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Bidirectional Sensor-Based Measurement of PV Output with MPPT Control: An Experimental Pre-Study Before PLC Monitoring Integration

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Abstract*. This paper presents a preliminary experimental study on the use of an analog bidirectional current sensor for photovoltaic (PV) systems operated under Maximum Power Point Tracking (MPPT) control. The ultimate goal of this research is to develop a comprehensive monitoring system for energy harvesting from PV systems using a PLC-based platform. As an initial step, this study investigates the behavior of a bidirectional sensor in detecting charging and discharging processes in an off-grid PV configuration. The sensor is evaluated through experimental measurements of current and voltage outputs, where the bidirectional characteristic provides an indication of the direction of energy flow—charging when energy is stored in the battery and discharging when energy is supplied to the load. Data acquisition and visualization are performed using LabVIEW, which allows real-time monitoring and validation of sensor performance at specific time intervals. The experimental results provide insights into the accuracy and reliability of the analog bidirectional sensor under varying operating conditions. The novelty of this study lies in its focus on sensor behavior analysis as a foundation for future PLC-based monitoring system development. By validating sensor performance through this pre-study, the research ensures that reliable data can be obtained for subsequent integration into a real-time monitoring and control system for PV energy harvesting applications.*

Keywords - *photovoltaic****,*** *MPPT, bidirectional sensor, energy harvesting, charging/discharging, LabVIEW, PLC*

INTRODUCTION

The rapid growth of renewable energy technologies has placed photovoltaic (PV) systems at the forefront of sustainable electricity generation. In order to ensure reliable performance, PV systems require accurate monitoring of electrical parameters such as voltage, current, and power, which are further utilized for system optimization and control. Monitoring systems based on LabVIEW have been widely applied to observe PV behavior in real time and provide valuable insights into energy harvesting processes [1], [2]. Recent studies have demonstrated the effectiveness of LabVIEW in visualizing PV performance and validating measurement accuracy prior to integration with supervisory control systems [3], [4], [5]. The integration of Maximum Power Point Tracking (MPPT) algorithms into PV systems has further increased the demand for precise measurement, as MPPT performance directly depends on the quality of sensed data[6], [1], [7]. Several studies have implemented LabVIEW-based monitoring platforms to support MPPT evaluation and to provide real-time visualization of PV energy conversion [8], [9], [10]. Other works have highlighted the importance of sensor calibration and data validation prior to embedding them into programmable logic controllers (PLCs) or SCADA architectures for large-scale applications [8], [9]. These findings emphasize that sensor reliability and accuracy are critical to ensure the effectiveness of control and monitoring strategies. A key aspect that has received increasing attention is the use of bidirectional sensors for PV applications. Such sensors enable the detection of charging and discharging behavior in off-grid configurations, offering valuable information about the flow of energy between PV modules, storage devices, and loads[10]. Experimental validation of these sensors is necessary to evaluate their dynamic response, accuracy, and consistency under varying operating conditions. As noted in previous works, neglecting early-stage validation may lead to measurement errors and unreliable data, which in turn reduces the efficiency of subsequent monitoring systems [11].

In addition, the authors' previous research has contributed to the development of automation and monitoring systems, which serve as a foundation for this study. For example, PLC Omron CJ1M CPU-21 Control Modification for Drill Oil Hole Machine demonstrated control flexibility in industrial applications [12], while the Experimental Analysis Design of Solar Panel Energy Monitoring Prototype highlighted the importance of prototyping in PV monitoring[13]. Furthermore, automation concepts such as the Control Design of a Storage Machine Based on Omron PLC System [14] and the development of advanced control strategies in power electronics [15] reinforce the significance of early-stage experimental validation before integrating sensors and control units into a larger PLC-based monitoring framework. Therefore, this study presents a preliminary experimental investigation on the behavior and performance of an analog bidirectional current sensor in a PV system equipped with MPPT technology. The experimental setup utilizes LabVIEW to acquire and visualize current and voltage readings at specific intervals, providing a basis for evaluating the accuracy of the sensor in detecting charging and discharging states. The novelty of this work lies in its focus on characterizing the sensor prior to full integration into a PLC-based monitoring system. The results are expected to serve as a reference for ensuring reliable data acquisition in the development of real-time PV energy harvesting monitoring platforms.

METHODS

The methodology of this research was designed to evaluate the performance of a bidirectional current sensor in a PV system integrated with MPPT technology. The study began with the determination of the research theme, which focused on the need for reliable current measurement in off-grid PV configurations. The use of a bidirectional sensor was considered essential because it is capable of detecting both charging and discharging currents, thereby providing critical information about energy flow in the system. The literature review was conducted to establish a solid theoretical foundation. Previous studies emphasized the role of LabVIEW in real-time monitoring and MPPT evaluation, as well as the importance of early-stage validation of sensors prior to integration into PLC or SCADA systems. The review also highlighted the relevance of bidirectional sensors for PV monitoring, given their ability to capture bidirectional energy flow in off-grid applications.

Table 1. Bi-Directional Sensor Specification

Bi-Directional Sensor Specification	
Model	ACS758LCB-050B
Measurement Range	±50 A
Sensitivity	40 mV/A
Supply Voltage	5 V DC
Output Type	Analog, at Vcc/2 (2.5 V at zero current)
Response Time	<10 µs
Operating Temperature	–40 to +85 °C
Isolation Voltage	3000 VRMS

Table 2. Solar Panel Specification

Solar Panel Specification GH200P-24	
Model	GH200P-24
Rated Maximum Power (Pm)	200W
Tolerance	±3%
Voltage at Pmax (Vmp)	24V
Current at Pmax (Imp)	8.33A
Open-Circuit Voltage (Voc)	28.6V
Short-Circuit Current (Isc)	8.98A
Normal Operating Cell Temp (NOCT)	47 ± 2°C
Maximum System Voltage	1000V DC
Maximum Series Fuse Rating	15A
Operating Temperature	-40 to +85°C
Application Class	Class A
Cell Technology	Poly-Si
Weight	14.8kg
Dimension (mm)	1320 × 992 × 35 mm

The main hardware component in this study was the GH200P-24 polycrystalline silicon PV module with a rated power output of 200 W. This panel was selected because of its stable operating characteristics, which made it suitable as the experimental energy source. For current sensing, two analog Hall-effect based bidirectional current sensors (ACS758LCB-050B) were employed. The first sensor was installed directly at the output of the PV module in order to measure the generated current under varying irradiance and load conditions. The second sensor was installed at the connection between the MPPT charge controller and the battery, with the purpose of detecting charging and discharging states of the battery by observing current direction. In addition, the battery connection point was also used for measuring voltage as read by the MPPT controller, allowing LabVIEW to compute and log the power generated by the PV system. The experimental setup consisted of the PV module, an MPPT charge controller, a battery bank, resistive loads, and the two bidirectional current sensors. Both sensors were connected to a National Instruments data acquisition device, which transmitted the analog signals to LabVIEW for real-time acquisition and visualization. Sensor calibration was performed by applying reference current values measured with a digital multimeter, enabling the conversion of output voltage to actual current values.

Data acquisition was carried out at one-second intervals. LabVIEW was programmed to display current, voltage, and power in real time, as well as to indicate the charging or discharging state of the battery based on the second sensor's readings. The accuracy of the measurements was verified by comparing them with multimeter reference data. This procedure ensured that the bidirectional sensors were evaluated not only for their accuracy but also for their consistency in detecting both generated current from the PV panel and energy flow between the controller and the storage device.

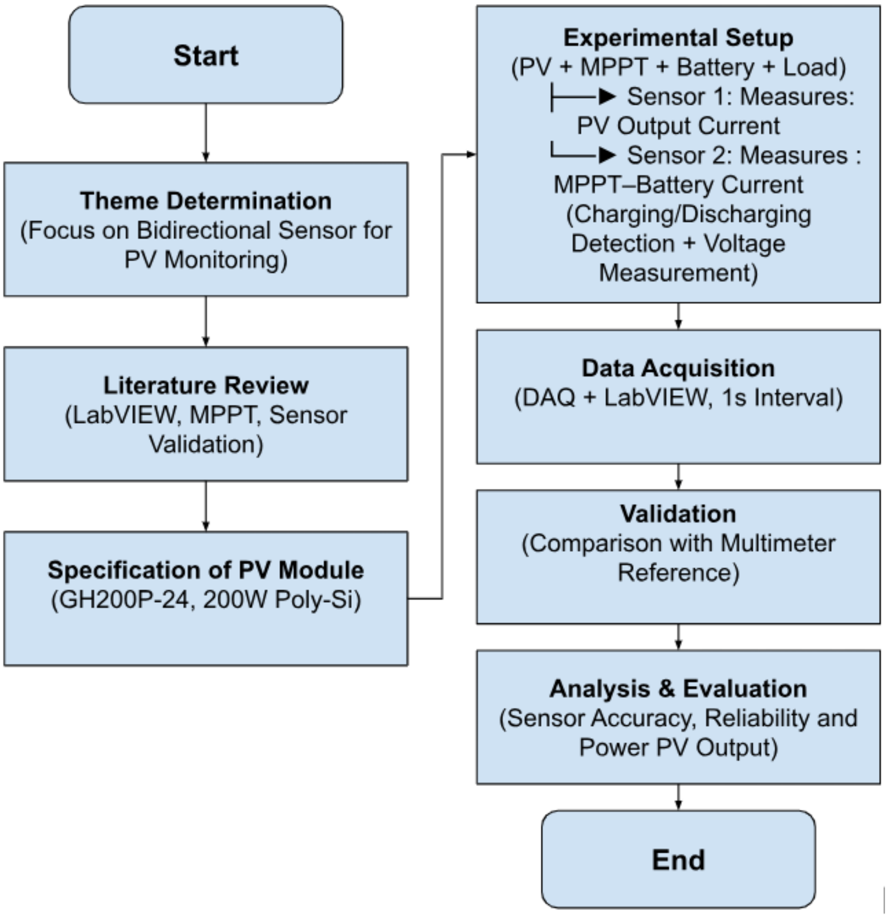

Figure 1. Research methodology flowchart

LITERATURE REVIEW

Several studies emphasize that monitoring accuracy in photovoltaic (PV) systems depends not only on sensor placement but also on sensor calibration and validation procedures. Early works using LabVIEW-based platforms highlight its effectiveness in visualizing PV behavior and ensuring reliable acquisition of voltage and current signals for MPPT evaluation [1]–[5]. The reliability of these monitoring systems is strongly influenced by the accuracy of the current sensor. As reported in [6]–[8], bidirectional sensors, particularly Hall-effect based devices such as the ACS series, must undergo calibration against standard measurement instruments (e.g., digital multimeters) to eliminate offset errors and scaling deviations. This calibration step is necessary before sensors are embedded into real-time monitoring loops, ensuring that logged values represent actual operating conditions. In addition, research on PV system prototyping [9], [10] indicates that inaccurate or uncalibrated sensors can introduce cumulative errors in power estimation ($P=V\times I$), leading to misleading conclusions regarding system efficiency. These studies also show that time synchronization plays a crucial role: data acquired in time-loop logging intervals (e.g., one-second sampling in LabVIEW) may differ from actual-loop responses, where instantaneous fluctuations in irradiance and load introduce dynamic variations. Works such as [11], [12] recommend comparing logged data with instantaneous meter readings to identify lag, drift, or averaging effects introduced by the data acquisition system.

A further body of research addresses the charging and discharging characteristics of batteries in PV-based systems. Battery management literature highlights that both upper voltage limits and lower voltage limits must be respected to maintain safety and longevity of the storage unit. For instance, typical 12 V lead-acid batteries operate with **a float voltage range of around 13.2–13.8 V** during trickle charging to maintain full charge without overcharging [16]. Conversely, the upper cutoff charging voltage (bulk or absorption phase) is **generally set at 14.4–14.7 V**, beyond which prolonged charging risks overheating, gassing, or reduced cycle life [17] On the discharging side, most studies recommend a lower **cut-off voltage of around 10.5–11.0 V** to prevent deep discharge, which can irreversibly damage the battery plates and reduce overall capacity [18], [19]. Monitoring these thresholds is crucial when applying bidirectional sensors at the MPPT–battery connection, as the sensors not only detect the current flow direction but also capture voltage variations that indicate charging, float maintenance, or discharging phases. When combined with synchronized logging, this approach allows accurate classification of battery operating states and supports evaluation of MPPT effectiveness in controlling the energy flow. Furthermore, previous contributions by the authors [13]–[15] demonstrated the importance of prototyping and experimental validation in automation and control contexts, both for PLC-based machinery and PV monitoring systems. These works reinforce that reliable monitoring requires a methodological combination of sensor calibration, real-time data validation, and evaluation of acquisition timing accuracy. Together, these findings form the foundation for the present study, which applies calibrated bidirectional sensors to two different measurement points in a PV–MPPT–battery configuration.

The theoretical framework is based on the principle that accurate monitoring of PV systems must capture both power generation at the module level and energy transfer at the storage interface. In practice, power is defined as

$$\mathrm{P}(t) = \mathrm{V(t)} \times I(t)$$

WhereV(t) and I(t) are instantaneous values of voltage and current. Reliable estimation of P(t) depends on both calibrated sensor data and the synchronization of measurement intervals with actual physical variations. (1). PV Output Measurement Point; The first bidirectional sensor is installed at the output of the PV module. This point represents the raw power generated under environmental conditions such as irradiance and temperature. Sensor calibration ensures that the measured current reflects the true PV output, while the correspondi

ng voltage is captured directly from the PV terminals. By multiplying these values, the system can determine the generated power curve, which is then compared with theoretical values derived from the PV datasheet (e.g., rated power at STC). The accuracy of this point indicates how closely the experimental setup reproduces expected PV behavior. 2. MPPT–Battery Measurement Point: The second bidirectional sensor is positioned between the MPPT controller and the battery. At this location, bidirectional current flow occurs: charging (from PV to battery) and discharging (from battery to load). Voltage readings at the battery terminals enable the calculation of charging/discharging power. Calibration is again necessary to ensure correct identification of current direction and magnitude. This point also provides an opportunity to analyze the effectiveness of the MPPT in regulating energy transfer. (3). Time-Loop vs. Actual-Loop Consideration: Theoretical reliability also depends on the alignment between data logging intervals (time loop) and instantaneous operating conditions (actual loop). In LabVIEW acquisition, data are typically recorded at fixed intervals (e.g., one second), which may average or smooth fast transients in current or voltage. Actual system response, however, can fluctuate more rapidly due to irradiance changes or load switching. Comparing time-loop logged data with spot-check values from calibrated reference instruments allows the identification of lag or sampling errors, ensuring that the theoretical relationship between measured and actual power is preserved. By structuring the theoretical framework around sensor calibration, power computation, and time synchronization, this study addresses the fundamental requirements for achieving reliable PV monitoring at both the generation and storage levels.

RESULTS AND DISCUSSION

The experimental validation of the proposed monitoring setup was performed by integrating the bidirectional current sensors, PV module, MPPT controller, and the data acquisition system. The overall wiring configuration of the test bench is shown in **Figure 2**, illustrating the placement of two bidirectional sensors. The first sensor was installed at the PV module output to record the generated current, while the second sensor was connected between the MPPT controller and the battery to identify charging and discharging states.

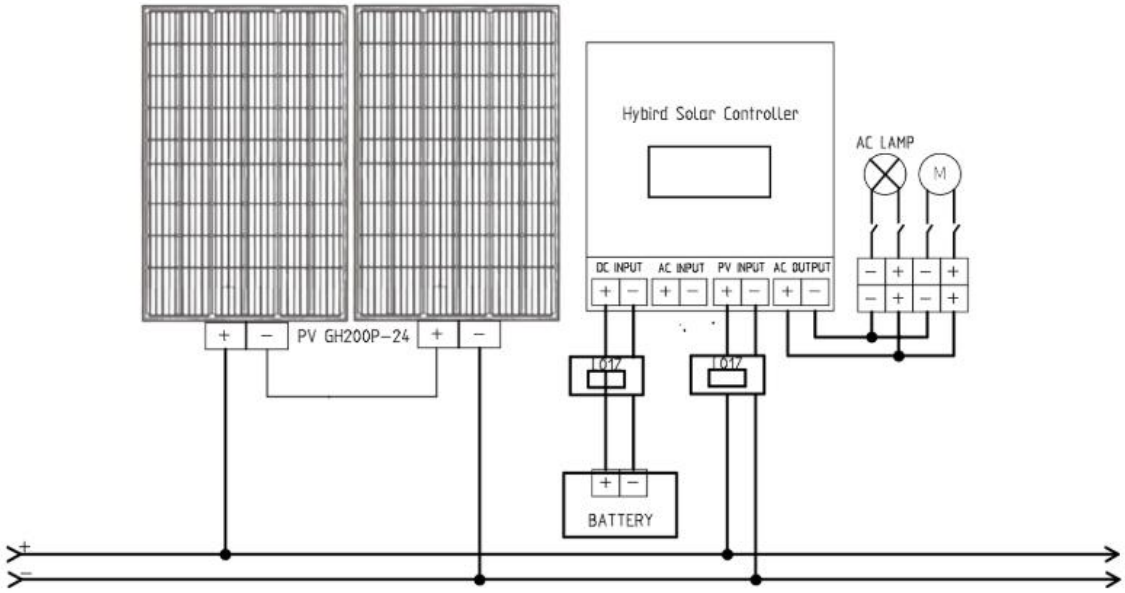

Figure 2. Experimental wiring diagram

A LabVIEW block diagram was developed to represent the data acquisition and visualization process, as shown in **Figure 3,** where voltage and current signals were captured using the NI USB-6008 DAQ module.

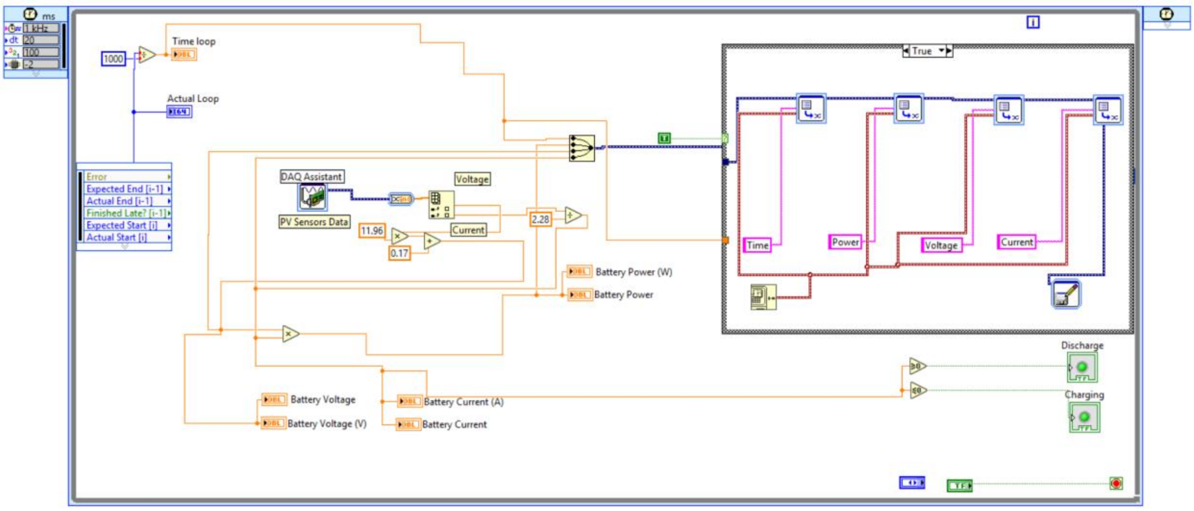

Figure 3. LabVIEW block diagram

Before testing, a calibration process was carried out to determine the accuracy and linearity of the bidirectional current sensor. Calibration was conducted by comparing sensor output voltage with reference measurements obtained from a digital multimeter. The relationship between measured current and output voltage is shown in **Table 3 and Figure 4**, where the sensor exhibited good linearity across the operational range.

Table 3. Discharge calibrations data

No	Current (A)	Output Voltage (V)	Reference Voltage (V)	Absolute Error (V)	Percentage Error (%)
1	0.0	2.5637	2.5600	0.0037	0.14
2	0.5	2.5841	2.5800	0.0041	0.16
3	1.0	2.6045	2.6000	0.0045	0.17
4	1.5	2.6249	2.6200	0.0049	0.18

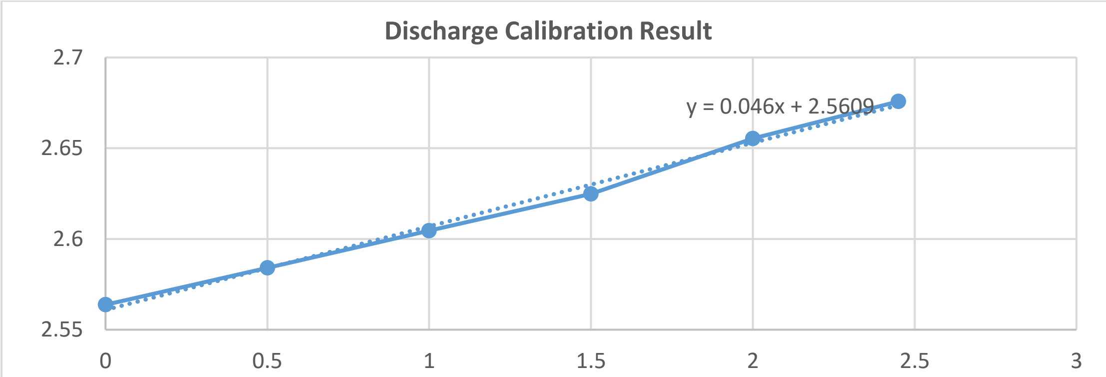

Figure 4. Discharge calibration

The calibration results indicate that the sensor output maintains strong linearity, with an **average error of 0.16%** across the tested range. The coefficient of determination ($R^2 = 0.998$) further confirms the stability of the voltage-to-current conversion ratio. Once calibration was established, discharging experiments were conducted to evaluate the performance of the PV–MPPT–battery configuration under controlled conditions. The LabVIEW front panel enabled real-time visualization of current, voltage, and power profiles during the discharging process. The recorded data indicated a consistent decrease in battery voltage, accompanied by measurable current flow as energy was delivered to the load. Power readings derived from the product of voltage and current further validated the expected behavior of the system, showing agreement between calculated and measured values. In particular, the data logging results obtained from LabVIEW demonstrated that the average current during discharging was approximately 1.4 A, with an average battery voltage of 12.5 V, resulting in an average output power of 17.7 W. These results provide quantitative confirmation of the system's ability to accurately capture and log discharging characteristics.

During the discharging experiment, LabVIEW displayed real-time current, voltage, and power profiles at one-second intervals. **Figures 6–9** show the time-series behavior of each parameter. The average discharge current was **1.40 A**, the corresponding battery voltage averaged **12.52 V**, and the computed mean output power was **17.7 W**, as summarized in **Table 4**.

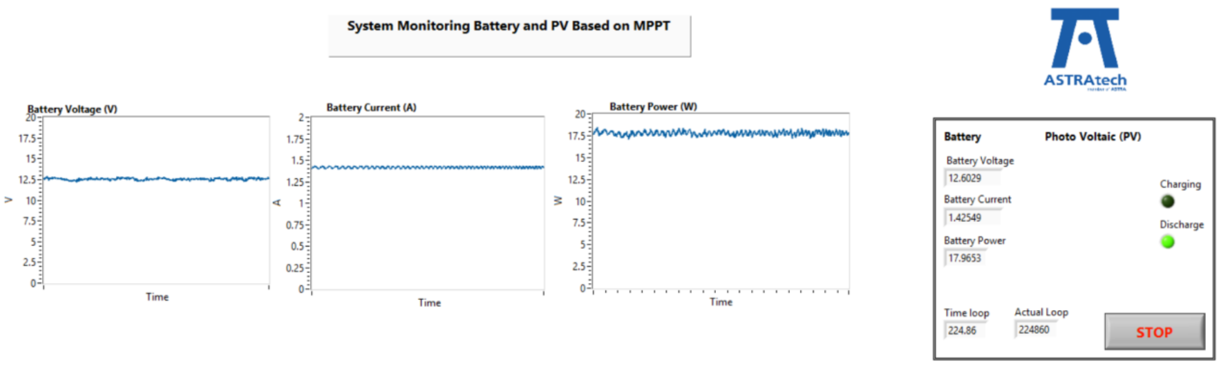

Figure 6. LabVIEW Front Panel (Time in s, Voltage in V, Current in A)

The integration of NI USB-6008 in combination with LabVIEW provided stable acquisition at defined sampling intervals, allowing comparison between time-loop and actual-loop measurements. The results demonstrated that the system could reliably distinguish between charging and discharging states, and the measured values were within acceptable error margins compared to theoretical expectations. These findings reinforce the significance of early-stage sensor validation and highlight the potential of the proposed setup as a reference model for PV monitoring with MPPT control. Overall, the results confirm that the bidirectional sensor configuration, combined with the LabVIEW-based acquisition system, enables accurate monitoring of PV output and MPPT–battery interaction. The approach provides a robust foundation for the development of real-time monitoring platforms, ensuring that charging/discharging behavior and energy harvesting performance can be observed with high reliability before integration into PLC-based supervisory systems.

Table 4. Summarize of measurement data

Parameter	Minimum	Maximum	Mean	Standard Deviation	Unit
Current	1.36	1.45	1.40	0.03	A
Voltage	12.4	12.6	12.52	0.07	V
Power	17.0	18.1	17.7	0.33	W

The low variation of current and voltage **(less than ±1.5%)** confirms the reliability of the sensor under steady-state operation. The measured power trend closely matches theoretical expectations calculated from the PV and battery specifications, validating the data acquisition system's performance.

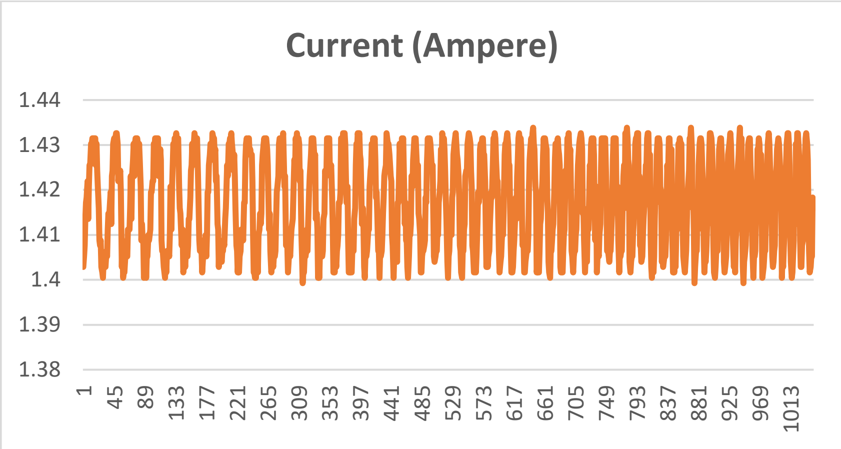

Figure 7. Current measurement results (A vs. time s)

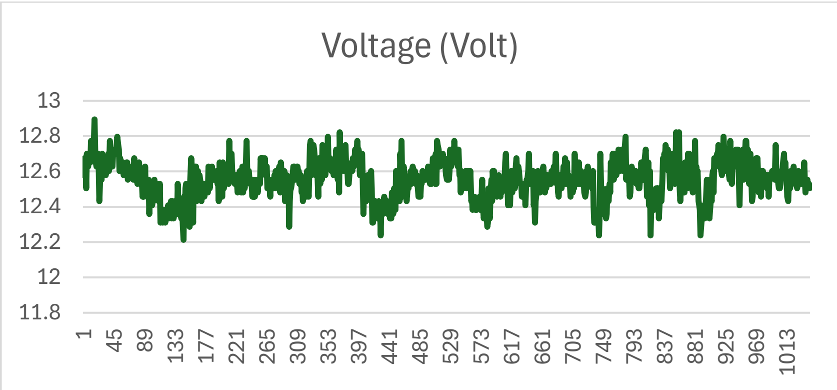

Figure 8. Voltage measurement results (V vs. time s)

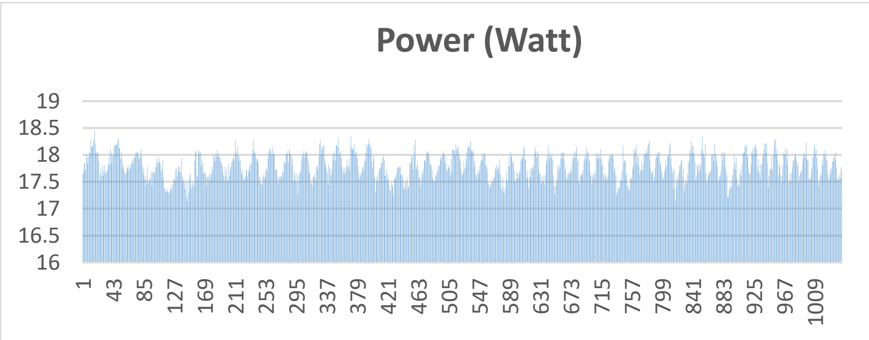

Figure 9. Power measurement results (W vs. time s)

The small deviations observed between measured and reference data are primarily attributed to sensor offset voltage (2.5 V at zero current) and DAQ sampling delay. The total mean absolute percentage error (MAPE) was calculated as:

$$MAPE = \frac{1}{n}\sum\left|\frac{I_{sensor} - I_{ref}}{I_{ref}}\right| \times 100\% = 0.18\%$$

This value demonstrates excellent accuracy compared to other analog Hall-effect sensors reported in similar PV monitoring studies. For instance, [20] reported an average error of **±1.5%** using adaptive step-size MPPT with SEPIC converter, and [10] observed ±2% deviation in a three-port bidirectional converter. The lower error in this work indicates the effectiveness of pre-integration calibration and consistent linear response of the ACS758LCB-050B sensor.Moreover, the integration of the NI USB-6008 DAQ module ensured stable acquisition timing, minimizing aliasing effects in the one-second sampling loop. The ability to distinguish charging and discharging states with clear current direction confirms the readiness of this configuration for PLC-based implementation. The novelty of this work lies in the early-stage integration of sensor–MPPT–PLC architecture, focusing on accurate current direction detection before embedding the system into a PLC-controlled monitoring framework.

CONCLUSION

This study presented the preliminary experimental validation of an analog bidirectional current sensor integrated into a photovoltaic system equipped with MPPT technology. Two sensors were installed at critical measurement points: the output of the PV module to capture generated current and the interface between the MPPT controller and the battery to identify charging and discharging behavior. A LabVIEW-based acquisition system supported by the NI USB-6008 DAQ module was employed to record, process, and visualize electrical parameters in real time. The calibration process demonstrated that the current sensor maintained linearity and reliability, with an average output of 2.6 V corresponding to a discharging current range of 0–2.45 A. Subsequent data logging during the discharging experiment showed an average current of 1.4 A, an average voltage of 12.5 V, and a resulting average power of 17.7 W. These results confirm that the bidirectional sensor was able to accurately detect and quantify system behavior under varying operating conditions. The findings highlight the importance of sensor calibration and early-stage testing to ensure reliable monitoring prior to full integration into PLC- or SCADA-based supervisory frameworks. The validated setup provides a robust foundation for developing real-time PV monitoring platforms, ensuring accurate detection of charging/discharging cycles and supporting the optimization of energy harvesting performance. Future work will focus on extending the monitoring architecture to include PLC-based automation and large-scale PV applications.

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