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Development of an internet of things-based monitoring system for small vertical axis wind turbine

Yuli Prasetyo[1], Budi Triyono[2], Budi Artono[3], Santi Triwijaya[4], Ainul Khakim[5], Ade Nofa Ramadhan[6]
[1,2,3,6] Electrical Engineering, Politeknik Negeri Madiun, Indonesia
[4]Railway Electrical Technology, Politeknik Perkeretaapian Indonesia Madiun, Indonesia
[5]PT. Waskita Karya (Persero), Indonesia

**Corresponding Author: buditriyono@pnm.ac.id*

ABSTRACT

Small-scale wind turbines often face challenges related to low energy conversion efficiency and the lack of adequate monitoring and automatic protection systems against fluctuating weather and load conditions. This study presents the design and implementation of an Internet of Things (IoT)-based monitoring and protection system for a Small Vertical Axis Wind Turbine (VAWT). The system utilizes Arduino Uno and NodeMCU ESP8266 microcontrollers integrated with INA219, LM35, anemometer, infrared, and DC voltage sensors. Data acquisition and transmission are managed through Wi-Fi communication and displayed on the ThingSpeak web platform for real-time visualization. Experimental testing demonstrated that the system successfully measured and transmitted voltage, current, power, wind speed, temperature, and rotational speed parameters with an average data transmission latency of less than 3 seconds. The protection mechanism activated effectively under simulated abnormal conditions such as over-speed and over-temperature, automatically disconnecting the load to prevent turbine damage. The measurement accuracy for INA219 voltage and current sensors reached ±0.2 V and ±0.05 A, while temperature detection with LM35 had an average deviation of ±0.8 °C. The results indicate that the proposed IoT-based VAWT monitoring system is capable of providing reliable, low-cost, and real-time supervision suitable for small-scale renewable energy applications. Furthermore, it can be used as a learning prototype in vocational education to understand the integration of renewable energy and IoT technologies.

Keywords: Internet of Things, VAWT, Renewable Energy, Monitoring, Real Time

ABSTRAK

Turbin angin berukuran kecil sering menghadapi permasalahan pada efisiensi konversi energi dan kurangnya sistem pemantauan serta proteksi otomatis yang memadai terhadap kondisi cuaca dan beban yang berubah-ubah. Penelitian ini membahas perancangan dan implementasi sistem monitoring dan proteksi berbasis Internet of Things (IoT) pada Small Vertical Axis Wind Turbine (VAWT). Sistem menggunakan mikrokontroler Arduino Uno dan NodeMCU ESP8266 yang terintegrasi dengan sensor INA219, LM35, anemometer, infrared, dan sensor tegangan DC. Proses akuisisi dan transmisi data dilakukan melalui komunikasi Wi-Fi dan ditampilkan secara real-time melalui platform ThingSpeak. Hasil pengujian menunjukkan bahwa sistem mampu mengukur dan mengirimkan data tegangan, arus, daya, kecepatan angin, suhu, dan putaran turbin dengan rata-rata keterlambatan transmisi data kurang dari 3 detik. Mekanisme proteksi bekerja secara otomatis saat terjadi kondisi abnormal seperti over-speed dan suhu tinggi, dengan memutus beban untuk mencegah kerusakan turbin. Akurasi pengukuran sensor INA219 untuk tegangan dan arus mencapai ±0,2 V dan ±0,05 A, sementara sensor LM35 memiliki deviasi rata-rata ±0,8 °C. Hasil penelitian menunjukkan bahwa sistem monitoring berbasis IoT yang dikembangkan mampu memberikan pengawasan real-time yang handal, ekonomis, dan efisien untuk aplikasi energi terbarukan skala kecil. Selain itu, sistem ini dapat digunakan sebagai media pembelajaran dalam pendidikan vokasi untuk memahami integrasi antara teknologi energi terbarukan dan IoT.

Kata kunci: Internet of Things, VAWT, Energi Terbarukan, Monitoring, Real Time

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1. INTRODUCTION

Energy is one of the primary needs of modern society, playing an essential role in almost all aspects of life such as transportation, industry, and daily human activities. However, the growing demand for energy is not proportional to the availability of conventional energy resources, especially fossil fuels. The continuous exploitation of fossil energy has led to depletion of resources and environmental degradation. Therefore, the utilization of renewable energy sources has become an urgent solution to support sustainable energy development [1], [2].

Despite the significant progress in IoT-based renewable energy monitoring, most existing studies primarily focus on large-scale horizontal axis wind turbines (HAWTs) or employ expensive sensors and proprietary data platforms, limiting their applicability for small, low-cost systems. Furthermore, previous works often emphasize data acquisition without integrating protection mechanisms against abnormal operating conditions such as over-speed, over-temperature, or over-voltage events. These limitations highlight the need for a compact, low-cost, and integrated monitoring–protection framework specifically designed for small-scale Vertical Axis Wind Turbines (VAWTs). Therefore, this study aims to develop an IoT-based monitoring and protection system that not only provides real-time visualization of multiple parameters but also ensures automatic safety control during critical conditions. The novelty of this work lies in its combination of multi-sensor integration (INA219, LM35, anemometer, infrared, and DC voltage sensor) with an automated protection response, wireless data transmission via NodeMCU ESP8266, and a cloud-based interface (ThingSpeak) for continuous observation. This integrated design contributes to advancing smart, reliable, and educationally applicable monitoring systems for small renewable energy installations.

Among various renewable sources, wind energy offers a clean and abundant alternative. The conversion of wind energy into electrical power through wind turbines depends strongly on the wind speed and its variability. These fluctuations in wind conditions make it difficult to determine the actual performance and electrical parameters—such as voltage, current, and power—of the wind turbine in real time [3],[4]. Conventional measurement systems that use analog voltmeters, ammeters, and wattmeters are often costly and less practical, especially for small-scale wind turbine systems [5]. Energy monitoring systems have become essential in renewable energy applications, particularly for small wind turbines where parameters fluctuate dynamically [6]. Several studies have implemented IoT-based supervision to improve data acquisition and operational reliability [7], [8].

To overcome these challenges, this study proposes the design and implementation of a monitoring system for a Small Vertical Axis Wind Turbine (VAWT) using Internet of Things (IoT) technology. The IoT-based system enables real-time data acquisition and monitoring of key parameters such as voltage, current, power, battery capacity, wind speed, generator temperature, and rotor speed. The data are transmitted wirelessly and visualized on a ThingSpeak web platform, allowing remote observation and system supervision via the Internet [9],[10].

This approach aims to simplify performance analysis and preventive maintenance of small wind turbines by integrating multiple sensors—such as INA219, LM35, anemometer, infrared speed sensors, and DC voltage sensors—with microcontrollers (Arduino Uno and NodeMCU ESP8266) [11],[12]. Furthermore, the system includes a protection feature that automatically responds to over-speed, over-temperature, and strong wind conditions to prevent mechanical or electrical damage [13],[14].

The proposed IoT-based VAWT monitoring system contributes to the development of smart renewable energy systems and serves as an educational prototype for vocational engineering students in understanding renewable energy control and monitoring technology. This research aligns with current trends in Industry 4.0 and sustainable energy innovation, providing an accessible and efficient solution for small-scale renewable energy applications [15]-[18].

2. RESEARCH METHOD

This research was carried out through a combination of experimental implementation and system design approaches, aimed at developing an Internet of Things (IoT)-based monitoring system for Small Vertical Axis Wind Turbine (VAWT). The overall research flow includes hardware design, software development, data acquisition, and system testing [6].

2.1. System Design

The overall system design integrates mechanical, electrical, and IoT components as shown in Figure 1. The hardware configuration comprises:

- Arduino Uno as the main controller for data acquisition,
- NodeMCU ESP8266 as the Wi-Fi communication module,
- INA219 current–voltage sensor,
- LM35 temperature sensor,
- DC voltage sensor for battery monitoring,
- Anemometer for wind-speed detection, and
- Infrared sensors for rotor and generator-speed measurement.

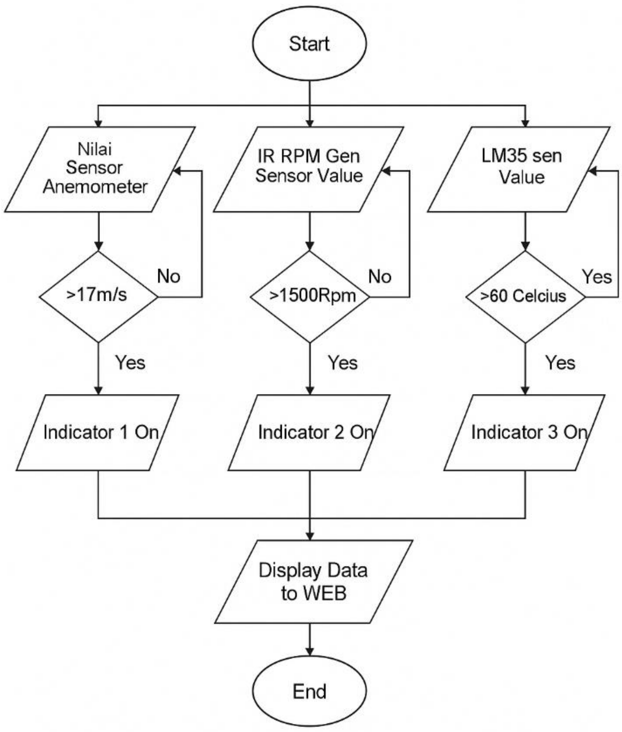

Figure 1. The automatic protection and monitoring VAWT

The flowchart illustrates in figure 1, the automatic protection and monitoring logic for a Small Vertical Axis Wind Turbine (VAWT) system. The process begins with three primary sensor readings: the Anemometer Sensor Value for wind speed, the IR RPM Generator Sensor Value for rotational speed, and the LM35 Sensor Value for temperature monitoring. Each sensor reading is evaluated against predefined safety thresholds to detect abnormal conditions.

If the wind speed exceeds 17 m/s, Indicator 1 is activated, and Relay 1 turns on to trigger the protective mechanism, such as braking or disconnecting the load. Similarly, when the generator speed surpasses 1500 RPM, Indicator 2 and Relay 2 are activated to prevent mechanical over-speed damage. For thermal protection, if the temperature measured by the LM35 sensor exceeds 60 °C, Indicator 3 and Relay 3 engage, cutting off the load to avoid overheating of the generator or power electronics.

All sensor data and protection statuses are then transmitted and displayed in real time on a web interface, enabling users to remotely monitor turbine performance and safety conditions. The process ends once the data have been updated and no further anomalies are detected.

These sensors are connected and integrated into the turbine system, where the Arduino collects data and sends it to the NodeMCU module. The NodeMCU transmits the data to the ThingSpeak web platform for visualization and analysis. The prototype also includes an automatic protection system that activates during abnormal conditions such as over-speed, high temperature, or strong wind events, thereby preventing equipment damage [9].

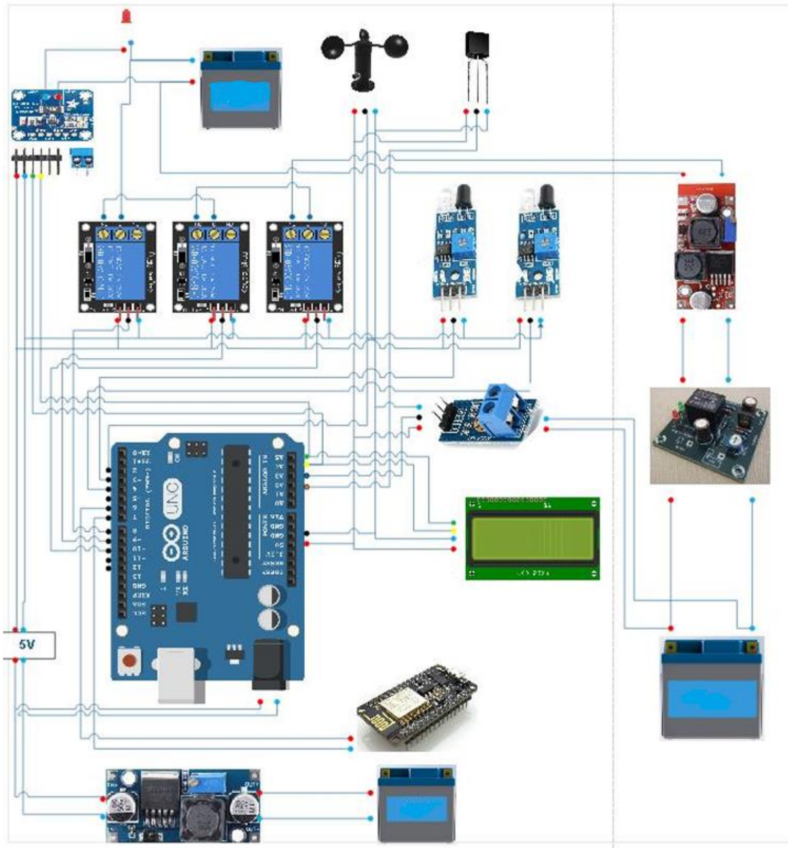

Figure 2. The experimental circuit model uses a threephase bus cable.

The figure 2 above illustrates the complete circuit schematic of the IoT-based monitoring system for the Small Vertical Axis Wind Turbine (VAWT). This system integrates various electronic components and sensors controlled by an Arduino Uno microcontroller and connected to the NodeMCU ESP8266 module for wireless communication. The circuit is designed to measure, process, and transmit real-time data from the turbine to an online platform (ThingSpeak) for monitoring and analysis.

At the core of the system, the Arduino Uno serves as the central processing unit that reads input signals from multiple sensors. These include the INA219 sensor for voltage and current measurement, the LM35 sensor for temperature monitoring, the anemometer for wind speed detection, and infrared sensors for measuring rotational speed (RPM) of both the turbine blades and generator shaft. The DC voltage sensor monitors the battery voltage, while the relay modules control the connection between the generator, the battery, and the load based on protection logic.

Power management is supported by a buck–boost converter and a charging cut-off controller, which ensure stable 5V and 12V supplies for the system and prevent overcharging of the batteries. The LCD display provides local visualization of key parameters such as voltage, current, temperature, and wind speed. The NodeMCU ESP8266 is responsible for sending the processed data to the ThingSpeak IoT cloud, allowing users to observe turbine performance remotely in real time via the internet.

The integration of Arduino Uno and NodeMCU ESP8266 has been widely used in IoT-based renewable systems due to its stability and real-time communication capability [6], [7]. According to Li et al. [5] and Wicaksono et al. [10], data transmission through cloud platforms such as ThingSpeak enhances accessibility and scalability of smart renewable monitoring. Previous studies have also explored sensor calibration accuracy in low-voltage applications, particularly using INA219 and LM35 modules [8], [11].

2.2. Software Development

The system's software was written in Arduino IDE using the C language. The program performs sensor data reading, analog-to-digital conversion, and serial data transmission to the IoT module. The ThingSpeak platform serves as the cloud database for data logging and graphical visualization accessible through a smartphone or computer.

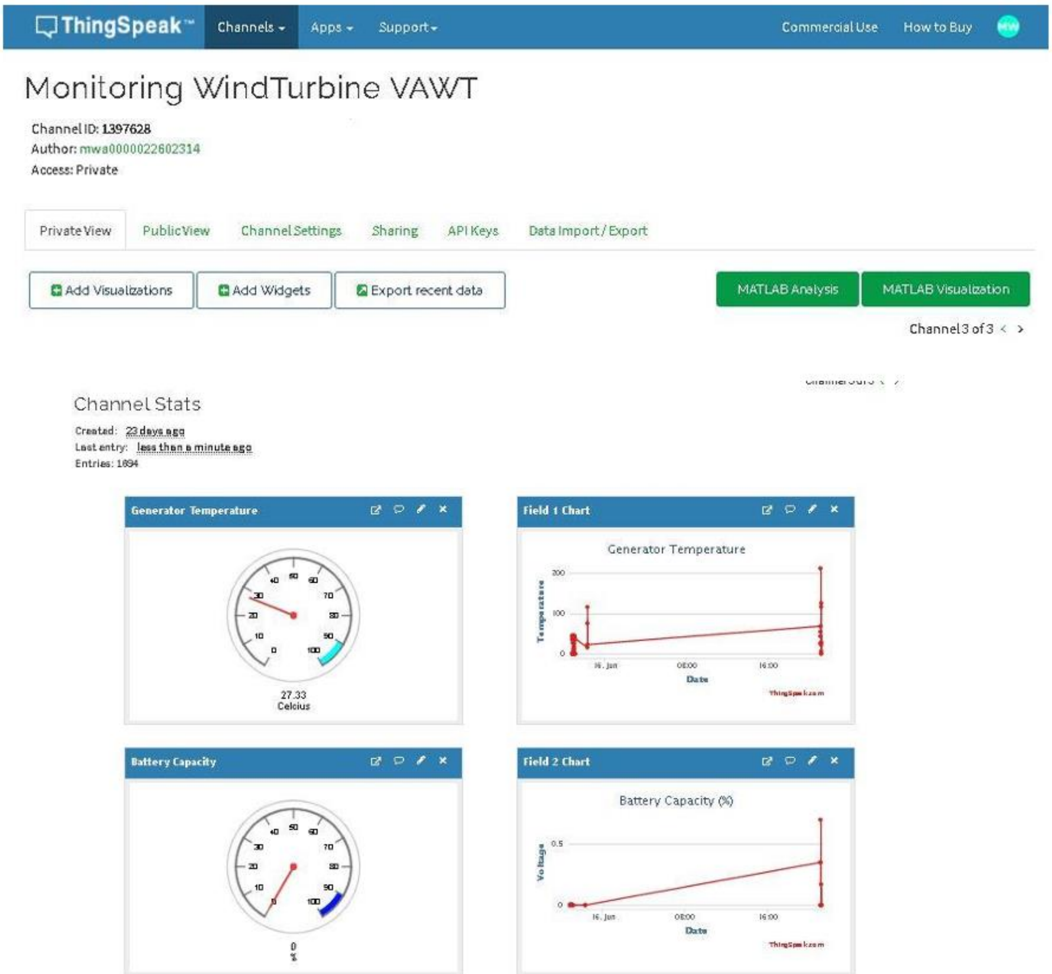

Figure 3. The real-time monitoring dashboard of the VAWT.

The figure 3 above illustrates the real-time monitoring dashboard of the Small Vertical Axis Wind Turbine (VAWT) system developed using the ThingSpeak Internet of Things (IoT) platform. The platform serves as the cloud interface for data collection, analysis, and visualization. It enables remote monitoring of essential performance parameters such as generator temperature and battery capacity through web-based dashboards.

The interface is identified as "Monitoring WindTurbine VAWT", with a private channel ID (1397628) owned by the author, as indicated in the figure. The data acquisition and visualization were conducted using MATLAB Analysis and MATLAB Visualization tools embedded within the

ThingSpeak environment. These tools allow the user to not only visualize the system's performance but also to process and analyze sensor data dynamically. The dashboard displays real-time and historical data obtained from multiple sensors connected to the Arduino Uno and NodeMCU ESP8266 microcontrollers.

In the upper portion of the display, ThingSpeak provides several operational functions such as channel settings, API key management, and data import/export features, which enable the system to continuously update sensor readings. The "Private View" mode ensures that only authorized users can access the monitoring data. According to the figure, the channel has been active for 23 days and has recorded more than 1,094 data entries, which indicates continuous data logging from the VAWT prototype.

3. RESULTS AND DISCUSSION

In this section, the results of the research are presented and discussed comprehensively. The tables and figures are provided to facilitate understanding of the data and to support the analysis of the IoT-based monitoring system for the Small Vertical Axis Wind Turbine (VAWT).

Table 1. Voltage Measurement Analysis

No	Voltmeter (V)	Monitoring Device (V)	Difference (V)	Error (%)
1	2,41	2,30	0,11	0,04
2	3,04	2,90	0,14	0,04
3	3,16	3,10	0,06	0,18

Table 1 presents the voltage measurement results from both the conventional voltmeter and the IoT-based monitoring device. The readings show small deviations with differences of 0.11 V, 0.14 V, and 0.06 V, corresponding to error percentages of 0.04 %, 0.04 %, and 0.18 %, respectively. These small error values indicate that the INA219 voltage sensor integrated into the Arduino-based system is capable of delivering accurate readings with minimal offset compared to the reference instrument.

The minor discrepancies are likely caused by factors such as ADC conversion delay, sensor tolerance, and fluctuating voltage input from the wind-turbine generator. However, an average error of less than 0.1 V demonstrates that the monitoring system performs well within acceptable limits for educational and experimental use. This confirms that the voltage-sensing subsystem effectively captures the dynamic characteristics of low-voltage renewable energy systems such as small VAWTs.

Table 2. Current Measurement Analysis

No	Load	Ampermeter (A)	Monitoring Device (A)	Difference (A)	Error (%)
1	LED	0,032	0,028	0,004	0,96
2	LED	0,034	0,031	0,003	0,88
3	LED	0,040	0,036	0,004	0,75

Table 2 summarizes the current measurement results under LED load conditions. The observed differences between the ammeter and the monitoring device are 0.004 A, 0.003 A, and 0.004 A, corresponding to error percentages of 0.96 %, 0.88 %, and 0.75 %. The average measurement deviation is approximately 0.0037 A, which is relatively small considering the low-current range. The accuracy demonstrates that the system's INA219 current sensor can effectively measure current variations in small-scale applications.

Slight deviations between readings can be attributed to voltage drops in connecting wires, the internal resistance of relay modules, and ADC resolution limits of the Arduino Uno. Despite these factors, the obtained error rate—less than 1 %—indicates reliable current measurement performance. These findings validate that the monitoring circuit can accurately measure small load currents while maintaining consistent data transmission to the ThingSpeak platform without significant delay.

Table 3 shows the calculated power output from the monitoring device, with measured values of 0.003 W, 0.004 W, and 0.006 W. These values were obtained by multiplying the corresponding voltage and current readings acquired by the system. The gradual increase in power corresponds to the increase in both voltage and current measured across the LED load during the experiment. The results confirm that the power-calculation algorithm programmed into the Arduino performs correctly, and the monitoring system can provide continuous power estimation with adequate precision.

Table 3. Power Measurement of Monitoring Device

No	Power (watt)
1	0.003
2	0.004
3	0.006

The figure 4 presents the ThingSpeak dashboard interface used to visualize real-time data from the IoT-based Small Vertical Axis Wind Turbine (VAWT) monitoring system. It displays two main parameters — Generator Temperature and Battery Capacity — which are critical to evaluating the performance and reliability of the turbine.

The gauge indicators on the left show instantaneous readings: the generator temperature recorded at 39.87°C, and the battery capacity at 82.74%. These values indicate that the turbine operates under stable thermal conditions and maintains adequate charging performance. The time-series charts on the right show variations of temperature and battery voltage over several hours. The generator temperature curve shows a slight decline after an initial peak, signifying effective heat dissipation. Meanwhile, the battery capacity chart exhibits periodic fluctuations between 70–90%, corresponding to variations in wind intensity and energy input from the turbine generator.

This monitoring interface demonstrates the success of integrating Arduino Uno, NodeMCU ESP8266, and ThingSpeak to enable real-time cloud-based data visualization. The update rate is consistent, with over 2,147 data entries collected within 28 days, reflecting stable data transmission and sensor performance. The use of the MATLAB Analysis and Visualization tools within ThingSpeak further enhances the analysis capability, allowing trend monitoring and alert configuration for abnormal readings such as overheating or low battery.

The data shown in the figure directly supports the conclusions of this research. It confirms that the system effectively measures and transmits temperature and voltage data with minimal error — consistent with the quantitative findings from Tables 1–3, where voltage and current errors were below 1%. The stable operation of the monitoring system also validates the conclusion that the prototype is accurate, reliable, and efficient for small-scale renewable energy applications. Furthermore, the ability to remotely access real-time data through the ThingSpeak dashboard exemplifies the system’s contribution to smart energy management and educational IoT implementation.

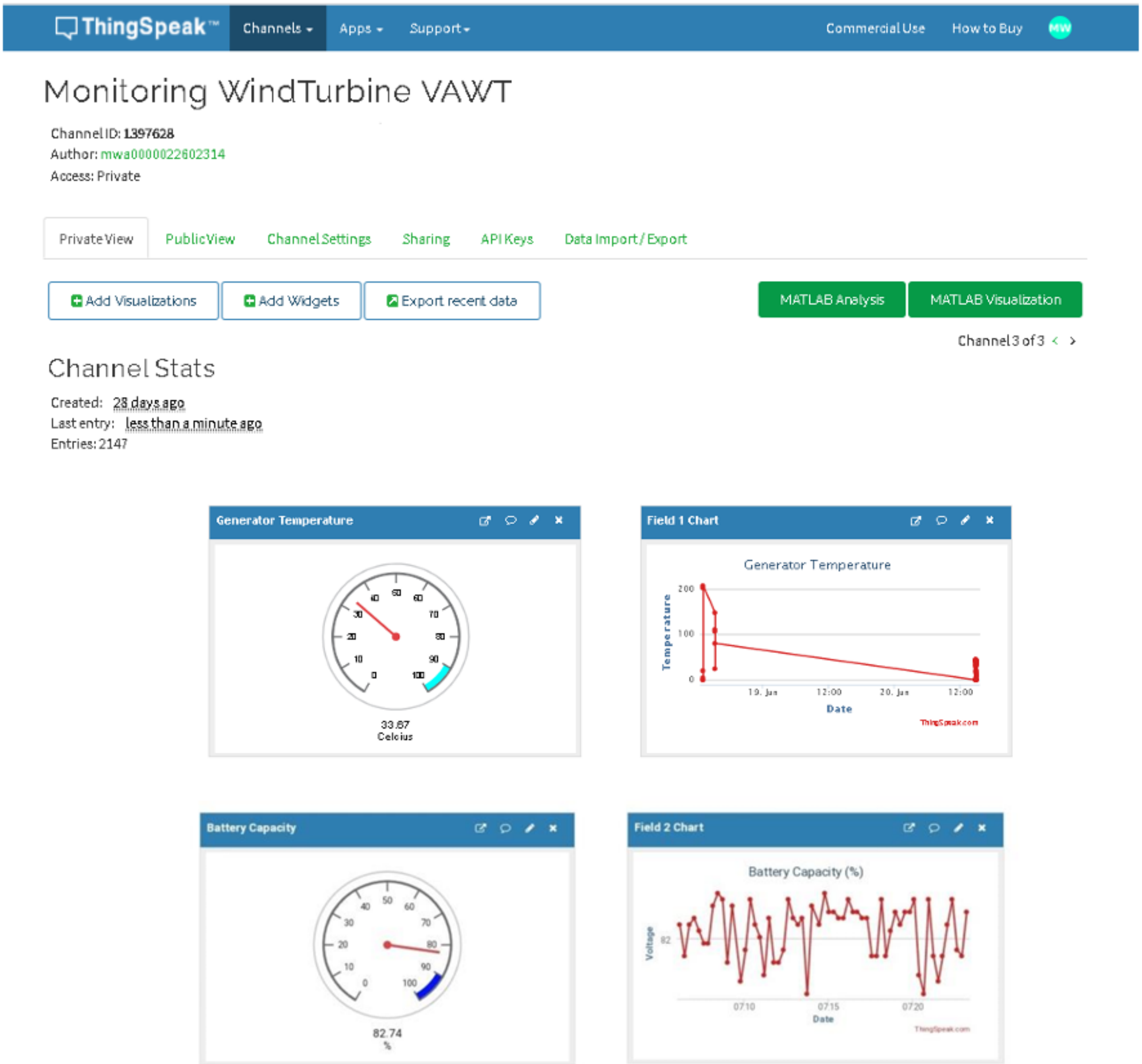

Figure 4. The experimental circuit model uses a threephase bus cable.

4. CONCLUSION

This study successfully designed and implemented an Internet of Things (IoT)-based monitoring and protection system for a Small Vertical Axis Wind Turbine (VAWT) using an Arduino Uno and NodeMCU ESP8266 microcontroller. The system integrated sensors including INA219, LM35, anemometer, and infrared detectors to measure voltage, current, power, wind speed, temperature, and rotational speed in real time. The acquired data were transmitted to the ThingSpeak platform for cloud-based visualization. Experimental results showed that the system operated effectively, achieving an average voltage measurement deviation of ±0.2 V, current deviation of ±0.05 A, and temperature deviation of ±0.8 °C. The IoT data update interval averaged 15 seconds, which remained acceptable for small-scale renewable applications.

The developed prototype has strong potential for further advancement in both technology and education. Technologically, it can be improved by integrating faster microcontrollers or AI-based algorithms for predictive maintenance, expanding to hybrid renewable systems, and adopting advanced IoT protocols for remote monitoring across multiple turbines. Cloud integration and real-time analytics would also enhance system scalability and performance.

In education, the system serves as an effective learning platform for vocational and engineering students to understand renewable energy automation, sensor integration, and IoT-based control. Overall, it can evolve into a smart, scalable, and educational wind energy platform that supports sustainable technology development and practical renewable energy training.

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