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Design of a wind system operating with an air trap system

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Abstract:

This study aims to improve the performance of horizontal-axis wind turbines (HAWTs) under low wind speed conditions by designing and fabricating a turbine with an air trapping system (cave system) using a conical metal structure to direct and accelerate airflow towards the turbine. Field tests at a wind speed of 4 meters per second showed a maximum power output of 12.63 W, with a power factor of 0.30 and a tip speed ratio of 3.20. The power output increased to 16.66 W with a power factor of 0.35 when the air trapping system was used, demonstrating the effectiveness of the system in improving turbine performance. However, the torque values at each wind speed are higher when the air concentrating system is in place than when it is not in place. At a wind speed of 3.5 m/s, the torque with the system is approximately (1-1.5) Nm higher than without it. This increase is due to the effect of the air concentrating system in the airflow onto the turbine blades, increasing the intensity and energy of the wind directed at the turbine.

Key words : Wind turbine, air trap system, turbine torque, power factor .

تصميم منظومة رياح تعمل بنظام الحصر الهوائي

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مستخلص:

تهدف هذه الدراسة إلى تحسين أداء توربينات الرياح ذات المحور الأفقي (HAWTs) في ظل ظروف سرعة الرياح المنخفضة من خلال تصميم وتصنيع توربين بنظام الحصر الهوائي (نظام الكهوف) باستخدام هيكل معدني مخروطي لتوجيه وتسريع تدفق الهواء نحو التوربين. أظهرت الاختبارات الميدانية بسرعة رياح تبلغ 4 أمتار في الثانية أقصى خرج للطاقة يبلغ 12.63 واط، مع معامل قدرة يبلغ 0.30 ونسبة سرعة طرفية تبلغ 3.20. زاد خرج الطاقة إلى 16.66 واط مع معامل قدرة يبلغ 0.35 عند استخدام نظام الحصر الهوائي، مما يدل على فعالية النظام في تحسين أداء التوربين. ومع ذلك، تكون قيم عزم الدوران عند كل سرعة رياح أعلى عندما يكون نظام الحصر الهوائي في مكانه مما هو عليه عندما لا يكون في مكانه. عند سرعة رياح تبلغ 3.5 متر/ ثانية، يكون عزم الدوران مع النظام أعلى بحوالي (1.5−1) نيوتن متر منه بدونه. وتأتي هذه الزيادة نتيجة تأثير نظام تركيز الهواء في تدفق الهواء على شفرات التوربين، مما يؤدي إلى زيادة شدة وطاقة الرياح الموجهة إلى التوربين.

الكلمات المفتاحية : توربين الرياح ، منظومة الحصر الهوائي ، عزم التوربين ، معامل القدرة (C_p).

1-Introduction

Amid growing environmental and economic challenges, the shift toward renewable energy sources has emerged as an indispensable strategic option for achieving sustainable development. It has become widely accepted that reliance on renewable energy sources such as solar, wind, hydroelectric, and biomass energy is a fundamental pillar in energy transition strategies for the near future[1]. The substantial progress in photovoltaic and third-generation solar cell technologies has enhanced the efficiency of solar energy utilization, while continuous improvements in wind turbine designs, particularly large offshore turbines, have expanded the scope of wind energy use[2]. In Nevertheless, current trends indicate an accelerated pace of energy transition, supported by technological advancements, cost reductions, and growing global awareness of the importance of shifting toward more sustainable energy systems[3,4].

In this context, wind turbines are among the most prominent technological solutions that have effectively contributed to reducing dependence on fossil fuels. Since the development of the first commercial turbine in the 20th century, this technology has made significant progress, making it an effective means of producing clean electricity. Wind turbine efficiency has notably increased over the past decade due to technological innovations affecting various turbine components. One of the most prominent developments has been the increase in turbine blade diameters, with turbines now featuring blades with diameters of 150 meters or more, enabling them to generate large amounts of energy even at low wind speeds. Furthermore, blade design is a crucial element in improving wind turbine efficiency. Composite materials like carbon fiber have facilitated the design of longer and more durable blades, increasing the turbines' ability to generate higher energy output. Significant improvements have also been made in the aerodynamics of these blades using advanced computational techniques, carefully analyzing airflow to determine geometric shapes that enhance aerodynamic efficiency.[5, 6].

In 2019, Magade Pramod B and others conducted an experimental study to develop wind turbines aimed at improving power generation. A horizontal turbine was designed with modifications to the number of blades and rotor diameter, concluding that a rotor with a 90 cm diameter and five blades could generate 40 watts at a wind speed of 10 m/s. They also found that it was possible to increase the generated power to 60 watts at the same wind speed by increasing the rotor diameter to 1.20 meters and increasing the number of blades to eight[7]. In 2021, Dr. Ravinder Kumar and others studied a horizontal wind turbine blade made of aluminum and epoxy to improve turbine efficiency and achieve higher power production at a wind speed of 10 m/s. The results showed good performance and favorable values for the lift and drag coefficients at an attack angle of 19.9°, and it was found that turbine efficiency depends mainly on the geometric design of the rotor blade and the TSR coefficient[8]. In this research paper, the design of a confined air wind system and a comparative study of a wind system with and without confined air will be highlighted, with calculations to measure the effect of ambient conditions on system performance, output power, and efficiency.

2- Theoretical Equations

The power coefficient (Cp) is a metric used to evaluate the efficiency of converting wind energy into mechanical energy in wind turbines. It is denoted by the symbol (Cp) Equation for the Power Coefficient (C_p):[9]

$$C_p=\frac{P_{disk}}{1/2A\rho {u^2}_{\infty}}=4a(1-a)^2 \quad ...... (1)$$

Turbine torque is the mechanical force generated by the turbine as a result of the rotation of its blades due to the impact of the wind. It is defined as the torque produced by the wind acting on the blades.

Equation for the Turbine Torque:[10]

$$T = 2\rho A a(1-a)u^2 \quad .... (2)$$

Where:

$$a = \frac{v1-v2}{v1} \quad .... (3)$$

3. Experimental Part

The practical component of this study is divided into two main sections:

3.1 Wind Turbine Construction

Initially, a horizontal-axis wind turbine was designed and constructed, consisting of six blades, each 55 cm in length. The width of each blade begins at 13 cm at the root (where it connects to the mounting disk) and gradually decreases towards the tip. The turbine tower was fabricated using a circular iron tube, 2 meters in height and 2 cm in diameter, capable of supporting varying loads. The tower was firmly anchored to the ground to minimize vibrations and structural movement during turbine operation and to maintain stability under different wind speeds.

A bearing was installed at the top of the tower to allow the turbine to align with the wind direction during operation. This alignment is maintained by the yaw mechanism, which keeps the rotor oriented opposite to the wind direction with a yaw angle of 0°, controlled by a tail vane.

The turbine base, located atop the tower, was made of iron in the form of a circular plate with a diameter of 10 cm and a thickness of 2 cm. It includes four peripheral holes for mounting and a central opening to accommodate the tower. A slip ring assembly was affixed to the upper side and welded to the yaw bracket, allowing free rotation. This slip ring consists of three insulated copper rings that transmit electrical current from the stator (coils) to the external load. The rings are mounted on a solid steel shaft (2 cm diameter, 10 cm length) supported by two bearings and aligned horizontally.

The rotor disk, made of aluminum (15 cm diameter, 2 cm thickness), is centrally mounted on the shaft and drilled with twelve holes. Each pair of holes is used to secure a single blade. The blades were fabricated from 3 mm thick plastic tubing, chosen for its low weight, durability, and water resistance. The blades are capable of slight deformation under high wind loads. The blade width gradually decreases from 13 cm at the root to 3 cm at the tip, with a twist angle ranging from 20° at the root to 2° at the tip.

The tail vane, made of lightweight aluminum (50 cm length, 24 cm width, 2 mm thickness), is connected to a conical housing that encloses the generator, providing protection from environmental damage. The tail helps maintain a yaw angle of 0° relative to the wind direction.

The generator is an axial flux type with permanent magnets, suitable for a range of wind speeds. It was constructed using insulated copper coils arranged into 36 windings, each consisting of 400 turns of 0.25 mm diameter wire. The stator comprises laminated iron to reduce eddy current losses, with slots for coil placement. The generator is configured in three phases with twelve permanent magnets. Mechanical power is transmitted directly from the blades to the generator via the shaft, causing the rotor (containing the magnets) to rotate and generate a time-varying magnetic field, which induces an electric current through the slip rings.

Figure (1) : Fully assembled wind turbine.

3.2 Wind Concentrator System

In the second phase, a wind concentrator system was designed and fabricated. The base was made from lightweight square-section iron bars (¾)inch ≈ 19 mm), selected for their strength and ease of transport. The base includes four legs: two front legs (adjacent to the system's larger diameter) measuring 95 cm in length, and two rear legs (adjacent to the smaller diameter) measuring 125 cm. All legs were anchored to the ground to enhance structural stability and reduce vibration under high wind conditions.

The concentrator frame was constructed in two stages. First, two circular rings were fabricated — a front ring with a 2.5 m diameter and a rear ring with a 1.5 m diameter. These were connected by welding thirteen iron rods, each 96 cm long, forming a 1-meter-long conical tunnel.

The entire frame was covered with 0.42 mm thick galvanized steel sheets, fastened with screws.

The wind turbine was positioned inside the concentrator system, near the smaller rear ring, at a depth of 90 cm. A clearance of 5 cm was maintained between the blade tips and the inner surface of the concentrator to prevent contact and friction. Figure (2) shows the air confinement system.

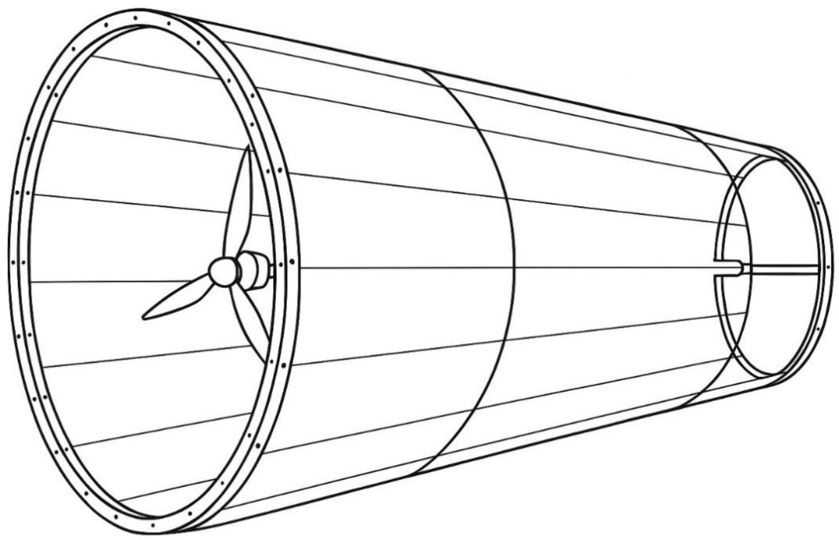

Figure (2): Air confinement system.

After completion of the system fabrication, the turbine was installed inside the concentrator tunnel near the rear end (narrow diameter), as illustrated in Figure (3). This configuration aims to direct and accelerate airflow toward the turbine rotor, thereby enhancing aerodynamic performance.

Field measurements were conducted under identical conditions for both scenarios: (1) the standalone turbine, and (2) the turbine installed within the concentrator system. Wind speed upstream and downstream of the turbine was measured using an anemometer. The rotational speed (RPM) was recorded using a tachometer, and electrical parameters (voltage and current) were measured using an avometer. Based on these data, the mechanical and electrical performance of the wind turbine was evaluated in both configurations.

Figure (3):. Final configuration of the integrated system.

4- Results

1-4 Power Coefficient (C_p) and Wind Speed

The power coefficient (C_p) was calculated using Equation (1) for the wind turbine in two conditions: without the concentrator system and with the concentrator system, using the same wind speeds, as shown in Table (1). It was observed that the power coefficient increases with increasing wind speed. Figure (4) illustrates the effect of installing the air concentration system on the power coefficient (C_p) of the wind turbine at various wind speeds. By comparing the performance before and after the installation of the system, a noticeable increase in the power coefficient values was clearly observed after the air concentration system was implemented. The values increased at every wind speed, which can be attributed to the role of the concentrator system in directing and accelerating the airflow toward the turbine. This system functions by concentrating the wind and increasing its density at the turbine's inlet, thereby increasing the amount of kinetic energy available for conversion into mechanical energy. Furthermore, the system's design helps reduce dispersion and air loss around the turbine's perimeter, thus improving operational efficiency and enhancing the energy extraction rate from the wind. This result has significant practical implications, indicating that turbine performance can be improved through relatively simple modifications to their surrounding environment without altering their internal components or increasing their physical dimensions. In summary, the air concentration system effectively enhanced the wind turbine's efficiency by improving the wind flow conditions, representing a qualitative advancement in the design of small- and medium-sized wind turbine systems, particularly in low to medium wind speed environments.

Table (1): Wind Speed and Power Coefficient

wind speed(m/s)	Power factor before installing the system (watt)	Power factor after system installation (watt)
2.75	0.25	0.30
3	0.27	0.32
3.5	0.29	0.33
4	0.30	0.35

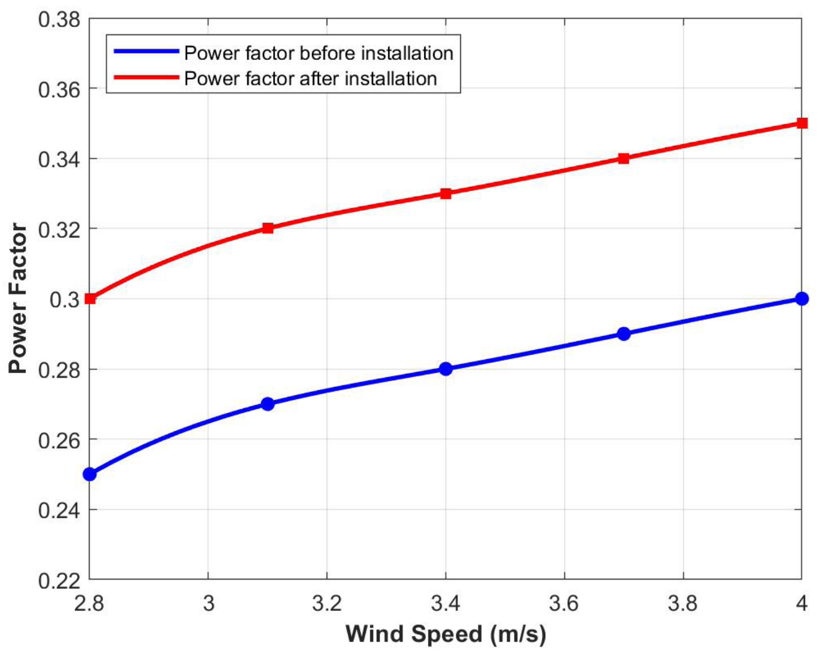

Figure (4): Relationship between Wind Speed and Power Coefficient

2-4 Turbine Torque and Wind Speed

Turbine torque refers to the rotational force generated by the turbine as a result of the airflow impacting its blades. It is expressed in Newton-meters (N·m) and serves as a measure of the turbine's capability to produce rotational motion around its axis. The torque was calculated using Equation (2) and is presented in Table (2). Figure (5) depicts the relationship between wind speed (m/s) and turbine torque (N·m) in two cases: without the air concentrator system and with the air concentrator system. A visual analysis of the data reveals that the turbine torque increases progressively with increasing wind speed in both cases. This behavior is physically expected, as wind energy increases with the cube of the wind speed. However, it is notably evident that the recorded torque values at each wind speed are higher when the air concentrator system is in place compared to when it is absent. For instance, at a wind speed of 3.5 m/s, the torque with the system is approximately 1 to 1.5 N·m higher than without it. This increase is primarily attributed to the effect of the air concentrator system in focusing the airflow onto the turbine blades, thereby increasing the density and energy of the wind directed at the turbine. In conclusion, the use of an air concentrator system effectively enhances the performance of the wind turbine by increasing the generated torque, thanks to the greater concentration of wind energy directed toward the turbine. This reinforces the technical feasibility of using such systems to improve the efficiency of wind energy production.

Table (2): Turbine Torque and Wind Speed

Wind speed (m/s)	Turbine torque without system (N.m)	Turbine torque with system (N/m)
2.75	4.72	5.05
3	5.62	6.09
3.5	7.5	8.40
4	10.18	10.92

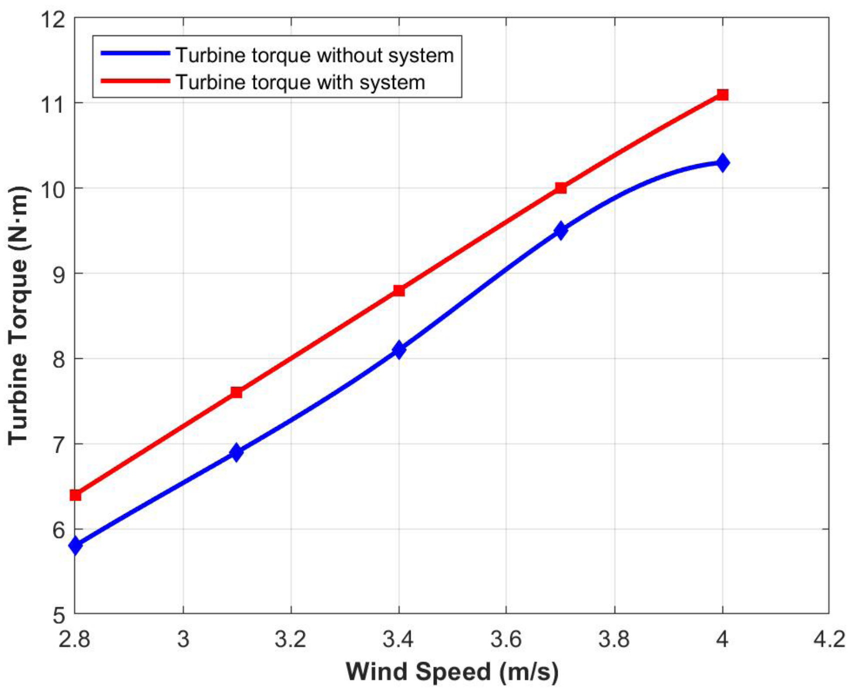

Figure (5): Turbine Torque vs. Wind Speed

5- Conclusions

The results of this study demonstrate that integrating the horizontal axis wind turbine with the air entrapment system leads to a significant improvement in performance at low wind speeds. The generated power increased by approximately 32%, along with enhancements in the power coefficient, rotational speed, and tip speed ratio. This improvement is attributed to the system's effectiveness in concentrating the airflow and reducing losses, making the proposed configuration suitable for deployment in areas with limited wind resources.

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