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Research Paper

Design of Doubly Salient Permanent Magnet Generator for Output Power Enhancement using Structural Modification

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Abstract. The doubly salient permanent magnet generator (DSPMG) is widely known as an efficient machine for electrical production from renewable energy. In this paper, we aim to improve the output power of the DSPMG using a structural modification, which is targeted for low-speed electrical generations. Structural parameters including the stator pole depth, thickness of permanent magnet, stator pole arc, and number of winding turns were adjusted, then an optimal value of those parameters was selected based on the characteristics of the generator tested during no-load and on-load conditions. Simulations were based on the finite element method. The generator was targeted to be used for the rated power of 200 W. It was found that the optimally designed generator had a higher electromotive force of 36.1%, a lower cogging torque of 20%, and a higher output power of 12.2% than the conventional structure. The leakage flux of the proposed structure was also improved from the conventional one. Thus, the generator designed in this work could be another capable choice for electrical generation from renewable energy. The proposedly modified technique can also be adapted for output profile improvement of the doubly salient permanent magnet machines which are extensively used for renewable energy production nowadays.

Keywords: Rotating machines, Permanent magnet machine, Permanent magnet generator, Doubly salient permanent magnet generator.

1. Introduction

Permanent magnet (PM) machines are utilized extensively in many rotating applications, mainly because of its inherent PM excitation and the absence of excitation losses [1, 2]. Plenty of literature surveys claim that the PM machines are high torque density machines with high output power, and efficiency [3-7]. PM machines are categorized into two types, namely the stator PM machines and the rotor PM machines. The rotor PM machines, in which PMs are attached to the rotor, were introduced about two decades ago. These machines are suitable for high rotating speed applications due to their high robustness [8, 9]. The stator PM machines, in which PMs and armature windings are attached to the stator, were proposed after the rotor PM machines [1, 11]. Based on its component arrangement, the rotor of stator PM machines has low weight with low inertia. As a result, stator PM machines can be used efficiently with low-speed applications [12-14], and it is currently receiving a lot of research attention in renewable energy generation applications. Three main types of the stator PM machine that have been widely researched for use as an electrical generator are the flux-reversal PM generators, the switch-flux PM generators, and the doubly salient permanent magnet generators (DSPMG) [15-17]. Recently, several research attempted to improve the performance of DSPMGs, aiming for application in growing area of renewable energy generation [18-23]. The DSPMG's outstanding merits, such as its high power, high efficiency, and low inertia and torque ripple, serve as selection criteria for renewable energy generation, such as wind and hydropower [24, 25].

It can be seen in the literature surveys that the Doubly salient permanent magnet machines (DSPM) have received much research attention in the past few decades until the current situation. In 2006, the three phases DSPM was introduced as the wind turbine generator, indicating that this machine had high performance for standalone wind power generation [26]. In 2015, a pole-matching topology applied to the doubly salient brushless dc generator was proposed for wind power generation [27]. After that, Z. Z. Wu et al. proposed the partitioned-stator technique for DSPMG aiming to reduce deterioration, a significant improvement of EMF was demonstrated [28]. In 2019, L. Zhang et al. proposed the PM arrangement technique applied to the partitioned stator DSPM for enhancing the electrical performance and thermal condition [29]. In the same year, the square envelope technique was proposed to increase the magnetic flux potential of DSPM [30]. After that, the stator structural configuration design was proposed for enhancing the output power of DSPMG for low-speed applications [31, 32]. Recently, several techniques have been developed to improve the performance of DSPMGs [33-37].

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Table 1. The dimension of conventional DSPMG.

Parameters	Value
Number of stator poles	18
Number of rotor poles	15
Stator outer radius (mm)	150
Outer stator yoke radius (mm)	121.7
Inner stator yoke radius (mm)	98.85
Rotor outer radius (mm)	53
Rotor inner radius (mm)	34.7
Stack length (mm)	83.33
Air gap length (mm)	1.7
Stator pole arc (°)	11.46
Rotor pole arc (°)	11.46
Stator pole depth (mm)	98.85
Number permanent magnets	18
Permanent magnet thickness (mm)	10.7
Number of winding turns per phase	124
Winding coil diameter (mm)	1.291
Rated speed (rpm)	400

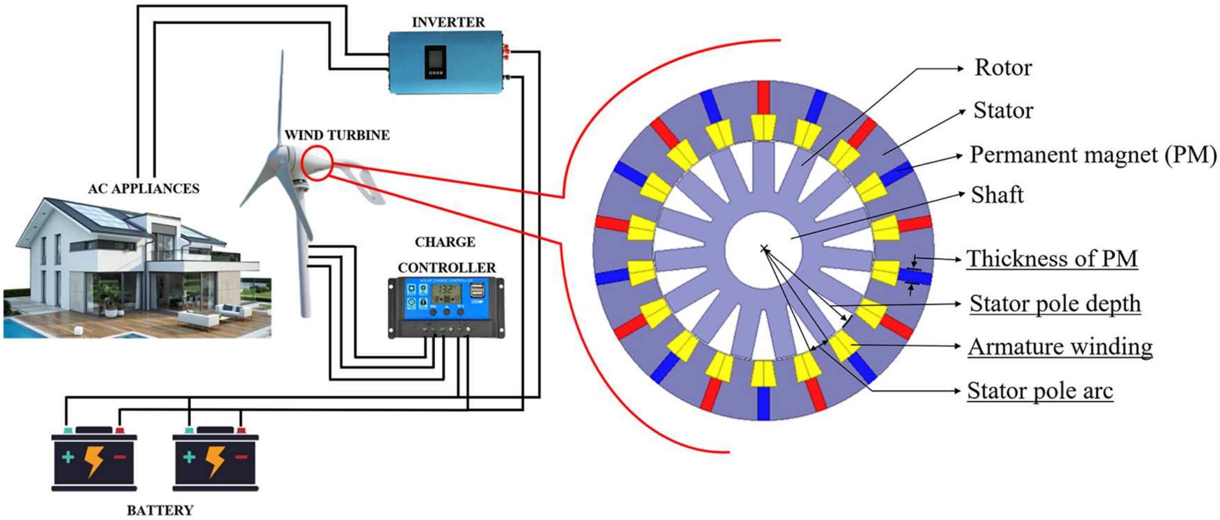

Fig. 1. Cross-sectional view of the conventional DSPMG structure having 18/15 poles.

Literature demonstrate that the development of DSPMG is still an interesting research topic in the field of electrical generators for renewable energy generation. Therefore, in this paper, we aim to enhance the output power of the DSPMG using a structural modification technique. The modified parameters included the stator pole depth, PM thickness, stator pole arc, and number of winding turns. The proposed structure was expected to reach the rated output power of 200 W for use in low wind speeds small-scale wind power applications. Design and analysis were based on the finite element method (FEM).

The rest of this paper is organized as follows. Machine design and analysis is described in Section 2. Results and discussion are explained in Sections 3. Conclusion is lastly given in Section 4.

2. Machine Design and Analysis

2.1 Machine topology

Figure 1 shows the schematic configuration for connecting the wind turbine to the grid. The DSPMG is built inside the turbine case. The enlarged figure on the right indicates the cross-sectional view of the conventional DSPMG structure having 18 stator poles and 15 rotor poles, which is written as 18/15 poles, as adopted from the previous study [38]. The stator and rotor poles are salient poles. This structure has the inner-rotor and the outer-stator containing Nd-Fe-B PMs inserted with different polarities. The armature winding is installed at the stator yoke, as shown by the circle in Fig. 1. The dimension of conventional DSPMG is detailed in Table 1. Lossless laminate steel was used in the machine structure, while copper was used as the armature winding. The temperature of 293.14 K was set with a pressure of 1 atm. The remanent flux density and the relative permeability of the Nd-Fe-B PMs were set to be 1.08 T and 1, respectively.

2.2 Performance analysis

We proposedly designed the DSPMG using a structural modification. The simulations were done based on the two-dimensional FEM. The focused design parameters were stator pole depth, PM thickness, stator pole arc, and number of winding turns, as indicated in Fig .1 with underlined text. These parameters were selected due to their following impacts on the generator performance. Stator pole depth is a part of the generator structure that typically acts as the magnetic field path. Accordingly, optimizing the stator pole depth could possibly improve the capability of the generator. The thickness of PMs normally affects the magnetic field strength or magnetic flux linkage produced by the magnet. To maximize the performance of the generator, the magnetic flux linkage flowing through the generator structure should be suitably set. The flux-leakage also needs to be considered while adjusting the PM thickness. The stator pole arc directly influences the dimension of a pole which serves as a magnetic field path. So, this parameter should be optimally adjusted to improve the capability of magnetic flux flowing. Number of winding turns is typically the influential parameter related to the generator performance. In this work, number of winding turns is assumed to be corresponded with the stator slot area. The order of parameter modification begins from the stator pole depth followed by the PM thickness and the stator pole arc, respectively. This modification was ordered starting from the parameter that is supposed to have a higher impact on the generator profile, which was summarized from several previous studies. The design process is detailly summarized as a flowchart shown in Fig. 2. In this work, we assumed that the number of winding turns is counted based on the fully installed winding in the available stator slot area. After the modification of structural parameters, the generator performance was evaluated under no-load and on-load conditions. No-load generator measurements includes the electromotive force (EMF), cogging torque, magnetic flux-linkage and magnetic field distribution, while on-load performance measurement is the output power. The generator having the best performance will be selected at the end of this work.

3. Results and Discussion

3.1 Influences of stator pole depth on the generator performance

In this section, the influences of stator pole depth on the no-load generator profile were examined. We proposedly reduce the stator pole depth from 98.85 mm (conventional value) to 80 mm, this depth reduction could provide a larger area for installing the armature winding. Table 2 shows the number of winding turns at various stator pole depths. It shows that approximately 20 winding turns can be installed additionally for 5 mm of stator pole depth reduction.

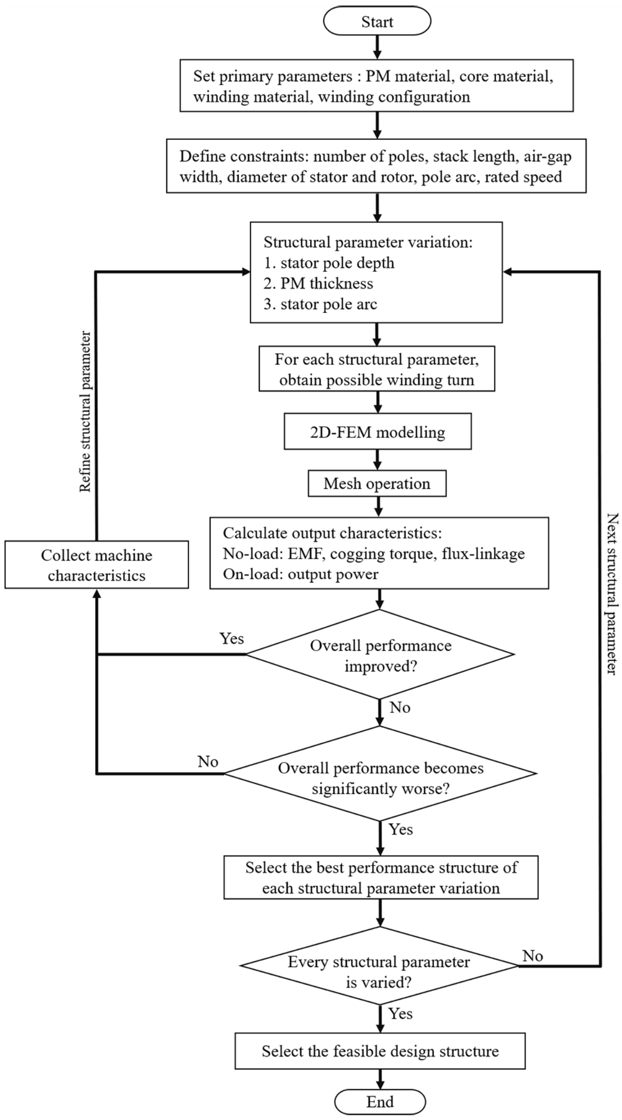

Fig. 2. A flowchart indicating the proposed design process.

Table 2. Relationship between stator pole depth and winding turns.

Stator pole depth (mm)	Winding turns
98.85 (Conventional)	124
95	141
90	161
85	181
80	191

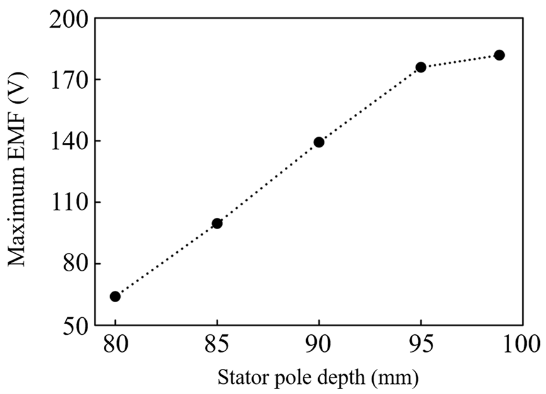

Fig. 3. The maximum value of EMF with varying stator pole depths.

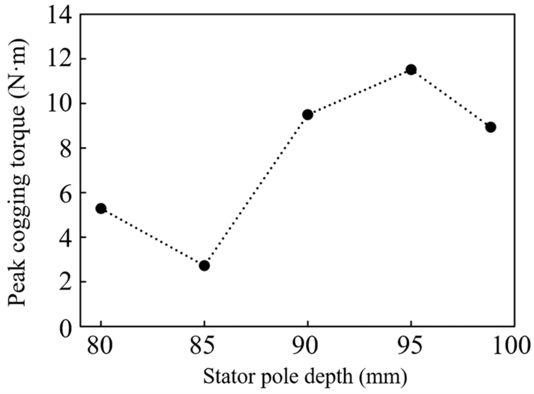

Fig. 4. The peak cogging torque with varying stator pole depths.

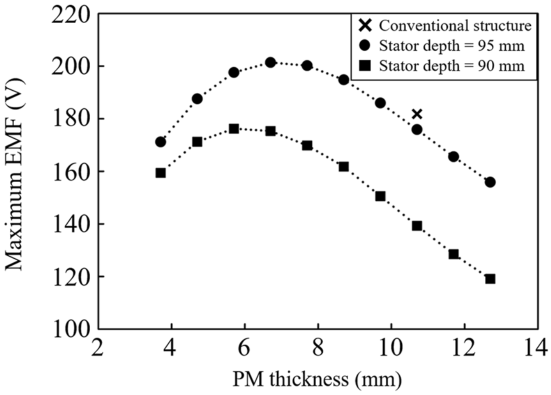

Fig. 5. The maximum value of EMF with varying PM thicknesses.

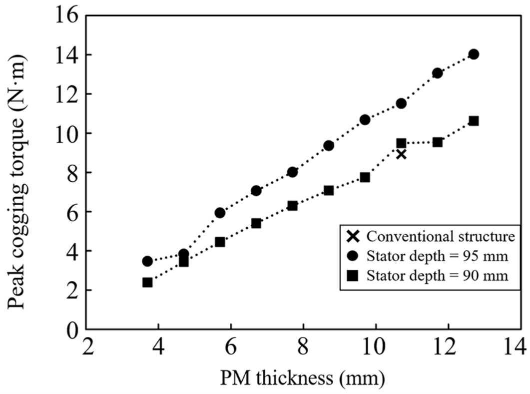

Fig. 6. The peak cogging torque with varying PM thicknesses.

Figures 3 and 4 show the EMF and cogging torque of the DSPMG having different stator pole depths. From the results, the scale of EMF and cogging torque tends to be decreased by reducing the stator pole depth. Although the winding can be additionally installed at shorter stator pole depth, a reduction of stator pole depth also causes a longer path of magnetic field flowing between the stator and rotor. Unfortunately, the flowing distance has a higher influence on the EMF than the winding turns number, causing a reduction of the EMF in this experiment. When reducing the stator depth, the rotor part is moved farther from the permanent magnet. Therefore, the reduction of cogging is because the magnetic force generated from the permanent magnet acting on the rotor part becomes weaker.

From this investigation, the conventional DSPMG with stator pole depth of 98.85 mm had the highest EMF scale, while the structure with stator pole depth of 85 mm had the lowest cogging torque as its lowest possible length without magnetic field interference from adjacent poles. The best three structures in this evaluation were the DSPMG having stator pole depth of 98.85 mm, 95 mm, and 90 mm, respectively. These three structures were selected for further consideration in a modification of PM thickness.

3.2 Influences of PM thickness on the generator performance

In this section, the dependence of PM thickness on the generator profile was investigated. The range of PM thickness variation was 3.7 to 12.7 mm with a step size of 1 mm. This range could completely cover the possible trend of results. The PM variation was made for two structures selected from the previous section, while maintaining the PM thickness of the conventional structure to keep it as a reference structure. The EMF and cogging torque profiles of the DSPMG having different PM thicknesses are shown in Figs 5 and 6, respectively. It was found that the EMF produced from the generator reached its peak before it decreased. The EMF was peaked due to the equilibrium of magnetic field flowing in the machine structure as a result of its appropriate magnet volume. Beyond the turning point, the permeability of PMs can be lower than steel at a very high PM thickness. This results in the overall lower magnetic flux path permeability; therefore the magnetic flux going out from the PMs becomes reduced. Accordingly, the magnetic flux-linkage and the EMF are reduced. It is also seen from Fig. 6 that the generator having the thinner magnet exhibits a better cogging torque. This is because the magnetic field strength generated from the thinner magnet is typically weaker, which is a reason for a cogging torque reduction. Based on the EMF profile with consideration of cogging torque, it was determined that the appropriate PM thickness for the generator with stator pole depths of 95 mm and 90 mm was 6.7 mm and 5.7 mm, respectively. However, the generator having a stator pole depth of 95 mm with 6.7 mm PM thickness exhibits a significantly better performance and is selected for further modification of the stator pole arc.

3.3 Influences of stator pole arc on the generator performance

In this section, the influence of the stator pole arc on the no-load generator profile were evaluated. Only the DSPMG having a stator pole depth of 95 mm with 6.7 mm PM thickness is focused on this modification. The stator pole arc varied from 11.46 (conventional value) to 4.67 degrees. The stator pole tip was made as a trapezoid while varying stator pole arc for a better magnetic flux path. Table 3 shows the number of winding turns at various stator pole arcs. This table indicates that approximately 10 winding turns can be installed additionally for 1 narrower pole arc.

Table 3. Relationship between stator pole depth and winding turns for the DSPMG having stator pole depth of 95 mm and PM thickness of 6.7 mm.

Stator pole arc (degree)	Winding turns
11.46	141
9.51	163
7.83	179
6.22	196
4.67	212

The EMF and cogging torque profiles of the DSPMG having different PM stator pole arcs are shown in Figs 7 and 8, respectively. It is seen that the EMF of this structure reaches a maximum value at the stator pole arc of 9.51 degree, and then decreases with narrowing stator arc. Obviously, the stator pole arc of 9.51 degree is the suitable value for this particular generator since this value could provide the highest EMF with a reasonable cogging torque scale. This suitable stator pole arc is due to the equilibrium of magnetic field distribution of the structure. The best structure selected in this work can produce a maximum EMF of 248 V, which is 36.1% improved from the conventional structure. The cogging tends to become better at a narrower stator pole arc due to the narrower magnetic path to conduct the magnetic field from the magnet to the rotor. The cogging torque of the selected structure was 20% reduced from the conventional structure.

3.4 Electromagnetic performance

To further investigate the performance of the selected DSPMG structure, the waveform of magnetic flux linkage, EMF, and cogging torque, as well as the magnetic field distribution, were compared. The output power profile was also characterized by on-load condition. Figures 9 and 10 show that the proposed DSPMG structure provides higher magnetic flux linkage and EMF than the conventional one. Although the EMF waveform of the proposed structure contains a slightly higher harmonic than the conventional structure, the harmonic scale is in an acceptable scale. A lower cogging torque magnitude at all rotor positions, as well as the lower peak value, of the proposed structure was obviously illustrated in Fig. 11, indicating its better performance at starting condition. The magnetic field distribution of the conventional and the best designed structure is shown in Fig. 12. It shows that the proposed structure demonstrates a significantly lower flux-leakage than the conventional structure at both stator and rotor poles, as indicated by the circles. This clearly demonstrates its better equilibrium of the optimal structure as well as its better magnet utilization, which are the main reasons for its greater electromagnetic profile, as well as higher torque and power per PM volume. The use of less PM in the optimal structure also results in a lower fabricating cost.

The output power profile during an on-load condition was characterized for the conventional and the best proposed structure. The load current was varied until the rated power of 200 W was reached. Figure 13 clearly indicates that the proposed structure can produce higher output power than the conventional structure at all loads. The maximum power of 230 W can be reached at the load current of 0.6 A, which is 12% higher than the conventional value. This can demonstrate that the DSPMG structure proposed in this work is better at delivering electrical energy than the conventional structure and can be efficiently used for renewable energy generation.

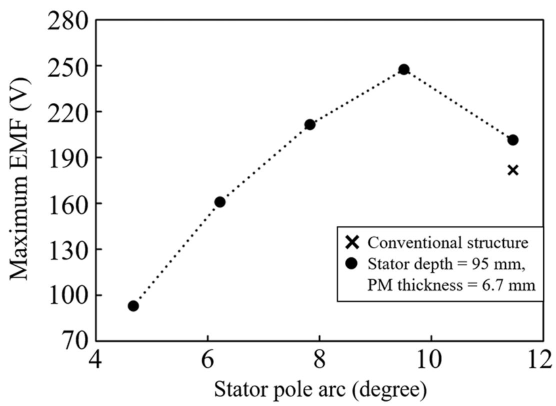

Fig. 7. The maximum value of EMF with varying stator pole arcs.

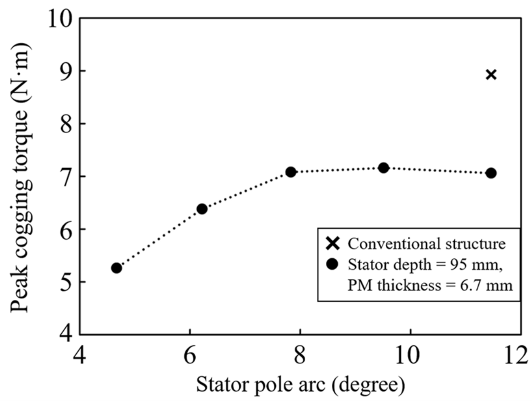

Fig. 8. The peak cogging torque with varying stator pole arcs.

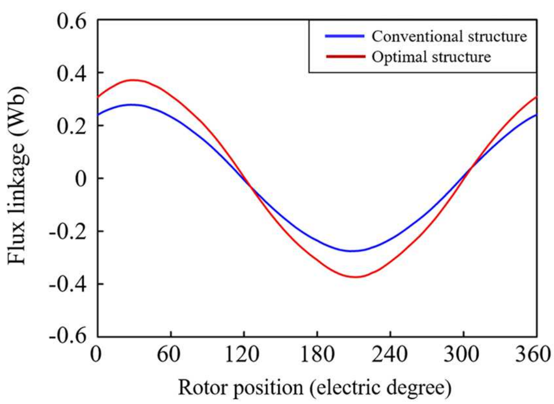

Fig. 9. Flux-linkage waveform of the conventional and optimal DSPMG structures.

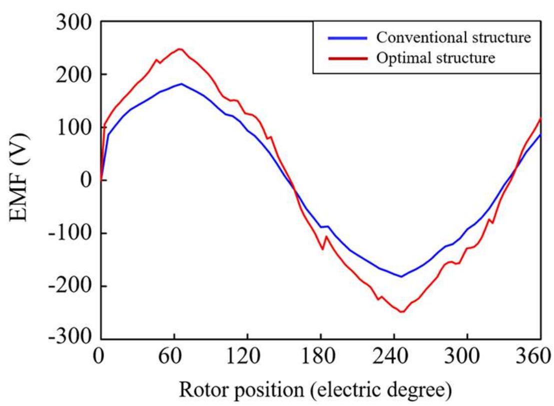

Fig. 10. EMF waveform of the conventional and optimal DSPMG structures.

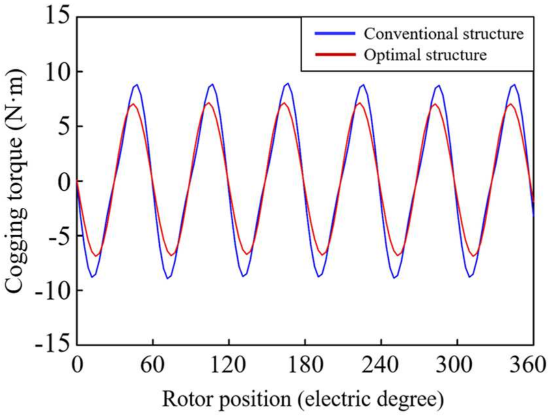

Fig. 11. Cogging torque waveform of the conventional and optimal DSPMG structures.

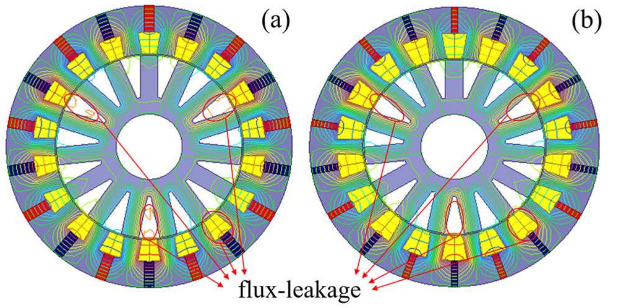

Fig. 12. The magnetic field distribution of (a) conventional and (b) optimally designed DSPMG.

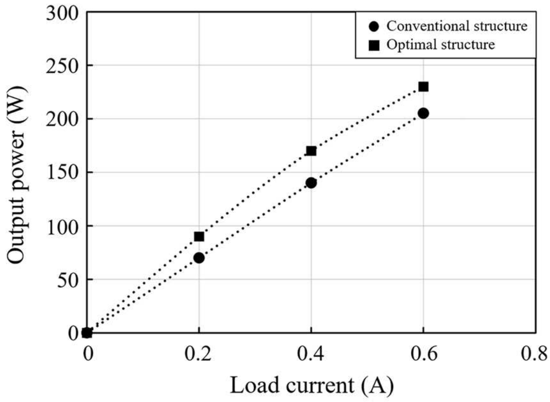

Fig. 13. Output power profile of the conventional and optimal DSPMG structures.

4. Conclusion

In this paper, we introduced the structural modification technique for improving the output power of the DSPMG, targeted for low-speed electrical generation from renewable energy. The methodology to optimally adjust the stator pole depth, PM thickness, stator pole arc, and number of winding turns was proposed using finite element analysis. The results showed that the optimal generator structure, with a stator pole depth of 95 mm, a PM thickness of 6.7 mm, and a stator pole arc of 9.51 degrees, could produce a better EMF of 28% and a cogging torque of 20%, as well as a 12% increase in output power over the conventional structure. The proposed structure also indicates a better flux-leakage. The DSPMG designed in this work can be used for electrical generation from renewable energy. This design technique benefits in improving the output power of the DSPM machines.

Author Contributions

Pattasad Seangwong and Pirat Khunkitti planned the scheme, initiated the project, and suggested the experiments; Pattasad Seangwong conducted the experiments and analyzed the empirical results; Pattasad Seangwong and Pirat Khunkitti developed the mathematical modeling and examined the theory validation. Apirat Siritaratiwat, Warat Sriwannarat, and Nuwantha Fernando did vitualization. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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