The effect of the number of NACA 4412 airfoil blades on the performance of a horizontal axis wind turbine

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ABSTRACT

This work reports an experimental investigation of the effect of blade number on the performance of a small-scale horizontal-axis wind turbine (HAWT) using NACA 4412 airfoil blades. Two turbine prototypes (one with 7 blades and one with 9 blades) were fabricated and tested under controlled wind speeds (3.4–6.0 m/s). The turbine outputs were measured using INA219 current/voltage sensors and a TCRT5000 rotations per minute (RPM) sensor interfaced to an Arduino-based system for real-time data acquisition. Results show that the 9-blade turbine consistently generated higher electrical power and achieved a higher power coefficient than the 7-blade design. For example, at 3.4 m/s the 7-blade turbine produced about 0.0297 W versus 0.0471 W for the 9-blade turbine. The peak power coefficient reached ≈0.198 for the 9-blade rotor (vs. ≈0.195 for 7 blades) at the same wind speed. Sensor calibration indicated high accuracy (errors <1.2%), confirming the reliability of the measurements. These findings suggest that, for the tested design, increasing the number of blades improves small-HAWT performance. The developed wireless monitoring system and experimental results provide guidance for optimizing blade count in future small turbine designs.

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1. INTRODUCTION

Modern horizontal-axis wind turbines (HAWTs) commonly utilize three-blade rotor configurations as a practical balance between aerodynamic efficiency, mechanical stability, and manufacturing cost [1]-[4]. While two-blade rotors are capable of higher rotational speeds, they typically suffer from increased vibration, acoustic noise, and reduced operational smoothness. Conversely, adding more blades can improve starting torque and reliability, especially in low-wind scenarios, but also introduces greater aerodynamic drag and increased material costs [5]-[7]. Several studies have demonstrated that blade number significantly affects turbine performance across different wind regimes. For instance, a field study conducted in Indonesia revealed that three-blade rotors perform better at wind speeds below 5 m/s, while rotors with more than three blades are advantageous at wind speeds above 7 m/s [8]-[11].

Numerous experimental investigations have sought to characterize the performance implications of blade number in small-scale HAWTs. Bakırcı *et al*. [12] conducted wind tunnel tests comparing 2-, 3-, and 6-blade rotors, concluding that both blade count and blade twist play critical roles in determining the power coefficient of the turbine. Several other studies [13]-[16] have supported this observation. Widiyanto *et al*.

[13] further showed that increasing the number of blades enhances torque output at low speeds but reduces the maximum tip-speed ratio, thereby affecting high-speed efficiency, in line with additional reports [17]-[20]. Similarly, Kalyanraj *et al*. [21] found that a three-blade rotor achieved higher rotational speeds compared to a five-blade rotor under identical wind conditions, while Clavijo-Camacho *et al*. [22] reported that additional blades can increase the power output of small turbines [23]. Collectively, these studies highlight a fundamental trade-off: more blades favor low-speed energy capture, whereas fewer blades optimize high-speed efficiency.

In addition to rotor geometry, airfoil selection plays a critical role in turbine performance. The NACA 4412 airfoil is frequently chosen in small wind turbine applications due to its favorable aerodynamic properties, particularly its high lift-to-drag ratio under low Reynolds number conditions [24]-[26]. Wen *et al*. [27], Reddy and Bhosale [28] demonstrated that this airfoil achieves a maximum lift coefficient of approximately 1.92 at a moderate angle of attack, making it well-suited for low-speed wind environments. Building on these findings, the present study evaluates the effect of increasing blade number in small-scale HAWTs using standardized NACA 4412 blades [10], [29]. Two rotor configurations (7-blade and 9-blade) were designed and tested under variable wind conditions. A real-time monitoring system, employing INA219 and TCRT5000 sensors, was integrated to capture voltage, current, and RPM data.

2. METHOD

Two HAWT prototypes with identical configurations—except for blade count (7 vs. 9)—were constructed using NACA 4412 blades, a 0.5 m rotor diameter, and a 12 V DC permanent-magnet generator. Mounted on a rigid 2.2 m×0.65 m frame with a 0.5 m hub height, both turbines were tested using two 16″ axial fans generating wind speeds between 3.4 and 6.0 m/s, regulated by a dimmer-controlled voltage source. Electrical output (voltage and current) was measured using an INA219 sensor, while rotational speed was captured via a TCRT5000 optical sensor, both interfaced to an Arduino Mega 2560 and wirelessly transmitted via an ESP32 module to a remote server. Real-time data were displayed on a thin-film transistor liquid crystal display (TFT LCD), and performance metrics were recorded as 60-second averages for each wind setting.

Figure 1 illustrates the block diagram function (BDF) of the monitoring system, where sensor inputs generate measurable outputs. The INA219 sensor records current and voltage, while the TCRT5000 measures rotational speed. These signals are processed by the Arduino Mega 2560 and then presented via a TFT LCD and website interface. The displayed data serve as the final output, providing real-time monitoring results directly to the user.

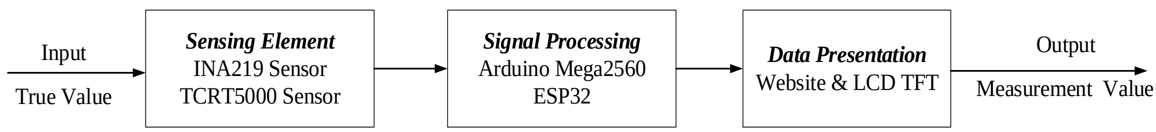


Figure 1. Block diagram for wind turbine measurements

3. RESULTS AND DISCUSSION

The following are the results of the design and manufacture of a horizontal axis wind turbine monitoring system with a variation in the number of blades 7 and 9 blades:

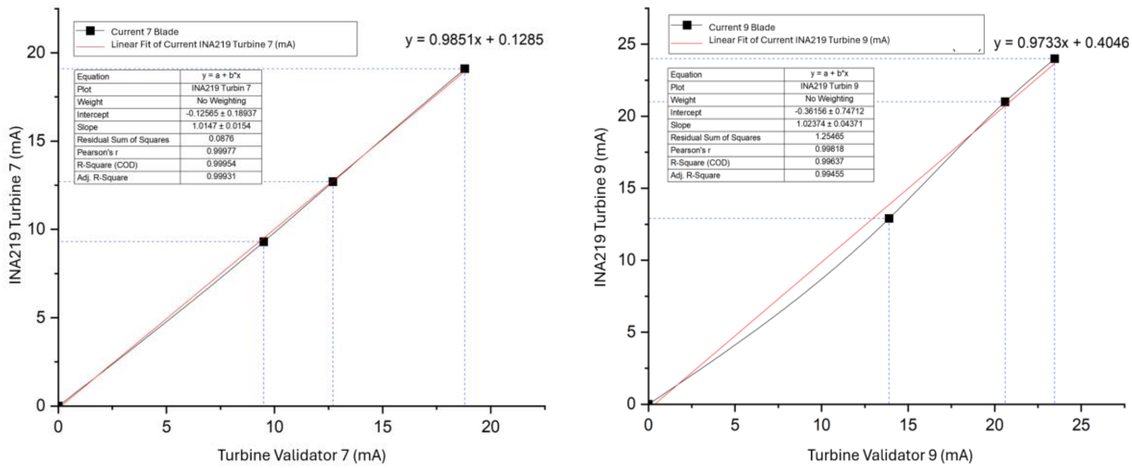
The Figure 2 showed that hardware prototype of the system. The plant consists of a wind fan as the wind source, wind turbines with 7 blades and 9 blades, an electrical wiring panel box, and a mounting table for supporting the fan and turbines. The mounting table has dimensions of 220×115×45 cm with 2 levels of support. The panel box above is an integral part of the monitoring system for the HAWT in the plant. The Arduino Mega 2560 acts as the main controller of the system, collecting data from the sensors, controlling the operation of the wind turbine, and displaying data on the TFT LCD. Power supply provides power to all components in the system, a buck converter to regulate voltage and electric current, and an LCD TFT that functions as a human-machine interface (HMI) displaying system performance information to users.

The sensors used in this system consist of two types: the INA219 voltage and current sensors, and the TCRT5000 RPM sensor. The INA219 voltage and current sensors are used to measure the output voltage and current of the wind turbine, while the TCRT5000 RPM sensor is used to measure the turbine's RPM. During the validation of the INA219 voltage and current sensors, sensor readings were compared against values measured using a multimeter for corresponding voltage and current. Meanwhile, during the validation of the TCRT5000 RPM sensor, sensor readings were compared against values measured using a tachometer.

Figure 2. Hardware system wind turbine

Before testing the turbines, sensor accuracy was verified. The INA219 readings were compared to a laboratory multimeter over the operating range. A linear fit of INA219-measured current yielded $R^2 \approx 0.996$, corresponding to about 99.1% accuracy and ≈1.1% error. The TCRT5000 RPM sensor likewise showed $R^2 \approx 0.995$ (99.4% accuracy, ~0.6% error). In both cases the measurement error was well below 5%, confirming that the sensors provided reliable data. Testing of the INA219 current and voltage sensors was carried out using fan speed variations to measure the current and voltage of the horizontal axis wind turbine output at a certain fan speed. Wind speed variations were used is 3.4 m/s, 4.7 m/s, and 5.6 m/s.

The results of the INA219 current sensor calibration are presented in Figure 3. In Figure 3(a), the sensor output was tested at a constant load of 7 mA under three wind speed modes. The current values measured by the INA219 showed a strong linear correlation with the multimeter readings, yielding a regression coefficient of R=0.999, which is very close to unity. Similarly, Figure 3(b) shows the sensor response at 9 mA with wind speeds of 3.4 m/s, 4.7 m/s, and 5.6 m/s. The linear relationship between the INA219 and multimeter measurements is again confirmed, with a slightly lower correlation of R=0.996. To further evaluate the sensor accuracy, Table 1 compares the INA219 readings with manual measurements using an Avometer (multimeter).



(a) (b)

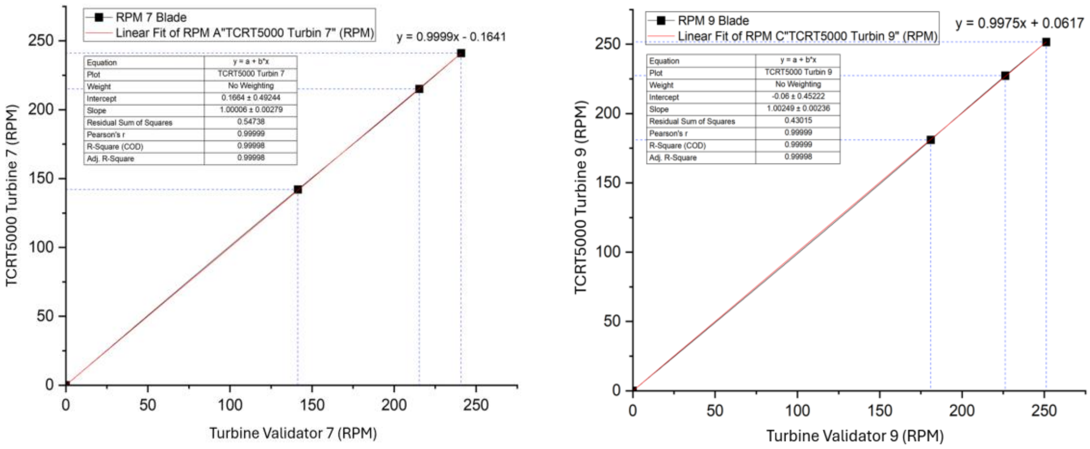
Figure 3. Graph of current sensor validation for; (a) 7 mA and (b) 9 mA

Table 1. Static characteristic INA219 (voltage)

Static characteristics	Voltage	Current
Range	3.2-4.68 V	8.4-23.9 mA
Span	1.48 V	2.08 mA
Error	0.13%	1.13%
Accuracy	99.86%	99.08%

From the static characteristics in Table 1, it can be concluded that the pressure gauge has an average accuracy of 99.08% with an error value of 1.13% respectively. The sensor validation results prove that the error percentage is below 5%, indicating that the INA219 sensors are suitable for measuring the current and voltage output from the turbine.

The calibration results of the TCRT5000 RPM sensor are presented in Figure 4. Figure 4(a) shows the turbine rotational speed measured with 7 blades under wind speeds of 3.4 m/s, 4.7 m/s, and 5.6 m/s. The RPM values obtained by the TCRT5000 sensor exhibited a strong linear correlation with those recorded by the tachometer, yielding a regression coefficient of R=0.999. Similarly, Figure 4(b) illustrates the validation test using a 9-blade configuration at the same wind speed variations. The linear relationship between the tachometer and sensor readings is again confirmed with R=0.999, indicating that the TCRT5000 RPM sensor provides highly accurate measurements. These results demonstrate the sensor's feasibility for turbine RPM monitoring. Furthermore, the static characteristic values obtained from the validation tests are summarized in Table 2.



(a) (b)

Figure 4. RPM sensor validation graph for; (a) blade 7 and (b) blade 9

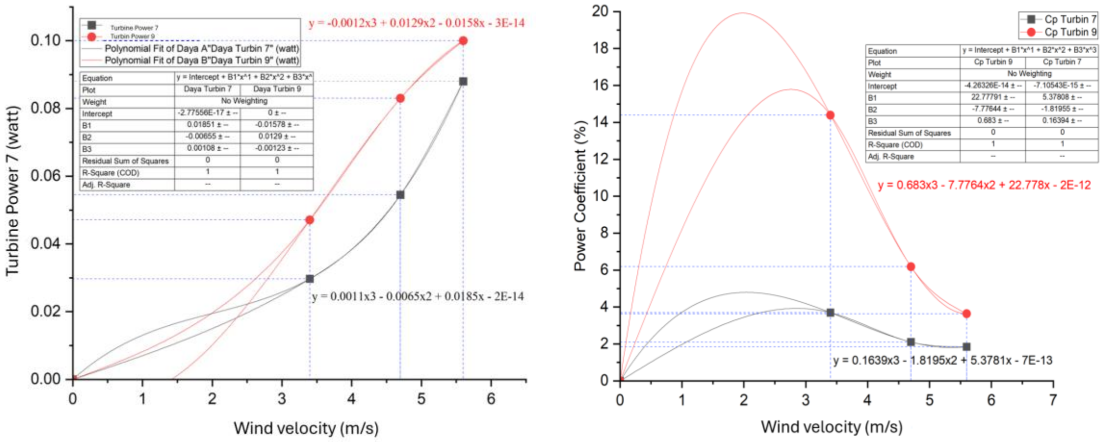
Table 2. Static characteristics

Static characteristics	TCRT5000
Range	132-252.8
Span	120.8
Error	0.59%
Accuracy	99.4%

From the static characteristics above, it can be concluded that the TCRT5000 sensor has an average accuracy of 99.4% with an error value of 0.59% respectively. The validation results of the sensor prove that the error percentage is below 5%, indicating that the TCRT5000 sensor is suitable for measuring the RPM of the turbine. The sensor validation results prove that the percentage error rate is below 5% so that the TCRT5000 sensor is suitable for use in this project as a wind turbine RPM reading sensor.

Figure 5(a) plots measured output power versus wind speed for the 7-blade and 9-blade turbines. As expected, power increased with wind speed for both rotors. Crucially, the 9-blade design consistently outperformed the 7-blade one. For example, at v=3.4 m/s the 7-blade turbine produced about 0.0297 W while the 9-blade produced about 0.0471 W. At 4.7 m/s, these values were ≈0.088 W (7 blades) and ≈0.100 W (9 blades). The computed power coefficients (Cp) are shown in Figure 5(b). The 9-blade turbine achieved a slightly higher peak Cp: about 0.198 at 3.4 m/s compared to about 0.195 for the 7-blade rotor. In both cases

Cp declined at higher speeds (e.g., at 5.6 m/s Cp dropped to ≈0.137 for 9 blades and ≈0.114 for 7 blades), due to blade stall effects as airflow separated.



(a) (b)

Figure 5. Performing testing; (a) turbine power and (b) power coefficient testing

These results demonstrate that adding blades improved performance in this small HAWT. The higher torque available from nine blades allowed the 9-blade rotor to extract more energy at each wind speed, consistent with previous findings that output power increases with blade count [6]. In summary, the 9-blade turbine delivered greater electrical power and maintained higher efficiency (Cp) under identical wind conditions, matching trends observed in similar studies.

For the 9-blade turbine, the higher blade count leads to significant aerodynamic and mechanical advantages over the 7-blade design, thereby explaining its superior performance. Increasing the blade number from 7 to 9 raises the rotor's solidity (the fraction of the swept area covered by blades), which means more blade surface is available to interact with the wind at any given time. A higher solidity allows the turbine to generate greater aerodynamic force and torque for a given wind speed. In practical terms, the 9-blade configuration can produce more starting torque than the 7-blade configuration, enabling the turbine to overcome inertia and friction more easily during startup. This improved startup behaviour means the 9-blade turbine can begin rotating at lower wind speeds and reach its operating speed more quickly. In contrast, the 7-blade turbine, with its lower solidity, captures less wind at standstill and thus requires a higher wind speed to initiate rotation or achieve the same torque output. The result is that, under identical wind conditions, the 9-blade turbine experiences a stronger and more continuous initial push, spinning up more readily and supplying higher torque to the generator.

In addition, having more blades distributes the aerodynamic load more evenly, which affects the angle of attack on each blade. Each blade of the 9-blade turbine carries a smaller portion of the total lift force required for power production than it would in a 7-blade system. Consequently, for a given rotor speed and wind speed, the blades in the 9-blade turbine can operate at a lower angle of attack compared to those of the 7-blade turbine. This angle-of-attack stability means that each 9-blade turbine blade is less likely to approach the stall angle under normal operating conditions, since it does not need to "work" as hard individually to generate torque. The blades can thus remain in a more linear lift regime, providing a steadier lift force. By avoiding high angles of attack that could induce stall, the 9-blade configuration maintains efficient lift generation on each blade over a range of wind speeds. The 7-blade turbine, on the other hand, must place a larger load on each blade (due to fewer blades sharing the load), which can push those blades closer to their stall point, especially at low rotational speeds or sudden wind gusts. This difference makes the 9-blade turbine's performance more stable and reliable, as it is less prone to sudden drops in lift or power due to aerodynamic stall on individual blades.

Aerodynamically, the increased blade count also influences the flow through the rotor in beneficial ways. With nine blades, the rotor behaves more like a continuous disk, substantially covering the swept area and creating a greater overall blockage for the oncoming airflow. This higher blockage (greater interference with the air stream) leads to a larger pressure drop across the rotor and a higher induced velocity in the turbine's wake – in other words, the 9-blade turbine slows the wind more effectively to extract energy from it. In classic wind turbine theory, an ideal rotor (with infinitely many blades) would maximize energy extraction by uniformly decelerating the airflow across the entire disc. A 9-blade rotor, having more blades than a 7-blade, moves closer to this ideal by reducing the gaps through which wind can pass untouched. Practically, this means the 9-blade turbine can capture more momentum from the wind: a greater portion of the wind's kinetic energy is transferred to the rotor as useful work. While adding blades does increase the overall drag and could cause more flow to circumvent the rotor if taken to extremes, the jump from 7 to 9 blades is moderate and primarily advantageous. The 9-blade design enhances energy capture without incurring a severe aerodynamic penalty, effectively increasing the turbine's power output. Moreover, by spreading the required torque generation across more blades, the 9-blade rotor likely reduces energy losses to the wake rotation (swirling airflow behind the turbine). Each blade in the 9-blade configuration imparts a smaller tangential force to the air (since more blades share the total torque), which means the wind leaves the rotor with less rotational kinetic energy wasted in the wake. This contributes to higher overall efficiency for the 9-blade turbine compared to the 7-blade turbine.

From a mechanical standpoint, a turbine with more blades also enjoys smoother and more balanced operation, which can further improve performance. In a 7-blade turbine, there are larger angular gaps between blades, so the torque on the shaft can fluctuate more as each blade enters and leaves the wind stream. In contrast, the 9-blade turbine has blades spaced more closely around the rotor, resulting in more continuous torque production with smaller pulsations. The nearly steady torque delivered by the 9-blade rotor reduces vibrations and mechanical stresses on the system. This smoother torque makes it easier for the generator to convert the mechanical rotation into electrical power without intermittent loading or hesitation. Additionally, the higher inertial mass of a 9-blade rotor (due to the additional blades) helps stabilize the rotational speed once the turbine is running, preventing sudden speed drops during minor wind lulls. The combined effect of these mechanical factors is that the 9-blade turbine operates more reliably and maintains optimal speed more effectively than the 7-blade turbine under the same wind conditions.

In summary, the 9-blade turbine's superior performance can be attributed to the synergy of its aerodynamic and mechanical advantages. The higher blade count increases solidity and starting torque, enabling earlier and stronger start-up, and allows each blade to operate under more favorable aerodynamic conditions (lower angle of attack and delayed stall). It also causes the rotor to extract energy more efficiently from the wind by creating a greater pressure drop and reducing wasted wake energy. Mechanically, the 9-blade configuration delivers power more smoothly and consistently. These factors explain why, at equal wind speeds, the 9-blade turbine consistently generated more power and attained a higher power coefficient (Cp) than the 7-blade turbine. Even as wind speed grows and both configurations eventually experience some performance decline due to flow stall at high angles, the 9-blade turbine mitigates these effects better by virtue of its distributed load – as evidenced by its more gradual drop in Cp at higher speeds. Therefore, the experimental observations of higher output and efficiency for the 9-blade HAWT are well supported by fundamental principles: increasing the number of NACA 4412 blades improves the turbine's torque characteristics and aerodynamic efficiency, leading to markedly better overall performance compared to the 7-blade design.

4. CONCLUSION

The experimental investigation confirms that, for the tested configuration, increasing the blade count from seven to nine significantly enhances the performance of a small-scale HAWT. The 9-blade rotor consistently delivered higher electrical output and exhibited a greater peak power coefficient than the 7-blade rotor across the tested wind speed range. Sensor calibration results demonstrated that both INA219 and TCRT5000 modules operated with accuracy exceeding 99%, validating the reliability of the real-time wireless monitoring system. These findings suggest that increasing blade number improves energy capture efficiency in low to moderate wind conditions for turbines using NACA 4412 blades. Future research could explore the impact of larger rotor diameters and higher blade counts to assess scalability. Additionally, testing under natural and turbulent wind environments is recommended to evaluate real-world applicability. Investigations into alternative blade designs—such as incorporating twist, varying pitch angles, or using different airfoil profiles may offer further insights into optimizing performance for diverse operational scenarios.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author.

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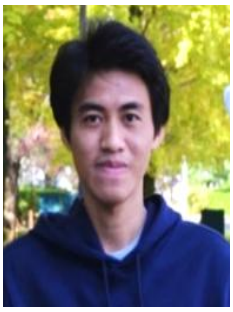

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