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IoT-based high-accuracy monitoring system for on-grid photovoltaic power system using NodeMCU ESP8266 and PZEM004T

Lastoni Wibowo [a, *], Retno Wahyusari [b], Teguh Yuwono [a], Aina Shofia [a]

[a] *Department of Electrical Engineering, Ronggolawe College of Technology*
Jl. Kampus Ronggolawe Blok B No. 1 Cepu, Blora, 58315, Indonesia

[b] *Informatics Department, Ronggolawe College of Technology*
Jl. Kampus Ronggolawe Blok B No. 1 Cepu, Blora, 58315, Indonesia

Abstract

Monitoring systems for on-grid photovoltaic power systems use IoT technology for real-time performance tracking via the internet. Typically, these systems involve current and voltage sensors to measure current, voltage, power, energy, and power factor (Cos φ). However, many existing systems do not thoroughly address the accuracy of these measurements. To ensure reliability, a system must achieve measurement accuracy above 90 %. This article presents an IoT-based on-grid photovoltaic power monitoring system designed to measure electrical parameters with high accuracy. The system uses the PZEM004T sensor and NodeMCU ESP8266, which transmits data to the Blynk IoT server over an internet connection. The system's accuracy is assessed using the mean absolute percentage error (MAPE) calculation. Results show that this system achieves an accuracy of 96.37 %, indicating high reliability and suitability for practical use due to its accuracy above 95 %. This makes the designed system highly reliable, effective, and feasible for monitoring on-grid photovoltaic power plants.

Keywords: IoT monitoring system; on-grid photovoltaic power; accuracy analysis; NodeMCU ESP8266; PZEM004T sensor.

I. Introduction

Regulation of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 2 of 2024 concerning rooftop solar power plants states that in 2024, customers of the National Electricity Company (PLN) who have rooftop solar power plants can export Electrical Energy from their rooftop solar power plants to the PLN electricity grid [1]. The implementation of this regulation has an impact on the number of solar power plants installed in both off-grid and on-grid systems[2][3][4]. In the off-grid photovoltaic (PV) power system, electrical energy is supplied to the load directly without being connected to the PLN electricity grid (PLN grid). The disadvantage of this system is that if the electrical energy from the photovoltaic power system is not able to meet the electrical load requirements, the electrical load will not work properly [2][3][5].

Meanwhile, in the on-grid photovoltaic power system, if the electrical energy from the photovoltaic power system is unable to meet the electrical load requirements, then the remaining electrical energy will be taken from the PLN grid [4][6][7]. Economically, the on-grid photovoltaic power system is also more

* Corresponding Author. : lastoni.wibowo@gmail.com (L. Wibowo)

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profitable for PLN customers [8] because there is a portion of electrical energy in the electricity load supplied by the photovoltaic power system, thereby reducing electricity consumption from PLN [9][10][11].

Furthermore, if the electricity production of the on-grid photovoltaic power system exceeds the electricity load requirement, the excess electrical energy can be exported to the PLN grid [8][9][12]. To find out the performance of the on-grid photovoltaic power system, the electrical energy produced by the photovoltaic power system needs to be measured to find out how much electrical energy is imported or exported to the PLN grid [13][14][15]. Currently, the measurement implementation that has been carried out is that PLN has installed an export-import kWh meter measuring instrument to calculate how much electrical energy is taken from the PLN grid and also how much electrical energy is sold or exported to the PLN grid. The weakness of the export-import kWh meter from PLN is that it can only be seen through the screen on the kWh meter and only displays electrical energy for a moment. The development of an on-grid photovoltaic power monitoring system, which has been carried out by several researchers, is an online monitoring system that can be done via the internet [16][17][18]. The use of the Internet to display data is often called the Internet of Things (IoT) [19][20][21]. One of the advantages of using the Internet of Things in On-Grid photovoltaic power system monitoring systems is that monitoring can be done anywhere and at any time via the Internet network [22][23][24].

Measuring electrical energy in photovoltaic power systems is often done by installing current and voltage sensors [25][26][27]. By knowing the current and voltage values in the photovoltaic power system, which are measured via sensors, the electrical parameters of current, voltage, power, energi, and power factor can be known [28][29][30]. The PZEM004T sensor is a current and voltage sensor module that has a high level of accuracy [31]. Implementation of the PZEM004T sensor in photovoltaic power system monitoring is carried out by connecting the PZEM004T sensor to the microcontroller. NodeMCU ESP8266 is a microcontroller that can process data from the PZEM004T sensor. The ESP8266 NodeMCU can also connect to the Internet via a WiFi network, so it can be used for IoT applications [32][33][34]. Measurement data is often displayed on various low-cost platforms [17][25][35]. Some commonly used applications are Blynk [15], web [36], Node-Red [37], and other applications that have responsive dashboard designs [18]. One display platform that can be used in IoT applications is the Blynk IoT Application. The Blynk IoT application can display up to 10 parameters simultaneously. Apart from that, the Blynk application also has an attractive appearance [15]. However, photovoltaic power monitoring systems that have been created by previous researchers have not discussed the level of system accuracy in measuring electrical parameters. A reliable electrical parameter monitoring system is a monitoring system that can measure electrical parameters with a high level of accuracy or has a low error value [38]. Therefore, it is necessary to create a reliable and accurate monitoring system. A reliable monitoring system is a monitoring system that can measure electrical parameters with an accuracy level above 90 %.

In this article, an internet of things-based on-grid photovoltaic power monitoring system is designed that is capable of measuring the electrical parameters of current, voltage, power, and power factor (Cos φ) on the photovoltaic power system side and the PLN grid side. In the designed monitoring system, electrical parameter measurements are carried out using two PZEM004T sensors, which are installed on the side of the photovoltaic power system and the PLN grid. The PZEM004T sensor measurement data is sent to the NodeMCU ESP8266 microcontroller as a data processing tool. IoT implementation is carried out by sending electrical parameter data by the NodeMCU ESP8266 to the Blynk server using a WiFi connection connected to the internet network.

This article also discusses the level of accuracy of the designed on-grid photovoltaic power monitoring system. Discussion of the level of accuracy of the designed on-grid photovoltaic power system was carried out by comparing the electrical parameter reading values by the PZEM004T sensor with a comparison measuring instrument in the form of a calibrated power meter. The analysis of the level of accuracy is carried out by calculating the Mean Absolute Percentage Error (MAPE) and calculating the accuracy. The monitoring system is designed to measure electrical energy from the on-grid photovoltaic power system and electrical energy from the PLN grid, which can be monitored in real-time via the internet network using the Blynk IoT application viewer.

II. Materials and Methods

In this article, the monitoring system is installed on an on-grid photovoltaic power system with a capacity of 800 Wp. Then, to determine the performance of the designed monitoring system, an electrical load in the form of a resistive load of 800 Watts is installed on the on-grid photovoltaic power system.

A. Materials

The design and manufacture of the on-grid photovoltaic power monitoring system requires a PZEM-004T sensor, NodeMCU ESP8266, and the Arduino IDE application is used to program the NodeMCU ESP8266.

1) Photovoltaic power system

In this article, the generation of electrical energy from solar energy is done through polycrystalline solar panels. The installed photovoltaic power system consists of 4 polycrystalline solar panels, each with a capacity of 200 Wp 24 Volt, so the total installed solar panel power is 800 Wp. Figure 1 shows the setup of the photovoltaic power system in the experiment.

2) PZEM-004T sensor

The PZEM-004T sensor is a sensor module that can measure the parameters of voltage, current, active power, frequency, power factor, and energy [31]. The PZEM-004T sensor can measure voltage from 80V to 260 V. When measuring current, the PZEM-004T sensor can measure from 0 to 10A. In power measurements, the PZEM-004T sensor can measure from 0 to 2.3kW. The PZEM-004T sensor can measure power factor from 0.00 to 1.00. Frequency measurements can also be carried out by the PZEM-004T sensor from 45Hz to 65Hz. Meanwhile, the PZEM-004T sensor can measure energy from 0 to 9999.99kWh. The physical form of the PZEM-004T sensor module is presented in Figure 2 [39].

3) NodeMCU ESP8266

NodeMCU ESP8266 is a microcontroller module with open source Lua based firmware that can be used for IoT-based applications [33], [34]. The firmware running on the NodeMCU is firmware from Espressif Systems. The firmware is embedded in the ESP-12 hardware. The NodeMCU ESP8266 has 16 GPIO pins and 1 Analog pin, which can be used for various IoT application needs. The physical appearance of the NodeMCU ESP8266 is presented in Figure 3 [40].

B. Methods

In this article, several steps are taken in the research, namely, the installation process of the on-grid photovoltaic power system, followed by the design and manufacture of the on-grid photovoltaic power monitoring system. The design and manufacture process of the on-grid power monitoring system is carried out in several stages, namely, the design and manufacture of a prototype, then the design and manufacture of source code and programming of the ESP8266, and continued with design and manufacture of the display on Blynk IoT. After all the design and manufacturing processes are completed according to the design, the next step is the process of taking data on the parameters of voltage, current, power, energy, and power factor (Cos φ). The results of the data collection will be analyzed to determine the error and accuracy values. The research stages in this article are presented through a flowchart in Figure 4.

1) Design and prototype manufacturing of on-grid photovoltaic power monitoring system

The entire concept and overall relationship between materials and equipment in this Online Monitoring System is presented in Figure 5. In this research, an online monitoring system for the on-grid photovoltaic power system was built with the design presented in Figure 5. In Figure 5, there are two main research blocks,

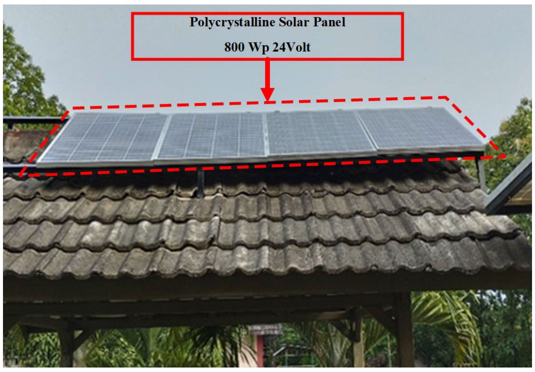

Figure 1. Photovoltaic power system setup.

Figure 2. PZEM-004T sensor module.

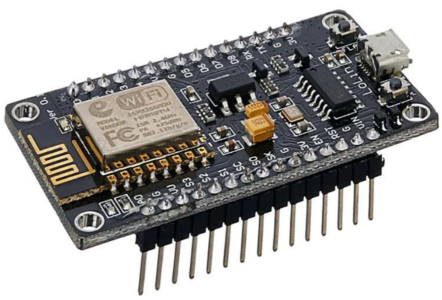

Figure 3. NodeMCU ESP8266.

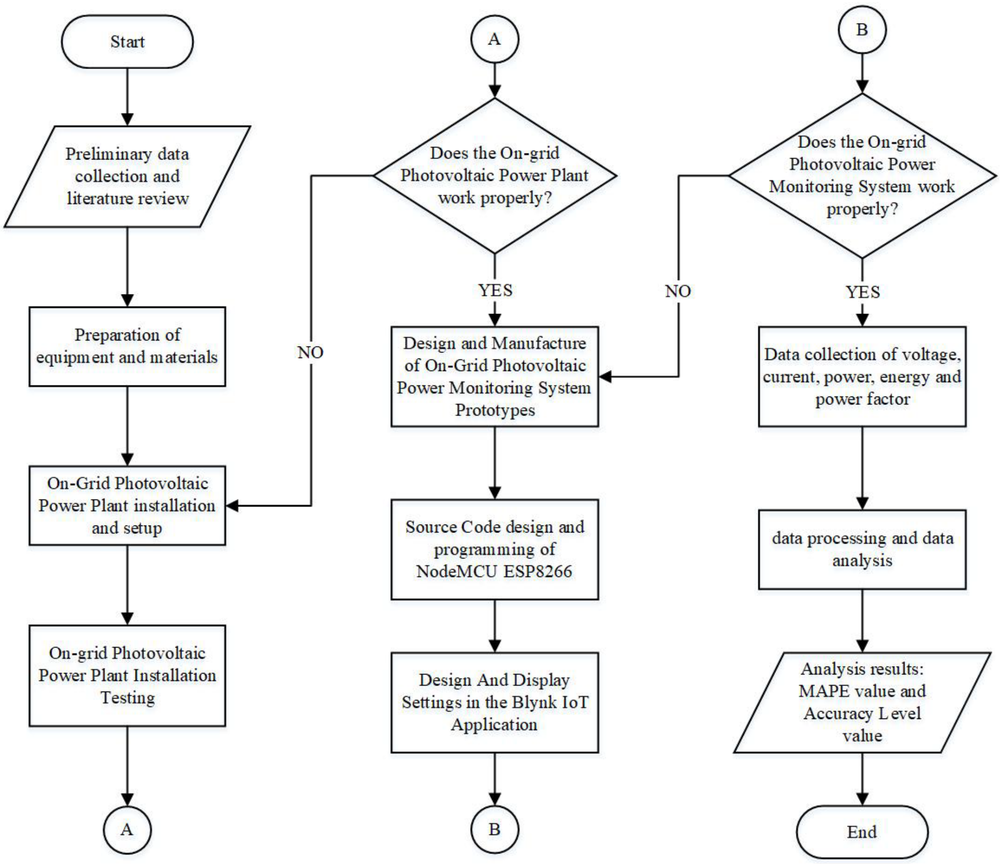

Figure 4. Research Stages Flowchart.

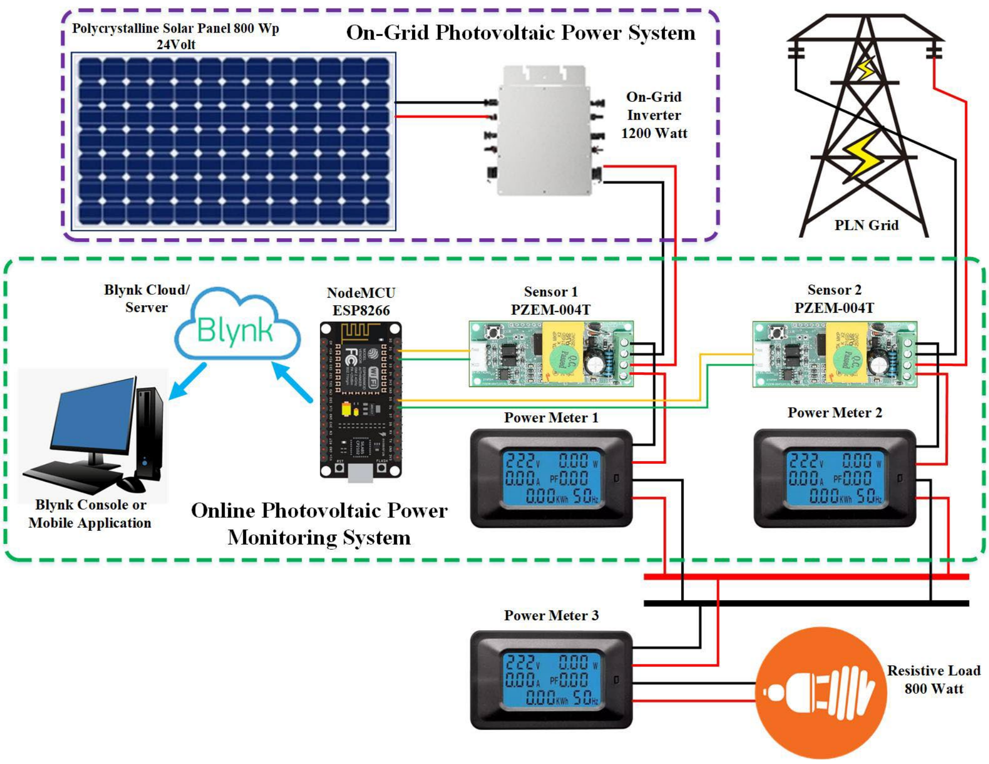

Figure 5. Proposed online photovoltaic power monitoring system.

namely the 800 Wp on-grid photovoltaic power system block and the monitoring system block. The on-grid photovoltaic power system block consists of 800 Wp solar panels to turn solar energy into DC electricity. Electricity from solar panels is converted into AC electricity by a 1200 Watts microgrid inverter. AC electricity from the inverter is distributed to the PLN grid and to the electrical load in parallel.

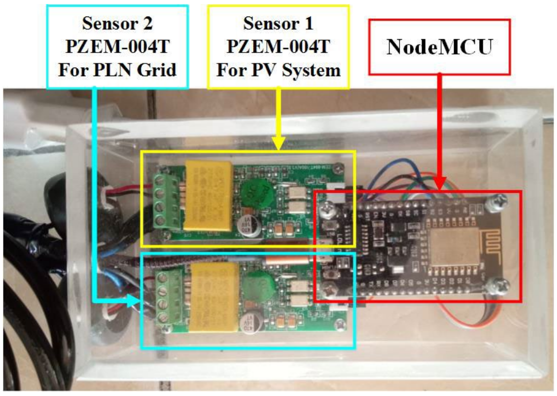

Figure 6. Prototype of on-grid photovoltaic power monitoring system.

In the online monitoring system block, there are 2 PZEM-004T sensors, which function to retrieve electrical energy parameter data from the on-grid photovoltaic power system and electrical energy from the PLN grid, which is distributed to the 800 W electrical load. The data obtained from the 2 PZEM-004T sensors is then processed by the NodeMCU ESP8266 microcontroller to determine the values of electric current, voltage, power, energy, and power factor (Cos φ). The results of data processing from the NodeMCU esp8266 are then sent to the Blynk Iot server via the internet. On Blynk IoT, the data received from the NodeMCU ESP8266 is then displayed on the dashboard of the application as a display of electrical parameter values for the on-grid photovoltaic power system and the PLN grid. The results of the design and manufacture of the prototype of the on-grid photovoltaic online monitoring system are presented in Figure 6.

In this article, two calibrated power meters are installed and used as a comparison for the PZEM-004T sensor reading results. Power meter 1 is used to measure electrical parameters on the photovoltaic power system side. The power meter 1 measurement results are used as a comparison for the first PZEM-004T Sensor measurement data. Power meter 2 is used to measure electrical parameters on the PLN grid side. The power meter 2 measurement results are used as a comparison for the second PZEM-004T sensor measurement data. An additional power meter is also installed to check the power used by the load. Figure 7 shows the results of the power meter installation.

2) Source code design and programming of NodeMCU ESP8266

Source code design was carried out via Arduino IDE version 1.8.19. The PZEM004Tv30.h library is used in the source code so that the NodeMCU ESP8266 can read data from the PZEM-004T sensor, while the

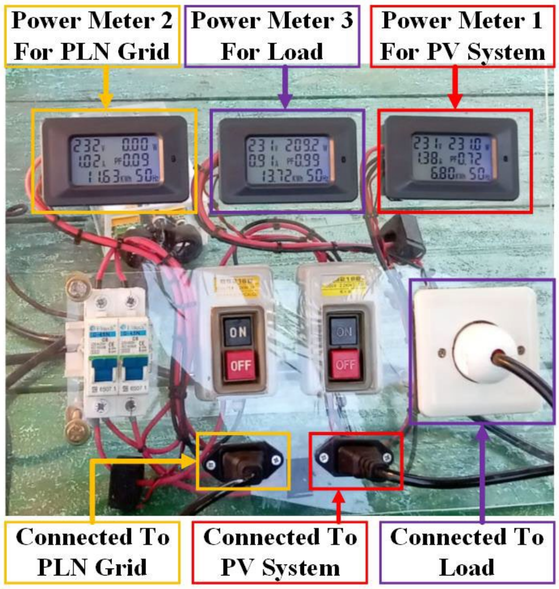

Figure 7. Power Meter Installation

BlynkSimpleEsp8266.h library is used to send PZEM-004T reading data to the Blynk server [15]. The source code display in the Arduino IDE is presented in Figure 8.

3) Design and display settings in the Blynk Iot application

In this research, the IoT method is applied through the Blynk IoT application. Blynk IoT is used as a display to show the results of monitoring electrical parameters on the on-grid photovoltaic power system and the PLN grid. The Blynk IoT application can be accessed via smartphone or via a browser on a computer [15]. Figure 9 shows the Blynk IoT dashboard display of the results of measuring electrical parameters on the on-grid photovoltaic power system and the PLN grid via the browser on the computer.

4) Method of collecting data

The data collection methods that have been carried out are as follows:

- The data needed in this research is voltage, current, power, energi, and Cos φ data on the on-grid photovoltaic power system and PLN grid side.
- Measurement and monitoring of electrical parameters are carried out by the PZEM-004T sensor, which is then processed by the NodeMCU ESP8266 microcontroller and displayed online on the Blynk IoT application.
- The electrical load used in this research is a resistive electrical load of 800 W.
- The analysis was carried out on electrical parameter measurement data, which was carried

out in July 2023 for 14 days, starting from 9 am to 4 pm.

- The data analysis carried out was to calculate the level of accuracy of the PZEM-004T sensor reading results and compare it with the calibrated power meter reading results.

5) Data analysis method

The data analysis that has been carried out is error value analysis and accuracy value analysis of measurement results. The accuracy value can be determined by calculating the error rate. The accuracy level is in the high category if the accuracy value is

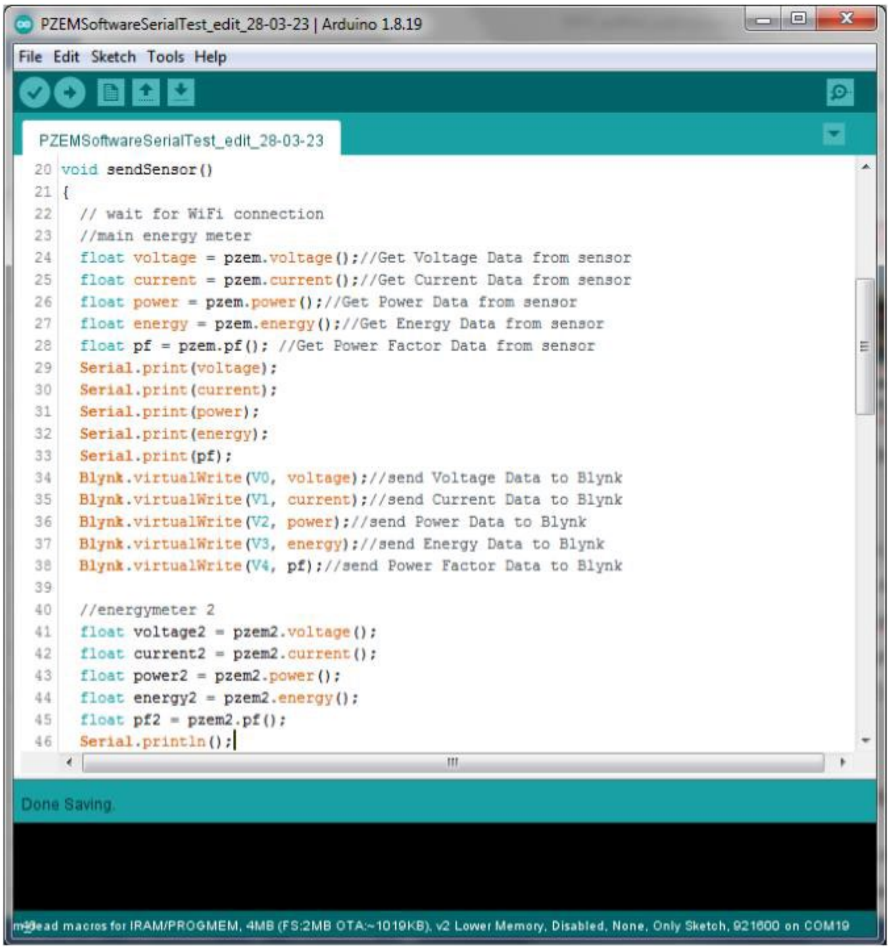

Figure 8. Source code on the Arduino IDE.

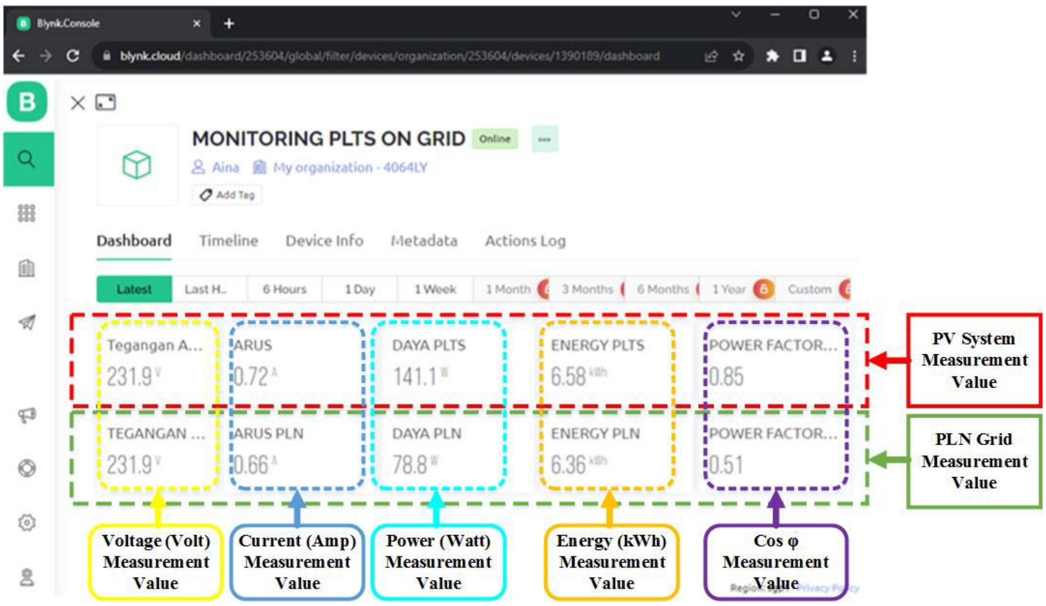

Figure 9. Photovoltaic online monitoring system display design in the Blynk IoT application.

above 90 %, and the accuracy level is in the very high category if the accuracy value is above 95 %. A high accuracy value indicates that the monitoring system works well and is reliable [38]. Accuracy level calculations are successively carried out using equation (1) to equation (7). The error level calculation is done using equation (1), while the accuracy level calculation is done using equation (7) [38].

$$\text{Error} = \text{Measurement} - \text{True Value} \quad (1)$$

$$\text{Absolute Error} = |\text{Error}| \quad (2)$$

$$\text{Mean Absolute Error (MAE)} = \sum_{t=1}^{n} \frac{|\text{Error}|}{n} \quad (3)$$

$$\text{Mean Square Error (MSE)} = \sum_{t=1}^{n} \frac{(\text{Measurement} - \text{True Value})^2}{n} \quad (4)$$

$$\text{Root Mean Square Error (RMSE)} = \sqrt{\sum_{t=1}^{n} \frac{(\text{Measurement} - \text{True Value})^2}{n}} \quad (5)$$

$$\text{Mean Absolute Percentage Error (MAPE)} = \sum_{t=1}^{n} \frac{\frac{|\text{Measurement} - \text{True Value}|}{\text{True Value}}}{n} \quad (6)$$

$$\text{Accuracy} = 100\% - \text{MAPE} \quad (7)$$

In this research, the results of sensor 1 readings were compared with the results of power meter 1 readings to determine the level of accuracy of the monitoring system on the on-grid photovoltaic power system side. The results of sensor two readings are compared with the results of power meter 2 readings to determine the level of accuracy of the monitoring system on the PLN grid side. The parameters compared are current, voltage, power, energy, and Cos φ. Accuracy calculations are carried out by comparing the measurement results using a power meter with the measurement results using the designed monitoring system.

III. Results and Discussions

In this section, an analysis of the error level and accuracy level calculations is carried out using the online on-grid photovoltaic monitoring system measurement results. The electrical parameters analyzed are the parameters voltage (V), electric current (I), power (P), energy (kWh), and power factor (Cos φ). The data analyzed is data from measurements carried out in July 2023 for 14 days, starting from 9 am to 4 pm. Measurements were carried out from 9 am to 4 pm because from 9 am to 4 pm, the photovoltaic power system received sufficient sunlight radiation to work properly. All measurement results for each parameter are calculated as the average value of the photovoltaic power monitoring system measurement results and power meter measurement results. The monitoring system measurement results are compared with the measurements of the calibrated power meter. The calibrated power meter measurement results are used as reference values for accurate measurement results.

A. Analysis of voltage measurement results

The results of voltage measurements on the photovoltaic power monitoring system and the results of power meter measurements are presented in Figure 10. The data presented in Figure 10 calculates the error, absolute error, MSE, and MAPE values for each voltage data. After knowing the absolute error and MAPE values for each data set, the MAE, MAPE (%), standard deviation, and accuracy values of the voltage measurements are calculated.

The calculation results show that the MAPE (%) value for voltage measurement is 0.14 %, and the accuracy value is 99.86 %, with a standard deviation of

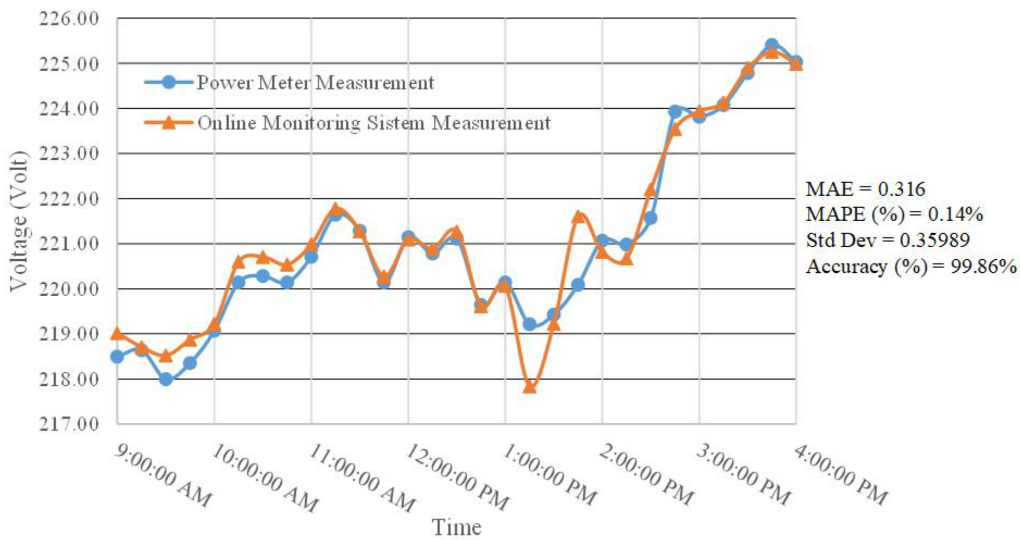

Figure 10. Voltage measurement results.

0.35989. The voltage measurement accuracy value is 99.86 %, indicating that the designed system is capable of carrying out voltage measurements with a very high level of accuracy. So, it can be concluded that the system designed is very accurate, very reliable, and very suitable for application for measuring voltage parameters in on-grid photovoltaic power systems because it has an accuracy level of above 95 %.

B. Analysis of current measurement results

The results of electric current measurements carried out using the photovoltaic power monitoring system and the results of electric current measurements carried out using a power meter are presented in Figure 11. The data presented in Figure 11 calculates the error, absolute error, MSE, and MAPE values for each Electric Current data. After knowing the absolute error and MAPE values for each data set, the MAE, MAPE (%), standard deviation, and accuracy values of the electric current measurements are calculated.

The calculation results show that the MAPE (%) value for electric current measurement is 3.79 %, and the accuracy value is 96.21 % with a standard deviation of 0.03412. The accuracy level for measuring electric current is 96.21 %, indicating that the designed system is capable of carrying out current measurements with a very high level of accuracy. So, it can be concluded that the system designed is very accurate, very reliable, and very suitable for application in measuring current parameters in on-grid photovoltaic power systems because it has an accuracy level of above 95 %.

C. Analysis of power measurement results

The results of power measurements using the photovoltaic power monitoring system and the results of power measurements using a power meter are presented in Figure 12. From the data presented in Figure 12, the error, absolute error, MSE, and MAPE values for each electrical power data are calculated. After knowing the absolute error and MAPE values for

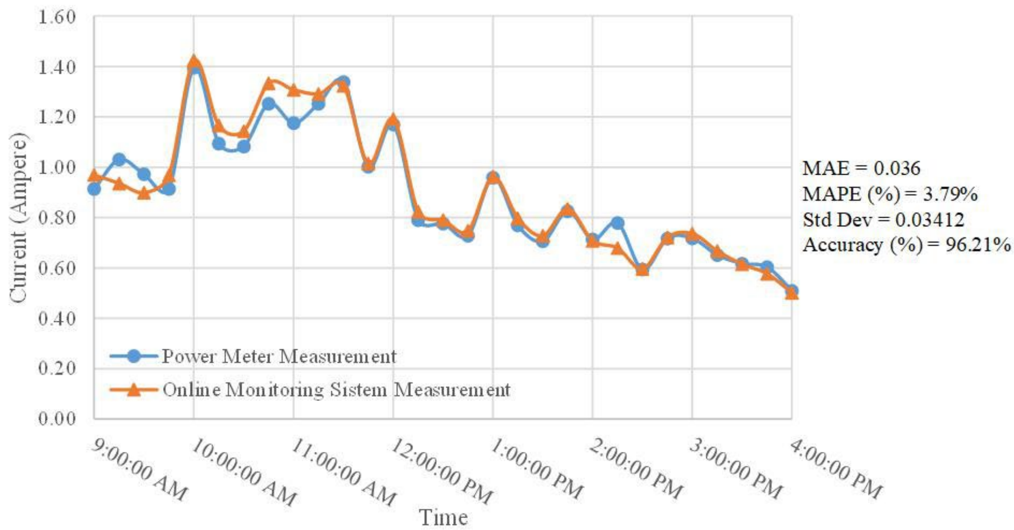

Figure 11. Current Measurement Results.

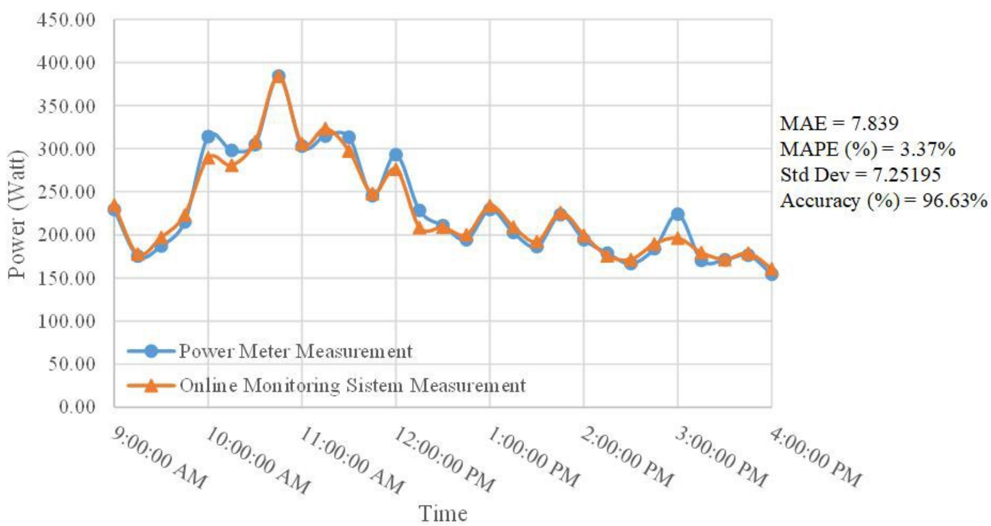

Figure 12. Power Measurement Results.

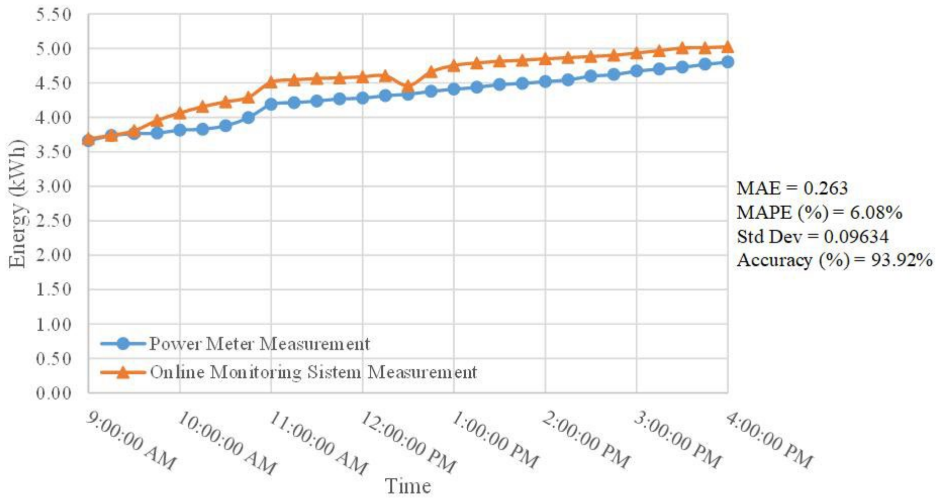

Figure 13. Energy measurement results.

each data set, the MAE, MAPE (%), standard deviation, and accuracy values of the power measurements are calculated.

The accuracy value for power measurements is 96.63 %, and the MAPE (%) value is 3.37 %, with a standard deviation of 7.25195, as presented in Figure 12. The monitoring system designed is considered to have a very high level of power measurement accuracy because it has the power measurement accuracy value of 96.63 %. From the results of this analysis, it can be concluded that the system designed is very accurate, very reliable, and very suitable for application in measuring power parameters in on-grid photovoltaic power systems because it has an accuracy level of above 95 %.

D. Analysis of energy measurement results

The results of energy measurements using the photovoltaic power monitoring system and the results of energy measurements using a power meter are presented in Figure 13. The data presented in Figure 13 calculates the error, absolute error, MSE, and MAPE values for each energy data. After knowing the absolute error and MAPE values for each data set, the MAE, MAPE (%), standard deviation, and accuracy values of the energy measurements are calculated.

The accuracy value for energy measurements is 93.92 %, and the MAPE (%) value is 6.08 % with a standard deviation of 0.09634, as presented in Figure 13. The designed monitoring system is considered to have a high level of power measurement accuracy because it has a value energy measurement accuracy of 93.63 %. From the results of this analysis, it can be concluded that the system designed is accurate, reliable, and suitable for application in measuring energy parameters in on-grid photovoltaic power systems because it has an accuracy level of above 90 %.

E. Analysis of Cos φ measurement results

The results of measuring Cos φ using the photovoltaic power monitoring system and the results of measuring Cos φ using a power meter are presented

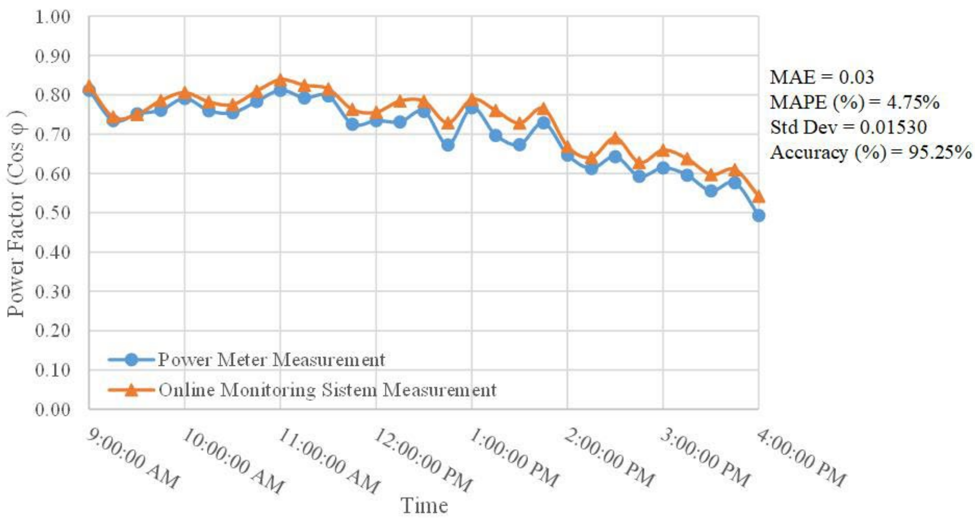

Figure 14. Power factor (Cos φ) measurement results.

Table 1.
Average MAPE value and average accuracy value of measurement results.

No.	Parameter	Mean absolute percentage error (MAPE)	Accuracy
1	Voltage	0.14 %	99.86 %
2	Current	3.79 %	96.21 %
3	Power	3.37 %	96.63 %
4	Energy	6.08 %	96.63 %
5	Cos φ	4.75 %	93.92 %
	Average	3.63 %	96.37 %

in Figure 14. From the data presented in Figure 14, the error, absolute error, MSE, and MAPE values for each Cos φ data were calculated. After knowing the absolute error and MAPE values for each data, the MAE, MAPE (%), standard deviation, and accuracy values of the Cos φ measurements are calculated [38].

The accuracy value for Cos φ measurements is 95.25 %, and the MAPE (%) value is 4.75 % with a standard deviation of 0.01530, as presented in Figure 14. The monitoring system designed is considered to have a very high level of accuracy for Cos φ measurements, with a Cos φ measurement accuracy value of 95.25 %. From the results of this analysis, it can be concluded that the system designed is very accurate, very reliable, and very suitable for application for measuring the Cos φ parameter in the on-grid photovoltaic power system because it has an accuracy level of above 95 %.

F. Accuracy analysis of online on-grid photovoltaic monitoring system measurement results

From the analysis of the accuracy of the measurement results on the parameters of voltage, current, power, energy, and Cos φ, the average MAPE and Accuracy values were calculated. The calculation results of the average MAPE value (%) and accuracy values are presented in Table 1.

The average accuracy value of the measurement results is 96.37 %, and the average MAPE (%) value is 3.63 %, as presented in Table 1. The monitoring system designed is considered to have a very high level of measurement accuracy because of the analysis results [33]. The average measurement accuracy value is 96.37 %. From the results of this analysis, it can be concluded that the system designed is very accurate, very reliable, and very suitable for application in measuring electrical parameters in on-grid photovoltaic power systems because it has an accuracy level of above 95 %.

IV. Conclusion

The analysis results show that the On-Grid Photovoltaic Power Monitoring System has a voltage measurement accuracy value of 99.86 %, the accuracy value of the electric current measurement results is 96.21 %, the accuracy value of the power measurement results is 96.63 %, The accuracy value of the energy measurement results is 93.92 %, and the accuracy value of the Cos φ measurement results is 95.25 %. The analysis results show that the voltage measurement results have the highest accuracy value with an accuracy value of 99.86 %, while the energy measurement results have the lowest accuracy value with an accuracy value of 93.92 %. The analysis results show that the designed on-grid photovoltaic power monitoring system has an average accuracy value of measurement results of 96.37 % with a MAPE (%) value of 3.63 %. From the results of the analysis, it can be concluded that the on-grid photovoltaic power monitoring system designed has very high accuracy, is very reliable, and is very suitable for application for measuring electrical parameters in the on-grid photovoltaic system because it has an average accuracy value of above 95 %.

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Declarations

Author contribution

L. Wibowo, R. Wahyusari, T. Yuwono and A. Shofia contributed equally as the main contributor of this paper. All authors read and approved the final paper.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The use of AI or AI-assisted technologies

During the preparation of this work the authors used **ChatGPT** in order to help summarize several sentences and/or paragraphs to meet the word count standards in the article. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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