Design and Development of a Solar Irradiance Monitoring System for On-Grid Solar Power Plants Using the Internet of Things

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Abstract. Geographical conditions provide great potential for harnessing solar energy, contributing to SDGs 9: Industry, Innovation, and Infrastructure. To enhance the efficiency of On-Grid Solar Power Plants, it is essential to have a monitoring system that can monitor solar irradiation and electrical parameters in real time. The Internet of Things (IoT) technology offers an efficient and effective solution for this purpose, supporting SDGs 12: Responsible Consumption and Production by optimizing resource use. This study focuses on designing and developing a monitoring system that employs a pyranometer sensor for measuring solar irradiation and a PZEM-004t module for recording electrical parameters such as voltage, current, power, and energy. Data is gathered and transmitted to the Google Firebase platform using an ESP32 MCU board. The research methodology includes the design and integration of hardware and software, sensor calibration, and both laboratory and field testing. The test results indicate that the system can provide accurate and consistent data with minimal measurement error. The monitoring system measures solar irradiation with an average deviation of less than 2% and records electrical parameters with high precision. The hardware and software design for the solar irradiation monitoring system and load distribution in grid-connected solar power systems was successfully implemented, integrating components such as the PZEM-004t sensors and pyranometer. The firmware played a critical role in ensuring seamless interaction between hardware and software, enabling real-time data collection and transmission to Firebase, with data transmission latency averaging 0.274 seconds. Both laboratory and field tests confirmed the system's accuracy, with the pyranometer demonstrating an accuracy of 97.97% and a sensitivity of 0.0814, showcasing its potential for effective solar energy monitoring. The findings of this research are expected to promote the optimal utilization of solar energy in the future, advancing both industrial innovation and sustainable resource management.

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1. Introduction

The geographical potential for solar energy offers a promising pathway toward advancing SDG 9: Industry, Innovation, and Infrastructure. By integrating Internet of Things (IoT) technology, this potential can be effectively harnessed, providing efficient solutions that optimize resource utilization. This integration aligns with SDG 12: Responsible Consumption and Production, as it enables more sustainable energy use and improved resource management. The convergence of solar energy and IoT technology represents a significant step toward fostering innovation and responsible industrial development while addressing global sustainability challenges. This study explores the synergy between geographical solar potential and IoT-driven optimization in achieving these sustainable development goals. As a tropical country, Indonesia has significant potential for solar energy utilization, with average solar radiation levels of 4.8 kWh/m^2/day [1]. The growing demand for electricity and the need to reduce reliance on fossil fuels make solar power an attractive alternative [2]. Solar energy, which is abundant, limitless, and ecologically friendly, is becoming more popular [3],[4]. Solar Power Plants (SPPs) offer a viable solution, converting solar energy into electricity. However, the performance of SPPs can be affected by various factors such as weather conditions and solar irradiation[5]. To optimize the efficiency of on-grid SPPs, real-time monitoring systems are essential[6] . Previous research has focused on developing monitoring systems using technologies such as the PZEM-004t module and ESP32 microcontroller to track electrical parameters[7]. However, there is still a need for comprehensive systems that include both solar irradiation and electrical load monitoring[8].

The scope of this study encompasses the design and development of a monitoring device for measuring solar irradiation and the distribution of electrical loads from on-grid Solar Power Plants (SPPs) located at the shared lecture building of Universitas Airlangga. The monitoring system is specifically focused on the output post-inverter, excluding pre-inverter components[9]. The system's performance and characteristics will be thoroughly tested in both laboratory and real-world field conditions. Utilizing Internet of Things (IoT) technology, the system aims to provide accurate, real-time data collection, thus enhancing the efficiency and reliability of SPP operations[10]-[14]. IoT-enabled sensors are widely employed in electrical grid scheme to communicate valuable data over the internet and web apps, allowing for better grid management[16]

This paper presents the design and development of a real-time monitoring system for on-grid SPPs, incorporating pyranometer and PZEM-004t sensors, based on the Internet of Things (IoT) using ESP32 [17]. The proposed system aims to provide accurate, real-time data on critical parameters, improving system performance and preventing potential damages. This study offers a novel approach to SPP monitoring, contributing to the efficient utilization of solar energy in Indonesia [18].

2. Method

The research was conducted at Airlangga University's C campus in Surabaya, focusing on two primary tests: one in the Control Systems Laboratory of the NREE Research Center and the other on the on-grid SPPS in the Joint Lecture building. The study involved planning and designing electronic circuits, hardware, and software for the monitoring system, followed by testing and evaluation to ensure proper functionality.

2.1 Hardware Design

The hardware design consist of two main components: the PZEM sensor for electrical measurements and the pyranometer sensor for solar irradiation measurements. The PZEM sensor was integrated into the monitoring system to measure electrical parameters such as current, voltage, and power with high accuracy. The pyranometer sensor measured solar irradiation intensity, requiring proper calibration and integration with the data logging and analysis systems to ensure reliable and accessible data. For the PZEM-004t sensor, calibration involved adjustments and reprogramming to align with industry standards, ensuring accurate measurements of current, voltage, and power. Calibration was performed using a standard multimeter. In the data processing of the measurements within the sensor, several equations are involved to measure AC electrical parameters. The equations used are as follows:

$$\boldsymbol{P = V\ x\ I\ x\ cos\varphi}$$

$$\boldsymbol{E = P\ x\ t}$$

Where, V is Voltage (Volts), I is Measured Current (Amperes), $Cos\ \boldsymbol{\varphi}$ is Power factor, E is Electrical energy (Wh), t is Time (hours).

2.2 Calibration Pyranometer

Calibration of the pyranometer can be performed using a solar power meter. Thi process is crucial due to the sensor's sensitivity to atmospheric conditions, which ca significantly affect readings[19]. Calibration is typically conducted in a controlle environment designed to replicate natural conditions as closely as possible, ensurin accurate field performance. This device is capable of capturing the light spectrur from 400 to 1100 nm, which is crucial for photovoltaic and meteorologic applications.

By measuring the level of solar irradiance using a pyranometer, it is expressed by th following equation During calibration, key characteristics such as accurac precision, and linearity are assessed[20], [21], [22], [23]. These characteristics ar vital to ensure the sensor's correct functionality and the reliability of the data produces. For this study, the calibration process focused primarily on accurac precision, and linearity, considering the need for time-efficient testing.

$$\boldsymbol{E_{Solar}} = \frac{\boldsymbol{V_{out}}}{\boldsymbol{S}}$$

Where, $\boldsymbol{E_{Solar}}$(W/m^2) is Solar irradiance, $\boldsymbol{V_{out}}$ Pyranometer output voltage (mV), is Sensitivity (μV/W/m^2)

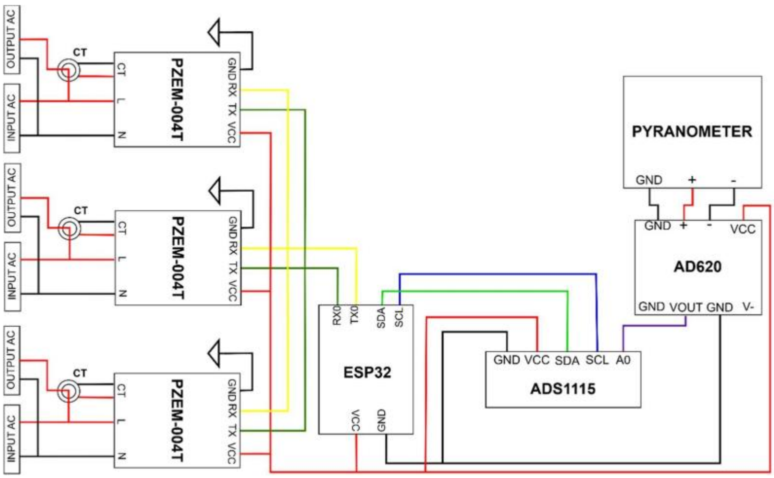

Fig. 1. Schematic of SPPS monitoring device hardware

2.3 Monitoring System

The PV monitoring system is aimed to provide information about some paramet of PV system. The parameter to be measured for PV system are output voltage, out power, output current, output energy[24]. monitoring system was specifically developed to measure and analyze solar irradiation and electrical output parameters in grid-connected solar power installations. The schematic includes three PZEM-004t sensors, a Current Transformer (CT), an ESP32 microcontroller, ADS1115, AD620, and a pyranometer sensor. The system utilizes two types of sensors: PZEM-004t and pyranometer. The PZEM-004t is responsible for monitoring electrical parameters such as voltage, current, power, energy, power factor, and frequency from the AC source. This module can also measure electrical power up to 22 kW and electrical energy up to 99999 kWh [15]. PZEM-004T is equipped with an RS485 serial communication interface [25], [26], [27], [28], [29], [30]. The PZEM-004t configuration involves four pins connected to the ESP32 and four pins connected to the CT and AC source, requiring power from both the 3.3V ESP32 and the AC electricity. Data transmission is facilitated through serial communication (RX, TX).

A pyranometer is an instrument used to measure solar radiation [16]. For the pyranometer sensor, the design involves using the ESP32, AD620, and ADS1115. The analog output signal from the pyranometer is connected to the AD620, which amplifies the signal. The amplified signal is then read by the ADS1115 module, enhancing the accuracy of the pyranometer readings. The ADS1115 utilizes the I2C communication protocol, enabling fast and efficient data exchange with the ESP32.

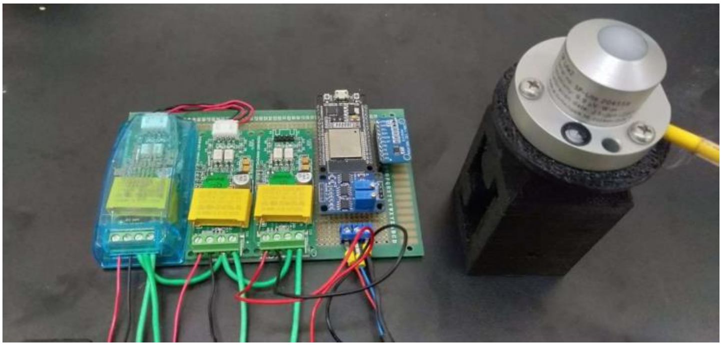

Fig. 2. The final results of the irradiation monitoring device and SPPS output

Figure 2 illustrates the hardware design of the solar irradiation monitoring device and load distribution system for grid-connected solar power installations. The firmware design is crucial for bridging the hardware and software, providing basic instructions that enable hardware-software interaction. Four main processes must be executed in parallel: initializing the ADS1115, connecting to the WiFi network, setting up Firebase configuration, and updating the database path.

Once these setup processes are completed, the program enters the "Main Loop," which is the core of the program's continuous operation. This loop handles periodic monitoring and data transmission tasks, ensuring Firebase is ready to receive data and that 60 seconds have elapsed since the last data transmission. The collected sensor data is then structured into a JSON object, facilitating both human-readable and machine-processable formats[21]-[23]. Upon successful data transmission, the program logs the transmission status, serving as a record for debugging and verification purposes. This log is crucial for ensuring that all processes function as intended and for identifying issues in case of errors.

Software design and integration are key to managing data collected by sensors, allowing real-time data collection and storage for future use. The system's website leverages the web app feature from Google Firebase for data visualization and management. Once the system is fully integrated, laboratory testing verifies the basic functions, followed by field testing to assess system performance under real-world conditions [10]-[15].

2.4 Data Processing

In this research, data processing involved collecting measurement data from monitoring devices and comparing them with standard reference data. Laboratory testing included calibration tests for the PZEM-004t sensor and pyranometer, with sensor measurements validated against standard instruments[31]. Field testing observed parameters such as solar irradiation, power, and energy to evaluate the system's performance[32].

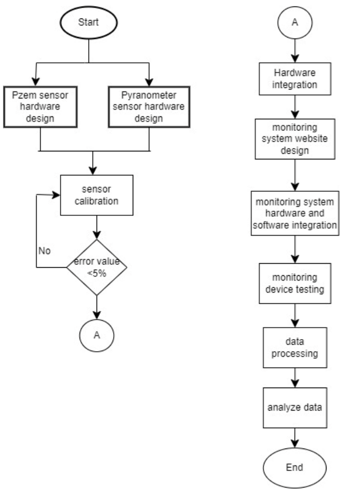

Fig. 3. Data processing flow chart

3. Results and Discussions

3.1 Sensor Characterization

This section involves testing to determine the characteristics of the sensors used in the developed monitoring device. The sensor characterization includes accuracy, precision, linearity, and sensitivity[31]. The results of these tests are essential to ensure that the device provides valid and reliable data under various operational conditions.

Thus, the solar radiation and load distribution monitoring device for the grid-connected photovoltaic system can operate optimally by providing accurate and precise measurements. The testing covers two main components: the PZEM-004T sensor, which measures electrical parameters, and the Pyranometer, which measures solar radiation. Calibration of the PZEM-004T sensor is performed by comparing its measurements with those of a calibrated standard measuring instrument. Testing involves measuring voltage, current, and power under various loads to ensure that the sensor readings are consistent with the reference instrument.

3.2 Pyranometer Sensor Testing

Pyranometer calibration is also conducted by comparing its measurements with a reference sensor used in the laboratory. Testing is performed under different light intensities to ensure that the Pyranometer accurately measures solar radiation. Each test is conducted with repeated measurements under the same conditions to assess measurement consistency.Measurements are taken at specific time intervals to ensure there is no drift or significant change in the results over time.

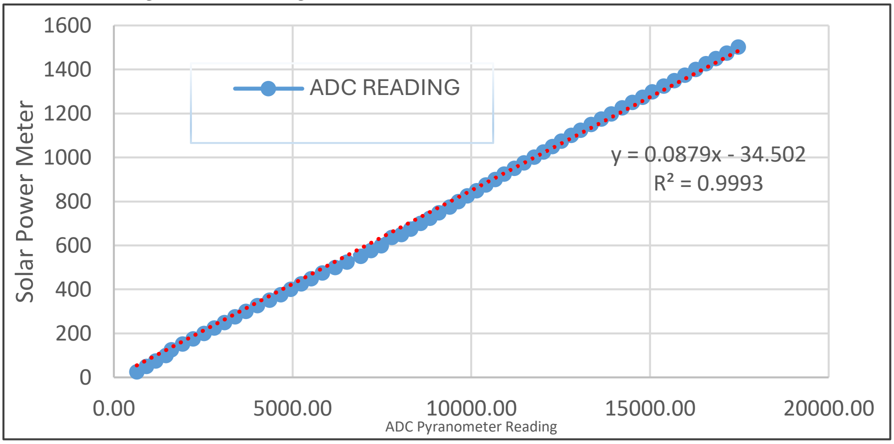

Fig. 4. Pyranometer Calibration Test Graph

Figure 4 shows the linear relationship between ADC readings from the sensor and Solar Power Meter (SPM) values used as a reference standard. The x-axis represents ADC readings, while the y-axis represents SPM values. A linear regression analysis yields the equation y=0.0879x−34.502y = 0.0879x - 34.502y=0.0879x−34.502, with the red line indicating the regression line. This line predicts SPM values based on ADC readings. The data appears linear, with an average linearity error of 1.20% (see Appendix 1). The red line closely fits most data points, indicating a strong linear relationship. The ADC readings range from 640.75 to 17,468.62, while SPM values range from 25 to 1,502. The pyranometer's sensitivity is 0.0814, meaning each unit increase in ADC reading corresponds to a 0.0814 increase in SPM value. This range illustrates the sensor's measurement capacity and scale.

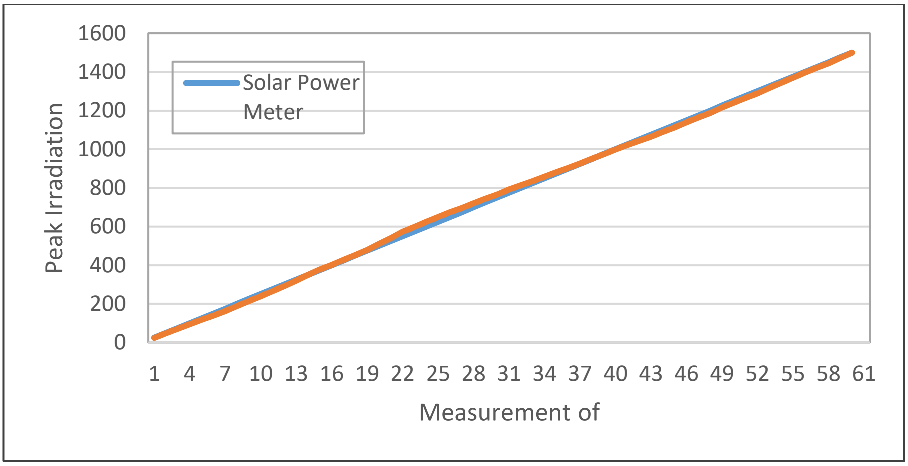

Fig. 5. Comparison of Pyranometer and Solar Power Meter Data

Figure 5 compares solar radiation measurements from the pyranometer and Solar Power Meter (SPM). The graph shows that both instruments have nearly identical responses to light intensity changes, with their lines overlapping throughout the 25 to 1500 range. This indicates that the SPM results are very similar to those from the pyranometer. However, there are slight discrepancies, notably a 10.84 difference at measurement 21 and a 24.82 difference at measurement 25. Despite these differences, the pyranometer shows a close linear relationship with the SPM, with an average error of 2.03% and an accuracy of 97.97%. This suggests good accuracy, though some deviation exists.

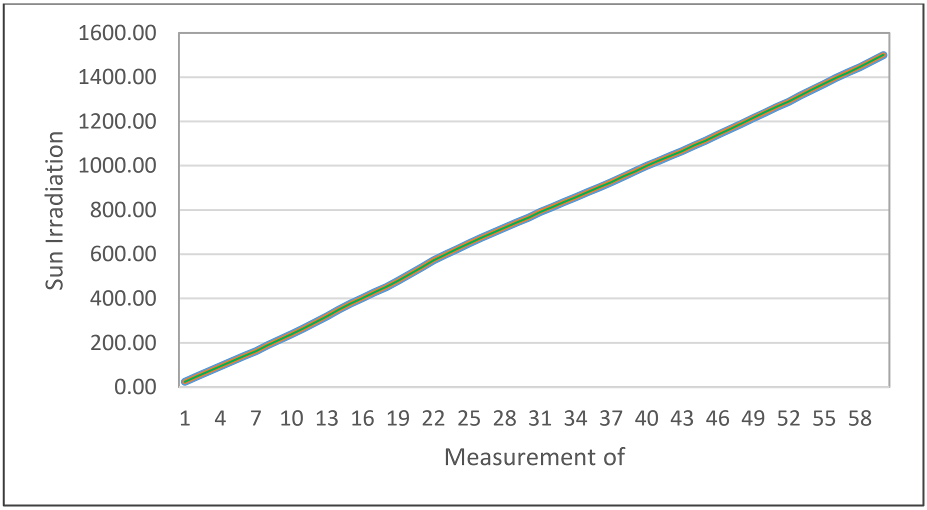

Fig. 6. Repeated Testing of Pyranometer

Figure 6 displays repeated tests of the pyranometer to assess precision. Three tests, shown in blue, red, and green, cover the 0 to 1500 W/m² range and yield nearly overlapping results, indicating high consistency. The average standard deviation from these tests is 0.2062, indicating a measurement uncertainty of ±0.2062 W/m². This low uncertainty confirms that the pyranometer provides consistent measurements.

Overall, the pyranometer has a measurement range of 0-1500 W/m², with an average linearity error of 1.20%, sensitivity of 0.0814, average measurement error of 2.03%, and accuracy of 97.97%. Its consistency, with a standard deviation of 0.2062, shows it is accurate and reliable for measuring solar radiation intensity.

3.3 PZEM-004t Testing

PZEM-004T testing is done by measuring and comparing measurement data with standard measuring instruments such as multimeters. Testing is done in a controlled manner with different electrical loads. The results of this test are important to ensure that the on-grid SPPS monitoring system can function properly and provide valid data to users.

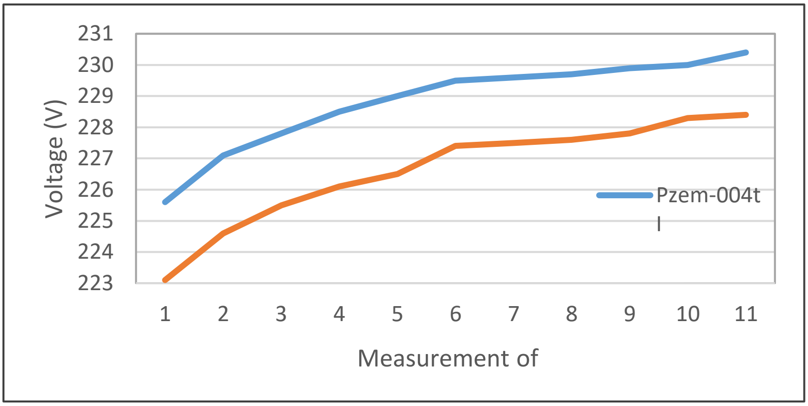

Fig. 7. Measurement of Voltage using PZEM-004T I

Figure 7 shows pzem 1 registers a voltage of 2 25.6 V, while the multimeter registers 223.1 V, indicating a difference of 2.5 V. The average difference between the pzem sensor and the multimeter was 2.2 V. The measurement uncertainty value is ±1.461 V.

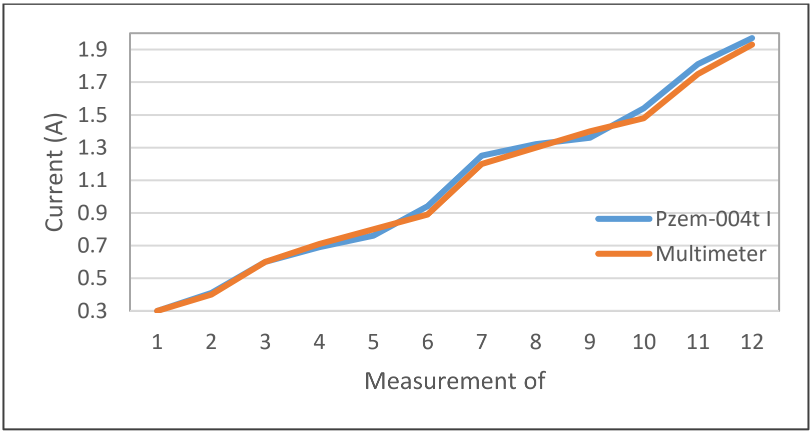

Fig. 8. Measurement of Current using PZEM-004T I

Figure 8 shows the same current of 0.3 A, indicating that both have consistent starting points and good calibration. Because it shows that the current readings on the pzem are quite linear, with a difference in readings of less than 0.1A.

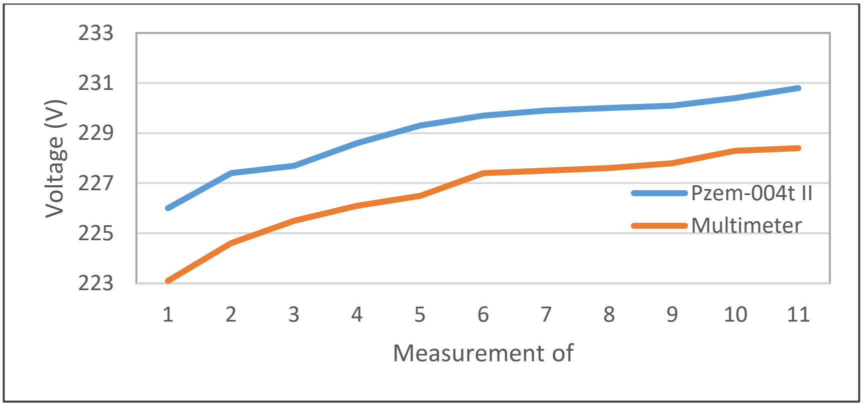

Fig. 9. Measurement of Voltage using PZEM-004T II

Figure 9 shows that the average difference in the pzem voltage reading with the multimeter is 2.49 V. In addition, a standard deviation value of 1.4793 is obtained. Based on the standard deviation value, it shows that the measurement uncertainty is ±1.4793 V.

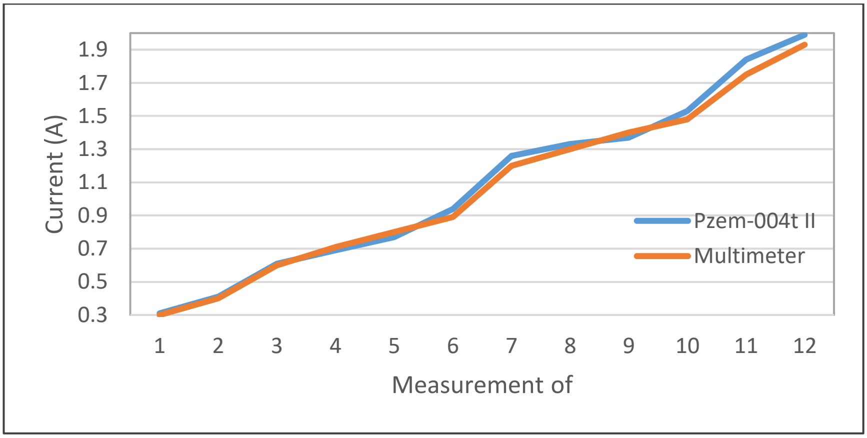

Fig. 10. Measurement of Current using PZEM-004T II

Figure 10 shows the graphic data also obtained an average difference in current reading pzem with a multimeter of 0.0367 A. In addition, the standard deviation value of 0.5619 was obtained. based on the standard deviation value shows that the measurement uncertainty is ±0.5619 A.

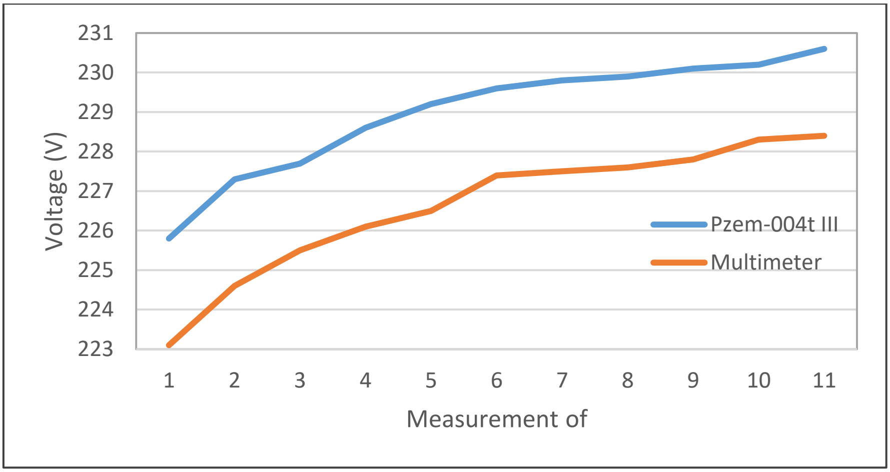

Fig. 11. Measurement of Voltage using PZEM-004T III

Figure 11 shows the graphic data obtained the average difference in current readings pzem with a multimeter of 2.36 V. In addition, the standard deviation value is 1.466. Based on the standard deviation value, it shows that the measurement uncertainty is ±1.466 V.

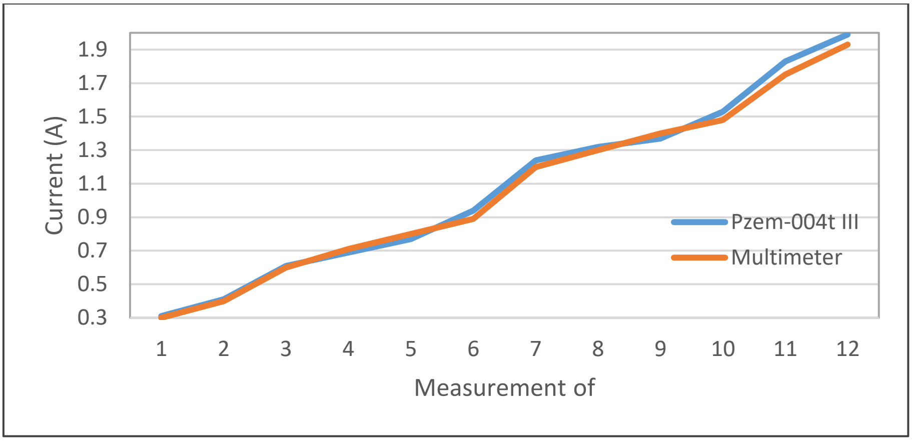

Fig. 12. Measurement of Current using PZEM-004T III

Figure 12 shows the graphic data also obtained an average difference in the reading of the pzem current with a multimeter of 0.035 A. In addition, a standard deviation value of 0.5603 was obtained. Based on the standard deviation value is ±0.5603 A. indicating that the measurement uncertainty.

The graph indicates that the PZEM-004T III, once calibrated with a multimeter, provides accurate and reliable current measurements. Despite minor discrepancies, the results remain within acceptable limits for practical applications. The PZEM-004T III demonstrates strong capability in tracking changes in current as measured by the multimeter, showing a linear and consistent response.

2.4 Testing of Solar Radiation Monitoring Devices and Load Parameters of On-grid Solar Power Plants (SPPS)

This study focuses on testing solar radiation monitoring devices and load parameters in grid-connected solar power plants (SPPS). The aim is to ensure the accuracy and reliability of devices used to measure solar radiation and to assess how load parameters impact the overall energy output and efficiency of the solar power system.

Test Result Data

Test data was taken from a weather station that was previously installed near the SPPS. For the power and energy parameters of the SPPS, it was compared with data from the S-Miles platform, which is a monitoring platform for the SPPS of the Airlangga University joint lecture building, which has valid data. Parameters were taken from morning to evening, namely at 05.20 - 17.20 WIB. The measurements were based on the time of sunrise and sunset.

Irradiation Measurement Data

Figure 4.10 shows a comparison graph of solar radiation measurements in W/m² throughout the day on May 19-23, 2024. Each daily graph shows the variation in solar irradiance recorded by both devices from 05:20 to 17:20. The pyranometer device consistently recorded higher irradiance values than WS Davis.

Power Measurement

Power measurements were conducted to understand and compare data from the solar monitoring device measurements with data from the S-Miles platform. This data is for one day on May 19, 2024 starting from morning to evening, when the sun rises to sunset. Figure 4.11 shows several differences in the power measurements, with an average difference in the power measurements of the monitoring device compared to the data from S-Miles of 6.51%.

Energy Measurement

Figure 4.12 shows the cumulative energy in 51 kilowatt hours (kWh), ranging from 0 to 25,000 kWh, while the x-axis shows the time from 5:30 a.m. to 5:30 p.m. in 30-minute intervals. Both devices show nearly identical results, with the blue line representing S-Miles and the red line representing pzem-004t

Device Transmission

Transmission data of monitoring devices obtained through the time of sending data from the monitoring device reading to the website. The data shown in the following table 1. includes various important parameters such as voltage, current, power, energy, and irradiation, as well as the time required for data transmission by the monitoring device and realtime.

Table 1. Performance of the monitoring system for SPP load.

Voltage (V)	Current (A)	Power (W)	Energy (kWh)	Irradiation	Device time	Website time	Transmition time
230.4	0.03	0	143.78	-0.2	19:10:49.849	19:10:50.486	0.637
230.4	0.03	0	143.78	-0.12	19:11:50.062	19:11:50.094	0.032
230.4	0.03	0	143.78	-0.03	19:12:50.120	19:12:50.230	0.11
230.4	0.03	0	143.78	-0.12	19:13:50.216	19:13:50.708	0.492
230.4	0.03	0	143.78	-0.03	19:14:50.338	19:14:50.412	0.074
230.4	0.03	0	143.78	-0.12	19:15:50.629	19:15:50.748	0.119
230.4	0.03	0	143.78	-0.03	19:16:50.893	19:16:51.315	0.422
230.4	0.03	0	143.78	-0.03	19:17:51.040	19:17:51.690	0.65
230.4	0.03	0	143.78	0.06	19:18:51.303	19:18:51.400	0.097
230.4	0.03	0	143.78	-0.03	19:19:51.622	19:19:52.380	0.758
230.4	0.03	0	143.78	-0.03	19:20:51.941	19:20:51.973	0.032
230.4	0.03	0	143.78	-0.03	19:21:52.133	19:21:52.198	0.065
230.4	0.03	0	143.78	-0.03	19:22:52.297	19:22:52.966	0.669
230.4	0.03	0	143.78	-0.03	19:23:52.578	19:23:52.612	0.034
230.4	0.03	0	143.78	0.06	19:24:52.761	19:24:52.843	0.082
230.4	0.03	0	143.78	-0.03	19:25:52.859	19:25:53.378	0.519
230.4	0.03	0	143.78	0.06	19:26:53.149	19:26:53.253	0.104
230.4	0.03	0	143.78	0.06	19:27:53.227	19:27:53.386	0.159
230.4	0.03	0	143.78	0.06	19:28:53.407	19:28:53.854	0.447
230.4	0.03	0	143.78	0.23	19:29:53.475	19:29:53.583	0.108
230.4	0.03	0	143.78	0.23	19:30:53.750	19:30:54.016	0.266

230.4	0.03	0	143.78	0.23	19:31:53 .831	19:31:54 .302	0.471
230.4	0.03	0	143.78	0.15	19:32:53 .904	19:32:54 .010	0.106
230.4	0.03	0	143.78	0.23	19:33:54 .126	19:33:54 .239	0.113
230.4	0.03	0	143.78	0.23	19:34:54 .458	19:34:54 .146	0.288

The data shows that the voltage and current measurements are stable, with voltage at 230.4 V and current at 0.03 A, indicating effective operation of the ESP32 micro-controller and sensors with minimal fluctuation, reflecting system stability. Power measurements remained at zero and energy constant at 143.78 kWh, suggesting a very low or absent load during data collection. Data transmission latency ranged from 0.032 to 0.758 seconds, with an average of 0.274 seconds. This low average latency indicates efficient data transfer, although some higher latency values highlight the need for further network evaluation. Overall, the device performs reliably over time, but additional optimization could enhance the accuracy and efficiency of the monitoring system, supporting more stable and efficient SPP operations.

The appearance and features of the monitoring website

Fig. 13 Real-time reading section on the website

The website of the solar irradiation monitoring device and the distribution of on-grid SPPS loads developed aims to provide real-time data visualization by users. This website can be accessed via computers, tablets, and smartphones. The main features of the website include real-time data display for voltage, current, power, energy, and solar irradiation.

Fig. 14 graphic appearance on website

Figure 4.14 shows the SPPS monitoring website feature shows a power graph for three phases: Phase R, Phase S, and Phase T. Each graph displays the power value measured by the sensor at a certain time.

Hide data

Timestamp	Voltage (V)			Current (A)			Power (W)			Energy (kWh)			Power Factor			Frequency (Hz)			Irradiance (W/m²)
	R	S	T	R	S	T	R	S	T	R	S	T	R	S	T	R	S	T	
2024/05/24 09:09:38	227.50	228.40	227.40	3.68	3.96	4.01	835.90	904.30	911.40	47.06	54.93	60.31	1.00	1.00	1.00	50.00	50.00	50.00	757.33
2024/05/24 09:08:38	227.50	228.30	227.30	3.79	4.10	4.14	861.20	934.50	940.70	47.05	54.92	60.29	1.00	1.00	1.00	50.00	49.90	50.00	790.87
2024/05/24 09:07:38	227.60	228.40	227.50	3.62	3.92	3.98	822.40	894.70	903.20	47.03	54.90	60.27	1.00	1.00	1.00	50.00	49.90	49.90	753.82
2024/05/24 09:06:38	227.60	228.70	227.60	3.49	3.80	3.86	794.20	868.60	876.90	47.02	54.89	60.26	1.00	1.00	1.00	50.00	50.00	50.00	729.24
2024/05/24 09:05:38	227.40	228.70	227.70	3.43	3.66	3.72	779.00	835.70	845.90	47.01	54.87	60.24	1.00	1.00	1.00	50.00	50.00	50.00	704.92
2024/05/22 03:02:58	230.40	231.40	230.10	0.06	0.06	0.18	0.00	0.00	15.30	33.39	39.30	43.92	0.00	0.00	0.36	50.00	50.00	50.00	0.15
2024/05/22 03:01:57	230.00	231.10	230.20	0.06	0.06	0.19	0.00	0.00	15.80	33.39	39.30	43.92	0.00	0.00	0.36	50.00	50.00	50.00	0.06
2024/05/22 03:00:57	230.40	231.80	230.50	0.06	0.06	0.18	0.00	0.00	15.40	33.39	39.30	43.92	0.00	0.00	0.36	50.00	49.90	50.00	-0.03
2024/05/22 02:59:57	231.10	232.60	231.30	0.06	0.06	0.18	0.00	0.00	15.50	33.39	39.30	43.92	0.00	0.00	0.37	50.00	50.00	50.00	0.15
2024/05/22 02:58:57	231.30	232.70	231.40	0.06	0.06	0.18	0.00	0.00	15.40	33.39	39.30	43.92	0.00	0.00	0.36	50.00	50.00	50.00	0.15
2024/05/22 02:57:57	231.00	232.30	231.20	0.06	0.06	0.19	0.00	0.00	15.60	33.39	39.30	43.92	0.00	0.00	0.36	50.00	50.00	50.00	0.06
2024/05/22 02:56:56	231.10	232.40	231.00	0.06	0.06	0.18	0.00	0.00	15.40	33.39	39.30	43.92	0.00	0.00	0.36	50.00	49.90	50.00	0.15
2024/05/22 02:55:56	231.10	232.30	230.90	0.06	0.06	0.18	0.00	0.00	15.50	33.39	39.30	43.92	0.00	0.00	0.36	50.00	50.00	50.00	0.15
2024/05/22 02:54:56	229.90	231.10	229.70	0.06	0.06	0.19	0.00	0.00	15.50	33.39	39.30	43.92	0.00	0.00	0.36	50.00	50.00	50.00	-0.03
2024/05/22 02:53:56	229.70	230.80	229.50	0.06	0.06	0.19	0.00	0.00	15.30	33.39	39.30	43.92	0.00	0.00	0.36	50.00	50.00	50.00	0.06
2024/05/22 02:52:56	229.70	231.10	229.80	0.06	0.06	0.19	0.00	0.00	15.60	33.39	39.30	43.92	0.00	0.00	0.36	50.00	50.00	50.00	-0.03
2024/05/22 02:51:56	229.30	230.80	229.30	0.06	0.06	0.19	0.00	0.00	15.30	33.39	39.30	43.92	0.00	0.00	0.36	50.00	50.00	50.00	0.06

Fig. 15 table view on website

Figure 4.15 shows the features on the SPPS monitoring website to display a real-time data table that includes various electrical parameters from the SPPS on-grid system. The parameters displayed include the time of data collection, RST phase voltage, RST phase current, RST phase power, RST phase energy, RST phase power factor, RST phase frequency, and solar irradiation.

4. Conclusion

The design and testing of the monitoring device for solar irradiation and load distribution in on-grid Solar Power Plants (SPPs) have yielded significant findings. The system, incorporating an ESP32 microcontroller, PZEM-004t sensor, and pyranometer, was successfully implemented, demonstrating effective functionality. The hardware and software integration enabled real-time data collection and monitoring via the Firebase platform. The system achieved a pyranometer sensor accuracy rate of 97.97% and a sensitivity of 0.0814, with a measurement range 37.29% greater than the WS Davis. Power and energy measurements showed consistent trends with high accuracy when compared to the S-Miles platform. Additionally, the system's sensitivity to parameter changes was commendable. The monitoring system provided users with accurate and timely information, accessible through a web interface, allowing for efficient real-time monitoring and analysis with an average data transmission time of 0.274 seconds. These results underscore the system's potential to enhance the operational efficiency of on-grid SPPs while offering a reliable and user-friendly interface for monitoring and managing solar power production.

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