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Solar Power Plant (PLTS) Power Monitoring System Based on the Internet of Things (IoT) Using the Blynk and Telegram Platforms

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Abstract – *Solar energy is one of the renewable energy sources that has the potential to be developed in Indonesia. However, monitoring the performance of Solar Power Plants (PLTS) is generally still carried out conventionally so that the data obtained is not real-time and makes it difficult to detect disturbances. The Internet of Things (IoT)-based PLTS electric power monitoring system is designed to monitor electrical parameters in real-time, including voltage, current, power, temperature, and humidity. The system design uses PZEM-004T, PZEM-017, and DHT11 sensors integrated with an ESP32 microcontroller as the main controller. The measurement data is displayed on an OLED screen and sent to the Blynk and Telegram applications as remote monitoring media with an automatic notification feature. The test results show that the system works well and has a high level of accuracy. During daytime testing, the highest DC and AC voltage values were recorded at 18.22 V and 233.8 V, respectively, while at night they reached 12.36 V and 228.1 V. The maximum DC current and power values were 0.44 A and 7.9 W, respectively. Comparison with manual measuring instruments showed very small measurement differences, namely 0.01–0.05 V for DC voltage and 0.1% for humidity, with an average error of only 0.07%. These findings prove that the developed IoT-based monitoring system is stable, accurate, and efficient in monitoring the condition of the solar power plant in real-time, and has the potential to be further developed on a larger scale through the integration of cloud storage and intelligent energy management.*

Keywords – *PLTS; IoT; Blynk; Telegram; Electric Power Monitoring.*

I. Introduction

IMPROVEMENT in electrical energy demand along with population growth and technological development pushes the utilization of New and Renewable Energy (NRE), particularly solar energy, which is very potential because Indonesia is located on the equator so that sunlight is available throughout the year [1]. Solar energy is utilized through photovoltaic (PV) modules in Solar Power Plants (PLTS), where the cleanliness of the panel surface becomes an important factor because the panels installed in open areas are easily exposed to dust [2]. The development of PLTS from household scale to large-scale installations requires routine maintenance so that potential damage can be minimized. In addition, the efficiency of PV systems is significantly affected by environmental factors such as temperature, light intensity, and surface cleanliness; therefore, adaptive monitoring strategies are required to maintain system performance [3].

However, PLTS management and monitoring still face challenges, such as limited real-time data access, less responsive manual checking, and monitoring system limitations that cause disturbances to remain undetected for a long time [4]. Limitations in electrical infrastructure and accessibility in outermost, remote, and underdeveloped areas (3T) also result in barriers for learning technology and public services that rely on stable electricity supply. Therefore, developing an independent PLTS-based energy solution not only enhances technical performance but also provides socio-economic benefits, for instance supporting educational devices and self-learning platforms in regions that are not yet connected to the electricity grid [5]. Independent solar power supply has been proven to enhance accessibility to education and digital services through the provision of stable energy for computer devices, internet networks, and information systems in 3T areas [6].

One of the most promising technical solutions that can be implemented to enhance the performance

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and operational reliability of solar power systems is the utilization of the Internet of Things (IoT) for automatic PLTS monitoring. IoT facilitates seamless connectivity between devices through a communication network, enabling operational and environmental data to be transmitted and accessed remotely in real time [7]. Numerous studies have highlighted the advantages of IoT in PLTS applications, particularly due to its high effectiveness in detecting system faults, identifying voltage–current deviations, performing early diagnosis of failures, and optimizing energy output through continuous data analytics that support informed decision-making [8]. Building upon these advancements, this research provides a meaningful contribution by developing a robust IoT-based PLTS monitoring system that integrates two digital platforms simultaneously, namely Blynk for real-time parameter visualization and Telegram for rapid delivery of critical notifications. The monitoring process is equipped with an adaptive mechanism capable of identifying potential operational disruptions, such as low battery voltage conditions (below 11 V), excessive panel temperatures (above 45°C), and anomalies in the power supply system.

In addition, this study implements a dual-side monitoring approach for both DC and AC electrical characteristics using PZEM-017 and PZEM-004T sensors, allowing comprehensive observation of the system's electrical behavior and resulting in improved characterization of PLTS performance compared to similar works that rely on single-side measurements. The system developed in this work is also recommended for implementation in Self-Study Platform (SSP) initiatives within 3T regions (remote, frontier, and underdeveloped areas), as it can strengthen access to reliable energy resources required for technology-assisted learning—therefore providing a broader social impact through the promotion of educational equality.

A multi-level alert mechanism is integrated into the system by utilizing a buzzer as a local alarm and Telegram as a remote notification medium. This combined security scheme provides faster response actions with user-friendly interaction while remaining cost-effective and is still rarely adopted in many previous PLTS monitoring implementations. The ESP32 microcontroller becomes an ideal core component because of its low cost, integrated Wi-Fi capability, sufficient processing power, and ability to measure essential performance indicators such as voltage, current, power, temperature, and humidity [9]. Moreover, the ESP32 is capable of performing on-device data processing (edge computing), enabling faster decision-making at the source node while reducing dependency on external cloud infrastructure [10], thus improving overall system resilience.

Furthermore, the utilization of the Blynk application facilitates user interaction by providing an intuitive dashboard capable of displaying real-time electrical data trends such as voltage stability, current flow dynamics, and power fluctuations [11]. At the same time, Telegram ensures immediate dissemination of early warning notifications to operators without requiring continuous manual surveillance. Prior research has proven that IoT-based notification frameworks significantly accelerate maintenance response times compared to conventional methods [12]. Natural disasters cause enormous damage and losses every year, both economic and in terms of human lives. It is essential to develop systems to predict disasters and to generate and disseminate timely warnings [13]. Beyond the operational and maintenance benefits, the deployment of reliable and accessible PLTS monitoring systems unlocks greater opportunities for widespread integration of renewable-based solutions into public services, especially in remote communities where energy accessibility remains a major challenge. Thus, the development and implementation of IoT-based PLTS monitoring technology not only reinforces sustainability in renewable energy management but also contributes to the advancement of social infrastructure such as education, aligning with national goals for equitable development in 3T areas [5]. With all these strengths, this research affirms that IoT-based PLTS monitoring represents a strategic innovation in enhancing reliability, sustainability, operational efficiency, and societal benefits of solar power technology [14].

II. Research Methods

This research focuses on the design and testing of an Internet of Things (IoT)-based electrical power monitoring system for Solar Power Plants (PLTS). The designed system is capable of transmitting real-time monitoring data to several media, namely an OLED display for local visualization, the Blynk application for remote monitoring, and the Telegram platform for automatic notifications. To validate the accuracy of transmitted data, sensor readings are compared with manual measurements using conventional electrical instruments. This study adopts an experimental approach in which performance data is obtained directly from field testing to evaluate the effectiveness of the proposed system.

WiFi communication performance evaluation shows satisfactory results. Measurement was performed using a ping test and connection monitoring during the testing period.

Response Time (Latency): The average data transmission latency from ESP32 to the Blynk server ranges from 150–300 ms under stable WiFi conditions with signal strength between -45 dBm and -65 dBm. This latency remains within acceptable limits for noncritical real-time monitoring.

Reliability: During continuous testing, the system successfully maintained a stable WiFi connection with an uptime of 98.5%. Connection disturbances were generally caused by AC power fluctuations, not device limitations.

Packet Loss: The recorded packet loss rate averaged 1.2%, which is classified as very good for IoT communication. Lost data can be recovered through the retry mechanism implemented on the ESP32 software.

Testing was conducted from April to July 2025 in Tinelo Village, Tilango District, Gorontalo Regency. Although data presented in this journal represents one daily test cycle, initial validation and repeated testing were conducted across a three-month period.

Field testing was conducted under three different operating conditions. In bright conditions with high sunlight intensity, the solar panel reached a maximum output voltage of 18.22 V with maximum power of 7.9 W, while ambient temperature remained between 38–41°C. Under cloudy conditions with medium sunlight intensity, the voltage was observed to range between 14–16 V and module efficiency experienced a reduction of approximately 15–25%; however, the polycrystalline panels were still able to generate power even under overcast weather. During nighttime operation with no sunlight available, the entire system was supplied by the battery, where the battery voltage decreased from 12.36 V to 11.22 V throughout three hours of continuous load usage, with system power consumption maintained around 3–4 W.

Limitations and Future Developments: Testing duration is still limited. Further work is recommended for long-term testing (6–12 months) to better evaluate performance under extreme weather variations.

i. Tool Design

The system is designed systematically to facilitate implementation and analysis. The design includes both software and hardware development. Software is built using the C language through Arduino IDE, while the hardware integrates an ESP32 microcontroller, sensors, and supporting modules.

ii. Tool Working System

Figure 1 illustrates the operation flow of the ESP32 system, starting from solar panel power input, sensor data acquisition, and real-time transmission to monitoring platforms.

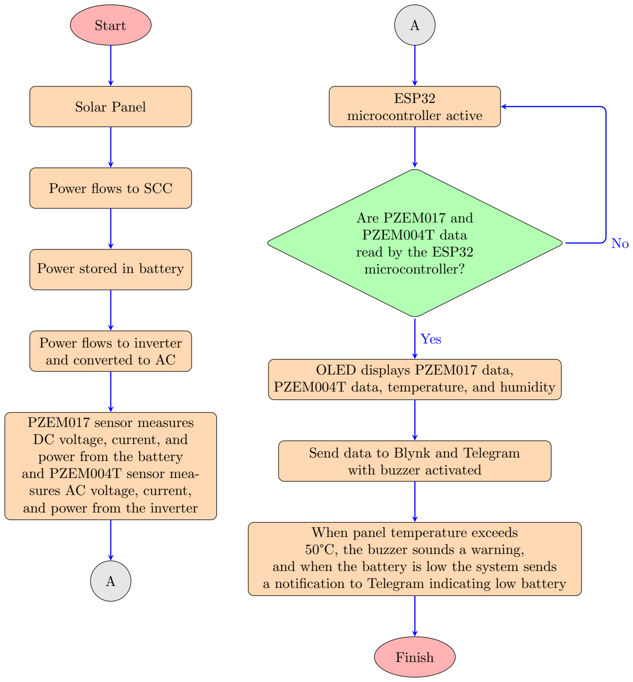

Figure 1: Program Flow on ESP32

iii. Wiring Schematic

The primary power source in the IoT-based PLTS monitoring system is a 30 Wp polycrystalline solar panel generating DC electrical output. The panel supplies a 60 A SCC which regulates charging for a 12 V 12 Ah battery to ensure safe operation. Energy from the battery is distributed to an inverter (500 W) for AC loads.

The ESP32 DevKit V1 serves as the main controller. A 12 V to 5 V LM2596 buck converter powers sensors and communication modules. The PZEM-017 is installed between the battery and the SCC to monitor DC parameters, while the PZEM-004T measures inverter AC output. A DHT11 sensor monitors temperature and humidity, visualized through a 1.3-inch OLED display using I2C communication. The system also includes an active buzzer that provides alarms during abnormal operational conditions.

The wiring schematic is shown in Figure 2.

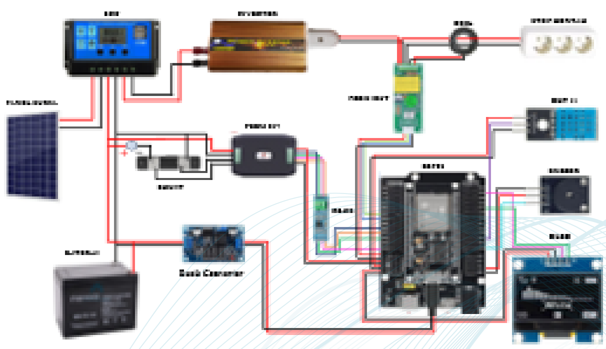

Figure 2: Solar Power Plant Monitoring System Circuit

iv. System Testing

Testing ensures that the integrated components operate synergistically and provide real-time accurate information [15]. The evaluation covered several aspects including sensor measurement accuracy, data transmission consistency to Blynk, Telegram notification functionality, WiFi connection stability during long-term operation, comparison with manual reference instruments such as a multimeter and clamp meter, and system performance under both daytime and nighttime conditions. Data was recorded periodically every hour and subsequently tabulated and analyzed in the form of tables and graphs for performance assessment [16].

III. Results and Discussion

The IoT-based solar power monitoring system is designed to monitor electrical parameters such as voltage, current, power, temperature, and humidity in real-time using the PZEM-004T, PZEM-017, and DHT11 sensors. Monitoring data is displayed on an OLED screen and transmitted to the Blynk and Telegram applications as remote interfaces. The system is equipped with an ESP32 microcontroller as the main controller and supports automatic notifications.

To verify measurement accuracy, statistical analysis was performed using Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and correlation coefficient (r) between the IoT-based monitoring system and manual measuring devices.

The results indicate that the monitoring system has a high degree of accuracy with correlation values close to 1 for all measured parameters, demonstrating a very strong linear relationship with reference instruments.

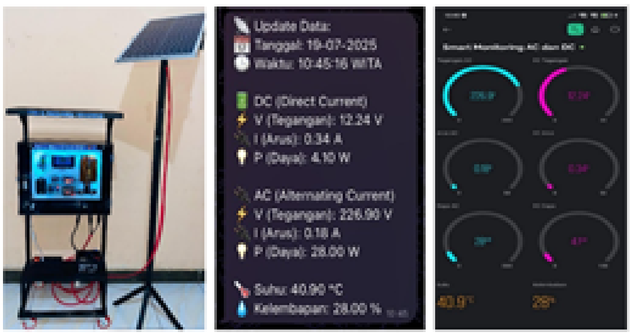

Figure 3: Final Design of the IoT-Based Solar Power Plant Monitoring System

To calculate measurement percentage error, the following equation is used:

$$\text{Error}(\%) = \frac{|X_{\text{measured}} - X_{\text{reference}}|}{X_{\text{reference}}} \times 100\%$$

Information: X_{measured} = Reading from IoT monitoring system $X_{\text{reference}}$ = Reading from manual instrument

The comparison results of system readings and manual measurements during daytime operation are shown in Table 2.

(Note: Table truncated — full table will be continued in the next page)

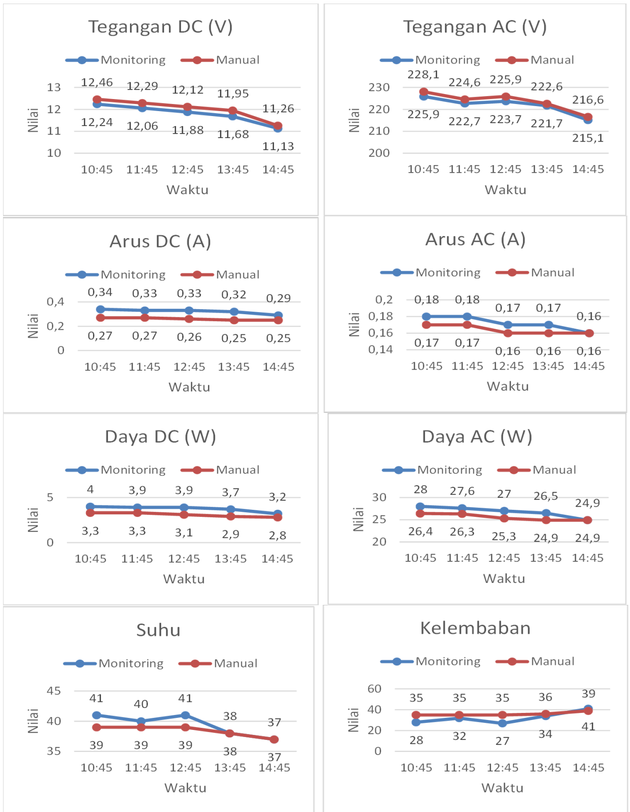

Figure 4: Voltage, Current, Power, Temperature, and Humidity Trend Graph During Daytime

Based on testing from 10:45 to 14:45, all key parameters (voltage, current, power, temperature, and humidity) showed consistent trends that correspond to environmental conditions and applied loads. This indicates that the proposed IoT monitoring system is capable of detecting performance changes accurately and in real-time.

In general, the test results show that voltage and current values (both DC and AC) gradually decreased over time. This occurs because the stored power in the battery decreases due to continuous load usage and reduced sunlight intensity as evening approaches [17]. This reduction also directly affects power generation, where DC power decreased from 4 W to 3.2 W, and AC power declined from 28 W to 24.9 W.

A small difference exists between monitoring results (blue) and manual instruments (red). However, these differences are very small, mostly around 0.1–0.3, thus it can be concluded that the ESP32 microcontroller-

Table 1: Statistical Accuracy Analysis of Sensor Measurements

No	Date & Time	Load type	Parameter	Monitoring tools	Manual tools	Percentage error (%)
1	07/19/2025 10:45	DC fan	DC voltage (V)	12.24	12.46	0.01
		DC fan	DC current (A)	0.34	0.27	0.20
		DC fan	DC power (W)	4.00	3.30	0.20
		AC fan + aroma therapy	AC voltage (V)	226.9	229.2	0.01
		AC fan + aroma therapy	AC current (A)	0.18	0.17	0.05
		AC fan + aroma therapy	AC power (W)	28.0	26.4	0.06
		AC fan + aroma therapy	Temperature (°C)	41	39	0.05
		AC fan + aroma therapy	Humidity	28	35	0.20
2	07/19/2025 11:45	DC fan	DC voltage (V)	12.06	12.29	0.01
		DC fan	DC current (A)	0.33	0.27	0.20
		DC fan	DC power (W)	3.90	3.30	0.10
		AC fan + aroma therapy	AC voltage (V)	225.4	227.6	0.01
		AC fan + aroma therapy	AC current (A)	0.18	0.17	0.05
		AC fan + aroma therapy	AC power (W)	27.6	26.3	0.04
		AC fan + aroma therapy	Temperature (°C)	40	39	0.02
		AC fan + aroma therapy	Humidity	32	35	0.08
3	07/19/2025 12:45	DC fan	DC voltage (V)	11.88	12.12	0.01
		DC fan	DC current (A)	0.33	0.26	0.20
		DC fan	DC power (W)	3.90	3.10	0.20
		AC fan + aroma therapy	AC voltage (V)	223.7	225.9	0.01
		AC fan + aroma therapy	AC current (A)	0.17	0.16	0.06
		AC fan + aroma therapy	AC power (W)	27.0	25.3	0.07
		AC fan + aroma therapy	Temperature (°C)	41	39	0.05
		AC fan + aroma therapy	Humidity	27	35	0.20
4	07/19/2025 13:45	DC fan	DC voltage (V)	11.68	11.95	0.02
		DC fan	DC current (A)	0.32	0.25	0.20
		DC fan	DC power (W)	3.70	2.90	0.20
		AC fan + aroma therapy	AC voltage (V)	221.7	222.6	0.01
		AC fan + aroma therapy	AC current (A)	0.17	0.16	0.06
		AC fan + aroma therapy	AC power (W)	26.5	24.9	0.06
		AC fan + aroma therapy	Temperature (°C)	38	38	0.00
		AC fan + aroma therapy	Humidity	34	36	0.06
5	07/19/2025 14:45	DC fan	DC voltage (V)	11.13	11.26	0.01
		DC fan	DC current (A)	0.29	0.25	0.10
		DC fan	DC power (W)	3.20	2.80	0.10
		AC fan + aroma therapy	AC voltage (V)	215.1	216.6	0.01
		AC fan + aroma therapy	AC current (A)	0.16	0.16	0.00
		AC fan + aroma therapy	AC power (W)	24.9	24.9	0.00
		AC fan + aroma therapy	Temperature (°C)	37	37	0.00
		AC fan + aroma therapy	Humidity	41	39	0.05

Table 2: Test Results During Daytime Operation.

No	Date & Time	Load type	Parameter	Monitoring tools	Manual tools	Percentage error (%)
1	07/19/2025 20:30	DC fan	DC voltage (V)	12.14	12.36	0.02
		DC fan	DC current (A)	0.33	0.27	0.20
		DC fan	DC power (W)	4.00	3.30	0.20
		AC fan + aroma therapy	AC voltage (V)	225.9	228.1	0.01
		AC fan + aroma therapy	AC current (A)	0.15	0.16	0.06
		AC fan + aroma therapy	AC power (W)	24.2	25.9	0.07
		AC fan + aroma therapy	Temperature (°C)	28	29	0.03
		AC fan + aroma therapy	Humidity	71	61	0.10
2	07/19/2025 21:30	DC fan	DC voltage (V)	11.78	11.98	0.02
		DC fan	DC current (A)	0.32	0.26	0.20
		DC fan	DC power (W)	3.70	3.10	0.20
		AC fan + aroma therapy	AC voltage (V)	222.7	224.6	0.01
		AC fan + aroma therapy	AC current (A)	0.14	0.15	0.07
		AC fan + aroma therapy	AC power (W)	23.6	25.2	0.06
		AC fan + aroma therapy	Temperature (°C)	28	29	0.03
		AC fan + aroma therapy	Humidity	68	61	0.10
3	07/19/2025 22:30	DC fan	DC voltage (V)	11.22	11.38	0.01
		DC fan	DC current (A)	0.31	0.25	0.20
		DC fan	DC power (W)	3.40	2.80	0.20
		AC fan + aroma therapy	AC voltage (V)	216.5	218.4	0.01
		AC fan + aroma therapy	AC current (A)	0.14	0.15	0.07
		AC fan + aroma therapy	AC power (W)	22.1	23.5	0.06
		AC fan + aroma therapy	Temperature (°C)	27	28	0.04
		AC fan + aroma therapy	Humidity	73	64	0.10

based system integrated with Blynk and Telegram has high real-time accuracy [18]. The system is able to display data without significant delay when compared to reference measurement instruments.

From environmental observations, the highest temperature recorded was 41°C at 10:45 and 12:45, indicating high sunlight intensity. Towards late afternoon, temperature dropped to 37°C, followed by increased humidity (28% to 39%), showing the inverse relationship between temperature and humidity.

Based on nighttime testing (20:30–22:30), voltage and current values gradually decreased due to decreasing battery capacity in the absence of solar charging [19]. This reduction also lowered electrical output power in both DC and AC.

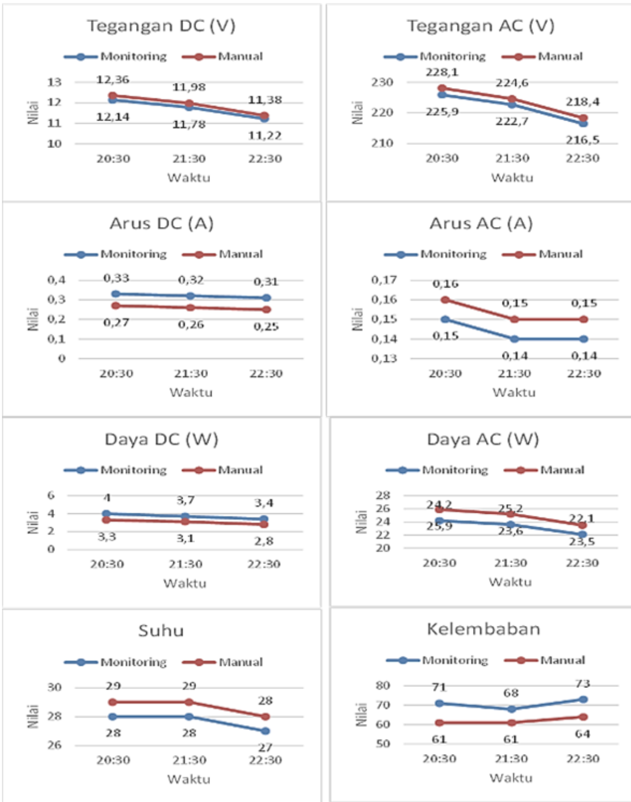

Figure 5: Nighttime Trend Graph of Voltage, Current, Power, Temperature, and Humidity

Environmental parameters showed cooling nighttime conditions (28°C to 27°C), while humidity increased (71% to 73%), confirming the inverse correlation between temperature and humidity.

Overall, both daytime and nighttime tests demonstrated accurate and reliable performance. The monitoring system successfully validated electrical parameters using DC fans, AC fans, and aromatherapy loads.

Based on testing conducted from 20:30 to 22:30, the Internet of Things (IoT)-based solar power plant (PLTS) monitoring system demonstrated stable and accurate results compared to manual measurements. The main parameters monitored included voltage, current, power, temperature, and humidity on both the DC and AC sides.

In general, the test results show that voltage and current values gradually decrease over time. This decrease is caused by a reduction in battery capacity due to continuous load use during nighttime conditions without power contribution from the solar panels [19]. As a result, the power (W) produced also decreases in line with the reduction in stored energy.

On the DC side, voltage decreased from 12.36 V to 11.38 V for manual results and from 12.14 V to 11.22 V for monitoring results. Meanwhile, AC voltage decreased from 228.1 V to 218.4 V (manual) and 225.9 V to 216.5 V (monitoring). The DC current value also decreased slightly from 0.33 A to 0.31 A (monitoring), while manual measurements showed a decrease from 0.27 A to 0.25 A. A similar decrease occurred in AC current which remained relatively stable in the range of 0.14–0.16 A.

These changes in voltage and current directly affect the electrical power (W). DC power decreased from 4 W to 3.4 W in the monitoring results, and from 3.3 W to 2.8 W in manual measurements. AC power followed a similar pattern, decreasing from 25.9 W to 23.5 W (monitoring) and from 26.0 W to 22.1 W (manual).

The monitoring results generally differ very slightly from the manual results, with deviations around 0.1–0.3 for most parameters. This indicates that the ESP32 microcontroller-based monitoring system integrated with Blynk and Telegram notifications has high accuracy and is capable of operating in real time without interference, compared to conventional measuring tools [20].

Regarding environmental parameters, nighttime temperatures tended to decrease from 28°C to 27°C in monitoring results, while manual readings decreased from 29°C to 28°C. Meanwhile, humidity increased from 71% to 73% (monitoring) and from 61% to 64% (manual), indicating an inverse relationship between temperature and humidity: as temperature decreases, humidity increases.

Based on the results of tests conducted both during the day and at night, the IoT-based solar power monitoring system demonstrated accurate and reliable performance in reading electrical and environmental parameters. Tests were performed on DC and AC voltage, current, power, temperature, and humidity using loads consisting of DC fans, AC fans, and aromatherapy devices.

The monitoring system developed has implemented several decision-based features, including the ability to detect low battery voltage (low battery warning), high temperature on solar panels (>45°C), and provide automatic notifications via Telegram when abnormal conditions are detected. Additionally, a threshold-based alert system is integrated, where a buzzer activates to provide an audible alert whenever the measured parameters exceed the defined limits, and push notifications are simultaneously sent to the user's smartphone through the Blynk application.

Recommendations for future development include the implementation of machine learning-based anomaly detection algorithms such as Isolation Forest or LSTM, predictive maintenance to estimate solar panel degradation, and automatic performance optimization based on energy production patterns generated over time.

This study highlights the importance of long-term data handling strategies to support trend analysis and the development of intelligent features. Below is a discussion regarding the current data architecture and future enhancement planning.

Current data architecture: The system currently relies on Blynk Cloud for real-time data storage, where data is kept with limited retention. The SuperChart widget provides historical visualization for up to seven days when using the free plan. In addition, Telegram is used as a complementary logging platform in which every notification is stored within the chat history, enabling manual retrospective analysis when required.

Planned cloud storage development: Future improvements include the implementation of Firebase Realtime Database or the Google Sheets API to store historical data without time limitations, using a structured format such as timestamp, DC/AC voltage, DC/AC current, DC/AC power, temperature, humidity, and system status.

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Scalability: The modular architecture allows seamless integration with enterprise cloud platforms such as AWS IoT or Google Cloud IoT to support large-scale deployment and advanced analytics.

IV. Conclusion

An IoT-based solar power monitoring system using ESP32 has been successfully designed and implemented according to the initial objectives. The system is capable of monitoring critical parameters such as voltage, current, power, temperature, and humidity in real time. The ESP32 microcontroller serves as both the central controller and communication backbone, integrated with power measurement sensors and WiFi connectivity to transmit data to the Blynk and Telegram platforms. While Blynk enables interactive visualization through graphical and numerical output, Telegram provides automatic notifications when abnormal or threshold-exceeding conditions occur.

Based on the test results, the system demonstrated high accuracy and reliable performance. During daytime testing, the highest DC and AC voltage values recorded were 18.22 V and 233.8 V at 10:45, while the lowest were 12.46 V and 225.7 V at 14:45. The highest DC current and power of 0.44 A and 7.9 W occurred at 11:45, along with a peak temperature of 41°C and lowest humidity of 28%. During nighttime operation, DC and AC voltages decreased from 12.36 V and 228.1 V to 11.22 V and 216.5 V, respectively, due to the absence of solar input. Temperature dropped from 28°C to 27°C, followed by humidity rising from 71% to 73%. Comparison with reference measuring tools showed very small differences, including 0.01–0.05 V for DC voltage and 0.1% for humidity, with an average error of only 0.07%. Thus, the designed system is proven to be stable, accurate, and efficient in real-time PLTS monitoring.

This system has strong potential for further development, including large-scale deployment, cloud-based historical data management, smart alert analytics, and intelligent energy optimization for improved solar power plant performance.

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