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MODELLING OF A PORTABLE WIND-POWERED ELECTRICITY GENERATION FOR SHRIMP POND IN KALANGANYAR VILLAGE

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Abstract

Currently, electricity generation for shrimp pond operations still predominantly relies on gasoline or diesel-powered generators. However, shrimp pond areas possess significant wind energy potential due to their favorable geographical location. This study presents the design, development, and performance evaluation of a portable horizontal-axis wind turbine (HAWT) with five blades for electricity generation in shrimp pond areas. The system incorporates an ESP32 microcontroller and the ThingSpeak platform to facilitate real-time tracking of key parameters. Experimental testing was conducted over six days, comparising three days under no-load conditions and three days under load condition. Under no-load conditions, the system achieved a maximum voltage of 30.25V at 1392 rpm and a wind speed of 3.16 m/s. Under load, it generated a maximum voltage of 12.31V with a current of 0.11A at 432 rpm and 2.08 m/s wind speed. The system reached an average energy conversion efficiency of 41.1%, approaching the bertz limit of 59.3%. These results demonstrate the viability of the system for small-scale renewable energy applications in aquaculture settings. Further improvements are recommended in blade design, generator efficiency, sensor calibration, and hybrid system integration to enchance performance and adaptability.

Keywords: Wind Energy, Portable Wind Turbine, Renewable Energy, Wind Power System.

Abstrak

Saat ini, pembangkitan listrik untuk kebutuhan operasional tambak masih banyak menggunakan bahan bakar bensin maupun solar dengan bantuan genset. Area tambak memiliki potensi energi angin yang cukup bagus karena letak geografisnya yang bagus. Penelitian ini menyajikan perancangan, pengembangan, dan evaluasi kinerja sistem pembangkit listrik tenaga angin portabel dengan konfigurasi turbin angin sumbu horizontal (HAWT) lima bilah yang ditujukan untuk kebutuhan penerangan di tambak udang. Sistem ini dilengkapi dengan pemantauan berbasis IoT menggunakan mikrokontroler ESP32 dan platform thingspeak untuk memfasilitasi pemantauan parameter secara *real-time.* Pengujian dilakukan selama 6 hari, mencakup 3 hari pada kondisi tanpa beban dan 3 hari dengan kondisi tersambung beban. Pada pengujian tanpa bebn, sistem menghasilkan tegangan maksimum sebesar 30.25V pada 1392 rpm dengan kecepatan angin 3.16 m/s. sedangkan pada pengujian dengan beban, sistem menghasilkan tegangan maksimum 12.31V dan arus 0.11A pada 432 rpm dengan kecepatan angin 2.08 m/s. Rata-rata efisiensi konversi energi mencapai 41.1%, mendekati batas teori bertz sebesar 59.3%. hasil ini menunjukkan bahwa sistem layak diterapkan untuk pembangkitan energi terbarukanskala kecil di lingkungan tambak. Diperlukan pengembangan lebih lanjut pada desain bilah, efisiensi generator, dan kalibrasi sensor dan integrasi dengan sistem energi hibrida untuk meningkatkan kinerja dan adaptabilitas sistem.

Kata kunci: Energi Angin, Turbin Angin Portabel, Energi Terbarukan, Sistem Pembangkit Listrik Tenaga Angin.

1. Introduction

Currently, wind power generation represents the most rapidly advancing energy conversion technology compared to other renewable energy sources [1]. Wind energy is a promising renewable resource because it can be converted into electrical energy via wind turbines [2], [3]. A wind turbine is a device that harnesses the force of the wind to rotate its shaft; a minimum wind speed of 10–15 km/h is required to initiate blade rotation [4]. Based on the orientation of their rotational axis, wind turbines are classified into two main types: vertical-axis wind turbines (VAWTs) and horizontal-axis wind turbines (HAWTs) [5], [6]. HAWTs feature a rotational axis parallel to the wind direction [7]. Their advantages include higher power output and superior efficiency under steady wind conditions [8], [9]. Conversely, VAWTs have an axis perpendicular to the wind direction [7]. The primary benefit of VAWTs lies in their ability to operate without yaw adjustment of the rotor, making them well suited for energy harvesting in urban, suburban, and rural environments [10].

At present, shrimp farm operators typically rely on gasoline-fueled generators to meet their electricity demands. Although alternative energy sources such as wind and solar are abundant in geographically favorable regions, their deployment remains limited [11]. Given the relatively stable wind speeds characteristic of shrimp farm locales, HAWTs are particularly appropriate for on-site power generation [12].

A prior study by Saputra and Arsianti [13] demonstrated that a Savonius-type VAWT tested at wind speeds of 3.1, 4.3, and 5.7 m/s produced power outputs of 160.91 mW, 234.74 mW, and 378.39 mW, respectively. However, these outputs are considered low relative to the wind speeds employed. Therefore, the present research focuses on HAWTs, which exhibit superior power-conversion efficiency. The wind turbine design adopted here employs a five-blade configuration, which has been shown to yield higher power output compared to four-blade HAWTs [14], [15].

This study introduces two key innovations. First, a portable five-blade HAWT is designed to enhance power efficiency and provide flexibility in deployment across shrimp farm sites. Second, the system incorporates IoT-based monitoring using an ESP32 microcontroller and the ThingSpeak platform to enable real-time tracking of system performance (voltage, current, generator speed, and wind speed) via a smartphone interface.

The objective of this research is to develop a portable five-blade HAWT power generation model integrated with an IoT monitoring system, aiming to deliver efficient, cost-effective, and easily installed and maintained illumination solutions for shrimp farms.

2. Method

2.1. Research Approach

The present study employs a quantitative research methodology, specifically a Research and Development (R&D) approach. This approach is commonly adopted in investigations that aim to produce a specific product and evaluate its performance or effectiveness. The test data from the portable wind-powered generation model will be presented in tabular and graphical form to facilitate the discussion of the experimental results.

2.2. Research Design

Figure 1 ilustrates the study planning flow, beginning with a literature review of relevant books and previous research articles. The next stage entails designing the portable wind-power generation system, once the device is assembled according to the design specifications, prototype testing is conducted. If the prototype performed is expected, the subsequent phase is data collection. Research variables are measured using sensors, and these readings are then validated by performing additional measurements or applying theoretical calculations to assess sensor accuracy. should any failures occur during testing, the system is repaired and retested. The final stage involves drawing conclusions and formulating recommendations based on the study's findin to guide future research.

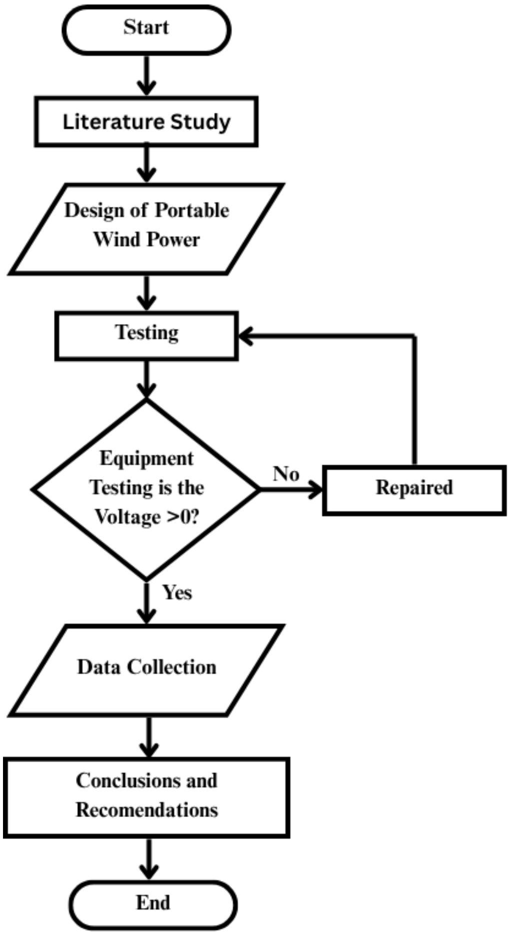

Figure 1. Research flow diagram

2.3. Prototype Wiring Diagram

The portable wind power generation system was designed using a five-blade horizontal axis wind turbine. The generator employed in this system is a low-speed permanent magnet DC generator. The output voltage from the DC generator is directed to a solar charge controller, which regulates the voltage both towards the battery for storage and towards the lighting load. The battery not only functions as an energy storage unit but also serves as a backup power source, providing electrical supply when the turbine's rotational speed is insufficient or unstable due to low wind speeds.

To measure the research variables, several sensors were utilized, including a voltage sensor, an ACS712 current sensor, a hall-effect speed sensor, and anemometer to measure wind speed around the turbine area. A minor adjustment was made to the voltage sensor to accommodate generator output voltages, which during no-load testing, occasionally exceeded 25V. The Hall-effect speed sensor was used to measure the generator's rotational speed by utilizing the Hall effect principle.

All sensor data were initially in analog form and subsequently converted into digital signals. These signals were transmitted to the ESP32 microcontroller and then forwarded to the ThingSpeak platform. An internet connection is required for the ESP32 to upload data to ThingSpeak. This platform allows researchers and aquaculture operatrs to easily monitor the measured variables. The ThingSpeak channel must be configured as a public channel to ensure convenient access without requiring a login. The data can be accessed using either a smartphone or a computer.

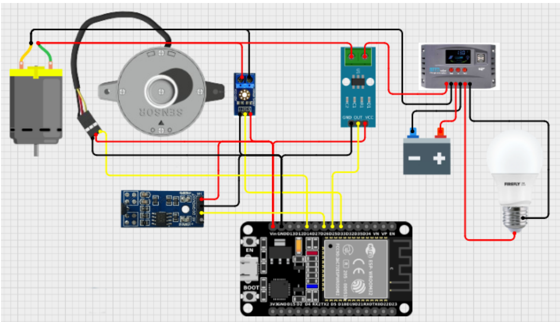

Figure 2 Wiring diagram system

2.4. Prototype Design

The wind power generation system used in this study employs a horizontal-axis wind turbine with five blades. The turbine blades are made from PVC pipes, each measuring 70 cm in length and a maximum width of 9 cm. The blades are mounted on a shaft using a rotor made of steel plate with a diameter of 6.8 cm and a thickness of 1.2 mm. The upper supporting structure consists of an iron pipe with a diameter of 3.4 cm and a length of 90 cm, connected to the main tripod-shaped support made of iron pipes, each with a length of 80 cm and a diameter of 3.6 cm. The height of the support is adjustable, ranging from 1.5 meters to 2 meters. The iron pipes used have a wall thickness of 1 mm.

To transmit mechanical energy to the DC generator, the turbine shaft is connected via a pulley system. The generator is installed beneath the turbine shaft and is connected using an aluminum pulley configuration with a 1:5 ratio, driven by a V-belt. Two protective enclosures are used for different purposes: the first box, located below the generator, contains a voltage sensor, a current sensor, and an ESP32 microcontroller for monitoring purposes. The anemometer sensor is placed in front of the wind turbine tail. The second box houses the solar charge controller, battery, and DC lighting components. The complete system design is illustrated in the figure below.

Figure 3 Prototype Design

2.5. Testing and Data Collection

The data collected during the testing of the portable wind power generator includes the generator output voltage, current flow, wind speed, and the rotational speed (RPM) of the generator. Data were collected periodically at 30-minute intervals over a period of six days. The testing was conducted in two phases: three days without an electrical load and three days with an electrical load. Data collection was carried out daily from 10:00 AM to 4:00 PM Western Indonesian Time (WIB).

3. Result and Discussion

3.1. Result of Prototype Testing

This study aims to evaluate the performance of a portable wind power generator. The testing was conducted by measuring the generator's output voltage, circuit current, generator rotational speed

(RPM), and wind speed around the wind turbine. Two testing methods were employed: no-load testing and loaded testing. The load consisted of two 12V DC, 5-watt LED lamps. Measurements were performed using a voltage divider circuit to assess voltage, a Hall effect sensor to measure generator RPM, an anemometer to record wind speed, and an ACS712 sensor to monitor current. An ESP32 microcontroller was utilized to facilitate real-time monitoring by reading sensor data and transmitting it to the ThingSpeak platform. Data transmission occurred every minute with a 15-second delay during transfer. ThingSpeak was selected due to its user-friendly interface, compatibility with various microcontrollers, and capability to simultaneously display data from up to eight sensors within a single channel.

3.1.1. No Load Testing

This experiment aimed to evaluate the electrical output of the DC generator under open circuit conditions. The parameters measured during the load test included wind speed, generator output voltage, electrical current, and generator rotational speed.

Table 1. shows the results of the first day of testing under no-load conditions. Weather conditions were relatively clear, with favorable wind speeds observed from the start to the midpoint of the test, though a sharp decline occurred toward the end. Wind speeds on this day ranged from 1.96 to 2.84 m/s. The highest recorded voltage was 27.42 V at a generator rotational speed of 1244.4 rpm, corresponding to a wind speed of 2.84 m/s between 14:00 and 14:30. The lowest voltage recorded on the first day was 7.33 V at a generator rotational speed of 215 rpm, observed during the final 30 minutes of testing when the wind speed was 1.96 m/s. Overall, wind speed exhibited considerable fluctuation—rising gradually from the beginning to mid-testing, then dropping significantly at the conclusion of the testing.

Table 1. First day of prototype testing no-load conditions

Time (WIB)	Wind Speed	DC Generator Voltage	Generator RPM
10:30	2.28 m/s	14.95 V	576.92 Rpm
11:00	2.21 m/s	17.13 V	682 Rpm
11:30	2.48 m/s	15.61 V	580 Rpm
12:00	2.36 m/s	15.9 V	608.97 Rpm
12:30	2.29 m/s	9.11 V	319.66 Rpm
13:00	2.28 m/s	12.53 V	473 Rpm
13:30	2.12 m/s	20.41 V	856.21 Rpm
14:00	2.49 m/s	25.91 V	1104 Rpm
14:30	2.84 m/s	27.42 V	1244.4 Rpm
15:00	2.51 m/s	21.62 V	882.74 Rpm
15:30	2.23 m/s	17.39 V	724 Rpm
16:00	1.96 m/s	7.33 V	215 Rpm

Table 2. shows the results of the second day of testing under no-load conditions. Weather conditions were relatively clear, with favorable wind speeds observed from the start to the end of the test. On this day, wind speeds ranged from 2.07 to 2.74 m/s. The highest recorded voltage was 20.61 V at a generator rotational speed of 857 rpm, corresponding to a wind speed of 2.74 m/s toward the end of the testing period. The lowest voltage recorded on the second day was 7.63 V at a generator rotational speed of 236.33 rpm, observed during the initial 30 minutes of testing when the wind speed was 2.07 m/s. The testing on the second day exhibited several differences compared to the first day. Notably, wind speed fluctuations were more stable on the second day than on the first. Additionally, wind speeds on the second day showed a consistent upward trend from the start to the end of testing, contrasting with the first day, where wind speeds dropped significantly toward the conclusion of the test.

Table 2. Second day of prototype testing no-load conditions

Time (WIB)	Wind Speed	DC Generator Voltage	Generator RPM
10:30	2.07 m/s	7.63 V	236.33 Rpm
11:00	2.23 m/s	12.18 V	417 Rpm
11:30	2.33 m/s	14.69 V	537.33 Rpm
12:00	2.32 m/s	12.92 V	445.91 Rpm
12:30	2.26 m/s	11.07 V	343.1 Rpm
13:00	2.31 m/s	13.77 V	485.71 Rpm
13:30	2.33 m/s	13.43 V	459.33 Rpm
14:00	2.44 m/s	16.91 V	628.67 Rpm
14:30	2.52 m/s	19.51 V	765.33 Rpm
15:00	2.45 m/s	17.71 V	704 Rpm
15:30	2.73 m/s	19.65 V	798.67 Rpm
16:00	2.74 m/s	20.61 V	857 Rpm

Table 3. Third day of prototype testing no-load conditions

Time (WIB)	Wind Speed	DC Generator Voltage	Generator RPM
10:30	2.32 m/s	13.6 V	469.67 Rpm
11:00	2.36 m/s	12.06 V	416 Rpm
11:30	2.52 m/s	16.9 V	614 Rpm
12:00	2.38 m/s	14.76 V	538.28 Rpm
12:30	2.39 m/s	15.08 V	566.33 Rpm
13:00	2.48 m/s	20.07 V	846.21 Rpm
13:30	2.62 m/s	13.20 V	449.67 Rpm
14:00	3.04 m/s	23.09 V	987.93 Rpm
14:30	3.08 m/s	27.1 V	1272 Rpm
15:00	3.16 m/s	30.25 V	1392.67 Rpm
15:30	2.62 m/s	19.51 V	764.48 Rpm
16:00	2.41 m/s	16.24 V	590.4 Rpm

Table 3. shows the results of the third day of testing under no-load conditions. Weather conditions were relatively clear, with favorable wind speeds observed from the start to the midpoint of the test, followed by a decline toward the end. Wind speeds on this day ranged from 2.32 to 3.16 m/s. The highest recorded voltage was 30.25 V at a generator rotational speed of 1,392.67 rpm, corresponding to a wind speed of 3.16 m/s between 14:30 and 15:00. The lowest voltage recorded on the third day was 12.06 V at a generator rotational speed of 416 rpm, observed between 10:30 and 11:00 when the wind speed was 2.36

m/s. In terms of wind speed fluctuations, the third day exhibited patterns similar to those observed on the first day of testing. However, the average wind speed on the third day was higher than that recorded on the first day.

3.1.2. Load Testing

This experiment aimed to evaluate the DC generator's output voltage and current under loaded conditions. The parameters measured during the load test included wind speed, generator output voltage, electrical current, and generator rotational speed.

Table 4. shows the results of the first day of testing under loaded conditions. On the first day of testing, the prototype was subjected to a load consisting of two 5-watt DC lamps connected directly to the generator. As shown in the table, wind speeds remained relatively stable throughout the day, ranging from 1.81 to 2.09 m/s. The highest recorded voltage was 12.31 V, with a circuit current of 0.10 A, a generator rotational speed of 431.25 rpm, and a wind speed of 2.08 m/s. This measurement was observed between 12:00 and 12:30. Despite relatively stable wind speeds on the first day, the duration of wind gusts was suboptimal, as evidenced by several voltage readings below 10 V, with the lowest recorded voltage measured at 5.88 V. Fluctuating weather conditions also significantly influenced wind speeds, where clear skies correlated with increased wind velocity.

Table 4. First day of prototype testing under loaded conditions

Time (WIB)	Wind Speed	DC Generator Voltage	DC Generator Current	Generator RPM
10:30	2.00 m/s	8.75 V	0.08 A	182.4 Rpm
11:00	2.00 m/s	11.47 V	0.09 A	367.78 Rpm
11:30	2.05 m/s	10.5 V	0.1 A	327.7 Rpm
12:00	2.08 m/s	10.21 V	0.1 A	303.6 Rpm
12:30	2.08 m/s	12.31 V	0.11 A	431.25 Rpm
13:00	2.01 m/s	8.68 V	0.06 A	196.25 Rpm
13:30	1.81 m/s	5.88 V	0.04 A	114.78 Rpm
14:00	2.09 m/s	10.32 V	0.08 A	323.33 Rpm
14:30	1.95 m/s	7.78 V	0.06 A	160.43 Rpm
15:00	2.05 m/s	9.35 V	0.10 A	213.33 pm
15:30	2.09 m/s	10.84 V	0.16 A	335.36 Rpm
16:00	2.09 m/s	9.91 V	0.09 A	288.26 Rpm

Table 5. shows the results of the second day of testing under loaded conditions. On the second day of testing, wind speeds remained consistently above 2.0 m/s. This performance was relatively better than the first day of loaded testing, where the lowest recorded wind speed was 1.81 m/s. The generator's output voltage remained relatively stable and consistently above 10 V, with only occasional readings below this threshold. The highest voltage observed on the second day was 12.27 V, with a circuit current of 0.13 A and a rotational speed of 406.8 rpm at a wind speed of 2.09 m/s. This measurement was recorded between 10:30 and 11:00. The minimum recorded voltage was 9.50 V. Both voltage and current remained relatively stable throughout the day, although a decline occurred in the afternoon due to reduced wind speeds, which significantly impacted the generator's rotational speed and output voltage.

Table 5. Second day of prototype testing under loaded conditions

Time (WIB)	Wind Speed	DC Generator Voltage	DC Generator Current	Generator RPM
10:30	2.09 m/s	11.44 V	0.12 A	376.55 Rpm
11:00	2.09 m/s	12.27 V	0.13 A	406.8 Rpm
11:30	2.09 m/s	11.02 V	0.11 A	366.92 Rpm
12:00	2.04 m/s	9.86 V	0.10 A	282.69 Rpm
12:30	2.08 m/s	10.75 V	0.12 A	336.21 Rpm
13:00	2.07 m/s	10.57 V	0.11 A	330.8 Rpm
13:30	2.09 m/s	10.83 V	0.12 A	340.38 Rpm
14:00	2.09 m/s	10.88 V	0.12 A	346.07 Rpm
14:30	2.09 m/s	10.29 V	0.12 A	323.08 Rpm
15:00	2.06 m/s	9.5 V	0.10 A	257.31 pm
15:30	2.05 m/s	9.92 V	0.11 A	290 Rpm
16:00	2.07 m/s	9.91 V	0.11 A	288.75 Rpm

Table 6. shows the results of the third day of testing under loaded conditions. On the third day of testing, initial wind speeds were relatively low, causing the turbine to struggle with consistent rotation. These low wind speeds persisted until the midpoint of the testing period. Afterward, wind speeds gradually increased before slightly declining again toward the end of the test. The highest recorded voltage on the third day was 11.50 V, with a circuit current of 0.18 A and a rotational speed of 398 rpm at a wind speed of 2.06 m/s, observed between 15:30 and 16:00. The lowest voltage generated by the turbine was recorded at 4.41 V, occurring at the start of testing when wind speeds were very low (1.34 m/s). These results demonstrate that both wind speed and the duration of wind gusts significantly influence the amount of electrical energy produced.

Table 6. Third day of prototype testing under loaded conditions

Time (WIB)	Wind Speed	DC Generator Voltage	DC Generator Current	Generator RPM
10:30	1.34 m/s	4.41 V	0.04 A	35 Rpm
11:00	1.76 m/s	7.61 V	0.05 A	134.48 Rpm
11:30	1.73 m/s	6.12 V	0.07 A	112 Rpm
12:00	1.98 m/s	9.84 V	0.07 A	231.25 Rpm
12:30	1.58 m/s	6.05 V	0.04 A	75 Rpm
13:00	1.98 m/s	6.82 V	0.05 A	178.97 Rpm
13:30	2.09 m/s	11.29 V	0.13 A	390.36 Rpm
14:00	2.09 m/s	11.36 V	0.16 A	394 Rpm
14:30	2.09 m/s	10.26 V	0.16 A	300 Rpm
15:00	2.09 m/s	11.35 V	0.18 A	294.14 pm
15:30	2.09 m/s	11.02 V	0.23 A	328.97 Rpm
16:00	2.06 m/s	11.50 V	0.18 A	398.4 Rpm

3.2. Discussion

The following figures shows the fluctuation of the measured research variables during both no-load and loaded testing conditions. Additionally, a comparison of voltage and current measurements is presented, contrasting data obtained from sensors with those from a multimeter. This comparison aims to determine the accuracy of the voltage and current sensors used throughout the testing process.

Figure 4. shows wind speed fluctuations during the no-load testing of the wind turbine, which ranged from 1.96 to 3.16 m/s. On the first day, wind speed exhibited a pronounced variation, particularly between 14:30 and 16:00. The second day showed more stable conditions, with only a slight decrease mid-session and a maximum reached at the end of the test period. In contrast, the third day displayed greater variability than the preceding two days, with its highest wind speed occurring between 14:30 and 15:00. Across all three days, the overall trend was an increase in wind speed, although the timing of the daily peak differed for each test day.

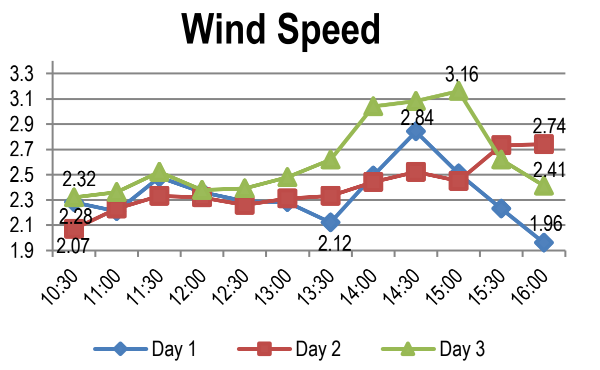

Figure 4. Fluctuations in wind speed over a three day no-load testing period

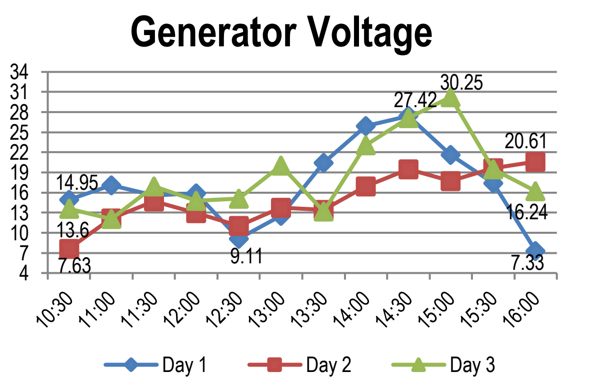

Figure 5. Fluctuations in generator voltage over a three day no-load testing period

Figure 5. shows the generator's output-voltage fluctuations during the no-load tests, with values ranging from 7.33 V to 30.25 V. The daily voltage profile exhibits an overall upward trend despite intermittent variability. On days 1 and 3, voltage swings were more pronounced, with the highest peaks occurring between 14:00 and 15:00. In contrast, day 2 displayed a more stable, gradual voltage rise throughout the test. The absolute maximum voltage of 30.25 V was recorded on day 3 between 14:30 and 15:00. Notably, significant voltage declines were observed at the end of the testing periods on days 1 and 3, whereas on day 2 the voltage reached its apex at the conclusion of the test.

Figure 6. shows the fluctuation in generator rotational speed during the no-load tests, ranging from 215 to 1,393 rpm. In general, rpm increased over time each day, exhibiting distinct fluctuation patterns. The highest speeds occurred during the midday to afternoon period, directly influenced by variations in wind velocity and stability. On the first day, generator rpm showed pronounced variability, rising sharply through the middle of the test before declining markedly toward the end of the session. By contrast, on the second day the rpm profile was considerably more consistent, with a gradual and stable increase throughout the measurement period. The third day recorded the highest overall rpm values of the three tests, with its peak occurring between 14:30 and 15:00, followed by a decline at the close of testing. These observations indicate that generator rpm is strongly dependent on both the speed and steadiness of the wind, which varied from day to day.

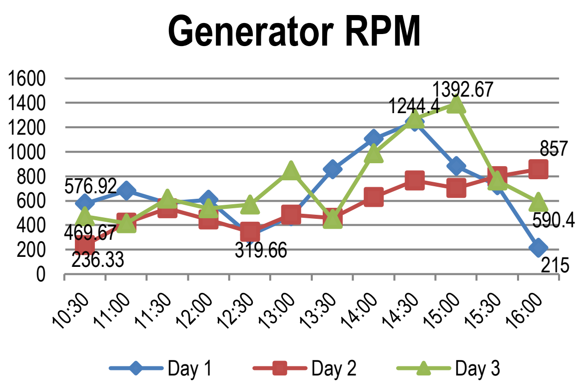

Figure 6. Fluctuations in generator RPM over a three day no-load testing period

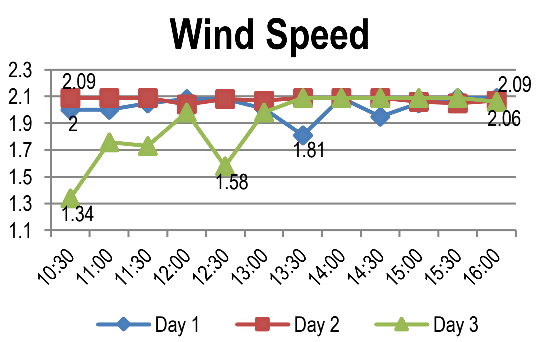

Figure 7. Fluctuations in wind speed over a three-day load-testing period

Figure 7. shows wind speed fluctuations during the load-testing period, which ranged from 1.34 to 2.09 m/s. On the second day of testing, wind speed remained relatively stable throughout the experiment, consistently within the range of 2.04 and 2.09 m/s. Meanwhile, the first day exhibited minor fluctuations. In contrast, the third day experienced significant variability. Initially, wind speeds were notably low at 1.34 m/s, but increased sharply at 11:00, and did not stabilize until after 13:30. Overall, the mean wind speed over the three days of loaded testing was 2 m/s, with the most significant fluctuation s recorded on the third day.

Figure 8. shows the generator output voltage during load testing, fluctuating between 4.41 to 12.31V. On the second day of testing, the generated voltage remained relatively stable between 10 and 11V with minor fluctuations. In contrast, the first day showed significant fluctuations, particularly during the mid-testing period, where voltage level consistently fluctuated throughout the experiment. During the third day, significant fluctuation was also observed the initial voltage was low due to reduced wind speed, but it increased gradually and became more stable after 13:00. The highest voltages recorded under load were 12.31V and 12.27V, occurring on the first and second days of testing, respectively. Overall, generator voltage was influenced by weather conditions and wind speed, with the greatest fluctuation occurring on the first day of testing.

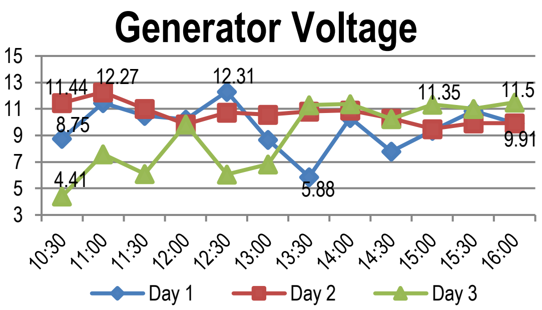

Figure 8. Fluctuations in generator voltage over a three-day load-testing period

Figure 9. shows the fluctations in generator current during the prototype wind turbine load tests, ranging from 0.04 to 0.23 A. On the second day of testing, the current was most stable, remaining between 0.14 and 0.16 A with no significant fluctuations. In contrast, the first day displayed irregular fluctuation patterns throughout the experiment. On the third day, the current increased gradually at the start of the test but then rose sharply after 13:00 to a peak of 0.23 A, before declining toward the end of the observation period. Based on this analysis, it can be concluded that the second day demonstrated the most stable current, the first day showed severe fluctuations, and the third day experienced a pronounced increase in the afternoon.

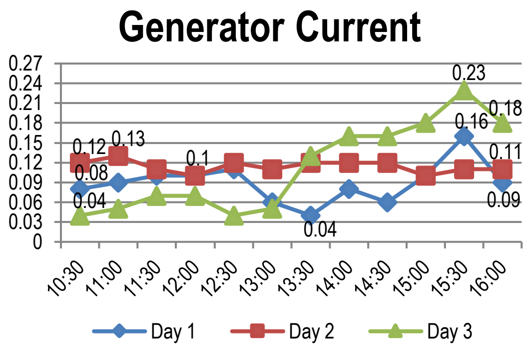

Figure 9. Fluctuations in generator current over a three-day load-testing period

Figure 10. shows a comparison of the generator's rotational speed (RPM) during the loaded wind turbine prototype testing under load conditions, ranging from 35 to 431 RPM. Connecting the generator to a load naturally results in lower RPM, as the rotational resistance increases significantly compared to no-load conditions. The data show that on the second day of testing the RPM was most stable, maintaining values between 257 and 407 RPM. In contrast, the first day show large fluctuations the speed climbed sharply to 431 RPM before dropping just as dramatically, indicating unstable generator operation. On the third day, the RPM increased gradually throughout the morning, reached its peak after 13:00, and then declined slightly during the final 30 minutes of the test. In summary, the second day yielded the most stable generator rotation, the first day was marked by high variability, and the third day showed a steady, controlled increase.

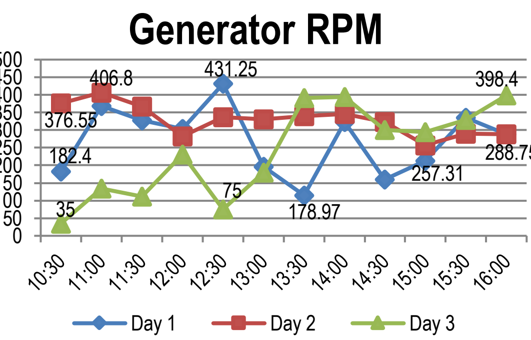

Figure 10. Fluctuations in generator RPM over a three-day load-testing period

Table 7. shows the comparison of voltage measurements obtained from the voltage sensor and a digital multimeter during load testing. The discrepancies between the two measurement methods are relatively small, with error rates ranging from 0.18% to 3.89% and an average error rate of 1.04%. The greatest discrepancy occurred in the 14:00–14:30 interval, where the sensor reading differed by 0.4 V from the multimeter value, corresponding to an

error rate of 3.89%. In contrast, the lowest error rate (0.18%) was observed during the 11:00–11:30 interval. Notably, the multimeter readings are not uniformly higher than those of the sensor; at certain intervals (11:00–11:30 and 14:00–14:30), the sensor yielded higher voltage values than the multimeter. The data also show that the voltage profile under load fluctuated over the course of the day, exhibiting a general downward trend in the afternoon, with the minimum voltage recorded at 16:00. When compared to the no-load test, the load test generated a marginally higher average error rate (1.04% versus 0.77%). Nonetheless, the overall mean error remains close to 1%, demonstrating that the voltage sensor maintains adequate accuracy under loaded conditions and can be reliably used for voltage measurement in the portable wind turbine prototype.

Table 7. not only presents a comparison of voltage measurements but also illustrates the current measurements obtained using the ACS712 sensors and those recorded by a digital multimeter under load conditions. The ACS712 sensor yields more stable and consistent readings but is highly susceptible to zero-point drift, which progressively degrades its accuracy. By contrast, the multimeter provides more accurate values, as it measures the circuit's current flow directly and thus reflects the true instantaneous current. From the table, the greatest deviation occurs in the 11:00–11:30 interval, where the sensor reading differs by 0.1 V from the multimeter, corresponding to an error rate of 8.33%. The smallest deviation shows an error rate of 2.56%. The mean error rate over the entire test is 4.78%, indicating generally small discrepancies even though the error occasionally spikes due to the sensor's zero-point drift. These results underscore the necessity of regular monitoring and periodic calibration to preserve the ACS712 sensor's measurement accuracy.

Table 7. Differences voltage and current measurements between the sensor and the multimeter during load testing

Time (WIB)	Load-Test					
	Voltage			Current		
	Sensor Reading	Multimeter Reading	Error Rate (%)	Sensor Reading	Multimeter Reading	Error Rate (%)
10:30	11.44 V	11.4 V	0.35 %	0.12 A	0.127 A	5.51 %
11:00	12.27 V	12.2 V	0.57 %	0.13 A	0.139 A	6.47 %
11:30	11.02 V	11 V	0.18 %	0.11 A	0.12 A	8.33 %
12:00	9.86 V	9.91 V	0.51 %	0.1 A	0.095 A	5.26 %
12:30	10.75 V	10.6 V	1.4 %	0.12 A	0.117 A	2.56 %
13:00	10.57 V	10.65 V	0.76 %	0.11 A	0.115 A	4.35 %
13:30	10.83 V	10.75 V	0.74 %	0.12 A	0.124 A	3.23 %
14:00	10.88 V	10.95 V	0.64 %	0.12 A	0.126 A	4.76 %
14:30	10.29 V	10.69 V	3.89 %	0.12 A	0.113 A	6.19 %
15:00	9.5 V	9.7 V	2.11 %	0.1 A	0.097 A	3.09 %
15:30	9.92 V	9.87 V	0.5 %	0.11 A	0.107 A	2.8 %
16:00	9.91 V	10 V	0.91 %	0.11 A	0.105 A	4.76 %
	Average Error Rate		1.04 %	Average Error Rate		4.78 %

To validate the performance of the five-blade horizontal axis wind turbine with a blade length of 0.7 meters. The researcher compared the measured output of the system with theoretical calculations based on the wind turbine power equation. As a reference for evaluation, data samples were taken from the second day of testing under load conditions. The theoretical wind power equation used for the comparison is as follows:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot Cp$$

Where:
P : Wind power (watt)
ρ : Air density (1.225 kg/m^3)
A : Swept area of the turbine blades ($\pi \cdot 0.7^2 = 1.54$ m^2)
v : Wind speed (as shown in the table)
Cp : Power Coefficient (assumed to be 0.35 for small-scale wind turbine)

The electrical power measured by the sensors is calculated using the following equation:

$$P = V \cdot I$$

Where:
V : The voltage measured by the voltage sensor
I : The current measured by the ACS712 current sensor

Table 8. shows the theoretical power output remains relatively stable due to the minimal variation in the measured wind speed. In contrast, the sensor based measurement data exhibit greater variability, which can be attributed to mechanical and electrical factors. The peak measured power occurred at 11:00, with an efficiency of 52.95%. based on the validation results, the system efficiency ranges from 32.93% to 52.95%, which is considered satisfactory for a small-scale horizontal-axis wind turbine. This efficiency range is already approaching the theoretical maximum efficiency defined by Bert'z law, which is 59.3%. The observed fluctuations in efficiency are likely caused by inconsistent wind gusts, mechanical losses in the shaft and bearings, as well as the efficiency limitations of the DC generator used during testing.

Table 8. Validation results between sensor measurements and theoretical wind power calculations

Time (WIB)	Wind Speed	Measurement Results	Theoretical Results	Efficiency
10:30	2.09 m/s	1.37 Watt	3.01 Watt	45.57 %
11:00	2.09 m/s	1.59 Watt	3.01 Watt	52.95%
11:30	2.09 m/s	1.21 Watt	3.01 Watt	40.24%
12:00	2.04 m/s	0.99 Watt	2.8 Watt	35.19%
12:30	2.08 m/s	1.29 Watt	2.97 Watt	43.44%
13:00	2.07 m/s	1.16 Watt	2.93 Watt	39.72%
13:30	2.09 m/s	1.3 Watt	3.01 Watt	43.14%
14:00	2.09 m/s	1.31 Watt	3.01 Watt	43.34%
14:30	2.09 m/s	1.23 Watt	3.01 Watt	40.99%
15:00	2.06 m/s	0.95 Watt	2.88 Watt	32.93%
15:30	2.05 m/s	1.09 Watt	2.84 Watt	38.38%
16:00	2.07 m/s	1.09 Watt	2.93 Watt	37.24%
		Average Efficiency		41.1%

Based on the calculations performed, the system can be considered optimal when applied to small-scale wind turbines. The proposed design also performed reasonably well by successfully converting available wind energy into electrical energy. To improve the average efficiency, further in-depth research is required, particularly on the aerodynamic characteristics of the blades, the efficiency of the generator, and experimental trials under varying wind speed conditions to assess the turbine's maximum performance potential.

4. Conclusion

This study successfully designed, implemented and tested a portable horizontal-axis wind turbine (HAWT) system equipped with five blades for electrical power generation in shrimp pond environments. The prototype was able to convert wind energy into electrical energy with an average efficiency of 41.1%, which is considered satisfactory for small-scale wind energy systems and approaches the theoretical bertz limit of 59.3%. under no load conditions, the system achieved a peak voltage output of 30.25V at 1392 rpm under a wind speed of 3.16 m/s. under load conditions, the maximum voltage recorded was 12.31V, with a current of 0.11A, at a wind speed of 2.08 m/s and a generator speed of 432 rpm. The variation in power generation performance was significantly influenced by wind speed and its stability, as well as mechanical factors and the efficiency of components such as the turbine blades and generator.

The utilization of the ESP32 microcontroller and the IoT platform ThingSpeak enabled real-time system monitoring, enchancing the system's functionality for shrimp pond operations that require efficient energy use and ease of performance tracking to enchance the system's performance and applicability, several improvements are suggested. The turbine blade design should be optimized in terms of shape, pitch angle, and a material to improve energy conversion. A more efficient generator, better matched to low wind speeds, is recommended to increase output. Regular calibration of the ACS712 sensor is necessary to maintain measurement accuracy. The system's structure should be redesigned to be more compact and modular for easier installation and maintenance. Additional testing in varied seasons is advised to evaluate adaptability.

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