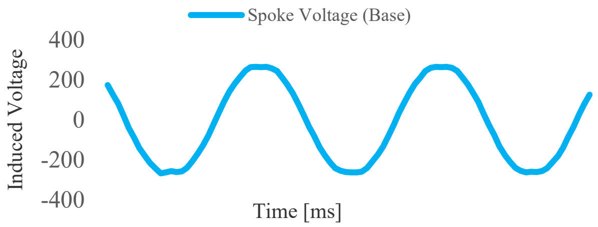


Figure 3. Basic model voltage in spoke vernier generator

4.2. Optimization variables and objective function

Table 4 shows the design parameters used as simulation factors in the design of the experiment. The range of changes of each of the factors is also shown in this table. Also, the selected optimization variables shown in Figure 4 are: A, B, C, D and as shown in Figure 4, respectively A is the length of the stator tooth with the initial size of 8 mm, B is the depth of the stator gap with The initial size is 5 mm, C shows the distance between two stator slots with the initial size of 5 mm, D shows the height of the opening of the slot with the initial size of 2.4 mm. The best optimized generator models are compared by choosing the objective functions of the highest effective voltage, the highest output power and the highest efficiency.

Table 4. Design factors and their level of changes

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
A	6	7	8	9	10
B	4	4.5	5	5.5	6
C	3	4	5	6	7
D	3.6	3.8	4	4.2	4.4

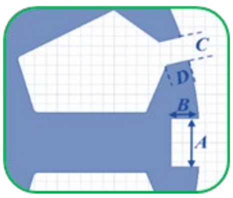


Figure 4. Design variables for Taguchi test design

5. Arrangement of experiments for spoke vernier machine

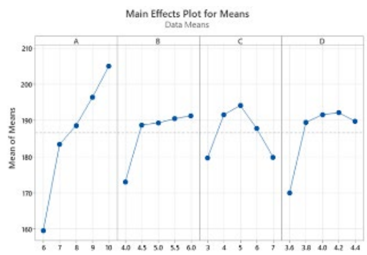
In Table 5, according to the number of factors and the levels of each factor and using the Taguchi orthogonal arrays table, the number of necessary trials and the composition of the levels of the factors in each trial and the results of the analysis of the spoke vernier machine are listed. As you can see, Taguchi's method has caused a significant reduction in the number of required tests from the total number of $5^4 = 625$ to 25. Considering the length of time of simulations in the finite element method, this reduction in the number of tests results in significant time savings until reaching the optimum point. The Taguchi method determines the best point based on the results obtained from this limited number of tests and using statistical calculations. The overall average of the calculated results is shown in Table 6.

Table 6. The overall average of the results

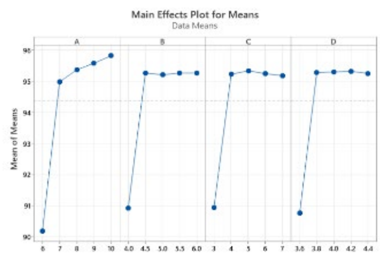
	V_{rms}	T_{rip_dif}	P_{out}	η
m	186.62	4.46	786	94.38

5.1. Taguchi analysis and choosing the optimal combination of design parameters

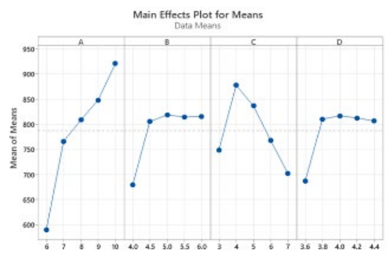
To optimize the Taguchi method of the Spoke vernier machine, once the combination of the design parameters with the aim of obtaining the highest effective voltage and once the combination of the design parameters with the aim of obtaining the highest efficiency and finally the combination of the design parameters with the aim of obtaining the maximum output power will be selected. To get the optimal model with the desired goals, the combination of design parameters will be selected after Taguchi analysis from Figure 5.



(A)



(B)



(C)

Figure 5. Choosing the combination of parameters with the aim of (a) maximum effective voltage, (b) maximum efficiency and (c) maximum output power in the spoke vernier generator

Table 5. Orthogonal arrays and spoke vernier machine analysis results

					Voltage (V)		Torque ripple (nm)			Output power (W)	efficiency (%)
Tests	**A**	**B**	**C**	**D**	V_{max}	V_{rms}	T_{rip_max}	T_{rip_min}	T_{rip_dif}	P_{out}	η
1	1	1	1	1	137	96.87	-26.38	-58.3	31.92	145	72.79
2	1	2	2	2	250	176.78	-6.49	-8.72	2.23	776	94.58
3	1	3	3	3	256	181.02	-5.77	-8.18	2.41	739	94.66
4	1	4	4	4	250	176.78	-5.21	-8.09	2.88	680	94.54
5	1	5	5	5	235	166.17	-4.05	-7.45	3.4	608	94.34
6	2	1	2	3	264	186.68	-6.04	-9.29	3.25	831	94.98
7	2	2	3	4	266	188.09	-6.29	-8.76	2.47	793	95.09
8	2	3	4	5	256	181.02	-5.21	-8.74	3.53	719	94.94
9	2	4	5	1	241	170.41	-4.18	-7.63	3.45	654	94.79
10	2	5	1	2	270	190.92	-6.44	-8.88	2.44	831	95.05
11	3	1	3	5	273	193.04	-6.92	-8.99	2.07	828	95.43
12	3	2	4	1	258	182.43	-5.6	-8.72	3.12	755	95.27
13	3	3	5	2	252	178.19	-4.84	-8.12	3.28	709	95.31
14	3	4	1	3	277	195.87	-6.89	-9.34	2.45	882	95.39
15	3	5	2	4	274	193.75	-6.66	-9.31	2.65	867	95.41
16	4	1	4	2	271	191.63	-5.88	-9.15	3.27	789	95.49
17	4	2	5	3	265	187.38	-4.83	-8.81	3.98	739	95.51
18	4	3	1	4	290	205.06	-6.56	-9.92	3.36	922	95.62
19	4	4	2	5	282	199.40	-7.18	-9.66	3.48	911	95.66
20	4	5	3	1	281	198.70	-6.87	-9.95	3.08	878	95.55
21	5	1	5	4	279	197.28	-5.56	-9.21	3.65	800	95.90
22	5	2	1	5	296	209.30	-7.14	-10.56	3.42	963	95.85
23	5	3	2	1	285	201.53	-7.30	-11.80	4.50	1002	95.46
24	5	4	3	2	297	210.01	-7.26	-9.97	2.71	944	95.92
25	5	5	4	3	293	207.18	-7.04	-6.46	9.6	892	95.93

Table 7. Combination of Taguchi parameters with the aim of maximum effective voltage, maximum efficiency and maximum output power in spoke vernier machine and its results

	mm				Voltage (V)		Torque ripple (nm)			Output power (W)	efficiency (%)
Tests	**A**	**B**	**C**	**D**	V_{max}	V_{rms}	T_{rip_max}	T_{rip_min}	T_{rip_dif}	P_{out}	η
Max Voltage	10	6	5	4.2	285	201.53	-6.81	-11.65	4.84	944	95.38
Max Efficiency	10	4.5	5	4.2	284	200.82	-7.25	-11.59	4.34	940	95.57
Max Power	10	5	4	4	287	202.94	-7.34	-11.85	4.51	1009	95.56

According to Taguchi's analysis, with the aim of calculating the maximum effective voltage, maximum efficiency and maximum output power, the combination of design parameters in Table 7 will lead to the maximum effective voltage, maximum efficiency and maximum output power.

6. Comparing the results of the optimal models using the Taguchi method

After analyzing the results of the Taguchi method and selecting the optimal models with the goals of the highest effective voltage, the highest efficiency and the highest output power, in Table 8 the comparison of the simulation results obtained from the Taguchi analysis method for the three optimal models of the spoke vernier generator, and the final three models with The objectives of maximum effective voltage, efficiency and output power are compared with the base model.

Table 8. Comparison of the final results of the optimized models.

Specifications	**Base**	**Model 1**	**Model 2**	**Model 3**	**Unit**
V_{max}	264	285	284	287	Volt
V_{rms}	186.68	201.53	200.82	202.94	Volt
T_{rip_max}	-6	-6.81	-7.25	-7.34	Nm
T_{rip_min}	-10.33	-11.65	-11.59	-11.85	Nm
T_{rip_dif}	4.33	4.84	4.34	4.51	Nm
Speed	1000	1000	1000	1000	rpm
P_{out}	870	944	940	1009	W
η	95	95.38	95.57	95.56	%

The goals of each of the optimized models in Table 8 are:

• Model 1: optimization with the aim of the highest effective voltage in the spoke vernier machine

• Model 2: optimization with the aim of maximum efficiency in the spoke vernier machine

• Model 3: optimization with the aim of maximum output power in the spoke vernier machine

Figure 6 also shows the structural difference in the three optimal models of effective voltage, optimal efficiency and optimal output power in Table 8.

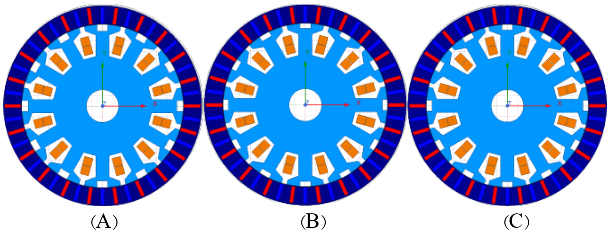


Figure 6. Structure of the model (a) optimal effective voltage, (b) optimal efficiency, (c) optimal output power

Figure 7 also shows the phase voltage of the optimal models in Table 8.

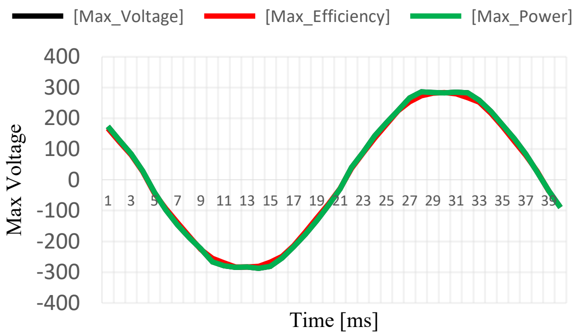


Figure 7. Phase voltage comparison of optimal models in the state of the highest effective voltage, highest efficiency and highest output power

7. Compare and choose the best design

In the comparison and evaluation of the optimal models of the spoke vernier machine, according to the results obtained with the help of Taguchi analysis method and also figure8, the vernier spoke generator has almost equal torque ripple in all its optimal models, it can be seen in the investigation of the effective voltage of the spoke design that the voltage of the optimal models is higher than the basic model, but in the comparison of the optimal models with each other, the voltage value is relatively close to each other, according to the other features that have been discussed, it can be seen that in the optimal output power model (model 3) With 1009 watts, they produce more power than other optimal models and in the optimal efficiency model (model 2) with 95.57% they deliver more efficiency than other optimal models.

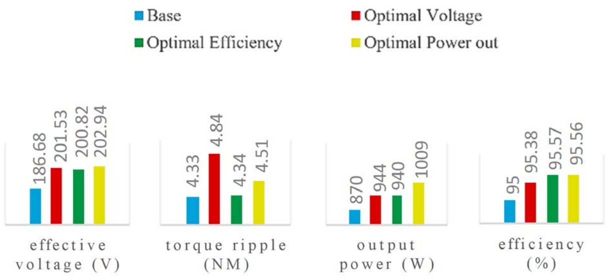


Figure 8. Comparison of the effective voltage, torque ripple, output power and efficiency of the simulation results obtained from the Taguchi analysis method optimization for the spoke vernier generator

7.1. Choosing the best design in the spoke vernier machine

In the comparison and evaluation of the optimal models of the spoke vernier machine, according to the results obtained with the help of Taguchi analysis method, the vernier spoke generator has an almost equal torque ripple in all its optimal models, so according to the other features of the optimal models It can be concluded that model 3 with higher effective voltage and relatively lower torque ripple as well as higher output power and efficiency than the base model and other optimal models is the best choice as the optimal model for making a vernier spoke generator. In the following, figure 9 and 10 show the maximum voltage and ripple torque in model 3.

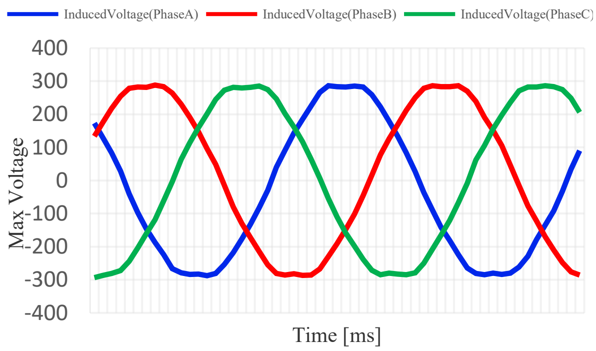


Figure 9. The maximum power out of the optimal model of the spoke vernier machine

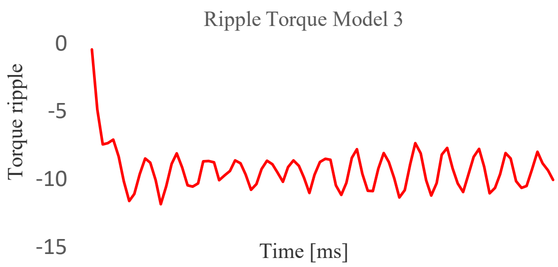


Figure 10. Torque ripple of the optimal model of the spoke vernier machine

8. Conclusion

The external rotor vernier machine has been used for some household electrical appliances and many new energy equipments such as wind turbines, waves, etc. In many cases this machine has been able to solve volume challenges easily, as mechanical interfaces for speed conversion have been eliminated and its structure simplifies its implementation for design engineers. In this article, Taguchi's analysis method was used to examine the external spoke rotor vernier machine. According to the number and level of design parameters, the table of orthogonal arrays was selected. In the Taguchi design method, by using the orthogonal array table, the number of tests required to increase the performance of the generator was reduced to 25 tests, and as a result, using the finite element analysis method reduced the time required to perform the test. According to the results obtained by Taguchi's analysis method, the vernier spoke generator had almost equal torque ripple in all its optimal models. In the investigation of the effective voltage of the vernier spoke generator, the voltage of the optimal models was higher than the basic model, but when comparing the optimal models, the voltage value was relatively close to each other, and it was also concluded that the output power in the optimal model (model 3) with 1009 W produce more power than other optimal models and in the optimal efficiency model (model 2) with 95.57% more efficiency was obtained than other optimal models. According to other features that were checked, it was concluded that the optimal output power model (model 3) with higher effective voltage and relatively lower torque ripple, as well as higher output power and efficiency than the base model and other optimal models, is the best It is selected as the final optimal model for the vernier spoke generator.

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] Atallah and D. Howe, "A novel high-performance magnetic gear," in IEEE Transactions on Magnetics, vol. 37, no. 4, pp. 2844-2846, July 2001, doi: 10.1109/20.951324.

[4] Liu, G., Yang, J., Zhao, W., Ji, J., Chen, Q., Gong, W. " Design and analysis of a new fault-tolerant permanent-magnet vernier machine for electric vehicles" IEEE Trans Magn, 2012.

[5] Fang, Z., Zhao, W., Ji, J., Zhao, J., Zhang, D., Du, Y. A primary-permanent-magnet vernier linear machine with improved fault-tolerant capability,” International Conference on Electrical Machines and Systems, ICEMS , pp. 1882–1885, 2013.

[6] J. Faiz, M. Ghods, MH. Arianborna, MA. Bazrafshan, "Single stator-single rotor permanent magnet Vernier machine topologies for direct-drive applications: Review and case study," 2021 Int TransElectr Energ Syst (ITEES), 2021;31:e13240. doi: 10.1002/2050-7038.13240.

[7] K.T. Chau, W. L. Li, and C. H. T. Lee, "Challenges and Opportunities of Electric Machines for Renewable Energy", Progress in Electromagnetics Research B, Vol.42 pp.45-74, 2012.

[8] J. Li, K. T. Chau, J. Z. Jiang, C. Liu and W. Li, "A New Efficient Permanent-Magnet Vernier Machine for Wind Power Generation," in IEEE Transactions on Magnetics, vol. 46, no. 6, pp. 1475-1478, June 2010, doi: 10.1109/TMAG.2010.2044636.

[9] B. Wang, L. Zhou, H. Wang and C. Lin, "Analytical Modeling and Design Optimization of a Vernier Permanent Magnet Motor," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), 2021, pp. 4480-4485, doi: 10.1109/ECCE47101.2021.9595230.

[10] F. Wu and A. M. EL-Refaie, "Permanent Magnet Vernier Machines: A Review," 2018 XIII International Conference on Electrical Machines (ICEM), 2018, pp. 372-378, doi: 10.1109/ICELMACH.2018.8507194.

[11] Karayan, A.I., Ferdian, D., Harjanto, S., Nurjaya, D.M., Ashari, A. and Castaneda, H., 2012. Finite Element Analysis Applications in Failure Analysis: Case Studies. InTech Open, pp.217-234.

[12] Sudhakar, P.R., 1994. Introduction of Quality Improvement Through Taguchi Methods. Decision, 21(1), p.127.

[13] Mitra, A., 2011. The taguchi method. Wiley Interdisciplinary Reviews: Computational Statistics, 3(5), pp.472-480, doi: 10.1002/wics.169.

[14] Karna, S.K. and Sahai, R., 2012. An overview on Taguchi method. International journal of engineering and mathematical sciences, 1(1), pp.1-7.

[15] karimpour SR, Besmi MR, Mirimani SM. Optimal design and verification of interior permanent magnet synchronous generator based on FEA and Taguchi method. Int Trans Electr Energ Syst. 2020; e12597. https://doi.org/10.1002/2050-7038.12597Tech report, A., 2003. Tech report title. Progress report 1, University of Higher Education, Cambridge, MA, May. See also URL http://www.abc.edu.