

Research on Electromagnetic Characteristics for an Outer Rotor Doubly Salient Permanent Magnet Reluctance Generator in Direct-drive Vertical Axis Fans

Zhe Zhou, Yifei Gao, Kuan Zhang, Ge Qi, and Shuai Xu

School of Electrical and Information Engineering
Zhengzhou University, Zhengzhou, Henan, 450001, China

Abstract – To enhance the operation efficiency of generators in variable wind conditions, this paper proposes an outer rotor doubly salient permanent magnet reluctance generator (ORDS-PMRG). First, the operation principles of ORDS-PMRG are presented. Then, the magnetic modulation effect of the multi-tooth structure on generator air-gap flux density is analyzed. Next, the operation modes of the proposed generator are analyzed and can be flexibly switched by changing the winding connection methods. Meanwhile, the electromagnetic characteristic analysis is developed based on the finite element model. The results indicate that the proposed ORDS-PMRG has more operation modes and higher power density compared to traditional doubly salient permanent magnet reluctance generators.

Index Terms – Electromagnetic characteristic, multi-mode operation, outer rotor, permanent magnet reluctance generator.

I. INTRODUCTION

A. Vertical axis wind turbine

As a clean energy source, wind power has emerged as a key focus area in renewable energy development. In the field of distributed generation, vertical-axis wind turbine (VAWT) has many advantages over horizontal-axis wind turbine (HAWT). Notable advantages include its ability to harness wind energy across full speed ranges, simplified installation procedures, and reduced mechanical complexity [1]. The direct-drive VAWT further reduces the transmission structure. The power generation efficiency and reliability of the system have been further improved [2].

In terms of generators, medium and large direct-drive VAWTs mostly use permanent magnet synchronous generators [3], electrically excited synchronous generators, and switched reluctance generators [4]. There are also some generators with hybrid excitation, such as induction reluctance motor [5] and permanent magnet assisted reluctance synchronous motor [6]. However, these generators are subject to problems such as large volume, high maintenance costs, and large

vibrations. It is difficult to apply in small direct drive VAWT.

In terms of fan speed regulation, VAWT still needs to pitch the blades to adjust the speed [7]. If the mechanical devices required for fan speed regulation can be reduced, the reliability and power generation efficiency of the power generation system will be further improved, and the cost will be reduced.

B. Permanent magnet reluctance generator

In recent years, permanent magnet vernier generators (PMVG) have been widely adopted because of their large torque and low speed [8, 9]. It is also widely used in the field of direct-drive wind turbines [10, 11]. This structure of the generator brings new inspiration to the doubly salient permanent magnet reluctance generators. The tangentially excited PMVG has the characteristics of high mechanical strength and strong excitation ability, which has received further attention [12]. However, in recent years, scholars have gradually noticed that although its power density is relatively large, there is still room for improvement [13]. Several methods are proposed to improve its power density, such as increasing the magnetic bridge to improve the no-load back EMF. Reference [14] investigated a structural design for enhancing power density in generators. By adding two connecting bridges at the stator ends, this configuration effectively increases power generation by over 15%. Reference [15] proposes an innovative asymmetric cross-section rotor design (featuring 45° skewed salient poles) for high-speed surface permanent magnet motors, achieving phase synchronization between reluctance torque and magnetic torque for the first time. The breakthrough enhances torque density by 20%.

However, the previous studies have not considered the matching relationship between the generator and wind speed under direct-drive conditions. It is difficult to achieve optimal matching between rotational speed and wind speed with a single operating mode. This paper aims to develop a multi-mode operating generator capable of switching the motor's operating mode according to different wind speeds.

C. Multi-mode operation

References [16, 17] mentioned some multi-mode operation strategies to control the generator power by changing the connection mode of the winding. However, scholars focus on the constant voltage control of the generator at different speeds. For wind power generation, this will lead to a decrease in power generation efficiency and wind energy utilization [18]. However, its proposed multi-mode operation principle gives the generator the potential for active speed regulation. However, traditional multi-mode operation motors have all adopted a dual-stator structure. This increases the mechanical complexity of the wind power generation system and elevates the probability of system failures. For VAWTs, however, low maintenance costs are one of their key advantages.

D. Contributions

Based on the above content, this paper designs an outer rotor doubly salient permanent magnet reluctance generator (ORDS-PMRG) with multi-mode capability for small direct-drive VAWT. Specifically, it can be summarized as

1. The dual-stator structure of the traditional multi-mode generator is simplified by combining the multi-tooth structure with the multi-mode operation. Reduce the production cost.
2. Electromagnetic analysis based on finite element is carried out. It is proved that the ORDS-PMRG has higher power density and torque density. And the effectiveness of multi-mode operation demonstrates good engineering value.

In this paper, section II introduces the structure and operating principles of generators. Section III analyzes the principles of multi-mode operation. In the section IV, the finite element simulation of ORDS-PMRG is carried out. Section V is the summary of the full paper.

II. ORDS-PMRG STRUCTURE AND WORKING PRINCIPLE

A. Structure of ORDS-PMRG

An ORDS-PMG is proposed in this paper, as shown in Fig. 1. Compared with the traditional structure, ORDS-PMRG is characterized by its multi-tooth structure which can form multiple sets of windings. It can improve the performance of the generator, which will be described in detail in part C of this section.

The ORDS-PMRG is designed for VAWT and adopts an outer rotor structure that can be directly connected to the blades. There is a magnetic bridge outside the rotor permanent magnet to connect a magnetic pole of the rotor. This structure has been proven to improve the performance of the tangentially excited PMG. The

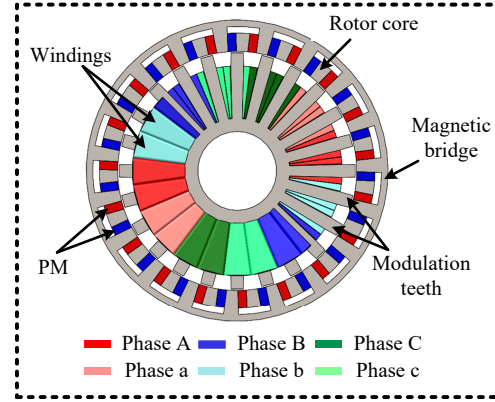


Fig. 1. Structure of proposed ORDS-PMRG.

24-slot structure improves the diversity of winding connections. It is convenient to realize the multi-mode operation of the generator.

The above-mentioned structural design not only simplifies the mechanical complexity of traditional dual-stator multi-mode generators, but also lays the foundation for subsequent multi-mode operation through the flexibility of the combination of the multi-tooth structure and the windings. The next section will further analyze how this structure achieves the low-speed high-torque operating characteristics, in combination with the principle of magnetic field modulation.

B. Principle of ORDS-PMRG

ORDS-PMRG follows the principle of magnetic field modulation [19]. The rotor magnetic field is modulated by the modulation teeth. The greatest advantage of the PMRG is its ability to achieve low-speed, high-torque operation. Because of the effect of the modulation teeth, the air gap flux density of the generator produces a specific number of harmonics. Its modulation effect can be derived by the following formula:

$$\begin{cases} B_{agr} = \sum_{m=1,3,5}^{+\infty} b_{rm}(c_r, r) \cos[m p_r (\theta - \omega_r t + \alpha_{0m})] \\ \Lambda = a_0(c_{st}) + \sum_{n=1,2}^{+\infty} a_n(c_{st}) \cos[n N_{st} (\theta + \beta_{0m})] \end{cases}, \quad (1)$$

where B_{agr} denotes the waveform of the magnetic field excited by the excitation source, which is a square wave with zero DC component in ORDS-PMRG. The parameter Λ quantifies the modulation effect induced by the modulation teeth, which is a square wave with a certain DC component. Additionally, c_r is the pole arc coefficient of the rotor, p_r is the number of permanent magnet poles, ω_r is the rotation speed of the rotor, a_{0m} is the angle between the rotor and the magnetic pole axis, and b_{rm} is the Fourier coefficient. c_{st} is the stator tooth arc coefficient, N_{st} is the number of stator teeth, β_{0m} is the deviation angle of the stator from the center of the slot, a_0 and a_n are Fourier coefficients.

Considering only the case where $m = 1$ and $n = 1$, by multiplying the two equations in equation (1) and then performing trigonometric transformations, the approximate expression of air gap flux density can be obtained:

$$\begin{aligned}
 B_{agr\Lambda} &= B_{agr}^{m=1} \times \Lambda^{n=1} \\
 &= a_0 b_{r1} \cos[p_r(\theta - \omega_r t + \alpha_0)] \\
 &+ a_1 b_{r1} \cos(m p_r(\theta - \omega_r t + \alpha_{0m})) \cos(n N_{st}(\theta + \beta_{0m})) \\
 &= a_0 b_{r1} \cos[p_r(\theta - \omega_r t + \alpha_0)] \\
 &+ \frac{a_1 b_{r1}}{2} \cos\left[(p_r + N_{st})\left(\theta - \frac{p_r \omega_r}{p_r + N_{st}} t + p_r \alpha_{01} + N_{st} \beta_{01}\right)\right] \\
 &+ \frac{a_1 b_{r1}}{2} \cos\left[(p_r - N_{st})\left(\theta - \frac{p_r \omega_r}{p_r - N_{st}} t + p_r \alpha_{01} + N_{st} \beta_{01}\right)\right]
 \end{aligned} \quad (2)$$

The following can be obtained:

$$p_a = |p_r - N_{st}|. \quad (3)$$

The variable p_a represents the number of pole pairs in the generator, which also corresponds to the effective harmonic order of the air gap magnetic field. The next step is to obtain the ratio between the electromagnetic speed and the mechanical speed of the ORDS-PMRG:

$$\omega_{smf} = \frac{p_r}{p_r - p_a} \omega_r = G_r \omega_r, \quad (4)$$

where ω_{smf} is the angular velocity of the effective harmonic, while ω_r refers to the angular velocity of the rotor. Finally, G_r symbolizes the variable gear ratio. From equation (1) to equation (4), the working principle of PMRG with low speed and high torque can be obtained.

Based on the above-mentioned magnetic field modulation principle, the ORDS-PMRG can output high torque at low speeds, meeting the requirements of direct-drive vertical-axis wind turbines. However, a single operating mode is difficult to adapt to the dynamic changes of wind speed, so it is necessary to combine a multi-mode operation strategy.

III. MULTI-MODE OPERATION

A. ORDS-PMRG with multi-mode operation

For the ORDS-PMRG mentioned in this paper, 24 modulation teeth can form a dual three-phase winding. The combination method is shown in Fig.1. Among them, A B C forms one set of three-phase windings, and a b c forms another set of three-phase windings. Similar to the above, A B C windings and a b c windings are distinguished by color. The two sets of windings are combined to produce different operation modes.

As mentioned above, the previous multi-mode generator needs to be realized by double stators. However, ORDS-PMRG has multiple stator teeth, it can be formed by the combination of different teeth. The method shown

in Fig.1 is a double three-phase winding with a 30° phase difference.

B. Principles of multi-mode operation

Reference [20] proposes a dual-stator generator that can achieve multi-mode operation. The principle is to adjust the output voltage by connecting the windings on the two misalignment stators. By changing the connection method of the inner and outer windings, a series of EMFs can be generated. As shown in Fig.2, the winding link diagram and EMF vector diagram of the four modes are given. The EMF generated by different operating modes can be approximately obtained by the following formula:

$$E_{mi} = 2E_g \cos\left(\frac{\theta_i}{2}\right), \quad (5)$$

where θ_i represents the electrical angle between windings, E_g represents the phase no-load back EMF amplitude. Affected by the winding connection mode and the stator angle.

When the winding link mode is switched, the voltage on the generator load will change. At the same time, the output power of the generator will change. This will affect the speed and torque of the VAWT input to the generator.

At the same time, the multi-mode operation generators often adopt the double stator structure. Because the realization of multi-mode operation requires a certain electrical angle difference between the dual three-phase

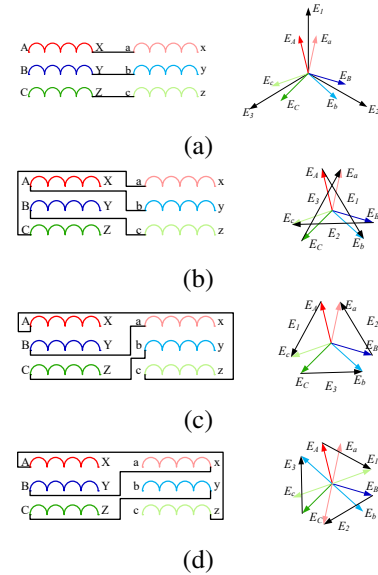


Fig. 2. Multi-mode operation schematic: (a) series connection of phase A and phase a, (b) reverse series connection of phase A and phase b, (c) series connection of phase A and phase c, and (d) reverse series connection of phase A and phase c.

windings, this makes the manufacture of such generators more difficult and costly. For ORDS-PMRG, a dual three-phase winding with a certain electrical angle difference can be realized without the dual-stator structure.

To verify the effectiveness of ORDS-PMRG and its multi-mode operation, the finite element software is used to simulate it. Key design parameters of the generator are shown in Table 1.

Table 1: Key design parameters of ORDS-PMRG

| Parameters | Value |
|-----------------------------|-------|
| Rated power/kW | 0.75 |
| Rated speed/rpm | 158 |
| PM poles pairs | 19 |
| Teeth number | 24 |
| Poles pairs | 5 |
| Frequency/Hz | 50 |
| Operation modes | 4 |
| Stack thickness/mm | 95 |
| Stator tooth width/mm | 7 |
| Modulation tooth width/mm | 6 |
| Stator yoke thickness/mm | 10 |
| PM length/mm | 14.5 |
| PM width/degree | 3 |
| Magnetic bridge/mm | 5 |
| Stator outer diameter/mm | 90 |
| ORDS-PMRG outer diameter/mm | 230 |
| Winding turns | 60 |
| Length of air gap/mm | 0.5 |

IV. FEA VERIFICATION AND COMPARISON

The finite element simulation of the generator was carried out using Altair Flux software. The 2D finite element models of ORDS-PMRG is established.

A. No-load characteristic

For convenience, the four operating modes of the generator are referred to as M1, M2, M3, and M4 respectively.

Figure 3 shows a comparative analysis of the magnetic density cloud images and magnetic force lines for uneven teeth and even teeth at the same moment. When the magnetic flux in a tooth reaches its maximum, there is a notable difference in the magnetic flux size in another tooth of the same group. The synchronization rate of the magnetic flux between the two teeth in each group is higher for uneven teeth. This results in a larger amplitude of EMF generated by a set of windings under the uneven teeth structure. Consequently, the no-load back EMF of the generator is also increased.

Figure 4 shows the no-load back EMF of the generator. It can be seen that the amplitude and phase of the no-load back EMF are different under different operating

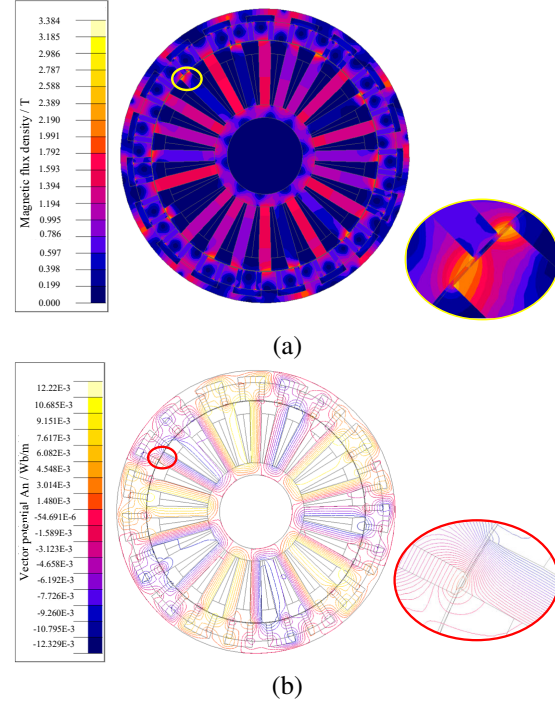


Fig. 3. (a) ORDS-PMRG magnetic density cloud and (b) ORDS-PMRG magnetic lines.

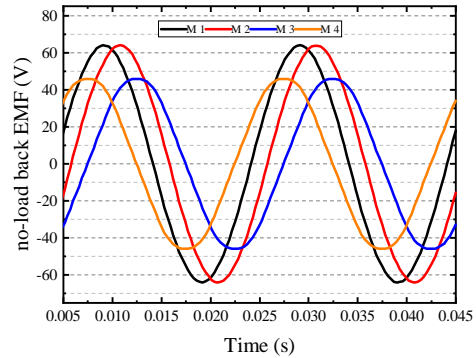


Fig. 4. No-load back EMF of ORDS-PMRG.

modes. The no-load back electromotive forces (EMF) of ORDS-PMRG are measured as follows: M1 = 65.93 V, M2 = 65.91 V, M3 = 46.44 V, M4 = 46.42 V.

In reality, there is a certain difference between the EMF value obtained by simulation and the value calculated by equation (5). This issue arises closely associated with the actual EMF waveform generated by the ORDS-PMRG. Owing to the influence of permanent magnets, partial magnetic saturation occurs on the stator teeth of the ORDS-PMRG, a phenomenon that is also evident in Fig.3 (a). As a result, the EMF waveform deviates from a purely sinusoidal shape. This phenomenon warrants enhancement in future work.

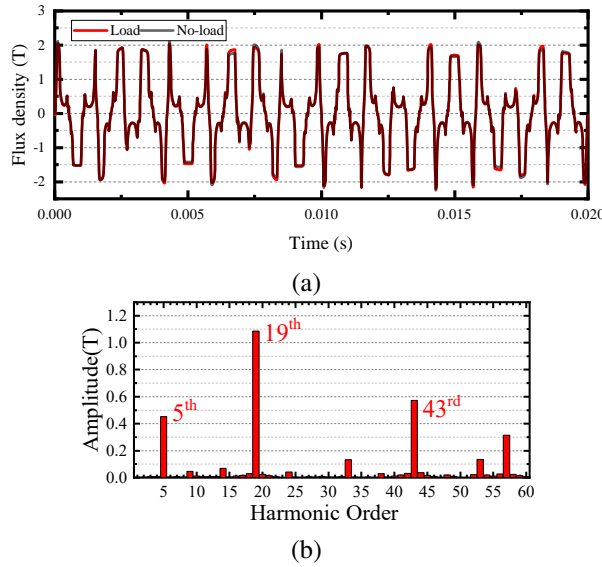


Fig. 5. Air gap magnetic density comparison: (a) Air gap magnetic density waveform and (b) Harmonic analysis.

Table 2: Performance characteristics of ORDS-PMRG

| Performance | M1 | M2 | M3 | M4 |
|----------------------|--------|--------|--------|--------|
| Average torque (N.m) | 47.0 | 47.0 | 27.6 | 27.6 |
| Torque ripple | 1.55% | 1.63% | 3.6% | 3.3% |
| Rated power (kW) | 0.75 | 0.75 | 0.45 | 0.45 |
| Total loss (W) | 70.5 | 70.6 | 41.0 | 40.9 |
| Efficiency | 90.93% | 90.92% | 91.03% | 91.06% |

Figure 5 shows a comparison of air gap magnetic density. An FFT analysis on Fig.5 (a) yields Fig.5 (b). Based on the operating principle of PMVG, the 5th, 19th, and 43th harmonics are the main no-load back EMF sources of the generator.

B. Load comparison

Figures 6 and 7 demonstrate the torque and load voltage characteristics across operational modes. While the ORDS-PMRG shows superior torque stability in M1 and M2 with less than 3% ripple variation, this multi-tooth configuration introduces minor trade-offs. The 24-19 stator-rotor poles architecture fundamentally suppresses cumulative pulsations through phase-misaligned dual salient-pole units, as mechanistically validated in [21].

Table 2 shows the performance of ORDS-PMR. Although the absolute value of torque ripple is large, the increase in average torque results is relatively small in its ratio. Furthermore, this structure does not introduce additional losses, maintaining the generator efficiency at a higher level.

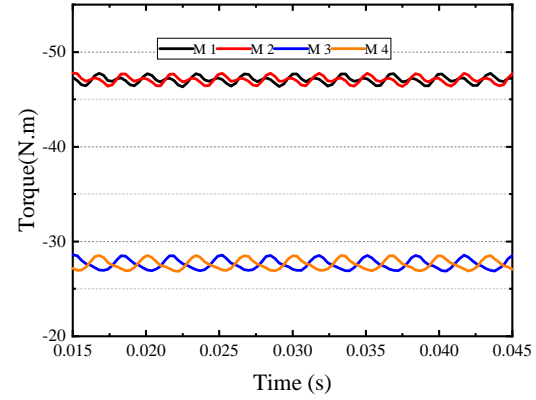


Fig. 6. The generator input torque in four operation modes.

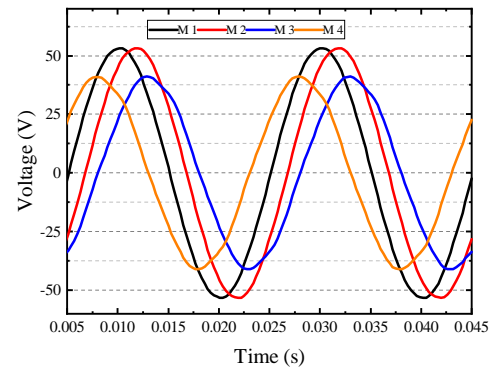


Fig. 7. The generator output voltage in four operation modes.

V. CONCLUSION

This paper proposes an ORDS-PMRG for small direct-drive vertical-axis wind turbines, featuring multi-mode operational capability. The design integrates a multi-tooth structure with adaptive operating modes, validated through finite element simulations demonstrating its structural efficacy and operational flexibility. Future directions include:

1. Enhancing power density via modulated tooth topologies and advanced magnetic materials.
2. Implementing model predictive control for real-time mode switching to optimize wind energy harvesting.

These advancements will establish theoretical foundations for next generation switched reluctance and hybrid-excitation motor designs.

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design.

Zhe Zhou received B.E. degree in electrical engineering in 2023 from Henan University of Science and Technology, Henan, China. He is currently pursuing a M.S. degree in electrical engineering at Zhengzhou University. His research interests include permanent magnet generator



phase permanent magnet synchronous motor.

Yifei Gao received B.S. degree in electrical engineering in 2024 from Henan University of Technology, Henan, China. He is currently pursuing a M.S. degree in electrical engineering at Zhengzhou University. His research interests include fault tolerant control of dual three-



Kuan Zhang received the B.E. degree from China University Mining and Technology, Xuzhou, China, in 2014. She is currently a Ph.D. student at the School of Control Science and Engineering, Zhengzhou University. Her current research interest is multi-motor control.



lecturer at Zhengzhou University of China. Her main research interests are design and control of special motors.

Ge Qi received the master's degree in electrical engineering from Harbin Institute of Technology, Harbin, China, in 2004, and the Ph.D. degree in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2010. Currently, she is a



Since 2021, he has been an Associate Professor at Zhengzhou University. His current research interests include motor design and control.

Shuai Xu (Member, IEEE) received the B.S. degree in electrical engineering and automation and the Ph.D. degree in electrical engineering from the China University of Mining and Technology, Xuzhou, China, in 2014 and 2019.