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Design and Implementation of a PLC-Based Data Logger for Solar Panel Battery Monitoring

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ABSTRACT:*The rapid deployment of photovoltaic (PV) systems in developing countries has highlighted the need for reliable monitoring of battery storage performance. Conventional manual measurement methods are prone to discontinuity, lack of data storage, and human error, limiting their effectiveness for long-term analysis and predictive maintenance. This study presents the design and implementation of a Programmable Logic Controller (PLC)-based monitoring system for solar batteries with integrated data logging and Human-Machine Interface (HMI) visualization. The system employs PZEM-017 sensors to measure voltage, current, and power, transmitting data via the Modbus RTU protocol to a Schneider Modicon M221 PLC. Measurements are displayed in real time through a GXU-series HMI and periodically logged onto a MicroSD card in .xls format at 30-second intervals. Experimental results validate the system's accuracy, with sensor readings deviating only 0.01–0.03 V from calibrated multimeter measurements. The logging mechanism proved reliable under continuous operation, while alarm thresholds embedded in the HMI successfully alerted operators to critical battery conditions. The proposed system combines industrial robustness with practical offline data storage, offering a scalable and cost-effective solution for PV battery monitoring in rural and industrial applications..*

KEY WORDS:*Photovoltaic systems; battery monitoring; Programmable Logic Controller (PLC); data logging; Human-Machine Interface (HMI); Modbus RTU.*

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I. INTRODUCTION

Despite the increasing deployment of PV systems, one of the critical challenges lies in the effective monitoring of battery performance within solar power installations [3]. Batteries, which serve as the primary storage medium, are highly susceptible to issues such as overcharging, deep discharging, and accelerated degradation under extreme environmental conditions [4]. Ineffective monitoring not only reduces battery lifespan but also jeopardizes system stability, leading to frequent downtime, inefficient utilization of generated power, and increased maintenance costs. Traditional manual measurements using multimeters remain widely practiced; however, they are limited by discontinuity of data collection, lack of real-time storage, and vulnerability to human error [5]. Such approaches fail to generate comprehensive datasets that are essential for predictive maintenance, life-cycle assessment, and optimization of PV system performance.

In recent years, researchers have proposed advanced monitoring solutions that integrate Internet of Things (IoT) platforms, microcontrollers, and cloud computing technologies [6]–[8]. These methods provide remote access, real-time visualization, and in some cases predictive analytics. Nevertheless, their reliance on stable internet connectivity represents a significant drawback, particularly in rural areas of Indonesia and other developing countries where network infrastructure is limited. Moreover, microcontroller-based systems often exhibit limitations in scalability, robustness under industrial conditions, and interoperability with standardized communication protocols. These constraints reduce their suitability for long-term or large-scale deployment.

Programmable Logic Controllers (PLCs), on the other hand, represent a mature and reliable technology widely adopted in industrial automation due to their robustness, deterministic performance, and compatibility with established communication standards such as Modbus RTU [9]. PLCs are specifically designed to operate in harsh environments, maintain continuous performance, and seamlessly integrate with Human-Machine

Interfaces (HMIs) and Supervisory Control and Data Acquisition (SCADA) systems. Leveraging PLC technology for solar battery monitoring therefore provides not only enhanced reliability but also ensures compatibility with existing industrial infrastructures.

This research addresses the identified gaps by presenting the design and implementation of a PLC-based battery monitoring system for solar panels with integrated data logging. The novelty of the proposed system lies in its ability to combine real-time monitoring with historical data recording, ensuring that critical parameters such as voltage, current, and power are continuously measured and archived. The system employs PZEM-017 sensors for accurate acquisition of electrical parameters, displays real-time data via an HMI for immediate operational insights, and logs measurements into a MicroSD card in .xls format at regular intervals. Unlike typical IoT-only solutions, this system guarantees data availability even in the absence of internet connectivity while maintaining the industrial-grade robustness offered by PLCs.

By integrating real-time monitoring with reliable offline data logging, the system supports immediate decision-making and enables in-depth analysis for efficiency improvement, early fault detection, and predictive maintenance strategies. The contribution of this work is particularly significant for developing countries, where cost-effectiveness, reliability, and scalability are critical for renewable energy adoption. Furthermore, the proposed system has the potential to serve as a benchmark for future developments in hybrid monitoring architectures that combine the resilience of PLCs with the flexibility of IoT platforms, thereby bridging the gap between established industrial standards and emerging smart energy solutions.

Several studies have investigated monitoring systems for PV installations, focusing on both real-time visualization and data storage. Khowarizmi and Setiyono (2025) integrated PLC and IoT for real-time monitoring of PV performance; however, their approach lacked an integrated data logging feature, thereby limiting the ability to perform long-term analysis [13]. Likewise, Azizah and Yuhendri (2022) developed an HMI-based monitoring system capable of displaying voltage, current, power, and temperature, but the solution required separate sensors for each parameter, leading to a more complex system architecture and higher implementation costs [14]. These examples highlight that although significant progress has been made in PV monitoring, existing systems still exhibit shortcomings in terms of simplicity, cost efficiency, and reliable data retention.

Other research efforts have employed microcontroller-based systems as low-cost alternatives. For instance, ESP32 and Arduino platforms have been widely used to collect PV data and transmit it through IoT frameworks such as Blynk, Firebase, and ThinkSpeak [6]–[8]. These solutions are attractive due to their affordability and accessibility, but they often trade robustness for flexibility. A major limitation is the absence of reliable offline data logging capabilities. Consequently, when network connectivity is unavailable—as frequently occurs in rural or isolated regions—critical datasets are lost, thereby undermining the reliability of such systems for continuous energy management. Furthermore, dependence on non-industrial hardware introduces risks in long-term deployments, as hardware degradation and protocol incompatibility can hinder scalability and industrial adoption [9].

Recent international studies have emphasized the necessity of combining real-time monitoring with reliable long-term data storage. Chen et al. (2023) highlighted that although cloud-based solutions enable powerful centralized analytics, they introduce challenges related to cybersecurity risks, latency, and heavy reliance on stable internet connectivity [10]. Kumar and Singh (2024) demonstrated the effectiveness of IoT-enabled PV monitoring but concluded that hybrid architectures—integrating local data logging with cloud access—provide the best balance between robustness and accessibility [11]. Similarly, Ramirez et al. (2022) stressed that continuous parameter tracking for PV batteries is essential, as inadequate monitoring accelerates degradation and diminishes the overall efficiency of renewable energy storage [12].

Comparative studies have also explored frameworks utilizing alternative communication protocols. For example, systems based on Modbus over TCP/IP have been proposed for distributed PV monitoring; however, such systems often demand more complex infrastructure and skilled technical expertise, which restricts their practicality in small-scale or rural applications. Additionally, SCADA-based architectures have been adopted in large PV farms, yet these solutions remain cost-prohibitive and unsuitable for decentralized, community-based solar installations. As a result, a notable research gap persists in the design of monitoring systems that are simultaneously low-cost, scalable, and sufficiently robust for industrial use.

In contrast to these prior approaches, the proposed system integrates a PZEM-017 sensor with a PLC to achieve robust real-time monitoring combined with MicroSD-based logging. This hybrid approach ensures both measurement accuracy and reliable historical data availability, even in environments without internet connectivity. Unlike microcontroller-based systems, PLCs provide industrial-grade reliability, scalability, and compliance with standardized communication protocols, making them more suitable for long-term deployment in challenging operating conditions. Furthermore, embedding the data logging function directly within the PLC framework reduces dependency on external cloud infrastructure while preserving opportunities for future IoT integration.

The contribution of this research lies in presenting a cost-effective, industrially robust, and scalable monitoring framework that effectively bridges the gap between microcontroller-based IoT solutions and high-cost SCADA systems. This work is particularly relevant for developing regions, where infrastructure limitations demand practical, resilient, and affordable solutions. By ensuring real-time monitoring, offline data availability, and adherence to industrial standards, this study advances the state of the art in PV battery monitoring and establishes a foundation for future hybrid architectures that combine the robustness of PLC technology with the flexibility of IoT platforms.

II. MATERIAL AND METHODS

A. Materials

The experimental setup employed a comprehensive combination of photovoltaic (PV) system components, industrial-grade controllers, and dedicated measurement modules. The selected hardware and software were chosen to ensure accuracy, robustness, and replicability under laboratory and near-industrial conditions. The primary materials are described below.

1) Photovoltaic Subsystem

The PV subsystem serves as the primary energy source and storage medium for the monitoring system. A commercial PV panel was utilized to emulate renewable energy generation during the testing phase, supplying power to the downstream components. Energy was stored in a deep-cycle 12 V lead-acid battery (Aki), chosen due to its wide availability and cost-effectiveness in rural electrification projects. To protect the battery from premature degradation, a solar charge controller was employed to regulate charging and discharging cycles. This controller ensured that the battery operated within safe voltage ranges, thereby maintaining its efficiency and prolonging service life.

2) Measurement Sensors

Accurate monitoring of electrical parameters was achieved through PZEM-017 energy meter modules. Each module is capable of measuring voltage, current, power, and accumulated energy consumption. Communication between the sensors and the controller was established using the RS-485 Modbus RTU protocol, which is widely adopted in industrial environments for its robustness against electrical noise and its ability to support long-distance communication. The sensors provided the raw data necessary for both real-time decision-making and long-term performance evaluation.

3) Controller and Interface

The Programmable Logic Controller (PLC), specifically the Schneider Modicon M221, served as the central processing and data logging unit. This industrial-grade PLC was selected for its deterministic performance, high reliability, and compatibility with multiple communication protocols. A Human-Machine Interface (HMI) from the Schneider GXU Series was used to visualize system parameters in real time, with displays configured to show both numerical values and graphical trends. To complement real-time monitoring, a MicroSD card module was integrated with the PLC, enabling offline logging of system data in spreadsheet-compatible (.xls) format. This ensured that historical datasets could be preserved even in the absence of internet connectivity.

4) Auxiliary Components

Auxiliary equipment was employed to simulate realistic testing conditions. A 24 V DC regulated power supply was used to power the PLC and associated peripherals, ensuring stable operation during experimental trials. Various loads were connected to the system, including resistive loads (incandescent lamps) and inductive loads (DC fans), to evaluate system performance under diverse electrical demands. Reliable connectivity between all subsystems was facilitated by shielded RS-485 communication cables and standard electrical wiring, which minimized interference and improved measurement accuracy.

5) Software Tools

Three main software platforms were utilized. EcoStruxure Machine Expert Basic was used for PLC programming, allowing the development of control logic, data polling routines, and logging functions. Vijeo Designer was implemented for HMI configuration, enabling the creation of user-friendly visualization dashboards and alarm indicators. Finally, Modbus Poll was employed as a diagnostic tool for testing communication channels and validating data transmission integrity, as illustrated in Fig. 1.

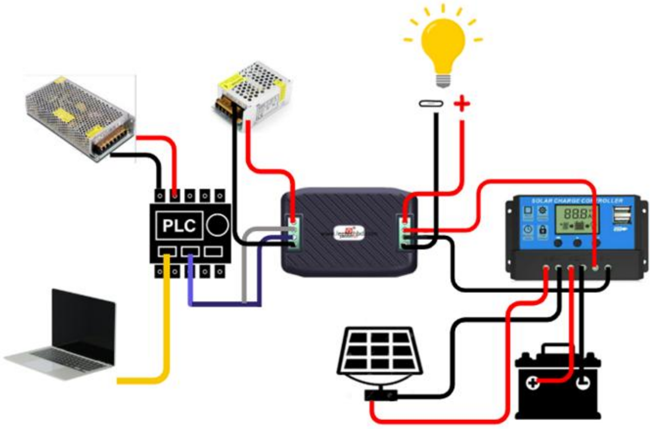

Figure 1:Overall system architecture of the PLC-based solar battery monitoring system.

B. Methods

The methodological approach adopted in this study followed a design–implementation–testing cycle, which ensured that both functional validation and performance evaluation could be carried out systematically.

1) System Design

The system architecture was designed around four main layers: the PV subsystem (energy source and storage), PZEM-017 sensors (data acquisition), PLC controller (data processing and logging), and the HMI/MicroSD modules (visualization and storage). The architecture was represented in a block diagram (Fig. 1), which highlights the flow of energy and information across the subsystems. This design was intended to bridge the gap between conventional microcontroller-based monitoring systems and industrial-grade automation frameworks.

2) System Implementation

During implementation, the PZEM-017 sensors were interfaced with the Schneider Modicon M221 PLC through the RS-485 Modbus RTU protocol. The PLC was programmed to continuously poll data from the sensors, validate the incoming values to filter out erroneous readings, and format them into structured datasets suitable for visualization and logging. The Schneider GXU HMI was configured to display parameters such as voltage, current, and power, using both numerical indicators and graphical trend plots. Additionally, alarm thresholds were implemented: the system issued a warning whenever the battery voltage dropped below 11.5 V or exceeded 14.8 V. For historical analysis, the PLC was programmed to log data onto a MicroSD card at 30-second intervals, with each record containing a timestamp alongside the measured parameters.

3) Testing Procedure

Experimental validation was performed by subjecting the system to different load conditions, including resistive lamps and inductive fans. Measurements obtained from the PZEM-017 sensors were cross-verified against a calibrated digital multimeter to assess measurement accuracy. The logging process was evaluated for continuity, ensuring that no data entries were missed during extended operation. The HMI's visualization and alarm functions were tested by gradually altering load conditions until threshold limits were reached, thereby confirming system responsiveness. The collected datasets were later analyzed to determine consistency, identify performance patterns, and explore potential applications for predictive maintenance.

This structured methodology ensured that the developed system not only met the requirements for real-time monitoring but also provided robust long-term data logging capabilities. The approach also validated the potential of PLC-based monitoring systems as a scalable and industrially reliable alternative to conventional microcontroller- or IoT-only solutions.

III. RESULTS AND DISCUSSIONS

The implementation results focus on the testing process of the monitoring system to ensure that all components and circuits operated properly, including the PLC M221, PZEM-017 sensors, solar charge controller, battery, photovoltaic panel, and HMI interface. During testing, each component was verified to function according to its intended specifications.

Throughout this stage, potential problems, limitations, or disturbances in the system could be identified at an early phase. The primary objective was to ensure that measurement data from the PZEM-017 sensor

modules were successfully displayed on the HMI in real time. If no disturbances were observed during testing, the system could be considered ready for effective operation. This step validated the performance of the integrated components, confirming their proper functionality in accordance with technical specifications.
Before connecting the PV panel, preliminary testing was conducted using a lamp load to measure voltage, current, and power in real time. After several trials, the measurements were successfully obtained, confirming that the devices functioned normally and reliably, Fig.2.PLC connected with PZEM-017 sensor module.

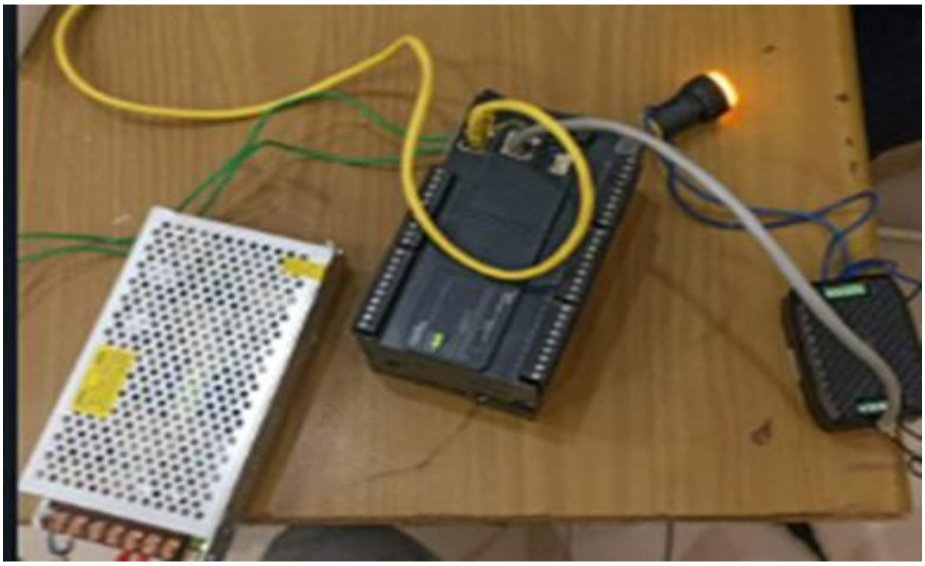

Figure 2:PLC connected with PZEM-017 sensor module

Fig.3.Illustrates the HMI screen developed using Vijeo Designer v1.2. The interface displays real-time measurement data—voltage, current, and power—obtained from the PZEM-017 sensor via the Modbus RTU protocol.

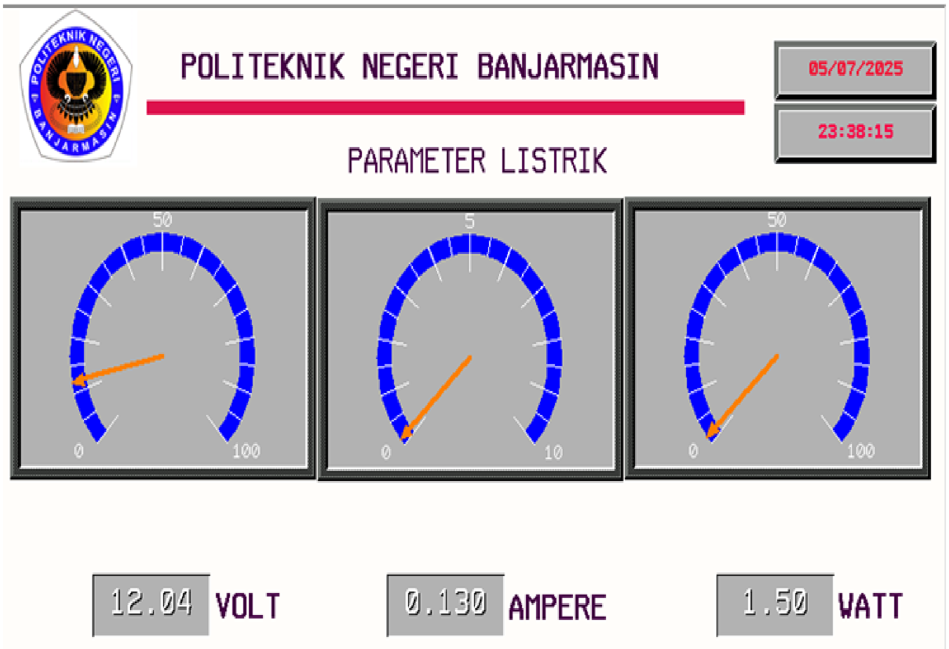

Figure 3:HMI interface developed in Vijeo Designer

When tested with three lamps and a 12 VDC fan, the HMI provided real-time monitoring of all parameters. Table (1) presents the corresponding measurement results.

Table I. Measurement results with 3 lamps and 12 VDC fan

Volt	Ampere	Watt
11.98	0.120	1.40

Fig 4. Shows a screenshot of the logged data for the 3-lamp and fan load. The data logger generated .csv files containing columns for timestamp, voltage, current, and power.

1	Timestamp	Volt	Ampere	Watt
2	18/07/25 11:29:07	11.99	0.12	1.4
3	18/07/25 11:29:38	11.99	0.12	1.4
4	18/07/25 11:30:09	11.98	0.12	1.4
5	18/07/25 11:30:40	11.98	0.12	1.4
6	18/07/25 11:31:11	11.98	0.12	1.4
7	18/07/25 11:31:42	11.98	0.12	1.4
8	18/07/25 11:32:13	11.98	0.12	1.4
9	18/07/25 11:32:44	11.98	0.12	1.4
10	18/07/25 11:33:15	11.98	0.12	1.4
11	18/07/25 11:33:46	11.98	0.12	1.4
12	18/07/25 11:34:17	11.98	0.12	1.4
13	18/07/25 11:34:49	11.98	0.12	1.4
14	18/07/25 11:35:20	11.98	0.12	1.4
15	18/07/25 11:35:51	11.98	0.12	1.4
16	18/07/25 11:36:22	11.98	0.12	1.4
17	18/07/25 11:36:53	11.98	0.12	1.4
18	18/07/25 11:37:24	11.98	0.12	1.4
19	18/07/25 11:37:55	11.98	0.12	1.4
20	18/07/25 11:38:26	11.97	0.12	1.4
21	18/07/25 11:38:57	11.98	0.12	1.4
22	18/07/25 11:39:28	11.98	0.12	1.4
23	18/07/25 11:39:59	11.97	0.12	1.4
24	18/07/25 11:40:30	11.97	0.12	1.4
25	18/07/25 11:41:01	11.97	0.12	1.4
26	18/07/25 11:41:32	11.97	0.12	1.4
27	18/07/25 11:42:03	11.97	0.12	1.4
28	18/07/25 11:42:34	11.97	0.12	1.4

Figure 4: Measurements with 3 Lamps and 12 VDC Fan

Fig.5. Present the logged graphs of voltage, current, and power, respectively, under a combined load of three lamps and 12 VDC fan. Data were logged at 30-second intervals from 11:29 to 12:51, producing 157 data entries.

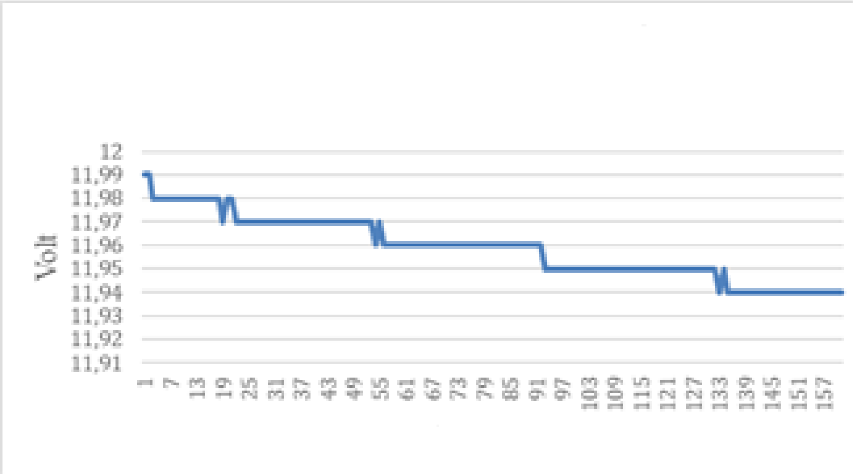

Figure 5:Voltage graph

Fig 6. Shows a comparison between the PZEM-017 sensor (a) and a calibrated digital multimeter (b). For example, the sensor measured 11.98 V, while the multimeter read 11.97 V, indicating a deviation of only 0.01 V, an acceptable level of accuracy.

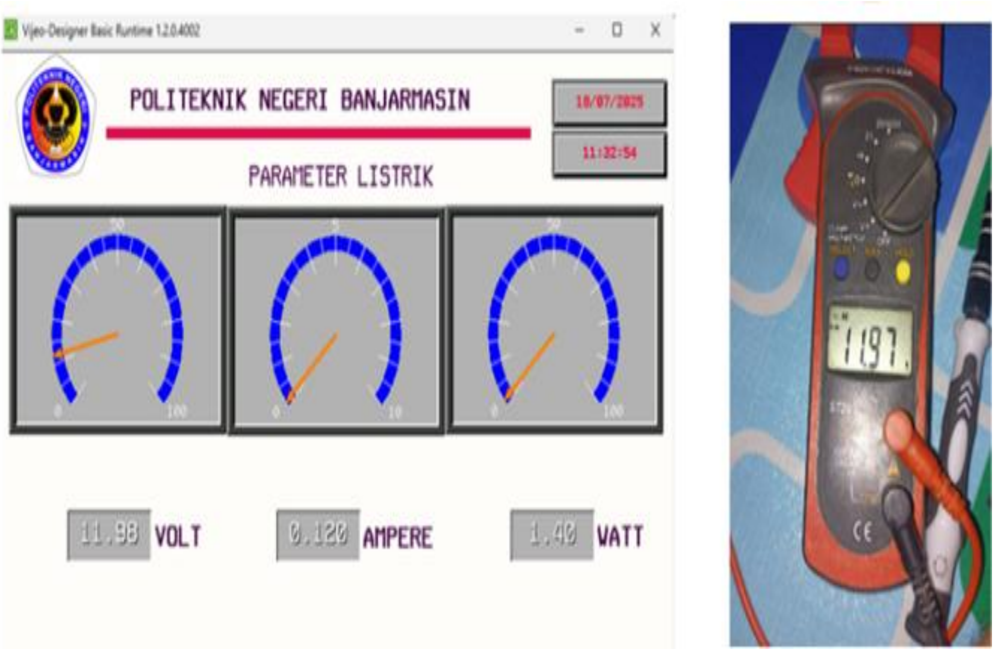

Figure 6: Comparison between sensor and multimeter readings

The experimental results confirmed that the PLC-based monitoring system operated reliably and met its design objectives. The integration of PZEM-017 sensors with the Modicon M221 PLC ensured accurate and stable measurements, with deviations of only 0.01 V compared to a calibrated digital multimeter. The HMI provided clear real-time visualization of voltage, current, and power, while the MicroSD logging mechanism consistently stored complete datasets at 30-second intervals without data loss. Graphical trend analysis demonstrated stable system performance across different load conditions, and the built-in alarm thresholds enhanced safety by alerting operators to critical battery states. Overall, the findings validate the system as a robust, accurate, and scalable solution for photovoltaic battery monitoring.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

This study successfully demonstrated the design, implementation, and validation of a PLC-based monitoring system for photovoltaic (PV) batteries. The system integrated PZEM-017 sensors, a Schneider Modicon M221 PLC, and a GXU-series HMI to provide real-time measurement, visualization, and offline data logging. Key conclusions are as follows:

1. **Accurate Measurement** – Sensor integration with the PLC yielded high measurement accuracy, with deviations of only 0.01–0.03 V compared to calibrated multimeter readings. This validates the suitability of PZEM-017 sensors for precise PV battery monitoring.
2. **Reliable Data Logging** – The MicroSD-based logging mechanism consistently recorded data at 30-second intervals without errors or missing entries, ensuring continuous availability of historical datasets even in the absence of internet connectivity.
3. **Effective Visualization** – The HMI provided real-time numerical and graphical displays of voltage, current, and power, with integrated alarm thresholds that enhanced operational safety by warning operators of critical battery conditions.
4. **Scalability and Robustness** – By employing industrial-grade PLCs and standard communication protocols (Modbus RTU), the system ensured robustness, deterministic performance, and scalability for deployment in both small-scale and industrial PV applications.
5. **Contribution to Sustainable Energy** – The system demonstrated the potential to reduce reliance on manual measurement methods, improve decision-making in PV energy management, and support predictive maintenance strategies, which are critical for sustainable renewable energy adoption in developing regions.

B. Recommendations

Based on the results, several recommendations can be made for future development and wider deployment of the system:

1. **IoT Integration** – Future versions should incorporate IoT platforms for remote access and cloud-based analytics while maintaining offline logging to ensure resilience in low-connectivity environments.
2. **Expanded Parameter Monitoring** – Adding environmental sensors such as temperature, humidity, and irradiance could enrich datasets and support more advanced performance analysis of PV systems.
3. **Advanced Analytics** – Integration of machine learning algorithms for predictive maintenance and fault detection could enhance system intelligence and operational efficiency.
4. **Field Deployment** – Long-term testing in real PV installations under varying weather and load conditions is recommended to validate durability and assess scalability for rural electrification projects.
5. **Cost Optimization** – Further efforts should focus on reducing system cost through component standardization, enabling wider adoption in developing countries where affordability is critical.

In summary, the PLC-based solar battery monitoring system presented in this study provides a practical, robust, and scalable framework for improving the reliability and sustainability of PV energy systems. Future research should build upon this foundation by integrating IoT technologies, expanding monitored parameters, and exploring intelligent data-driven strategies for energy optimization.

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