Experimental Investigation of Magnetic Gears for Multi-Rotor Wind Turbine

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***Abstract*—The increasing demand for renewable energy sources has sparked significant interest in innovative technologies that can enhance energy conversion efficiency. Among these, wind energy stands out as a viable alternative, with magnetic gears emerging as a promising solution to improve the overall performance of wind turbine systems. Traditional mechanical gearing systems often suffer from wear and inefficiency, leading to increased maintenance costs and reduced operational lifespan. In contrast, magnetic gears employ attractive and repulsive forces to transmit power without physical contact, minimising friction and mechanical degradation. This research will delve into the experimental investigation of magnetic gears tailored for a multi-rotor wind turbine applications, exploring their potential benefits, underlying principles, and comparative advantages over conventional gear systems. Furthermore, the findings aim to underscore the feasibility of integrating magnetic gearing technology into modern wind turbines, ultimately contributing to the advancement of sustainable energy solutions.**

Keywords: VAWT, Magnetic gears, TSR (Tip speed ratio), Wind Turbine, Renewable energy

I. INTRODUCTION

Wind energy has been one of the most important renewable energy source available from nature. There are many researches on wind power harnessing and electricity generation from large scale to mini scale turbine for multiple varied applications. Major study and research has been done for potential large scale applications including powering a grid, large backup source, power generation, etc. Energy generation for utilities in of small applications like running of vehicles, home utilities, and many more applications is not been much researched and is an area where developments can be made with achieving alternate source of energy in place of a conventional energy source. With mechanical power, much like in the past. Small WT is typically installed for minor production needs, rural locations, or residential applications. The possibility of modifying wind turbines to include HAWT and VAWT is being investigated in a research study. Vertical-Axis Wind Turbines (or VAWTs) have the main rotor shaft arranged vertically. One advantage of this arrangement is that the turbine does not need to be pointed into the wind to be effective, which is an advantage on a site where the wind direction is highly variable. It is also an advantage when the turbine is integrated into a building because it is inherently less steerable. Also, the generator and gearbox can be placed near the ground, using a direct drive from the rotor assembly to the ground-based gearbox, improving accessibility for maintenance. For the sake of this investigation, VAWT is used as small-scale wind turbine model is used and hub height is not considered as a factor to analyse performance. As explained below, a thorough literature review was conducted in order to get the concept and development.

This paper investigates wind turbine architectures employing magnetic gearing and multiple rotor configurations for enhanced power generation. Magnetic gears replace conventional mechanical transmission systems to facilitate contactless mechanical power transfer, thereby minimising frictional losses and mitigating mechanical wear. Furthermore, magnetic transmission enables the integration of multiple rotors, as demonstrated in this study, offering new avenues for efficiency optimization and system robustness.

The escalating demand for renewable energy sources has intensified research and development efforts in wind energy technology, with multi-rotor wind turbines emerging as a promising avenue for enhanced energy capture and efficiency (Liu et al., 2010). Multi-rotor systems, characterized by their array of smaller rotors, offer potential advantages over traditional single-rotor turbines, including increased power density, reduced structural loads, and improved scalability for diverse wind conditions (Siavash et al., 2019). However, the efficient integration and operation of these multiple rotors necessitate advanced power transmission mechanisms, with magnetic gears garnering significant attention as a potential alternative to conventional mechanical gearboxes (Gavali et al., 2021). Magnetic gears, which transmit torque through magnetic fields rather than direct mechanical contact, offer several compelling benefits, including inherent overload protection, reduced noise and vibration, minimal maintenance requirements, and the potential for higher reliability in harsh operating environments (Salameh et al., 2018). The exploration of magnetic gears in multi-rotor wind turbine applications necessitates a comprehensive understanding of their design principles, performance characteristics, and integration challenges, which this literature review aims to provide. Conventional wind turbine gearboxes have been identified as a significant source of failures and maintenance costs in wind energy systems (Arafa & Bedewy, 2010). The intricacies of gearbox systems, coupled with the non-stationary operating conditions typical of wind turbines, pose considerable challenges for fault diagnosis and condition monitoring (Castellani et al., 2020; Zhong et al., 2012). Magnetic gears are non-contact power transmission systems that use permanent magnets and magnetic fields to transmit torque between rotors. In wind turbines, they are particularly advantageous because they eliminate the need for lubrication, reduce maintenance, and provide high reliability in harsh environments (Wu et al., 2022) (Chumak et al., 2023). The use of multiple rotors in magnetic gears allows for the achievement of higher gear ratios and improved torque density, making them suitable for both small-scale and large-scale wind turbines (Moghimi et al., 2022) (Wang et al., 2022). Research has explored various multi-rotor configurations, such as triple-speed coaxial magnetic gears (TSCMGs), which consist of inner, middle, and outer rotors (Moghimi et al., 2022) (Moghimi et al., 2021). These configurations are designed to handle different torque levels and provide flexibility in wind turbine applications. For example, the TSCMG proposed in Paper 2 achieves a high gear ratio and torque density, making it suitable for high-power wind turbines. The arrangement of permanent magnets plays a significant role in the performance of magnetic gears. Halbach arrays, which are known for their ability to enhance magnetic field strength, have been widely used in magnetic gear designs ("Multi-Objective Optimisation Analysis of Magnetic Gear with HTS Bulks and Uneven Halbach Arrays", 2023; Zhan & Jing, 2023). Additionally, the use of spoke-type and consequent-pole arrangements has been explored to optimise torque density and reduce torque ripple (Wang et al., 2023) (Wang et al., 2022).

II. PROBLEM DEFINITION:

The efficiency, reliability, and operational lifespan of wind turbine systems are critically constrained by the limitations inherent to conventional mechanical gear transmissions. Mechanical gears, while effective in torque conversion, are susceptible to frictional losses, lubrication demands, material fatigue, acoustic noise, and catastrophic failure under overload conditions. These issues are exacerbated in small-scale and distributed wind energy applications, where maintenance access is limited and operational downtime significantly impacts energy yields. Magnetic gears, which facilitate torque transmission through contactless magnetic coupling, present a promising alternative by eliminating physical wear, offering inherent torque overload protection, and reducing acoustic emissions. However, despite their theoretical advantages and emerging interest in high-torque, low-speed applications, the empirical validation of magnetic gears within wind turbine systems remains limited. Multi-rotor wind turbines (MRWT) offer a structurally distributed and aerodynamically efficient approach to wind energy harvesting, capable of increasing energy capture per unit area while enhancing fault tolerance and modularity. Integrating magnetic gearing mechanisms into MRWT systems necessitates an in-depth understanding of magnetic flux interactions, gear stress distributions, torque transfer characteristics, and system-level dynamics under variable wind conditions. The present research undertakes an experimental investigation to characterise the mechanical and magnetic performance of magnetic gear systems implemented within a multi-rotor vertical-axis wind turbine configuration. The objective is to evaluate torque transmission efficiency, dynamic response, and structural integrity, thereby assessing the viability of magnetic gears as a core enabling technology for next-generation decentralised and resilient wind energy systems.

III. INTRODUCTION

The aim is to conceptualise, design, and fabricate a prototype magnetic gear system integrated into a multi-rotor vertical-axis wind turbine (MR-VAWT). This involves developing a system that leverages magnetic coupling for torque transmission, replacing traditional mechanical gearboxes to enhance efficiency and reduce maintenance.

A. Conceptual Design:

Multi-Rotor VAWT structures are designed to accommodate multiple rotors, ensuring synchronised operation and efficient torque summation through the magnetic gear system. Rotors for this research are designed using the 3d printing method. The rotor will accommodate the VAWT and act as magnetic gears. Two rotors are designed, one of which acts as the driver gear and will also accommodate the VAWT. The second rotor will be the driven gear upon which the output voltage will be measured. Magnetic Gear Configuration: The optimal arrangement of permanent magnets and ferromagnetic materials is done to achieve the desired gear ratio of 1:1.

B. Material Selection:

Permanent magnets are chosen due to their high energy density. Magnets like Neodymium-Iron-Boron (NdFeB) are used for their superior magnetic properties, ensuring compactness and efficiency. PLA (Polylactic Acid) is used to manufacture rotors using 3D printing method.

C. Fabrication & Assembly Process:

Prototype Manufacturing: 3d printing method and additive manufacturing techniques are used to fabricate rotors. Bar magnets are used to achieve the required effective magnetic coupling for magnetic transmission. A small-scale Vertical Axis Wind Turbine (VAWT) is used for the prototype of this experimental analysis. The turbine is assembled on the driver rotor, which also houses magnets that act as a magnetic gear. A DC generator is installed on the other end of the rotor. The generator of the driver gear is connected in series with the generator of the driven gear.

D. Testing and Validation:

Initial tests are conducted to measure torque transmission efficiency, magnetic flux distribution, and power output under controlled conditions. Controlled Trials: A Small prototype is tested under controlled conditions, and the output voltage is measured for both rotors connected in series

Designing and creating a vertical-axis wind turbine (VAWT) that can capture wind energy produced and convert it to electrical energy using magnetic gears and two different DC generators is the main goal of this project. The system seeks to lessen dependency on the vehicle's battery or the traditional fuel-driven alternator by using wind energy as an extra power source. This can result in increased range efficiency for electric or hybrid vehicles and better fuel economy for fuel-powered vehicles. The designed system aims to mitigate reliance on centralised electrical grids and conventional fossil fuel-based energy sources by harnessing ambient wind energy through an integrated multi-rotor vertical-axis wind turbine (MR-VAWT) equipped with magnetic gear transmission. By operating as a decentralised, supplemental energy generator, the system captures kinetic wind energy that would otherwise remain untapped, particularly in urban, semi-urban, and roadside environments where conventional large-scale wind turbines are impractical. The additional power generated by the system can significantly augment the supply to electric vehicle (EV) charging stations, reducing dependence on grid electricity and enabling greener transportation infrastructure. By providing clean energy directly at the point of use, the system facilitates a broader adoption of electric mobility solutions while reducing strain on centralised generation assets. Furthermore, the system offers distributed power generation capabilities for small and medium-sized enterprises (SMEs), especially in industrial, peri-urban, and remote areas where grid reliability is often inconsistent. Access to an on-site renewable energy source improves energy security, reduces operational costs, and contributes toward organisational sustainability goals. The MR-VAWT system also integrates naturally into microgrid architectures, enabling localised energy networks such as community power hubs, institutional campuses, or commercial complexes to achieve partial autonomy. By coupling magnetic geared turbines with energy storage systems or smart inverters, microgrids can enhance their resilience and operational flexibility. Finally, the decentralised nature of the proposed system contributes to improved resilience against grid outages. By maintaining a local renewable energy source, critical operations such as emergency services, communication systems, and essential infrastructure can continue to function during broader power disruptions, thereby increasing the reliability and robustness of the overall energy ecosystem. Through these multifaceted applications, the MR-VAWT with magnetic gears advances the concept of strategically distributed energy resources, facilitating a hybrid model where traditional grid supply is supplemented and strengthened by localised renewable generation, ultimately improving system efficiency, sustainability, and resilience.

IV. WIND ENERGY GENERATION CAPACITY

The energy contained in the wind is its kinetic energy.

Hence,

$$Kinetic\ energy = \frac{1}{2} \times m \times V^2 \quad (1)$$

Where m is in kilograms and V is in metres per second (m s-1) and mass of air is given by, $(m)\ air = Air\ density \times area \times velocity$

$$m = \rho \times A \times V \quad (2)$$

Therefore, substituting in the above equation (1) of kinetic energy, we get,

$$Kinetic\ energy\ per\ second = 0.5 \times \rho \times A \times V^3\ (joules\ per\ second) \quad (3)$$

Where ρ is in kilogram per cubic meter (kg m^{-3}), A is in square metres (m^2), and V is in meters per second (m/s)

As energy per unit time is equals to power, the power in the wind is P (watts) =Kinetic energy in the wind traversing the circular ring per second (joules per second), that is:

$$P = 0.5 \times \rho \times A \times V^3 \quad (4)$$

The main relation that is apparent from the above calculations is that the power in the wind is proportional to:

- The density of air
- The area through which the wind is passing (i.e through a wind turbine rotor
- The cube of the wind velocity
- Power Consumption of Electrical Components

TABLE I. VARIOUS ELECTRICAL COMPONENTS THAT USE ELECTRICITY ARE AS FOLLOWS:

Sr. no	Device Electrical Load	Typical Power Consumption (W)	Remark/Application Context
1	LED Lighting (5 bulbs @ 10W each)	50	Basic residential or rural area illumination
2	Ceiling Fan (single unit)	60–80	Indoor ventilation, continuous or intermittent use
3	Mobile Phone Charging (5 devices)	25	Community charging station or home use
4	Wi-Fi Router (Home/Office type)	8–15	Off-grid internet access or IoT communication
5	DC Water Pump (small-scale irrigation)	100–250	Suitable for agricultural fields or garden watering

V. DESIGN AND DEVELOPMENT

Figure 1 shows the project's SWT assembly. The science and study of the physical principles governing how things behave in air flows and the forces generated by these flows is known as aerodynamics. The shape of the aerodynamic profile is decisive for blade performance. Even minor alterations in the shape of the profile can greatly alter the power curve and noise level. Therefore, a blade designer does not merely sit down and outline the shape when designing a new blade. A vertical axis wind turbine is used in this project, considering the amount of space utilised by a Horizontal axis wind turbine. Also, special mechanisms are required to direct the HAWT towards the direction of the wind. Magnetic gears are designed with a ratio of 1:1 with trial and error to avoid gear slipping. Neodymium magnets are arranged in pole pairs as gear teeth. Cubicle metal fillings are used to compensate for the flux gap, which avoids gear slipping at higher RPM.

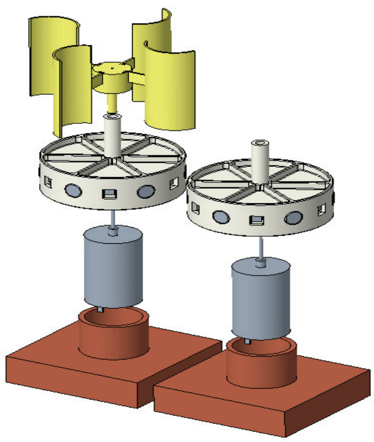

Fig. 1. Exploded view of Wind turbine prototype

Numerical Analysis of Vertical Axis Wind Turbine

Airflow Analysis of VAWT (CFD Analysis)

A simplified geometry was created to reduce the calculation time of the CFD solver. Geometry was created in Creo Parametric and then exported to IGES format. The model was then added to an Ansys Workbench project and the fluid flow module of Fluent. Mesh metrics were updated for mesh quality, aspect ratio, and Skewness to ensure the smooth running of the Solver. Pressure-based solver type was selected for this simulation. The K-epsilon turbulence model is used in this simulation with standard wall functions. Similarly, Cell zone conditions, boundary conditions were applied. A mesh interface was applied between the two main domains, hub domain and far-field domain. Solution method were applied using Coupled scheme for pressure-velocity coupling. Tolerance of 1e-06 is set for residuals and a monitor is set for moment coefficient. Hybrid initialization is used for Solution Initialization of this problem. 2000 iterations were done to obtain solution convergence. Quantitative values such as velocity values, power of turbine, etc., were visualized in CFD-post.

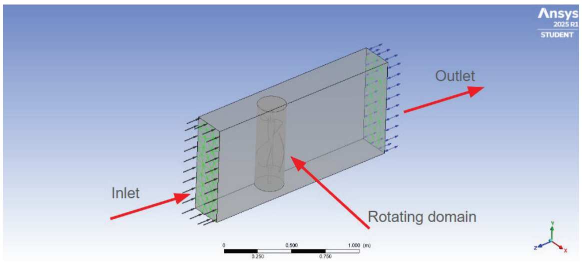

Fig. 2. Boundary conditions for CFD analysis of VAWT

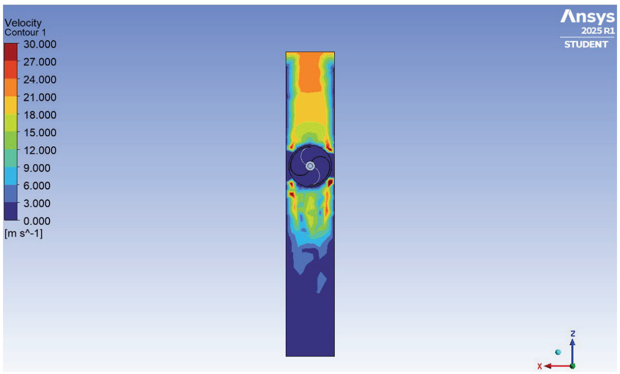

Fig. 3. Velocity in stationary frame, Circumferential Contour

Velocity visualisation in a stationary frame illustrates the air flow through the inlet and its interaction with the turbine.

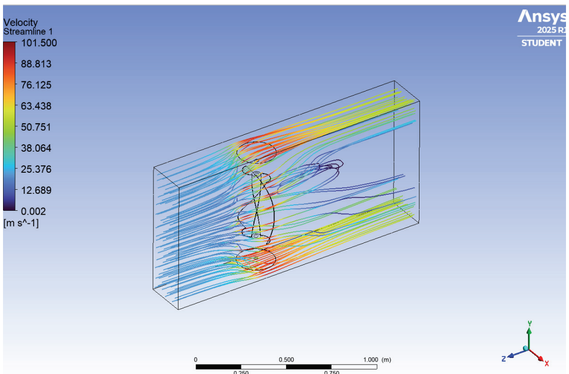

Fig. 4. Velocity streamline visualisation

The streamlines illustrate the path of the airflow and the velocity variations in the domain. At low velocities, the streamlines are less dense and exhibit gradual acceleration around the turbine, with minimal turbulence. At 15 m/s, the airflow becomes more streamlined, showing increased velocity gradients near the turbine. The streamlines demonstrate higher density and stronger curvature, indicating intensified aerodynamic effects, such as higher velocities and more noticeable wake regions.

Manufacturing, assembly

- Turbine Blade (Polypropylene)
- Rotor Manufacturing (PLA- 3D printing)
- Holder Manufacturing (PLA- 3D printing)

Assembly Process

Turbine Attachment: Turbine blades are assembled to the rotor.

Rotor and magnets: Rotors are integrated with magnets in a pole pair arrangement to form magnetic gears

Motor Mounting: The Generator is assembled between the holder and rotor assembly and connected to the load.

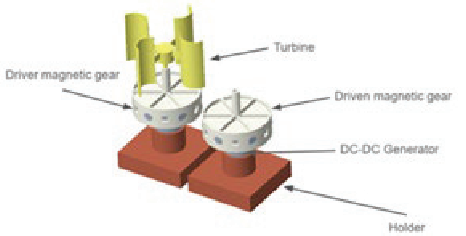

Fig. 5. Final assembly of Magnetic Gear Operated Wind Turbine

System Testing and Validation:

Testing the prototype in controlled conditions to measure power output and overall efficiency. To test how much voltage blades can produce, an external source of wind was needed. An Air Blower was used to depict this external wind source. The blades' rpm was noted using a non-contact digital tachometer. At different rpms, the voltage produced and measured using a digital multimeter was also noted.

To evaluate the performance of the fabricated magnetic geared multi-rotor wind turbine prototype, a controlled experimental setup was developed for consistent and replicable testing. Due to the unpredictable nature of ambient wind, an axial-flow industrial air blower (rated output velocity ~15 m/s) was used as a stable artificial wind source to simulate varying wind conditions in a laboratory environment.

The prototype was mounted on an adjustable test rig with a fixed base to align the wind stream perpendicularly to the turbine's vertical axis. The alignment was verified using a laser level to minimise angular deviation that could affect rotor performance.

Rotational speed (RPM) of the turbine blades was measured using a non-contact digital laser tachometer (UNI-T UT372), with a resolution of 1 RPM and a stated accuracy of ±(0.05% + 1 digit). Before experimentation, the tachometer was calibrated using a motor with a known reference RPM validated via the stroboscopic method. A reflective strip was applied to the rotor hub for consistent signal reflection.

Voltage output was recorded for both the driver and driven rotors using a True RMS digital multimeter (Fluke 115), with a voltage measurement accuracy of ±0.5% and a resolution of 0.01 V. Measurements were taken at 5-second intervals across a range of rotor speeds to account for transient fluctuations. The multimeter was calibrated using a reference voltage source before the start of testing.

The outputs of the two rotors were connected in series, and the combined voltage was measured to evaluate the additive behaviour of the dual-rotor configuration. Readings were repeated thrice for each RPM level to ensure repeatability.

The combined uncertainty for voltage measurements was estimated at ±0.53%, while RPM measurements carried an uncertainty of ±0.06%. These uncertainties are within acceptable margins for experimental validation at prototype scale and were used to compute error bars in result plots.

This enhanced testing protocol provided reliable empirical data on the turbine's power generation capacity, torque transmission efficiency, and magnetic coupling stability under simulated wind conditions.

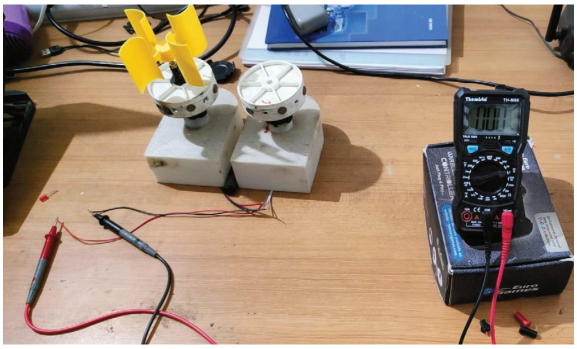

Fig. 6. Setup of SWT for testing

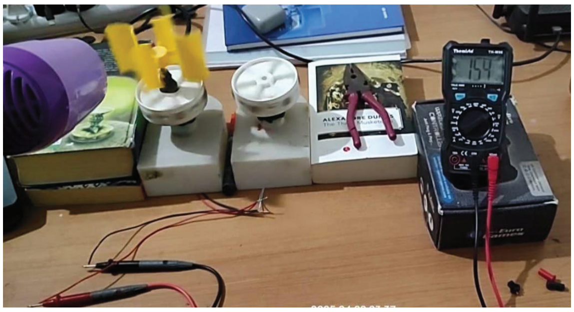

Fig. 7. Actual Testing of SWT

VI. RESULTS AND DISCUSSION

TABLE II. TEST SETUP READINGS

Wind Velocity (m/sec)	Turbine 1 RPM	Turbine 2 RPM	Voltage (V)	Current (A)	Power (W)
9	993	924	11	2.3	25.3
12	1486	1424	17.3	3.6	62.68

The experimental results validate the Magnetic Gear-operated Vertical Axis Wind Turbine (VAWT) as a viable alternative for low-maintenance, distributed wind energy systems. Performance metrics demonstrate a strong alignment with theoretical models of wind energy conversion and showcase the reliability of magnetic torque transmission at varying wind velocities.

A. Power Output and Wind Velocity Correlation

As expected from the theoretical wind power model, P∝v3, electrical output increased exponentially with wind velocity. At 9 m/s, the turbine operated at 900 RPM, producing 25.3 W. At 12 m/s, the speed increased to 1450 RPM, yielding 62.28 W — a 146% increase in power for a 33% rise in wind velocity. This confirms the system's ability to exploit increased wind energy effectively while maintaining efficient transmission through magnetic gearing.

B. Magnetic Gear Efficiency and Gear Ratio Validation

The magnetic gear set, designed with a 1:1 ratio, exhibited high rotational fidelity between the input (driver) and output (driven) rotors. At 993 RPM input, the output achieved 924 RPM (93.0% efficiency). At 1486 RPM, the output reached 1424 RPM (95.8% efficiency). This is competitive when compared to traditional mechanical spur gear systems, which typically exhibit 92–96% efficiency at similar scales but suffer from wear, vibration, and maintenance overheads.

Moreover, the absence of physical contact eliminated gear backlash and noise, contributing to smoother operation, particularly desirable in low-noise applications.

TABLE III. MAGNETIC VS MECHANICAL GEAR COMPARISON

Parameter	Magnetic Gear System	Mechanical Gearbox
Transmission Efficiency	93–96%	92–96%
Maintenance Requirements	Minimal	High (lubrication, wear)
Acoustic Noise	Very Low	Moderate to High
Overload Protection	Inherent Slip	Typically Absent
Torque Ripple (Slipping)	Low	Moderate
Suitability for Urban Installations	High	Limited (noise, maintenance)

This comparison highlights that while raw efficiency may be comparable, lifecycle and operational advantages favour magnetic gearing for small to medium-scale renewable systems.

C. Limitations and Low Wind Speed Performance

At low wind speeds (3 m/s), the turbine exhibited significantly reduced performance, producing only marginal power sufficient for ultra-low-power devices. This can be attributed to:

- Lower aerodynamic efficiency of the blades at low Reynolds numbers,
- Increased relative magnetic drag at low input torques,
- Inertia of the rotor system, which limits responsiveness at lower wind forces.

These findings suggest the need for improved blade profiles, higher blade solidity, or a variable magnetic coupling strategy to reduce starting torque requirements. Additionally, integrating a hybrid gear configuration or adaptive power electronics may further expand the effective operating range.

D. Application Scope and Future Outlook

At higher wind velocities (above 8 m/s), the turbine consistently delivered strong performance, making it ideal for use in coastal, industrial, or elevated urban zones. The compact design, low maintenance, and modularity make the system a strong candidate for powering off-grid sensor networks, microgrid infrastructure, or EV charging ports in windy environments.

VII. CONCLUSION

This study presents an experimental investigation of a Magnetic Gear-operated Vertical-Axis wind Turbine (VAWT) designed for small-scale, distributed energy generation. The prototype demonstrated reliable performance under controlled wind conditions, with results confirming the system's ability to convert wind energy into electrical power effectively. Performance improved significantly with increased wind velocity, reflecting the theoretical cubic relationship between wind speed and power output.

At a wind speed of 12 m/s, the turbine achieved a maximum power output of 62.28 W, demonstrating its potential to support low-to-medium load applications, particularly in environments with consistent wind availability. The magnetic gear system successfully transmitted torque with minimal losses, achieving rotational efficiency levels exceeding 93% while eliminating mechanical wear, reducing acoustic emissions, and improving operational reliability.

However, the prototype faced certain limitations during experimentation. At lower wind speeds (e.g., 3 m/s), power output was marginal, primarily due to suboptimal blade aerodynamics and the relatively high starting torque required to overcome system inertia. Additionally, minor alignment challenges during the magnetic gear assembly introduced initial flux leakage, which was mitigated through iterative adjustments. It is also important to note that the prototype components were fabricated using 3D printing, primarily for rapid prototyping and design flexibility. While this approach enabled quick iteration and assembly, it may have introduced performance limitations due to surface roughness, dimensional tolerances, and material rigidity, particularly affecting blade aerodynamics and magnetic gear alignment. These effects are expected to diminish in future versions fabricated with precision-machined or injection-molded components.

Despite these challenges, the results confirm that magnetic gearing offers a viable alternative to conventional mechanical transmissions, especially in applications requiring silent, maintenance-free operation. The system shows strong potential for deployment in urban microgrids, EV charging stations, and off-grid infrastructure, where modularity and reliability are essential.

Future research will focus on enhancing low-speed performance, integrating Maximum Power Point Tracking (MPPT) algorithms, and scaling the architecture for multi-stage turbine arrays. With continued refinement, the Magnetic Gear VAWT can serve as a key enabler for decentralised, clean energy generation across diverse environments.

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