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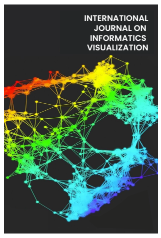

Solar Panel Monitoring System with Microcontroller Based Data Storage

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***Abstract*— Solar photovoltaic (PV) systems have been widely implemented in diverse applications, including buildings, traffic light systems, and public infrastructure, to reduce reliance on fossil fuels. However, the effectiveness of these systems depends on detailed and user-friendly monitoring, which remains a challenge due to cost and complexity barriers. This study addresses this gap by developing a low-cost, scalable PV monitoring system that integrates microcontroller-based sensors and data loggers to measure current, voltage, and power output in real time. The system is designed to be easily deployable and accessible, enabling broader adoption for renewable energy management. Using an experimental methodology, the system's accuracy was validated through voltage sensor error analysis, yielding an average error of 0.07%, demonstrating high precision. The proposed solution not only enhances monitoring capabilities but also contributes to the optimization of solar energy systems by providing reliable data for performance evaluation. This research underscores the potential of affordable monitoring tools to support the sustainable expansion of solar PV technology.**

***Keywords*— Solar PV systems; renewable energy monitoring; low-cost monitoring system.**

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I. INTRODUCTION

Indonesia, as a tropical country situated precisely on the equator, enjoys abundant and prolonged sunlight exposure compared to non-equatorial regions. This geographical advantage positions Indonesia as an ideal location for harnessing solar energy, a critical component of global efforts to transition from fossil-based energy systems to renewable alternatives. Among renewable energy technologies, solar power generation stands out due to its scalability and sustainability, offering a viable solution to the impending depletion of fossil fuels and their associated environmental degradation[1]. Solar energy systems have been widely adopted in diverse applications, including residential and commercial buildings, traffic light systems, and public infrastructure. These implementations aim to reduce reliance on fossil fuels, which are not only finite but also major contributors to pollution and climate change. However, the effectiveness of solar power systems hinges on real-time monitoring and user-friendly management, which remain challenging in many existing setups[2]–[5]. Current monitoring systems often lack accuracy, affordability, and ease of use, limiting their scalability and practical utility[6]–[8].

Previous research has explored various solar power monitoring systems, yet critical gaps persist. Studies have addressed data accuracy optimization and system cost reduction, but many solutions remain prohibitively complex or expensive for widespread deployment. For instance, while some systems achieve high precision, they require sophisticated hardware or proprietary software, rendering them inaccessible to smaller-scale users.

To address these limitations, this study proposes a low-cost, high-accuracy monitoring system capable of capturing real-time DC voltage and current data while providing trend analysis for voltage, current, and power measurements. The system prioritizes simplicity, user-friendliness, and scalability, integrating data storage capabilities and battery-powered operation to ensure reliability in diverse settings. By combining affordability with robust functionality, this research aims to democratize access to advanced solar monitoring, ultimately supporting Indonesia's renewable energy transition.

II. MATERIAL AND METHOD

This research uses the R&D (Research and Development) method. The R&D method is a research method used to produce a certain product and test its effectiveness.

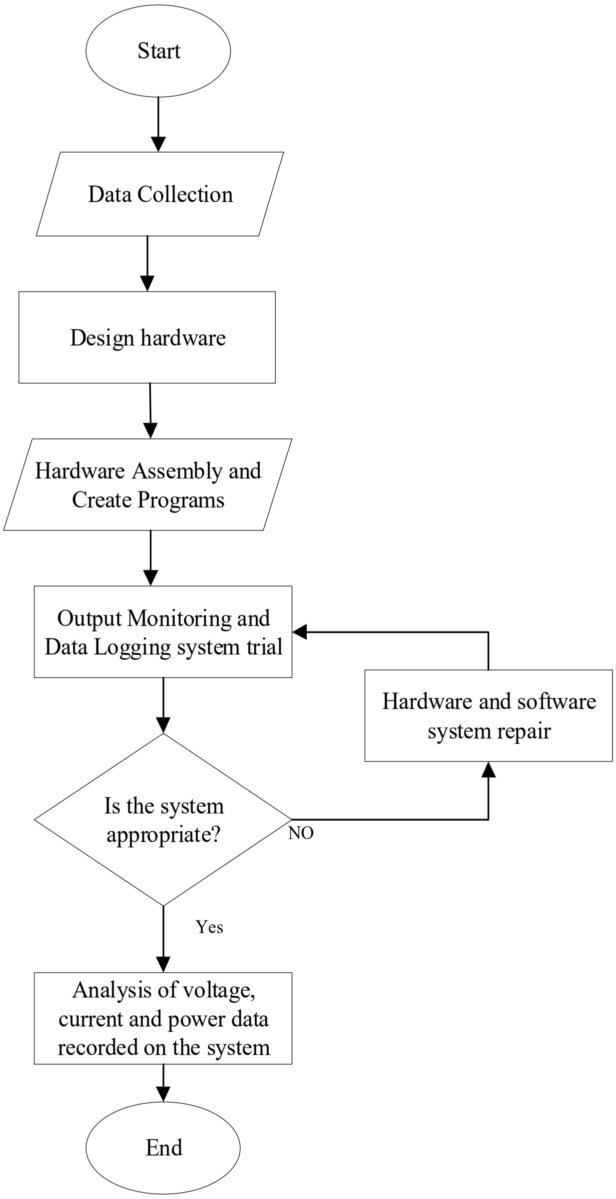


Fig. 1 Flowchart

As illustrated in the flowchart above, the research process begins with data collection, followed by hardware design and software development, including component selection and programming using the Arduino IDE software. Subsequently, the hardware and software are assembled, which involves constructing the device and uploading the program to the microcontroller. Next, the monitoring system is tested on the research object—in this case, a solar panel. The system is then evaluated to determine whether it functions according to the desired standards. If it meets the requirements, the photovoltaic system data (voltage, current, and stored power) is analyzed. If not, system improvements are made, including checking for assembly errors. If errors are detected, the hardware and software assembly process is repeated. However, if no assembly errors are found, a redesign of the hardware and software is conducted. The process is considered complete once the system operates in accordance with multimeter measurement standards.

The purpose of this research design is to facilitate the tool development process and produce a well-functioning device that meets the required specifications, taking into account the components used. Additionally, this research design aims to provide solutions to existing problems based on literature reviews and related projects.

A. System Block Diagram

The block diagram of the system is assembled, as shown in Figure 2.

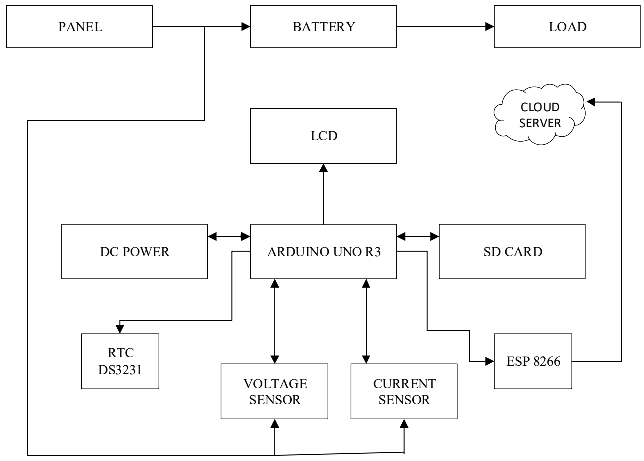


Fig. 2 System Block Diagram

B. Circuit Design

1) Current Sensor Circuit

ACS712 current sensor circuit has a function as a current detector in an electrical circuit [9]–[12]. The current sensor design can be seen in the picture below:

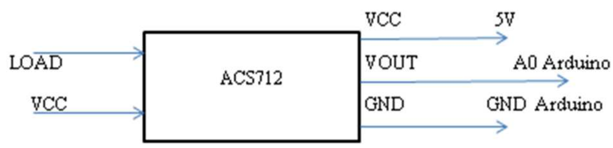


Fig. 3 ACS712 Sensor circuit.

Figure 3 is a current sensor circuit where the current sensor module has five pins, two pins that will be connected to the voltage source connected to the load. The other three pins are VCC, Vout, and GND pins. Where this VCC pin will be connected to the 5V source pin as a source for the current sensor module, the vout pin will be connected to the A0 analog pin on the Arduino which will display the output of the current data read by the current sensor. The GND pin is connected to the GND pin on the Arduino. For this ACS712, the current sensor module is capable of reading a current of 20A [1], [13], [14].

2) Voltage Sensor Circuit

The voltage sensor circuit has the function of reading the voltage value in an electrical circuit. The voltage sensor circuit can be seen in the picture below:

Fig. 4 Voltage Sensor circuit

3) Liquid Crystal Display Circuit

LCD + i2C circuit as a monitoring device where the results generated by the sensors will be displayed on the LCD screen. The LCD + i2C circuit can be seen in the picture below:

Fig. 5 Modul LCD + i2C Circuit

As seen in Figure 3.5 above, an LCD + i2C circuit has four pins. The advantage of this LCD + i2C module is that it only requires four pins, so it saves GPIO, which, if using an LCD module without an i2C module, requires 16 pins to connect it. The GND pin is connected to the Arduino GND pin, the VCC pin is connected to the Arduino pin-5V, the SDA pin is connected to the Arduino SDA pin, and the SCL pin is connected to the Arduino SCL pin.

4) Modul SD Card

The SD Card module circuit functions to store data (Data Logger) read on the sensor. The SD Card module circuit can be seen in the picture below:

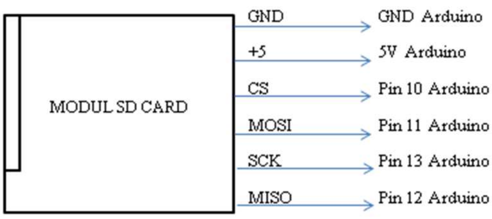


Fig. 6 SD Card Module circuit.

Figure 6 above is a picture of the SD Card module circuit (Data Logger). Where this module has 16 pins, but only six pins are used between the GND pin, + 5, CS, MOSI, SCK, and MISO pins. The GND pin is connected to the GND pin on the Arduino, pin + 5 is connected to the 5V pin, which is the source for turning on the module, pin CS (SS = Slave Select) is connected to pin ten on the Arduino, pin-MOSI (Master Out Slave In) is connected to pin-11 Arduino, pin-SCK (System Clock) is connected to pin-13 on the Arduino, pin-MISO (Master In Slave Out) is connected to pin-12 Arduino. This SD Card reader and writer module circuit allows the microcontroller to read and write data to the SD Card [15]–[18].

5) RTC DS3231 circuit

The DS3231 RTC circuit functions as a device that will display the time at that time and for real recording in the data logger [2]. The DS3231 RTC module circuit can be seen in the picture below:

Fig. 7 RTC DS3231 circuit

Figure 7 above is a picture of the DS3231 RTC circuit where this module uses four pins, namely the SCL, SDA, VCC, and GND pins.

6) Battery Circuit

This battery circuit has a function as a source used by the microcontroller. The battery circuit can be seen as shown below:

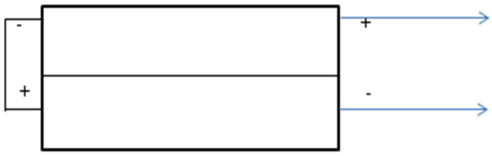


Fig. 8 18650 Battery circuit.

Figure 8 above is a picture of the battery circuit. The battery used is type 18650, with as many as two batteries [10], [15], [19], [20].

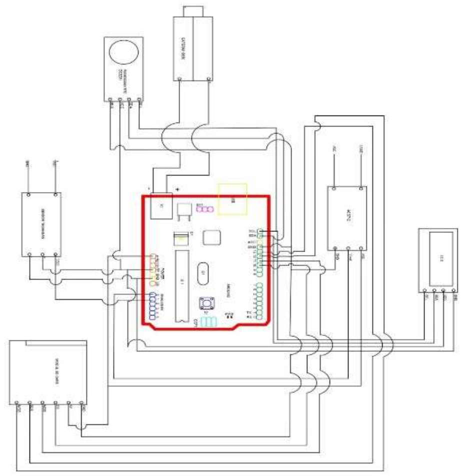


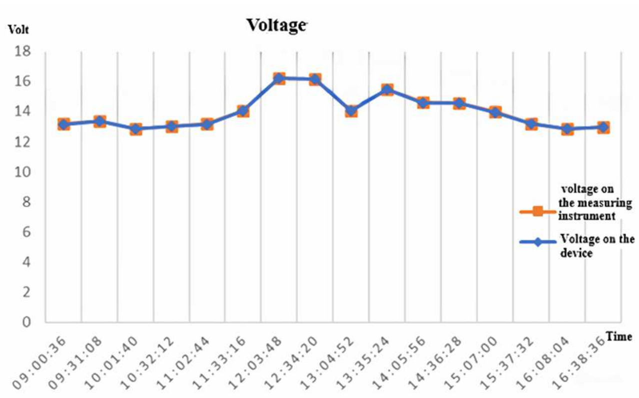
Fig. 9 Circuit flow diagram of the proposed model

Fig. 10 Suggested Prototype Models

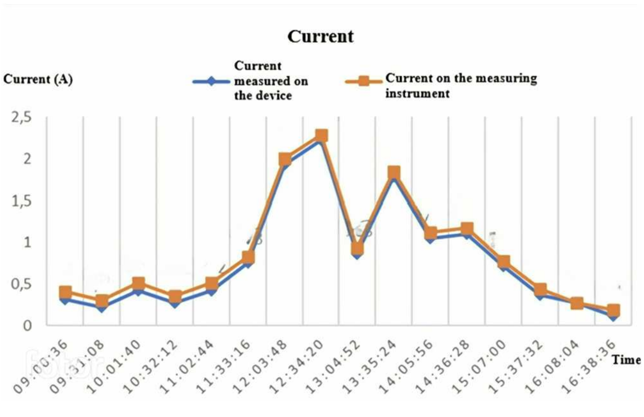
The figure above presents the component design and the structural layout of the constructed monitoring system. The system exhibits a compact design, owing to the small dimensions of its components. Following the completion of the component design phase, the subsequent stage involves system testing.

III. Result and Discussion

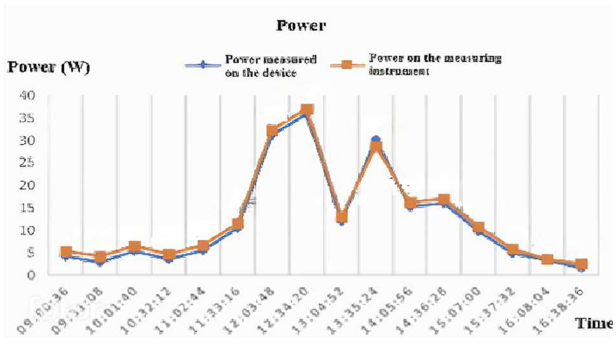
The output monitoring system and data recording on Arduino uno microcontroller-based solar panels can record the output measurement results from solar panels automatically on the SD card every 30 minutes, where the data stored on the SD card is in the form of date, month, year, hour, current, voltage, power, and temperature values, which are then stored in .txt format. The following is a graph of the test results of the voltage, current, power and temperature detection devices on solar panels.



(a)



(b)



(c)

Fig. 11 The measured parameters (a) voltage, (b) current, and (c) power of the solar panel were recorded between 9:00 AM and 4:00 PM

Figure 11 presents the data logger recordings from the implemented monitoring system over a 24-hour period. Under clear sky conditions, the current measurements demonstrate a distinct peak of 2.29A occurring at 12:34, corresponding to maximum solar irradiance levels during midday. This observed current profile directly influences the resultant power output, as evidenced by the parallel trends in the power measurement graph.

To validate system accuracy, rigorous comparative testing was conducted between the monitoring system's voltage measurements and those obtained from a calibrated reference multimeter. The subsequent data presentation provides a comprehensive evaluation of measurement accuracy, demonstrating the system's reliability and precision in photovoltaic performance monitoring.

TABLE I
Accuracy of the Monitoring System

No	Monitoring (V)	Multimeter (V)	Error
1	13,16	13,17	0,075%
2	13,37	13,38	0,074%
3	12,83	12,84	0,077%
4	13,04	13,05	0,076%
5	13,16	13,17	0,075%
6	14,03	14,04	0,071%
7	16,19	16,20	0,061%
8	16,14	16,15	0,062%
9	14,05	14,06	0,071%
10	15,48	15,49	0,064%
11	14,59	14,60	0,068%
12	14,57	14,58	0,0685%
13	13,96	13,97	0,071%
14	13,18	13,19	0,075%
15	12,83	12,84	0,077%
16	12,97	12,98	0,077%
	Average Error		0,071%

The presented table displays the accuracy assessment results of the developed monitoring system, obtained through comparative analysis with a calibrated multimeter as the reference measuring instrument. The experimental data demonstrate error values ranging from 0% (minimum) to 0.077% (maximum), yielding an average system error of 0.071%. These results confirm the measurement validity and reliability of the proposed monitoring system. The consistently low error margin (≤0.077%) indicates that the system maintains sufficient accuracy for practical implementation in real-world applications, establishing its viability as a dependable monitoring reference for solar power generation systems.

IV. Conclusion

Based on the test results and analysis conducted, it can be concluded that the Arduino Uno microcontroller-based monitoring system developed in this study has successfully achieved its purpose as a solar panel performance monitoring tool. The system effectively measures key parameters including current, voltage, power output, and temperature using integrated sensors, demonstrating excellent accuracy with an average error of only 0.071% when compared to precision measuring instruments. The system not only monitors data in real-time but also automatically records data to an SD card every 30 minutes, storing complete information including date, time, measurement values in .txt format for easier further analysis. The system's main advantages lie in its combination of high accuracy and affordable implementation cost through the use of standard components like Arduino Uno and conventional sensor modules. The research results prove that this solution is particularly suitable for small to medium-scale photovoltaic system monitoring applications, both for research purposes and field applications. Furthermore, this system provides a solid foundation for future development, such as adding wireless data transmission features or IoT platform integration that could enhance the system's functionality. With all its advantages and development potential, this monitoring system makes a significant contribution to efforts in optimizing solar energy utilization through accurate and cost-effective monitoring solutions.

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