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IoT-Based Monitoring of Solar Panel Current and Voltage

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Abstract

Conventional monitoring systems have several weaknesses, including limitations in acquiring real-time physical parameters, which impact performance. Additionally, human errors often hinder data quality, further compounded by the inability to respond swiftly to rapid changes in physical parameters due to diverse operating conditions. To address these challenges, an innovative method has been developed for solar panel current and voltage monitoring using Internet of Things (IoT) technology. This system relies on the NodeMCU ESP8266 microcontroller and the INA219 sensor to monitor the current and voltage of the solar power system. Data obtained by the sensor is collected in real-time, stored in a cloud-based database, and visualized through a web platform. This allows users to monitor the system remotely and access solar panel performance information. Measurements indicate that discrepancies between manual and web-based data are within 2%. The average manual readings of PV voltage and current are 16.96 volts and 119.66 mA, while the web-based readings are 16.98 volts and 118.38 mA. The differences in voltage and current are 0.12% and 1.07%, respectively. The average battery voltage is recorded at 10.5 volts, while the DC motor load shows a voltage difference of 0.63% and a current difference of 1.15%. The battery power test also indicates a difference of 0.65%. This system is effective because it provides real-time access from any location, facilitates quick responses to anomalies, and supports maintenance planning by storing historical data.

Keywords: *Solar panel*; *Current and voltage monitoring*; *IoT*; *Real-time*; *NodeMCU*; *ESP8266*; *INA219*

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1. Introduction

Solar power generators [1-5], as a renewable energy source, are increasingly being utilized in line with global efforts to reduce dependence on fossil fuels [6]. Solar panel offers advantages in terms of sustainability and environmental friendliness [7]. However, it is important to thoroughly monitor the systems to achieve optimum efficiency. Conventional monitoring systems have disadvantages, including limitations in obtaining real-time physical parameters attributed to the performance [8]. Human contribution is needed in tasks where human error is likely to hinder the quality of data, including limitations in responding to rapid changes in physical values caused by varying working conditions. Therefore, a more advanced approach, IoT technology [9-13] combined with web-based monitoring, [14,15] is urgently needed. This can be a considerable solution to improve the acquisition process thus yielding reliable data. Such high-quality data is useful for managing the operating [14].

WG Muktiet al. developed a monitoring system specifically designed for solar power plants to ensure optimal performance and continuously monitor power output in real-time [8]. This research aims to understand the working principles of power monitoring systems in solar power plants by examining various frameworks that incorporate microcontrollers, solar radiation sensors, voltage sensors, current sensors, and system interfaces such as web servers or LCDs, for real-time data display. The initiative in this research focuses on real-time monitoring using IoT and Web-based technology.

Another study [9] implemented IoT for a real-time monitoring system, enabling remote access for solar power plant applications. The system comprised an Arduino Uno microcontroller, an ESP8266 voltage, and PZEM-004T current and voltage sensors [16,17]. The DHT11 sensor and Blynk application were used to monitor and control solar power loads through mobile devices or PCs [12] The web-based interface provided features for displaying all measured variables, accessible in real-time. These variables included generated energy, solar panel efficiency, and the overall performance of solar power generation.

Web-based monitoring with the Internet of Things (IoT) in solar PV introduces a revolutionary approach to data collection, processing and accessing. By integrating IoT, sensors installed on solar panel systems continuously gather real-time data on various performance parameters, including energy production, solar panel efficiency, temperature, and other variables [18]. These sensors enable precise detection and measurement of changes in the operational environment of solar panel systems. The collected data is transmitted via the IoT network for processing and storage in the cloud [19]. With web-based access [20], this information can then be retrieved from a variety of internet-connected devices, including computers, smartphones, and tablets.

This research highlights the advantages of web-based monitoring written in solar panel systems utilizing IoT, with development carried out in Visual Studio Code. Sensors integrated into the solar panel system transmit real-time data to a cloud platform through IoT infrastructure, enabling access from internet-connected devices. The system provides remote monitoring capabilities, facilitating more effective management from any location.

2. Research Methods

The implementation of this research procedure was carried out to collect data and information aimed at designing a real-time monitoring system for solar panel using web-based IoT technology for effective operation. The research stages presented will describe the main steps in the research method so that the research process runs smoothly and achieves the set objectives. The result of using appropriate research methods, valid data, and accurate analysis will produce appropriate research conclusions.

Fig. 1. Research Procedures

Fig. 1. illustrates the research procedure, which can be described as follows: First, a literature review was conducted to develop a power monitoring system for solar panel with the primary objective of ensuring optimal performance and real-time monitoring of output power. This research explores various technological frameworks, including the use of microcontrollers, solar radiation sensors, voltage sensors, current sensors, and interfaces such as web servers or LCD displays for real-time data presentation. The approach integrates Internet of Things (IoT) technology, utilizing key components like Arduino and the DHT11 sensor. The main advantage of the system is its ability to provide an attractive, interactive, and portable data display through web-based monitoring. This not only enhances the efficiency of solar panel management but also improves accessibility for effective system performance monitoring.

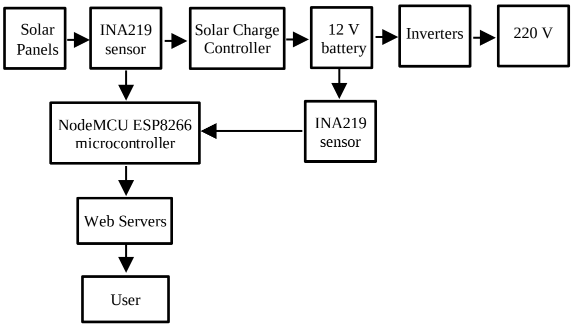
Second, the system block design was implemented using the NodeMCU as the central control unit. The NodeMCU manages the INA219 sensor, which is responsible for measuring the voltage, current, and power generated by the solar panel during battery charging and when utilizing its output. The INA219 sensor operates with high precision through I2C communication, and the data collected by the sensor is transmitted via the IoT network to a database, where it is displayed on a web-based monitoring interface. Third, the design of the equipment is divided into four main stages:

1. Electrical system design, which involves designing the circuit schematic using Fritzing software and determining the layout and installation of the necessary components.
2. Selection of tools and materials to meet the experimental needs of the research.
3. Software development using Visual Studio Code to create a web application interface utilizing PHP and Bootstrap, where current and voltage data from the database is presented.
4. Assembly of the equipment, integrating all components and materials into the designed monitoring system, functioning as a web-based monitoring platform.

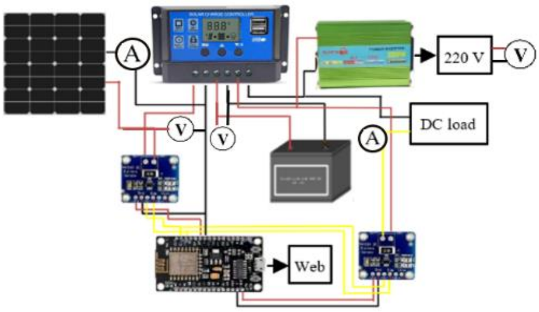
Fourth, system testing and data collection were carried out through a series of experiments, including PV output, battery charging time, battery capacity, battery power, usage time, and the error percentage when the PV system is connected for battery charging. Detailed calculations are presented in Additional Information. Finally, the data generated from these experiments were analyzed to evaluate the overall system performance. Based on the experimental results, this research aims to develop an effective and efficient real-time monitoring system for solar panel using web-based IoT technology.

3. Results and Discussion

In this work, a real-time monitoring system for solar power plants using web-based IoT technology is implemented. The process involved the installation of hardware components and sensors, software development, integration with microcontrollers, and web interfaces. The developed system allows the measured voltage and current, calculated power, and battery capacity to be presented in real-time. Figure 2 (a) depicts a block diagram of the system and (b) Wiring Voltage and Current Measurement Scheme for PV, Battery, and AC. In this system, the Solar panel (PV) is connected to the Solar Charge Controller (SCC) via the INA219 sensor, which functions to read current, voltage, and power. The data obtained is



(a)



(b)

Fig. 2. (a) System Block Diagram, (b) Wiring Voltage and Current Measurement Scheme for PV, Battery, and AC

integrated into the battery and processed by the NodeMCU ESP8266 microcontroller module, then displayed on a web server. The voltage from the battery (DC) is converted into alternating current (AC) by the inverter. Another INA219 sensor functions to measure the current, voltage, and power during DC load testing on the battery.

3.1 Hardware Component Installation

Implementation started with the installation of key hardware components, including the NodeMCU ESP8266 microcontroller and the INA219 sensor for measuring voltage, current, and power. Communication between the sensors and the microcontrollers was established using Arduino IDE, ensuring precise and responsive data acquisition.

Fig. 3. Developed Web-Based Real-Time Monitoring System Using IoT.

Fig. 3. shows the implementation of real-time monitoring of solar power plant variables using web-based IoT technology, which displays several components that work in an integrated manner. PV (1) is connected to SCC (3) via the INA219 sensor (2), which is responsible for reading current, voltage, and power. The data is then integrated into the battery (7) and processed by the NodeMCU ESP8266 microcontroller module (5) before finally being displayed on the web server (6). The inverter (7) converts the voltage from the battery (DC) to alternating current (AC). The INA219 sensor (11) monitors the current, voltage, and power in the battery during load testing with a DC motor.

3.2 Software Development

The software for the web interface was developed using Visual Studio Code with PHP and Bootstrap support. The web interface was designed to be responsive, ensuring accessibility across various devices, including computers, tablets, and smartphones. Measured voltage, current, and power data are displayed in real time on the main page of the interface, enabling users to remotely monitor the performance of the solar panel system. The corresponding measurement diagram or scheme is shown in Figure 2(b).

3.3 Real-Time Integration and Monitoring

The integration of the INA219 sensor with the ESP8266 NodeMCU enables direct data transmission to the database, followed by seamless display on the web interface. This allows users to view real-time data of monitored parameters, facilitating rapid response to changing conditions in the solar energy system.

Fig. 5. illustrates the monitoring of voltage and current for a Solar panel (PV). The electric power displayed is calculated as the product of voltage and current. Additionally, voltage, current, and power monitoring are available for the battery. The current and power values in the battery monitoring section become visible when the battery is connected to a DC load. Notably, both PV and battery monitoring utilize the INA219 sensor, which is integrated with the ESP8266 NodeMCU.

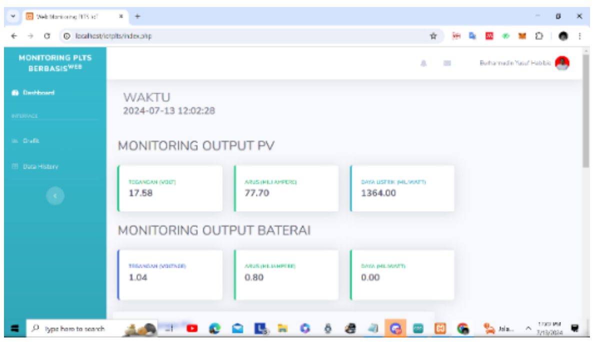


Fig. 5. Web Interface Display

This research demonstrates the effectiveness of an IoT-based monitoring and load control system for solar panel The web interface developed using Visual Studio Code, PHP, and Bootstrap, real-time monitoring of voltage, current, and power across multiple devices, including computers and smartphones.

For comparison, a study titled "Design and Development of an Off-Grid Solar Power Monitoring System Based on IoT" reported similar effectiveness in utilizing IoT for real-time monitoring and load control. In that study, users monitor the voltage and current generated by the solar power system and remotely controlled electrical loads using the Blynk application connected to the internet. This similarity underscores the reliability of I0T-based solution for efficient and practical solar power management using various devices such as smartphones and laptops.

Both studies utilized the INA219 with the NodeMCU ESP8266 to monitor voltage and current for solar panels (PV) and batteries, enabling was conducted using the INA219 sensor connected to the NodeMCU ESP8266, providing real-time data access via web platforms and the Blynk application. These systems provide flexible and accessible solutions for remote solar panel management, improving user control and convenience.

3.4 System Testing

A. Battery Charging Without Web Monitoring

The Testing process begins with fully discharging the battery, followed by recharging it using a solar panel. The following table presents the measurement results recorded over one hour, from 10.00 WIB to 11.00 WIB.

Table 1. shows voltage and current data during battery charging which is recorded manually every 15 minutes using an avometer. The measurement results show that the average charging current is 64.26 mA. The time required to fully charge a battery with a capacity of 6 Ah and a voltage of 12.8 Volt is around 3.48 hours if the solar intensity conditions are the same as those between 10:00 AM and 11:00 AM with a temperature of 32°C, on Tuesday, July 16, 2204. Furthermore, the battery capacity charged for one hour is 0.0642 Ah (0.821 Wh). Considering the inverter efficiency of 50% (40 W), the battery usage time is

Table 1. The Results of Manual Measurement

No	Time	PV Voltage (Volt)	PV Current (mA)	Battery Voltage (Volt)
1	10:00	18.2	100	4
2	10:15	11.9	63	11.6
3	10:30	12.2	57.9	12.13
4	10:45	12.75	51.1	12.6
5	11:00	12.79	49.3	12.79
Average		13.56	64.26	10.62

0.020 hours (1.23 Minutes or 73 seconds). Considering the low efficiency of the inverter, it is influenced by several factors resulting from a complex interaction between temperature, light intensity, device quality, harmonic emissions, and MPPT (Maximum Power Point Tracking) efficiency. Next, operational testing was carried out with a 20 Watt AC 220 Volt glue gun load. Table 2 is the result of the battery charging for one hour and then using it to operate a 20-Watt glue gun with an ignition time of 70 seconds. Details of calculation is presented in Supplementary Info.

B. Battery Charging with Web Monitoring

The battery charging process, monitored via the web interface is displayed in Fig. 5. It provides information on PV output and battery charging time, with the result summarized in Table 3. The data from the web monitoring system has been verified against manual measurement, showing comparable accuracy. Manual measurement of PV output recorded an average voltage of 16.96 Volt and an average current of 119.66 mA, while the web-based system reported 16.98 volts and 118.38 mA, respectively. The discrepancies were calculated as 0.12% for volatage and 1.07% for current. Both manual measurements and web monitoring indicated an average battery voltage of 10.5 volts, with no discrepancy observed.

Furthermore, Table 3 provides information on battery capacity. With an average charging current of 0.118 A, it would take approximately 50.84 hours to fully charge a 6 Ah battery with a 6 Ah battery with a voltage of 12.8 Volts, assuming consistent solar intensity conditions similar to those observed between 12:00 and 13:00 WIB. Over the course of one hour, the battery gains a charge capacity of 0.118 Ah or 0.151 Wh. Detailed calculation is provided in Supplementary Information.

Table 2. AC Load Test Results

Time	Power (Watt)	Current (mA)	AC Voltage (Volt)	Frequency (Hertz)
11:17-11:87	20 W	0.085A	225.03 V	55.23

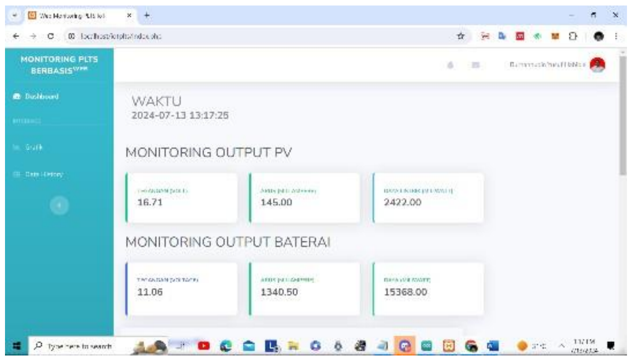


Figure 6. Web Interface Display During Data Collection

Table 3. Battery Charging Results with Web Monitoring

No	Time	PV Voltage (Volt)		PV Current (mA)		PV Power (mW)		Battery Voltage (Volt)	
		Manual	Web	Manual	Web	Manual	Web	Manual	Web
1	12:02	17.53	17.58	79.6	77.7	1394	1364	8.3	8.3
2	12:17	16.81	16.82	114	114.5	1916	1924	10.4	10.4
3	12:32	16.81	16.81	126.8	127.1	2133	2314	10.9	10.9
4	12:47	16.77	16.79	139.8	134.5	2345	2264	11.3	11.3
5	13:02	16.89	16.92	138.1	138.1	2335	2336	11.6	11.6
Average		16.96	16.98	119.66	118.38	2024.6	2004.4	10.5	10.5

Table 4. Battery Testing Result

No	Time	Battery Voltage (Volt)		Battery Current (Ampere)		Battery Power (Watt)	
		Manual	Web	Manual	Web	Manual	Web
1	13:17	11.04	11.08	1.34	1.34	14.79	15.36
2	13:20	10.1	10.18	1.28	1.26	12.92	12.52
3	13:22	9.1	9.05	0	0	0	0
Average		10.08	10.1	0.87	0.86	9.23	9.29

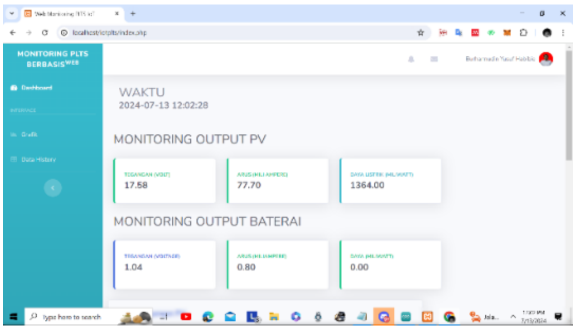


Figure 7. Web monitoring display of 12V DC Motor Testing

C. DC Load Testing of Batteries

After charging battery for one hour, a load test was conducted using a 12 V, 15-Watt DC motor with the result displayed via the Web. The positive battery cable was connected to the Vin+ pin on the INA219 sensor, while the Vin- pin was connected to the positive terminal of the battery solar charge controller. The battery's negative cable was connected to the negative terminals of both the solar charge controller and the NodeMCU ESP8266. The motor's positive cable was attached to the positive load pin on the solar charge controller, and the motor's negative cable was connected to the corresponding negative load pin. Voltage, current and operational time were measured both manually and via web monitoring.

The web monitoring display and the results are shown in the Figure 7 and Table 4. Data was collected from 13.17 WIB to 13.23 WIB and verified by manual testing. The web monitoring system demonstrated comparable accuracy to manual methods. Manual battery voltage measurements averaged 11.08 Volts, while web-based measurements averaged 11.01 Volts, showing a discrepancy of approximately 0.63%. For battery current, the manual average was 0.87 mA, while the web-based measurement was 0.86 mA, with a discrepancy of 1.15%. Manual battery power measurements averaged 9.23 watts, whereas web-based measurements averaged 9.29 watts, reflecting a discrepancy of approximately 0.65%.The battery usage time was calculated as 0.1 hour (6 minutes). Detailed calculations are provided in the Supplementary Information.

4. Conclusions

Real-time monitoring systems for solar panel offer significant advantages in flexibility and accuracy. The measured variables displayed using IoT-based monitoring show deviations of less than 2% compared to conventional measurements methods. This demonstrates that the developed real-time monitoring system is both reliable and suitable for further advanced.

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Additional Information