A coreless axial flux-switching generator for micro-wind turbine application

Mohsen Dehshiri | Abbas Ketabi

Department of Electrical and Computer Engineering, University of Kashan, Kashan, Iran

Correspondence
Abbas Ketabi, Department of Electrical and Computer Engineering, University of Kashan, Kashan 873175, Iran.
Email: aketabi@kashanu.ac.ir

Abstract
The efficiency, power density, and torque of axial flux generators are higher than those of radial flux generators. In this paper, a new axial flux switching generator with a coreless stator is designed for micro wind turbine applications. Generator parts are designed based on nominal values, and their dimensions are determined. Cogging torque is an undesired torque ripple intrinsic in the design of a permanent magnet generator, which should be minimized due to its effects: vibration and noise. In addition, since aerodynamic power is low during start-up at low wind speeds, the cogging torque must be as low as possible to achieve a low cut-in speed. The design, optimization, and fabrication of a new coreless axial flux-switching generator for micro-wind turbine application are investigated and compared with the conventional one. The prototype machine is an axial-field flux-switching permanent magnet generator with a two-rotor-one-stators configuration. The stator of the proposed generator is made up of coils and magnets and has no iron core. First, the generator's design to reduce cogging torque is investigated using nominal values, and the dimensions of the various parts of the generator are calculated according to these values. Then the designed generator was simulated three-dimensionally using the FEM. Finally, a prototype of the desired generator is built. Comparing the results obtained from the finite element method and laboratory testing shows that these results are broadly consistent.

KEYWORDS
axial field flux-switching permanent magnet generator, coreless stator, finite element method, Taguchi method

1 | INTRODUCTION
In recent years, due to environmental problems, many governments have turned their attention to the use of renewable energy. As a result, using wind turbines as the most straightforward method of using renewable energy has a growing trend. Different types of generators can be used in wind turbines. However, permanent magnet generators are a good option for this type of application due to their simple construction, efficiency, reliability,
and high power density.\textsuperscript{1} Much research has been done to improve the performance of permanent magnet generators connected to wind turbines.\textsuperscript{2} For example, a comparison has been made between three types of wind turbine systems: fixed speed doubly-fed induction generator, variable speed synchronous generator, and permanent magnet synchronous generator based on efficiency. This study shows that the efficiency of a permanent magnet synchronous generator is much higher than the other two systems. The design, finite element analysis, and practical testing of a permanent magnet generator for use in wind turbines are presented in Chen et al.\textsuperscript{3} The analysis shows that the generator has a reliable and excellent performance in a wide range of speed changes. In Lee et al.,\textsuperscript{4} the optimal design of a permanent magnet generator connected to a wind turbine is presented to reduce cogging torque and total harmonic distortion. In the optimization process, the high output power is also considered. The design variables of the pole arc, the thickness of the permanent magnet material, and the amount of the tooth arc have been selected, and different target functions have been used to achieve the optimal design. In McDonald and Bhuiyan,\textsuperscript{5} the optimal design of a permanent magnet generator for use in wind turbines has been done to reduce the cost of energy production. In the generator's rotor, a rare-earth magnet and a ferrite magnet have been used as permanent magnet material. Several objective functions have been proposed to achieve a suitable design. It has been shown that the cost of generating energy and consumables for a generator designed with a rare-earth magnet is much lower than that of a ferrite magnet.\textsuperscript{6,7}

The difference between axial flux generators and conventional radial flux generators is in the direction of flux in the air gap, which is parallel to the mechanical shaft in axial flux generators. Axial flux permanent magnet (AFPM) machines have significant advantages over radial flux machines, such as high torque density, low rotor losses, and high efficiency.\textsuperscript{8,9} AFPM machines can be classified based on the number of rotors and stators, the placement of the magnet, and the winding type. Based on the number of rotors and stators, they are divided into three categories: single-sided structure, double-sided structure, and multidisk structure. The double-sided structure is divided into two models: one stator/two rotors and two stators/one rotor. The magnet in AFPM machines can be placed in both the rotor and the stator. AFPM machines can be designed with surface-mounted- or interior (buried)-type permanent magnets on the machine. If the magnet is placed in the stator, the axial flux machine will be a type of the axial field flux-switching permanent magnet (AFFSPM) machine.\textsuperscript{10,11}

An AFFSPM machine is a novel permanent magnet (PM) machine that consists of PM and coil on the stator and no windings or PMs on the rotor. High power density, high efficiency, sinusoidal waveform back electromotive force (EMF), flux weakening capability, and good cooling are the advantages of this type of machine.\textsuperscript{12,13} However, because of doubly salient construction and the high flux density caused by the flux focusing effects, the cogging torque of the AFFSPM machine is higher than the classical PM one.\textsuperscript{14}

Compared to the slotted AFPM machines, the coreless stator brings additional advantages because of eliminating stator core and stator iron losses from the machine.\textsuperscript{15} Reduction of cogging torque, higher generator efficiency, and the smaller generator's stack are other advantages of coreless type AFPM machines. However, it has to be considered that the consumed PM in the coreless structure is more than that of the iron core type due to a bigger air gap, to achieve the same magnetic air gap flux density. In addition to the above benefits, cogging torque is also reduced in coreless AFPM generators due to the absence of core material and reluctance variation.\textsuperscript{16}

This paper evaluates the design and prototyping of a new coreless stator AFFSPM generator. This new AFFSPMG has some advantages compared to the conventional AFFSPMGs, such as elimination of the stator core loss, reduction of cogging torque, and lower cost. The innovative structure of rotor teeth and the new magnet arrangement caused a reduction in cogging torque. The proposed axial AFFSPMG discussed in this paper is shown in Figure 1. As it can be seen, the stator of this generator is coreless and consists of coils and PMs.
This paper is structured as follows: Section 2 shows the structure of the proposed AFFSPM generator, characteristics, design process, and geometry optimization. Section 3 investigates transient magnetic time-stepping FEM of primary and optimized machines. A comparison between the proposed with a conventional machine is presented. Section 4 includes the experimental results. The conclusions are included in Section 5.

2 SIZING EQUATIONS AND OPTIMIZATION

The conventional machine presented in Asgharpour-Alamdari\textsuperscript{17} has a coreless stator, coils, rectangular magnets on the stator, and two rotors with 14 teeth. Concerning Figure 1, inspired by the conventional machine, the proposed structure consists of two rotors and a coreless stator placed between two rotors.

Each rotor consists of 28 teeth, and the stator consists of 12 windings and 24 rectangular magnets. There are two magnets with opposite polarities surrounded by a non-overlapping coil. The rotor teeth are divided into two parts with an angle difference of 360°/28°, as shown in Figure 2.

As seen in Figure 2, the rotor contains two rows of teeth: an inner row of teeth and an outer row of teeth. The stator also contains two rows of magnets with opposite polarities, the inner row and the outer row of magnets. The flux generated by the inner row's magnets passes through the inner row of the rotor's teeth, and the flux generated by the outer row magnets passes through the outer row of the rotor's teeth. The teeth are located with an angle difference of 360°/28° on the rotor; when the flux of the outer path is high, the flux of the inner path is low. The interference between the outer and inner flux paths is minimized because there is only one tooth in front of a magnet at a time. As the machine rotates, the flux switches from the outer to inner teeth and vice versa and voltage is induced in coils due to changes in the flux linkage. In Table 1, Some of the main characteristics of the generator studied in this paper are summarized. The design process of AFFSPMG is very similar to coreless stator AFPM machines with two rotors.\textsuperscript{18,19} The two-dimensional model of the generator is shown in Figure 3. By ignoring the leakage flux, the magnetic equivalent circuit of the half pole of the generator is shown in Figure 4; where $R_g$ is the air gap.

| Parameter                  | Value |
|----------------------------|-------|
| Output power               | 1000 W|
| Number of stator magnets   | 12    |
| Number of rotor pole pairs | 14    |
| Rated frequency            | 350 Hz|

![Figure 2](image1.png)  
(A) Rotor teeth of the proposed AFFSPMG and (B) coils and magnets of proposed AFFSPMG. AFFSPMG, axial field flux-switching permanent magnet generator

![Figure 3](image2.png)  
Two-dimensional model of the proposed generator

![Figure 4](image3.png)  
The equivalent magnetic circuit
reluctance, $R_m$ is the magnet reluctance, $R_b$ is the back iron reluctance, $\phi_t$ is the magnet flux, and $\phi_{mg}$ is the air gap flux. Since air gap reluctance is too higher than rotor back iron and tooth reluctance, rotor reluctance can be neglected to have a more straightforward solution. According to the magnetic equivalent circuit, the air gap flux is calculated from (1), and the magnet reluctance and the air gap reluctance are calculated from (2) and (3), respectively,

$$\phi_{mg} = \frac{R_m \phi_t}{R_m + R_g},$$

(1)

$$R_m = \frac{M_h}{\mu_0 \mu_r A_{pm}},$$

(2)

$$R_g = \frac{g}{\mu_0 A_g},$$

(3)

where $M_h$ denotes the magnet height (mm), $g$ is the air gap length (mm), $A_{pm}$ is the magnet surface (mm), and $A_g$ is the air gap surface (mm). $B_{mg}$ is the maximum air gap flux density, and it is calculated from (6).

To design the generator, the relationship between the outer diameter and the output power should first be calculated by (4), where $\eta$, $A_{ac}$, $k_w$, $w_s$, $B_{mg}$, $\alpha_p$, $\lambda$, and $\cos(\phi)$ are efficiency, electrical loading, winding factor, rated speed (rpm), maximum air gap flux density (T), magnet width to pole pitch ratio, the ratio of magnet width to pole pitch, the generators inner to outer diameter ratio, and power factor, respectively. The number of turns per phase is defined by (5), where $f$ is the frequency (Hz) and $\phi_{mg}$ (Wb) is the maximum magnetic flux per pole. The frequency of the back EMF is calculated from (7), where $N_t$ is the number of rotor teeth, and $w_s$ is the rotor speed in rpm.

$$D_{out} = \sqrt{\frac{32\eta \pi A_{ac} k_w w_s B_{mg} (1 - \lambda^2)(1 + \lambda) \cos(\phi)}{\pi N_t k_w \phi_{mg}}},$$

(4)

$$N_t = \frac{E_f}{\pi \sqrt{2} f k_w \phi_{mg}},$$

(5)

$$\phi_{mg} = B_{mg} \alpha_p \frac{\pi}{8 N_t} \left(1 - \lambda^2\right) D_{out}^2,$$

(6)

$$f = \frac{N_t w_s}{60}.$$

(7)

Since one of the main disadvantages of the AFFSPM machine is cogging torque, it is necessary to reduce the cogging torque as much as possible in the design process. Therefore, the Taguchi method is used to reduce the maximum cogging torque of the machine. The steps of the Taguchi method are shown in Figure 5.

According to Figure 5, the optimization goal is first set. Then the parameters which should be optimized are selected, and the value of their changes is determined. Next, according to the variable parameters, a table of Taguchi experiments is determined, and the results of each experiment are extracted using the finite element method. The maximum torque and cogging torque for each experiment are calculated, and the most suitable combination is selected according to the results.

This study’s optimization goal is to reduce cogging torque based on the assumption that the output power of the optimized generator should not be less than the output power of the primary generator. Concerning Figure 6, the optimization parameters of the Taguchi method are the width of PM ($M_w$), the height of the PM ($M_h$), the height of rotor tooth ($T_h$), the rotor tooth width ($T_w$), and the rotor back iron height ($B_i$), respectively.

After optimizing the machine geometry, the best combination of variables was selected to achieve the lowest cogging torque. According to the optimization results, Table 2 summarizes the specification of the primary and optimized generators.
As reported in Table 2, without any change in output power, the amount of PM used in the machine is reduced, and the optimal axial length of the machine is 2 mm less than the primary one.

### Table 2: Specification of primary and optimized generator

| Parameter                          | Unit | Primary   | Optimized |
|-----------------------------------|------|-----------|-----------|
| Rated power ($P_{\text{out}}$)    | W    | 1000      | 1000      |
| Rated speed ($w_s$)               | rpm  | 1500      | 1500      |
| Number of phases ($m$)            |      | 3         | 3         |
| Number of stator coils ($Q_c$)    |      | 12        | 12        |
| Number of poles ($p$)             |      | 28        | 28        |
| Rotor outer diameter ($D_{\text{out}}$) | mm  | 240       | 240       |
| Air gap length ($g$)              | mm   | 1         | 1         |
| The ratio of inner to the outer diameter ($\lambda$) | | 0.6       | 0.6       |
| Magnet height ($M_{h}$)           | mm   | 7         | 5         |
| Magnet width ($M_{w}$)            | mm   | 16        | 20        |
| Number of turns per phase ($N_{\text{phase}}$) | | 400      | 400       |
| Magnet length ($M_{L}$)           | mm   | 20        | 20        |
| Tooth width ($T_{w}$)             | mm   | 16        | 14        |
| Tooth height ($T_{h}$)            | mm   | 9         | 11        |
| Tooth length ($T_{L}$)            | mm   | 20        | 20        |
| Back iron ($B_i$)                 |      | 7         | 5         |
| Magnet type                       |      | Neodymium iron boron: 42/15 | Neodymium iron boron: 42/15 |
| The axial length of the machine   | mm   | 49        | 47        |
| Rated current                     | A    | 7         | 7         |

3 | FEM ANALYSIS AND COMPARISON

To evaluate the accuracy of the results obtained in the previous section, a three-dimensional transient FEM simulation was carried out. Some of the main parameters of the machines, such as flux density, back EMF, torque, total loss, and output power were measured.

The magnetic flux density and the flux path in the primary and the optimized generators at rated current and speed are shown in Figure 7A and Figure 7B, respectively. Even though the amount of magnet consumed in the optimized machine has been reduced by 12%, maximum flux densities remained equal (almost 1.2 T in the yoke and teeth of both machines). Figure 8 shows the cogging torque in the primary and optimized generator. As seen, the cogging torque in the optimized design is less than in the primary design. Figure 9 demonstrates the back EMF at the rated speed. According to this figure, the peak voltage of the primary and optimized designs are about 79 and 85 V, respectively. In addition, Figure 10 shows the output electrical power curve of generators. According to this figure, the output power of the optimized design is higher than the primary design. Finally, Figure 11 demonstrates the torque at the rated speed. Thus, the optimized design offers better performance than the primary design.

To compare the performance of the proposed generator with a conventional generator, the machine mentioned in Asgharpour-Alamdari17 is simulated in generator mode. Both machines have similar specifications and geometries.

As shown in Figures 2 and 12, each magnet is surrounded by a coil, and rotor teeth are in one piece in the conventional structure. In contrast, in the proposed generator, two magnets with opposite polarities are
FIGURE 7  (A) Flux density and path in the primary generator and (B) flux density and path in the optimized generator

FIGURE 8  Cogging torque of optimized and primary designs

FIGURE 9  Back electromotive force at rated speed
surrounded by a coil, and the rotor teeth are divided into two parts. They are implanted in the rotor body with an angle difference of 360°/28°. Despite the different magnetic equivalent circuits, both generators' magnitudes of the air gap flux densities are equal. However, Figure 13 shows that the cogging torque in the proposed machine is less than the conventional one. Some parameters are given in Table 3. It is concluded from these parameters that the proposed machine offers better performance than the conventional one.

4 | EXPERIMENTAL RESULTS

To evaluate the accuracy of the analytical analysis of the previous sections, a prototype machine is built according to the results shown in the previous section. The exploded view of the proposed generator and its various components, including shaft, flange, bearing, rotor, stator, and housing, are shown in Figure 14. A no-load test setup was built to measure the characteristics of the proposed generator. The stator is coreless, consists of 24 magnets and coils, and the rotor has 14 teeth. Since the stator is coreless, it was made using epoxy resin. A mold was designed considering the position of the coils and magnets, and epoxy resin was poured into the mold. After the epoxy resin is dried, the stator is formed. The rotor and stator are shown in Figure 15A and Figure 15B, respectively. Cogging torque and the back EMF are the main parameters measured in the no-load test. The method used to measure cogging torque is discussed in Kamper et al.20 The generator was attached to a lathe machine; as the rotor rotated at low speed, a balanced beam was attached to the shaft and connected to the digital weight gauge. The torque is calculated using weight gauge data and the length of the balanced beam.
According to Figure 16, the generator shaft is connected to the lathe machine on both sides, and the generator windings are connected to the oscilloscope in the back EMF test setup. In this case, machine windings are open circuits; therefore, the oscilloscope indicates the resulting voltage of back EMF. The no-load voltage is measured and calculated through the finite element method. The voltage of back EMF and cogging torque are shown in Figure 17 and Figure 18, respectively. The experimental results and FEM results show that the no-load voltage and cogging torque are highly similar.

| Parameters             | Conventional machine | Proposed machine |
|------------------------|----------------------|------------------|
| Output power           | 1000 W               | 1000 W           |
| Total loss             | 69 W                 | 62.2 W           |
| Peak back EMF          | 82 V                 | 85 V             |
| Peak cogging torque    | 0.8 N m              | 0.5 N m          |
| Torque                 | 6.35 N m             | 6.45 N m         |
| Efficiency             | 93%                  | 94.1%            |

Abbreviation: EMF, electromotive force.

**Figure 14** Exploded view of the proposed generator

**Figure 15** (A) Rotor and (B) winding and magnet

**Figure 16** Back electromotive force test setup. AFFSPMG, axial field flux-switching permanent magnet generator.

**Figure 17** Phase voltage of axial field flux-switching permanent magnet, simulation, and experimental results. EMF, electromotive force

**Figure 17**
5 | CONCLUSION

The present study aimed to design, simulate, optimize, and build a prototype of a new AFFSPM generator with a coreless stator for micro-wind turbine application. Initially, the generator was designed considering the nominal values; after completing the design process, the model was optimized using the Taguchi method. Both machines were simulated using the three-dimensional finite element method. Finally, the optimized generator was constructed and tested; the obtained results were then compared with those calculated in the simulation section, indicating that the experimental and analytical results were highly consistent with others. Also, the results show an increase in the torque and the efficiency value and a considerable decrease (37.5%) in cogging torque of the optimized machine compared with the conventional one. Indicating an improvement in the AFFSPMG design, this approach could well be applied to designing and optimizing the performance of other types of AFFSPMGs.

ORCID
Abbas Ketabi © http://orcid.org/0000-0001-9970-2157

REFERENCES
1. Sun M, Min Y, Chen L, Hou K, Xia D, Mao H. Optimal auxiliary frequency control of wind turbine generators and coordination with synchronous generators. CSEE J Power Energy Syst. 2020;7(1):78-85.
2. Grauers A. Efficiency of three wind energy generator systems. IEEE Trans Energy Conver. 1996;11(3):650-657. doi:10.1109/60.537038
3. Chen J, Nayar CV, Xu L. Design and finite-element analysis of an outer-rotor permanent-magnet generator for directly coupled wind turbines. IEEE Trans Magn. 2000;36(5):3802-3809. doi:10.1109/20.908378
4. Lee S-H, Kim Y-J, Lee K-S, Kim S-J. Multiobjective optimization design of small-scale wind power generator with outer rotor

5. based on Box–Behnken design. IEEE Trans Appl Supercond. 2016;26(4):1-5. doi:10.1109/TASC.2016.2524620
6. McDonald A, Bhuiyan NA. On the optimization of generators for offshore direct drive wind turbines. IEEE Trans Energy Convers. 2017;32(1):348-358. doi:10.1109/TEC.2016.2624219
7. Bi Y, Pei Y, Chai F. A Novel Axial Flux Interior Permanent Magnet Motor with High Torque Density: 22nd International Conference on Electrical Machines and Systems (ICEMS). IEEE; 2019:1-5.
8. Jin P, Yuan Y, Xu Q, Fang S, Lin H, Ho SL. Analysis of axial-flux Halbach permanent-magnet machine. IEEE Trans Magn. 2015;51(11):1-4.
9. Kim JH, Liu M, Ding H, Sarlioglu B. Comparison of Dual Structure Axial Flux Switching Permanent Magnet Machines: IEEE Energy Conversion Congress and Exposition (ECCE). IEEE; 2017:328-333.
10. Zhang W, Liang X, Lin M, Hao L, Li N. Design and analysis of novel hybrid-excited axial field flux-switching permanent magnet machines. IEEE Trans Appl Supercond. 2016;26(4):1-5.
11. Xu D, Lin M, Fu X, Hao L, Zhang W, Li N. Cogging torque reduction of a hybrid axial field flux-switching permanent-magnet machine with three methods. IEEE Trans Appl Supercond. 2016;26(4):1-5.
12. Zhang W, Yang Z, Zhai L, Wang J. Speed sensorless control of hybrid excitation axial field flux-switching permanent-magnet machine based on model reference adaptive system. IEEE Access. 2020;8:22013-22024.
13. Zhao J, Quan X, Lin M. Model predictive torque control of a hybrid excited axial field flux-switching permanent magnet machine. IEEE Access. 2020:33703-33712.
14. Wang S, Lin K, Lin M, et al. Comparative study of E-and U-core modular dual-stator axial-field flux-switching permanent magnet motors with different stator/rotor-pole combinations based on flux modulation principle. IEEE Access. 2021;9:78635-78647.
15. Minaz MR, Akcan E. An effective method for detection of demagnetization fault in axial flux coreless PMSG with texture-based analysis. IEEE Access. 2021;9:17438-17449.
16. Wang X, Zhao M, Zhou Y, Wan Z, Xu W. Design and analysis for multi-disc coreless axial-flux permanent-magnet synchronous machine. IEEE Trans Appl Supercond. 2021;31(8):1-4.
17. Asgharpour-Alamdari H. Design optimization of coreless stator axial flux-switching motor. Sci Iran. 2021. doi:10.24200/sci.2021.58284.5652
18. Huang S, Luo J, Leonardi F, Lipo TA. A comparison of power density for axial flux machines based on general purpose sizing equations. IEEE Trans Energy Convers. 1999;14(2):185-192.
19. Gieras JF, Wang R-J, Kamper MJ. Axial Flux Permanent Magnet Brushless Machines. Springer Science & Business Media; 2008.
20. Kamper MJ, Wang R-J, Rossouw FG. Analysis and Performance Evaluation of Axial Flux Air-Cored Stator Permanent Magnet Machine with Concentrated Coils: 2007 IEEE International Electric Machines & Drives Conference, Antalya, Turkey, 3-5 May 2007. IEEE; 2007.
21. Roy RK. *A Primer on the Taguchi Method*. Society of Manufacturing Engineers; 2010.

22. Wang H, Liu S, Wu S, Guo L, Shi T. Optimal design of permanent magnet structure to reduce unbalanced magnetic pull in surface-mounted permanent-magnet motors. *IEEE Access*. 2020;8:77811-77819.

**How to cite this article**: Dehshiri M, Ketabi A. A coreless axial flux-switching generator for micro-wind turbine application. *Energy Sci Eng*. 2022;10:4804-4813. doi:10.1002/ese3.1309