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Compact Direct Drive PM-Generator for Low-speed Wind Applications

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Abstract: The increasing global focus on sustainable energy has accelerated the development of efficient and reliable wind power generation systems. This papert presents the design and analysis of a Compact Direct-Drive Permanent Magnet Generator (DD-PMG) specifically optimized for low-speed wind applications. By eliminating gear-based transmission, the proposed system achieves a simplified mechanical structure with reduced maintenance and improved energy conversion efficiency.

The primary aim of the project is to maximize electrical output at low wind speeds, making it suitable for regions with limited or variable wind resources. The study emphasizes the performance of Permanent Magnet Synchronous Generators (PMSGs) under low-speed operating conditions, focusing on key metrics such as power output, electromagnetic efficiency, and torque smoothness. A core objective is to reduce cogging torque, which affects startup behavior and stable power generation. To achieve this, a detailed investigation is conducted by varying skew angles and air gap lengths, enabling identification of optimal configurations for minimizing torque ripple and enhancing low-speed performance.

Simulation-based evaluations demonstrate that proper skewing techniques and air gap tuning significantly improve generator efficiency without compromising energy output. The compact generator design is well-suited for rural electrification, off-grid energy systems, microgrids, and hybrid renewable applications

Keywords: Vertical Axis Wind turbine, skew, Airgap, Cogging torque, Efficiency.

I. INTRODUCTION

The transition to sustainable energy systems has accelerated global interest in wind energy as a clean, decentralized power source. While conventional wind farms often rely on large-scale Horizontal Axis Wind Turbines (HAWTs), there is a growing demand for compact and adaptable solutions that can operate effectively in low-wind-speed environments and urban or remote settings. In response to these demands, Vertical Axis Wind Turbines (VAWTs) have emerged as a promising alternative due to their structural simplicity, omnidirectional wind acceptance, and suitability for distributed generation applications.

VAWTs are characterized by a vertical axis of rotation, which allows them to harness wind energy regardless of the direction of airflow, eliminating the need for yaw control systems that are essential in HAWTs. This attribute makes VAWTs particularly advantageous in urban or geographically constrained environments where wind patterns are variable and turbulent. VAWTs are generally categorized into two main types: drag-based designs and lift-based designs While drag-based turbines offer simplicity and self-starting capability, they suffer from low efficiency. In contrast, lift-based VAWTs can achieve higher tip-speed ratios and greater aerodynamic efficiency, making them more suitable for electricity generation. However, they present challenges related to starting torque, control, and mechanical stability, particularly under fluctuating wind conditions.

To address these limitations and improve energy conversion performance, this research focuses on the development of a Compact Direct-Drive Permanent Magnet Generator (DD-PMG) specifically optimized for integration with VAWT systems. Unlike traditional generator systems that depend on gearboxes to match rotor and generator speeds, a direct-drive configuration eliminates intermediary mechanical components, thereby reducing energy losses, enhancing reliability, and minimizing maintenance requirements. The direct coupling of the turbine to the generator also enables efficient power extraction at low rotational speeds, a critical requirement for most VAWT applications.

A central aspect of this study is the analysis and mitigation of cogging torque, a common issue in permanent magnet machines that can hinder turbine startup and cause power fluctuations. Cogging torque arises due to the interaction between the rotor magnets and stator slots and is particularly detrimental in low-speed systems like VAWTs. This project investigates the effects of various skew angles and air gap lengths on cogging torque reduction through detailed electromagnetic simulations. By optimizing these parameters, the proposed design aims to achieve smoother torque profiles, improved startup characteristics, and more stable electrical output under low and variable wind speeds.

The objectives of the paper is not only to enhance generator performance but also to develop a system that is practical for rural electrification, off-grid renewable integration, and urban microgrid applications. The proposed compact DD-PMG configuration, when integrated with a VAWT, presents a viable solution for sustainable power generation in diverse environmental and socioeconomic contexts. The research further explores future scalability through improvements in magnetic material selection, advanced cooling strategies, and the potential integration of smart grid technologies for real-time optimization.

Fig.1. Vertical Axis Wind Turbine

II. LITERATURE REVIEW

Research in the domain of Direct-Drive Permanent Magnet Generators (DD-PMGs) has significantly advanced in recent years, primarily to enhance the performance, reliability, and energy conversion efficiency of wind turbine systems. Various novel topologies and design optimizations have been proposed, each targeting specific operational challenges such as torque ripple, cogging torque, and mechanical losses.

Wasiq Ullah et al. [1] proposed a Counter-Rotating Dual Rotor Permanent Magnet Flux Switching Generator (CR-DRPMFSG), designed specifically for wind turbine applications. The study demonstrated that counter-rotating configurations effectively minimize cogging torque by approximately 66.87%, while simultaneously enhancing power output by 27.17% compared to conventional co-rotating architectures. This topology improves magnetic coupling and flux variation rates, thereby optimizing energy conversion.

Cichowicz et al. [2] conducted a detailed investigation into the design of a low-speed Permanent Magnet Synchronous Generator (PMSG) tailored for vertical-axis wind turbines (VAWTs). The comparative analysis of radial and tangential magnet arrangements revealed that radial magnetization significantly outperforms tangential configurations in terms of both torque stability and electromagnetic efficiency. The findings underline the importance of magnet orientation in achieving superior generator performance in VAWT systems.

In a separate study, Zin Mar Htun et al. [3] analyzed the operational advantages of direct-drive PM generators over traditional geared systems. The results highlight that eliminating the gearbox not only reduces mechanical complexity and wear but also improves overall efficiency, particularly under low-speed conditions typical of wind energy applications. The direct-drive topology thus emerges as a viable solution for enhancing the durability and reliability of wind turbine generators.

III. GENERATOR DESIGN CHARACTERISTICS

The proposed generator is based on a Direct Drive permanent magnet (PM) topology, where the magnetic field lines travel perpendicularly across the air gap from the rotor to the stator. This configuration is widely adopted in wind energy systems due to its robust structure, high efficiency at low speeds, and mechanical simplicity enabled by the direct-drive arrangement. The absence of a gearbox reduces maintenance requirements and enhances overall reliability.

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A. Magnet and Winding Configuration

The layout of the permanent magnets and stator windings plays a critical role in determining the electromagnetic performance and energy conversion efficiency of the machine.

1) Permanent Magnet Placement

The rotor carries surface-mounted Neodymium Iron Boron (NdFeB) magnets arranged circumferentially along the inner diameter. These magnets are positioned with alternating north and south poles to establish a consistent and strong radial magnetic field across the air gap. The magnet thickness and pole pitch are optimized to achieve maximum air gap flux density while minimizing cogging torque.

2) Stator Winding Structure:

The stator features a three-phase winding scheme housed within 54 distributed slots. Fractional-slot concentrated windings are used to enhance torque density and reduce harmonic distortion. The windings are symmetrically arranged to ensure balanced magnetic force distribution and effective thermal dissipation. Coil parameters such as number of turns, conductor size, and slot fill factor are selected based on thermal and electrical performance targets.

B. Magnetic Flux Direction and Optimization

The design of the magnetic circuit directly influences torque generation, efficiency, and losses. Key considerations in flux path management include:

1) Radial Flux Orientation: The magnetic flux produced by the rotor magnets traverses radially across the air gap into the stator teeth. This orientation provides strong electromagnetic coupling and contributes to the uniform development of torque along the rotor circumference. It also enables the use of standard lamination materials and manufacturing processes.
2) Electromagnetic Coupling with Windings: As the rotor rotates, the radial magnetic flux interacts dynamically with the stator windings, inducing alternating electromotive force (EMF) in each phase. The geometry of the stator slots and teeth is optimized using finite element analysis (FEA) to maximize flux linkage while minimizing core losses and flux leakage.
3) Magnetic Circuit Efficiency: The magnetic core is constructed using low-loss silicon steel laminations to reduce eddy current losses and improve thermal behavior. Additionally, techniques such as rotor skewing and pole shaping are implemented to mitigate cogging torque and improve torque smoothness. The overall magnetic circuit is designed to ensure minimal saturation, efficient flux guidance, and structural rigidity under operational loads.

This PM generator design combines radial magnetic flux, optimized magnet placement, and efficient winding configuration to achieve high torque density, minimal losses, and enhanced performance in low-speed wind turbine applications. The direct-drive architecture further supports improved reliability and reduced maintenance, making it suitable for long-term deployment in renewable energy systems.

Fig. 2. Slot design

Name	Value
HS(mm)	21
WS2(mm)	5
H1(mm)	1.12
WS1(mm)	3.177
HO(mm)	1.527
WO(mm)	6.354e-1
R(mm)	0.5

Table 1. Slot parameters

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The radial view of motor for the above dimensions and winding connections is shown in figure 2.

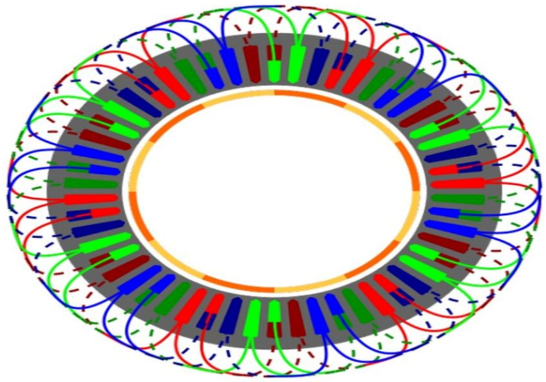


Fig.3. Radial view of winding connection

STATOR	
Outer diameter (mm)	170.0
Inner diameter (mm)	115.0
Length (mm)	40.0
No. slots	54
AIRGAP	
Length (mm)	1.0
ROTOR	
Outer diameter (mm)	113.0
Inner diameter (mm)	60.0
Length (mm)	40.0
No. poles	12

Fig.4. Stator and rotor characteristics

Name	Value
TM (mm)	4
R1(mm)	52.5
VP(mm)	30.0

Table 2: Magnet parameters

IV. RESULT AND ANALYSIS

The objective is to Achieve higher output Voltage at low speeds with machine dimensions under different skews and different air gaps. Table 3 represents cogging torques under different air gaps and skews that has been calculated using standard cogging torque formula

Airgap	Skew	Cogging Torque
0.8mm	0	35.75 Nm
0.8mm	0.5	22.75 Nm
0.8mm	1	0 Nm
1.0mm	0	35.44 Nm
1.0mm	0.5	22.56 Nm
1.0mm	1	0 Nm
1.2mm	0	35.24 Nm
1.2mm	0.5	22.43 Nm
1.2mm	1	0 Nm

Table 3. Cogging torque under air gap and skews

From table 3 it is observed that at air gap 1 skew 1 cogging torque is the lowest which gives increased efficiency at low speed and smooth torque production with improved starting performance

Name	Value	Name	Value
Operating mode	Generator		
Mech Torque(N.m)	4.34	Speed(rpm)	300
Mech power (W)	136.33	Machine Electrical Power (W)	125.692
Machine Efficiency (%)	92.197	Apparent power (VA)	125.763
Control angle(deg)	-1.301	Power factor	9.994e-1
Line current,rms(A)	3.768	Phase current,rms (A)	2.175
Line-Line Voltage ,rms (V)	19. 272	Phase Voltage, rms (V)	19.272

Table 4. Working Point Output air gap 1mm, speed 300rpm, skew 1

Name	Value	Name	Value
Operating mode	Generator		
Mech Torque(N.m)	11.28	Speed(rpm)	800
Mech power (W)	944.97	Machine Electrical Power (W)	888.791
Machine Efficiency (%)	94.052	Apparent power (VA)	892.27
Control angle(deg)	-3.577	Power factor	9.961e-1
Line current, rms(A)	10.023	Phase current, rms (A)	5.787
Line-Line Voltage, rms (V)	51.394	Phase Voltage, rms (V)	51.394

Table 5. Working Point Output air gap 1mm, speed 800rpm, skew 1

Name	Value	Name	Value
Operating mode	Generator		
Mech Torque(N.m)	15.456	Speed(rpm)	1100
Mech power (W)	1780.449	Machine Electrical Power (W)	1679.75
Machine Efficiency (%)	94.344	Apparent power (VA)	1692.26
Control angle(deg)	-4.864	Power factor	9.26e-1
Line current,rms(A)	13.825	Phase current,rms (A)	7.982
Line-Line Voltage ,rms (V)	70.67	Phase Voltage, rms (V)	70.67

Table 6. Working Point Output air gap 1mm, speed 1100rpm, skew 1

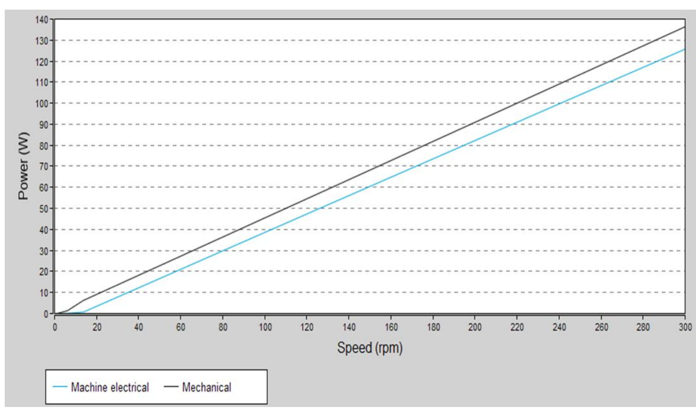


Fig 5. Power VS Speed

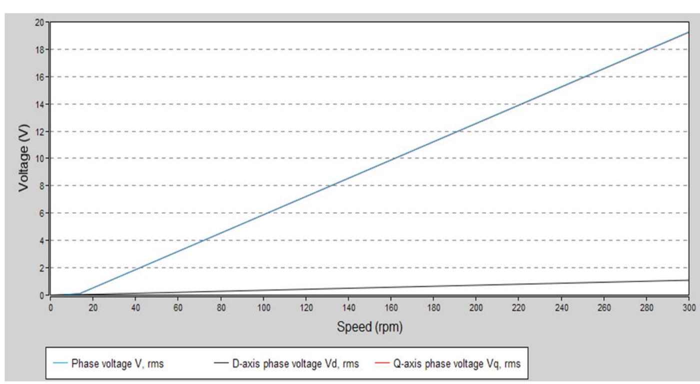


Fig 6.Voltage VS Speed

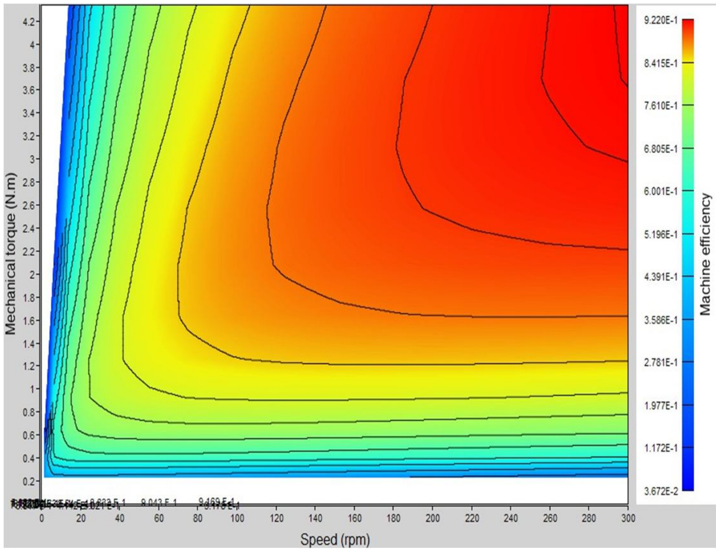


Fig 7. Efficiency in Torque Speed area

V. CONCLUSION

This research presents the design, analysis, and performance optimization of a Compact Direct-Drive Permanent Magnet Generator (DD-PMG) tailored for integration with Vertical Axis Wind Turbines (VAWTs) operating at low wind speeds. By eliminating mechanical gear systems, the proposed direct-drive configuration simplifies the generator architecture, reduces energy losses, and enhances system reliability.

A key focus of the study was the mitigation of cogging torque, which is critical for efficient startup and stable operation in low-speed wind environments. Through detailed electromagnetic simulations, the effects of varying skew angles and air gap lengths were analyzed, revealing optimal configurations that significantly reduce cogging torque without compromising power output.

The results demonstrate that the designed DD-PMG is well-suited for decentralized renewable applications, including rural electrification, microgrids, and hybrid energy systems. The findings not only contribute to the improvement of wind generator technology but also offer a scalable solution for low-wind-speed regions.

Future work will involve prototype development, integration with advanced control electronics, and further refinement in thermal management and material selection to support large-scale deployment and smart grid compatibility.

REFERENCES

[1] Htun, Zin & Ya, Aung & Ma, Win. (2017). Design and Analysis of Low Speed Direct-Drive Permanent Magnet Generator for Wind Power Application.

[2] Cichowicz, Michał & Pilecki, Wojciech & Wardach, Marcin & Prajzendanc, Pawel & Cierzniewski, Kamil & Palka, Ryszard. (2023). Low-speed permanent magnet generator for use in a compact wind turbine. COMPEL - The international journal for computation and mat

[3] W. Ullah, F. Khan and S. Hussain, "A Novel Dual Rotor Permanent Magnet Flux Switching Generator for Counter Rotating Wind Turbine Applications," in IEEE Access, vol. 10, pp. 16456-16467, 2022

[4] Errami, Y. and Ouassaid, M. (2011), "Modelling and control strategy of PMSG based variable speed wind energy conversion system", International Conference on Multimedia Computing and Systems (ICMCS).

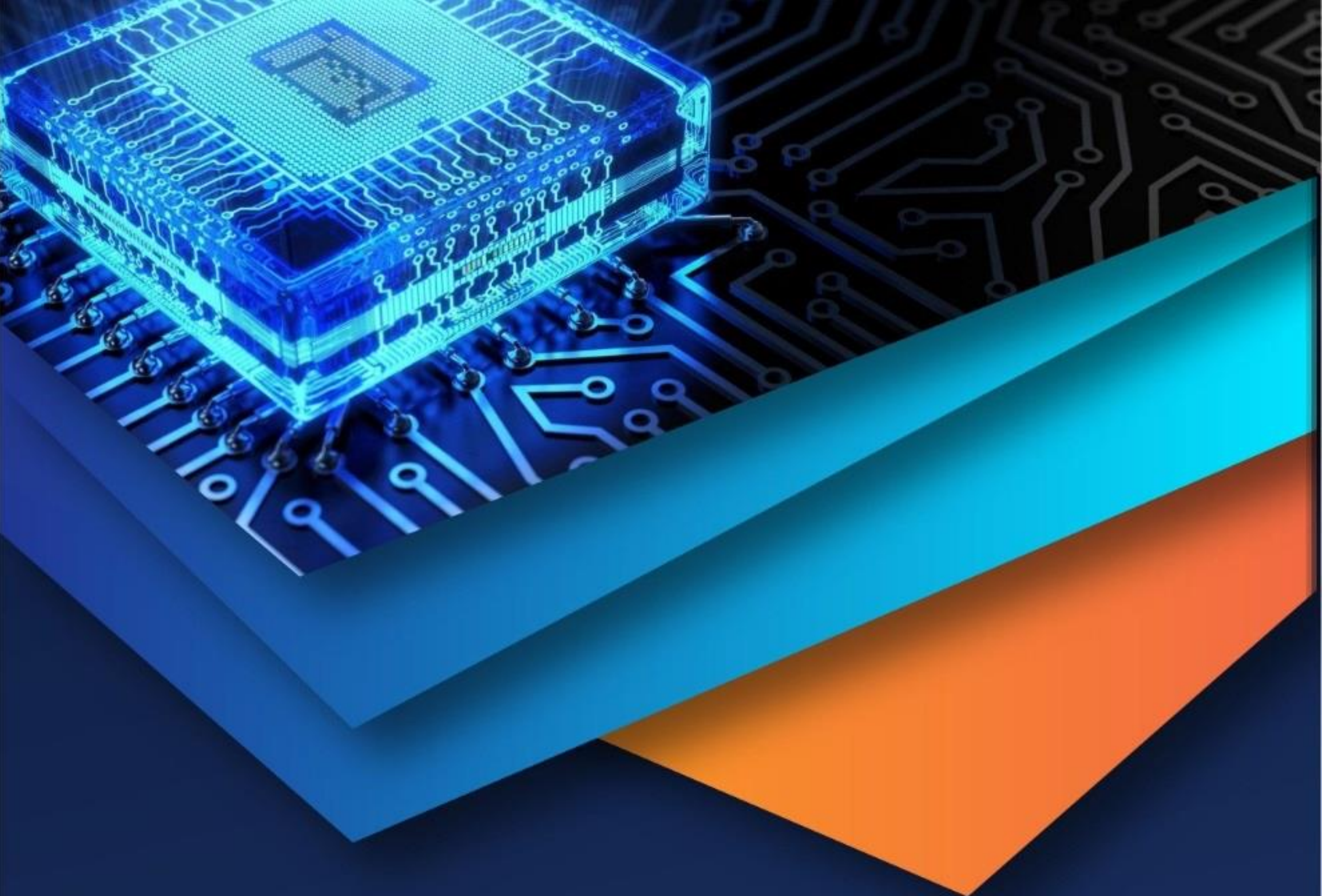
[5] Guo, T., Zhao, G., Zhao, Y., Cheng, R., Zhao, E. and Qi, C. (2011), "Torque simulation of wind turbine based on brushless DC motor", Transactions of the Chinese Society of Agricultural Engineering, Vol. 27 No. 5, pp. 111-116.

[6] WWEA. (2021). Accessed: Nov. 9, 2021. [Online]. Available:https://wwindea.org/information-2/statistics-news

[7] Apatya, Y.A., Subiantoro, A. and Yusivar, F. (2017), "Design and prototyping of 3-phase BLDC motor", 2017 15th International Conference on Quality in Research (QiR): International Symposium on Electrical and Computer Engineering, pp. 209-214.

[8] Cardenas, R., Ray, W. and Asher, G. (1995), "Switched reluctance generators for wind energy applications", Proceedings of PESC'95 – Power Electronics Specialist Conference, Vol. 1, pp. 559-564.8–1422, Mar. 2020.

[9] Carriveau, R. (2012), Advances in Wind Power, BoD – Books on Demand.



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