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Design of ACS712-based Current Sensing Monitoring Evaluation for PWM Solar Charge Controller

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Abstract

The rise of renewable energy has led to growing interest among researchers in optimizing renewable energy systems to harvest the highest possible energy output, especially in photovoltaic (PV) systems. Photovoltaic systems generate energy from sunlight, but the intermittent nature of sunlight poses a challenge for providing constant power. Another problem is that the most affordable conventional Pulse-Width Modulation (PWM) controllers on the market are unable to provide a current monitoring system. This issue is critical when users require detailed data to perform diagnostics on their PV systems. In this study, a monitoring system using microcontrollers and the ACS712 current sensor was developed and implemented to observe the behavior and performance of a photovoltaic (PV) charging system based on the current output from a PWM controller. The primary objective of this system is to develop a solution that can identify PV modules operating under suboptimal conditions, which can be caused by various factors such as increased solar cell temperature, cloud cover effects, PV module degradation, and the performance of the Pulse-Width Modulation (PWM) solar charge controller (SCC). This is crucial because PV modules can be susceptible to various environmental and technical factors that may impact their efficiency and power output. By closely monitoring the performance of each PV module using the ACS712-based current sensing system, the researchers aim to promptly detect and address any issues that may arise, ensuring the overall optimal operation of the PV system.

Keywords: ACS712, Current Sensing, PWM, Solar Charge Controller, Solar PV

INTRODUCTION

Electricity demand is rapidly growing worldwide as conventional energy sources become limited and harmful (Najmurrokhman et al., 2022; Bouabana & Sourkounis, 2012). This has led to increased interest in renewable energy as a sustainable alternative (Sai et al., 2020). To reduce reliance on fossil fuels and address the environmental, climate, and economic issues they cause, significant progress has been made in renewable energy sources (Khammassi et al., 2024). Among the various renewable options, solar power stands out as a particularly promising solution (Krishnan & Bharath, 2019; Uno & Kukita, 2015; Ostadrahimi & Mahmoud, 2020). Solar energy has several advantages - it is widely available, environmentally friendly, and has low operational and maintenance costs. Renewable energy, particularly photovoltaic (PV) technology, is a crucial solution to meet high energy demands while also reducing the greenhouse effect (Mohapatra et al., 2019). Photovoltaic (PV) technology enables the direct conversion of solar radiation into electricity through the photovoltaic effect (Alan et al., 2024). This process occurs within PV panels, which capture the kinetic energy of photons and convert it into direct current electrical energy (Khammassi et al., 2024). As such, renewable sources like solar are viewed as the future for powering entire nations. This shift towards renewable energy, especially solar, aims to meet the world's growing electricity needs in a cleaner and more sustainable manner (Eid, 2019; Rani et al., 2020; Ahsan et al., 2022).

Beside of that, extracting the maximum available power from a photovoltaic (PV) module is a challenging task. This is due to the nonlinear current-voltage (I-V) characteristics of the PV module, as well as its dependence on atmospheric conditions such as temperature and irradiance levels (Ostadrahimi & Mahmoud, 2020). Variations in these environmental factors can disrupt the panel's desired performance. Based on the situation, it is important to note that the consistent maintenance of such a system is crucial to ensure its desired operation. These monitoring systems can be susceptible to various environmental factors, such as the accumulation of particles, dust, and other airborne materials, which can create shading issues on the PV modules. In addition to the maintenance of the PV modules, it is also advised to perform periodic checks and inspections of the wiring and electrical components within the solar system. This is crucial to identify and address any potential issues or degradation in the wiring, which can also contribute to the overall performance and reliability of the PV system.

To reduce the frequency of required on-site assessments and inspections of photovoltaic (PV) installations, various technologies are being introduced to the market to enable remote tracking and monitoring of the electricity produced by these systems (Arefin et al., 2020). This is a crucial development, as it can help overcome the limitations of traditional approaches. One of the key challenges with the current technology in conventional pulse-width modulation (PWM) controllers is the lack of precision in assessing the input current status of the solar panels. While this could be a viable solution, accurately identifying and addressing any issues would still require on-site examinations and troubleshooting efforts.

In contrast, the latest smart micro-inverter technology offers a more sophisticated approach by continuously monitoring the total system power for each individual PV panel. However, this advanced technology comes at a significantly higher cost, making it less accessible for many individuals and smaller-scale installations (Fulzele & Umathe, 2023).

The primary reason for the high cost of smart micro-inverters is the requirement to install a dedicated inverter for each solar panel, along with the complex software programming that enables the comprehensive monitoring and management capabilities. This investment can be prohibitive for many users, limiting the widespread adoption of this technology.

To address these challenges, the project presented in this study introduces a novel solution: a customized wired current sensor monitoring system. This device is designed to record the current information for each input terminal in the PWM controller, as well as the overall voltage and current, making this data accessible through serial monitoring on a microcontroller.

Based on the work of Kumaresan et al. (2020), the ACS712 sensor plays an important role in measuring the electrical flow to devices in the research described. This sensor measures the AC and DC current flowing through the devices and provides real-time current values that are crucial for analyzing energy consumption. The measured current values are then displayed on an LCD and sent to the Thingspeak cloud service using an ESP8266 Wi-Fi module. Thingspeak analyzes this data to monitor and predict energy usage patterns. Arefin et al. (2020) refer to the uses of ACS712 for overcurrent protection in PV-Diesel Hybrid Mini Grid. The current sensor measures the output current from load, and if the measured current is higher than allowed current threshold, the control unit triggers the solid state relay to OFF state for grid overcurrent protection. In Khwanrit et al. (2018), the accuracy of different current sensors are also observed along with the ACS712 itself without external ADC.

This example of ACS712 application can be used for fundamental of current sensing development in this research. Beside of that, the absence of current accuracy improvement topology in Arefin et al. (2020) and Kumaresan et al. (2020) is concerning for reliable monitoring system. Hence that with several improvements such as implementing external ADC for better measurement and use of current averaging for more stable measurement will be discussed in this paper. Additionally, the system can be integrated with an LCD display for enhanced accessibility and user-friendliness. The key advantage of this approach is that it is more affordable compared to purchasing more sophisticated controllers with complex features. This makes it a more viable option for a wider range of users, potentially enabling more families to effectively harness solar energy and benefit from its renewable power. The study further elaborates on the centralized monitoring microcontroller-based PV monitoring system, providing a detailed overview of the proposed methodology and the expected results and conclusions.

METHODS

To address the challenges outlined above, this section presents the methodology employed in designing and implementing a customized monitoring system for photovoltaic (PV) installations. The proposed approach integrates a wired current sensor system to monitor input terminal currents in a pulse-width modulation (PWM) controller, along with overall voltage and current measurements. The methodology focuses on enhancing measurement accuracy and system reliability through the use of advanced techniques, such as external ADC implementation and current averaging. Furthermore, the integration of a user-friendly LCD display for data visualization and system accessibility is explored. The detailed steps and components of the methodology are outlined below.

A. Main Microcontroller

The main processing for this research study is using a microcontroller to calculate, process, and provide the final results of current monitoring. The Arduino UNO microcontroller is used as the microcontroller itself relatively cheap and reliable. This microcontroller consists of Atmel ATMega 328p for main processor. The main processor is able to provide 5 analog inputs (A0-A5) with internal 10-bit ADC chip. Figure 1 shows the Arduino microcontroller that used for this study.

Figure 1. The Main Arduino Microcontroller

B. ACS712 Hall-effect Current Sensor

The ACS712 sensor is a versatile integrated circuit that provides accurate current sensing capabilities (Arefin et al., 2020). Illustrated in Figure 2, the ACS712 current sensor operates on the principle of the hall effect, which allows it to precisely measure the current flowing through a conductor. By using this sensor, the monitoring system can track the input current information for each terminal of the PWM controller.

One of the key advantages of the ACS712 is its ability to measure current within a range of ±5 A, which covers the typical operating currents encountered in residential and small-scale PV systems based on Table 1. This broad measurement range ensures that the monitoring system can effectively capture the performance data of the PV installation (Bouabana & Sourkounis, 2016), even under varying load conditions and solar irradiation levels.

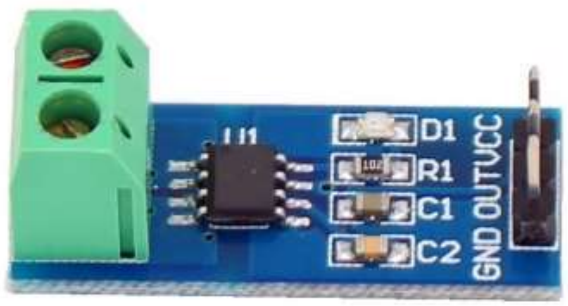

Figure 2. ACS712 Sensor

Table 1. ACS712 Specifications

No.	ACS712 Maximum Ratings	
	Parameters	**Specification**
1	Supply Voltage	8 V
2	Reverse Supply Voltage	-0.1 V
3	Output Voltage	8 V
4	Reverse Output Voltage	-0.1 V
5	Output Current Source	3 mA
6	Output Current Sink	10 mA
7	Overcurrent Transient Tolerance	60 A
8	Maximum Transient Sensed Current	60 A
9	Frequency Bandwidth	50 kHz
10	Sensitivity	178-193 mV/A

C. ADS1115 External ADC

The ADS1115 in Figure 3 is a high-precision, low-power, 16-bit analog-to-digital converter (ADC) that is I2C-compatible. This device is offered in an ultra-small, leadless X2QFN-10 package, as well as a VSSOP-10 package, making it well-suited for space-constrained applications. A key feature of the ADS1115 is low-drift voltage reference and an on-chip oscillator, ensuring stable and reliable analog-to-digital conversion. Additionally, the ADS1115 includes a programmable gain amplifier (PGA) and a digital comparator, further enhancing its capabilities.

The PGA in the ADS1115 offers a wide range of input voltage scales, from ±256 mV to ±6.144 V, allowing for precise measurement of both large and small signals (Bouabana et al., 2016). This versatility makes the ADS1115 well-suited for a variety of sensor measurement applications, particularly those with power and space constraints. Another notable feature of the ADS1115 is the integrated input multiplexer (MUX), which enables the device to perform two differential or four single-ended input measurements. This flexibility allows the ADS1115 to be adapted to different sensor configurations and measurement requirements.

The ADS1115 can perform conversions at data rates of up to 860 samples per second (SPS), ensuring that it can capture fast-changing signals with high accuracy. The device can operate in either continuous-conversion mode or single-shot mode, with the latter offering significantly reduced power consumption during idle periods. The combination of high-precision 16-bit resolution, programmable gain, input multiplexing, and low-power operation make the ADS1115 an excellent choice for implementing the analog-to-digital conversion functionality in the proposed PV monitoring system. Its versatility and performance characteristics align well with the requirements of the project, making it a suitable component for the overall system design.

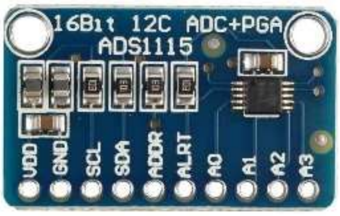

Figure 3. ADS1115 Chip

D. PWM Controller

Pulse Width Modulation (PWM) solar charge controller provide a direct connection between the solar array and the battery. They use a simple, rapid switching mechanism to modulate and regulate the battery charging process. Based on Figure 4, this traditional PWM charge controller design operates by keeping the switch (transistor) open until the battery reaches the absorption charge voltage (Sachin et al., 2021). At that point, the switch begins rapidly opening and closing (hundreds of times per second) to decrease the current and maintain a constant battery voltage.

This PWM controller approach that shown in Figure 5 is robust, cost-effective, and widely used in solar panel applications. An important design consideration is ensuring the nominal voltage of the solar panel matches the voltage of the battery system being charged. This voltage matching helps optimize the power transfer and charging efficiency of the overall solar energy system.

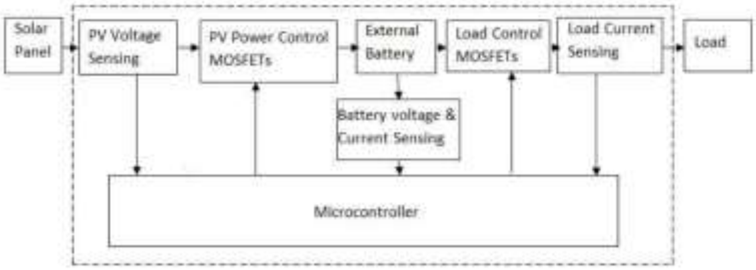

Figure 4. PWM based Controller [20]

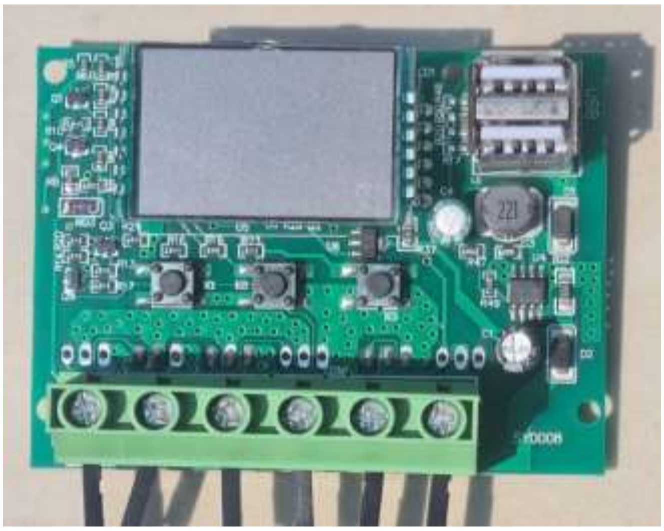

Figure 5. Conventional PWM Controller

While PWM solar charge controllers offer several benefits, there are also some notable disadvantages in their design. Firstly, the PWM charging pulses are not perfectly square wave, as there are some peaks present within the pulses (Vaz et al., 2019). Additionally, the mechanism does not have automatic detection capabilities to identify whether the connected battery is a 12V or 24V system, the system also cannot detect and monitoring the input current and output current in the module.

These identified drawbacks - the non-ideal PWM waveform, lack of auto-detection, and inability to monitor the current - can be considered as important design specifications to address in the next iteration or improved version of the solar charge controller with integration of this study.

E. Benchmark Topology

The benchmark topology with comparison with external ADC and without external ADC is shown in Figure 6 and Figure 7.

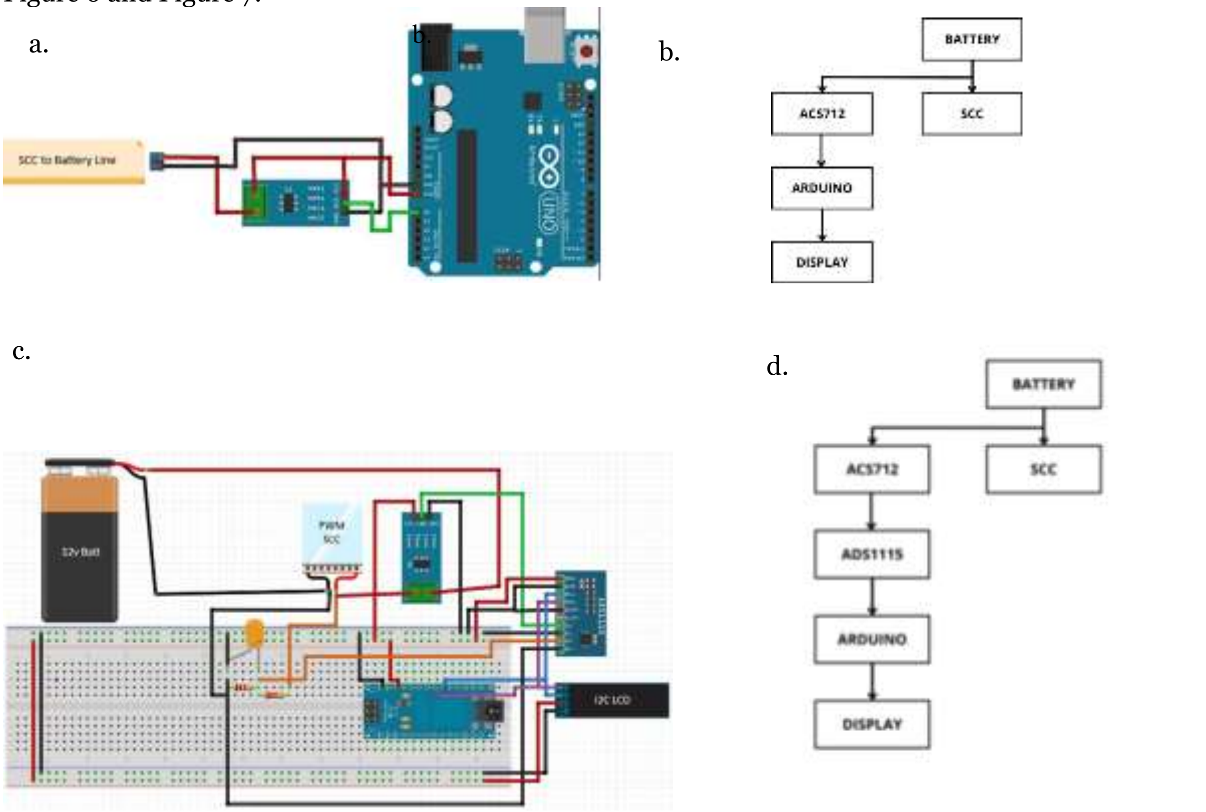

Figure 6. Proposed Current Monitoring System: (a) Schematic Diagram without External ADC, (b) Block Diagram Representation without External ADC, (c) Schematic Diagram with External ADC, (d) Block Diagram Representation with External ADC.

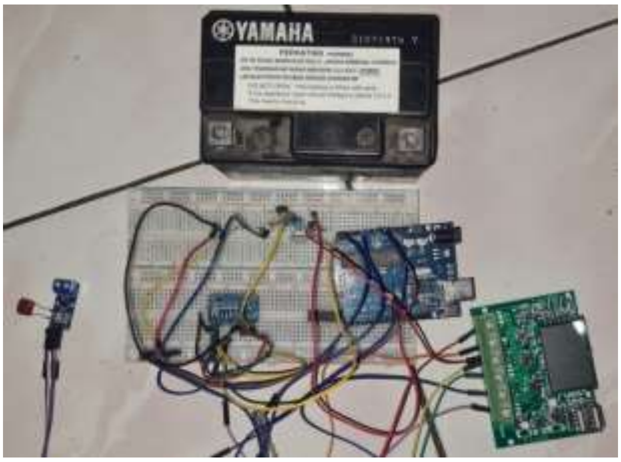

Figure 7. Prototype of Current Monitoring System

In the proposed design, the ACS712 current sensor is placed on the positive (V+) side of the load, rather than on the ground (V-) side. This is known as a high-side configuration. In the proposed system, the Arduino is being used as the microcontroller, and it has a reference voltage of 5 volts. When measuring without external ADC, the use of Arduino's analog-to-digital (A/D) converter that has a resolution of 10 bits will applies this Equation (1):

$$V_{A2}|V| = I = analogReadA2 \, . \frac{5}{1024} \quad (1)$$

Meanwhile when the proposed system is configured to use the external ADC ADS1115, the use of voltage divider resistor network must be applied to protects the ADC chip (Khwanrit et al., 2018; Datta et al., 2019). In Figure 6 and 7, the voltage divider circuit has been applied, with the simplified illustration in Figure 8. The equation applied in this circuit is:

$$V_{out} = \frac{V_{source} \cdot R_2}{(R1+R2)} \quad (2)$$

The V_{out} baseline is set to microcontroller's reference voltage.

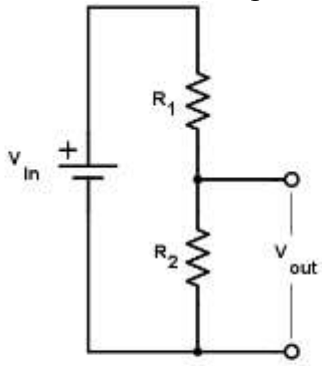

Figure 8. Voltage Divider Circuit Used in Proposed System

In the proposed system, the supposed voltage source is 13 V (standard battery charging based on the measurement). When the the Equation (2) is applied, the nominal resistor in R1 is 68 kΩ and R2 is 42 kΩ. This will convert the 0-13 V operating voltage to small scale in V_{out} within 0-5 V for addressing maximum operating voltage for ADS1115. With applying this Equation (3):

$$Voltage\ Divider\ Ratio = \frac{V_{source}}{V_{out}} \quad (3)$$

The result will be used for voltage divider ratio in ADS1115's library code. This will provides accurate calculation to convert the source of voltage with the maximum analog reference voltage in Arduino and external ADC.

RESULT AND DISCUSSION

The proposed current monitoring system is compared with different circuit topology: without external ADC and with external ADC. The data achieved with the proposed current monitoring system with external ADC is also compared to existing research study that uses ACS712 for current monitoring system in term of stability (which is the fluctuative reading currents will be considered as a main parameter of current monitoring system reliability). To achieve a comprehensive performance validation of the controllers, a SMPS DC power supply in Figure 9 is used in this benchmark session. The absence of a photovoltaic module is intentional, as the PV system itself cannot maintain a stable electrical output. The focus of this benchmark is on observing the stability and performance sustainability of the PWM controller and the current monitoring circuit, rather than using a realistic input power source (i.e., a photovoltaic system).

Figure 9. SMPS DC Power Supply

Table 2. ACS712 Specifications

No.	SMPS Maximum Ratings	
	Parameters	**Specification**
1	Input Voltage	100-240 VAC
2	Output Voltage	42 VDC
3	Output Current	2 A

A. Current Monitoring without External ADC

The benchmark results appeared in Figure 10. The charging is started when the battery goes to almost minimum cut-off point, which is near 10 V. The results shown that the current sensor result is fluctuates. This behavior is primarily due to the internal ADC of the microcontroller used in the system, which has a limited resolution and accuracy compared to standalone ADC chips. The fluctuations in the current readings make it challenging to accurately monitor and analyze the performance of the PV charging system.

The graph in Figure 10 shows several fluctuations in the data. At 0 seconds, there is a fluctuation with a value of -0.01. This is followed by a positive fluctuation of 0.01 at 85 seconds, which is then succeeded by a negative fluctuation of -0.01 at 240 seconds. The fluctuations continue, with values of 0.01 at 635 seconds and 780 seconds.

The most significant fluctuation occurred at 945 seconds, where a large value of -11.66 was recorded. At 1225 seconds, the fluctuation returned to a positive value of 0.04. Other fluctuations include 0.01 at 1485 seconds, -2.52 at 1755 seconds, and back to 0.01 at 1985 and 2215 seconds.

The graph also shows small fluctuations of 0.01 at 2430, 2530, and 2595 seconds, as well as a range from 2800 to 2810 seconds. These fluctuations indicate variations in the current measurements during the observation period, with the negative indicator is normal because the charging current will be reversed to battery. Current fluctuations value using standard deviation formula based on Figure 10 resulting 0.486 A (equal to 486 mA), which is considered as high in term of current deviation. This leads to highly measurement inaccuracy from the data measured.

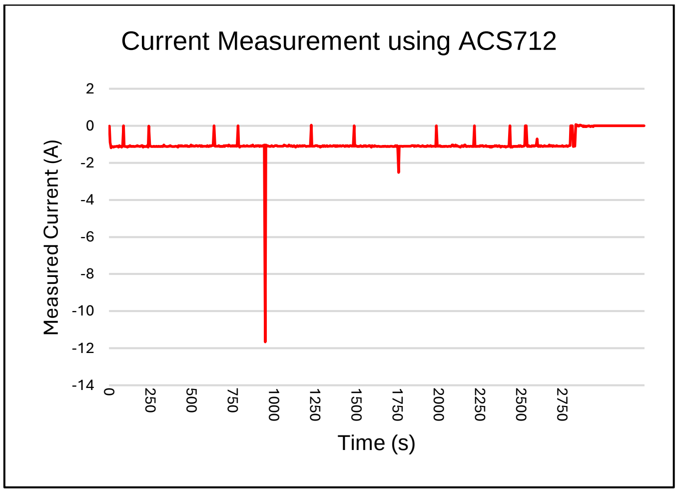

Figure 10. Results of Current Measurement without External ADC

B. Current Monitoring with External ADC

The benchmark results with external ADC applied is appeared in Figure 11. The charging is started when the battery goes to almost minimum cut-off point, which is near 10 V for the measurement baseline.

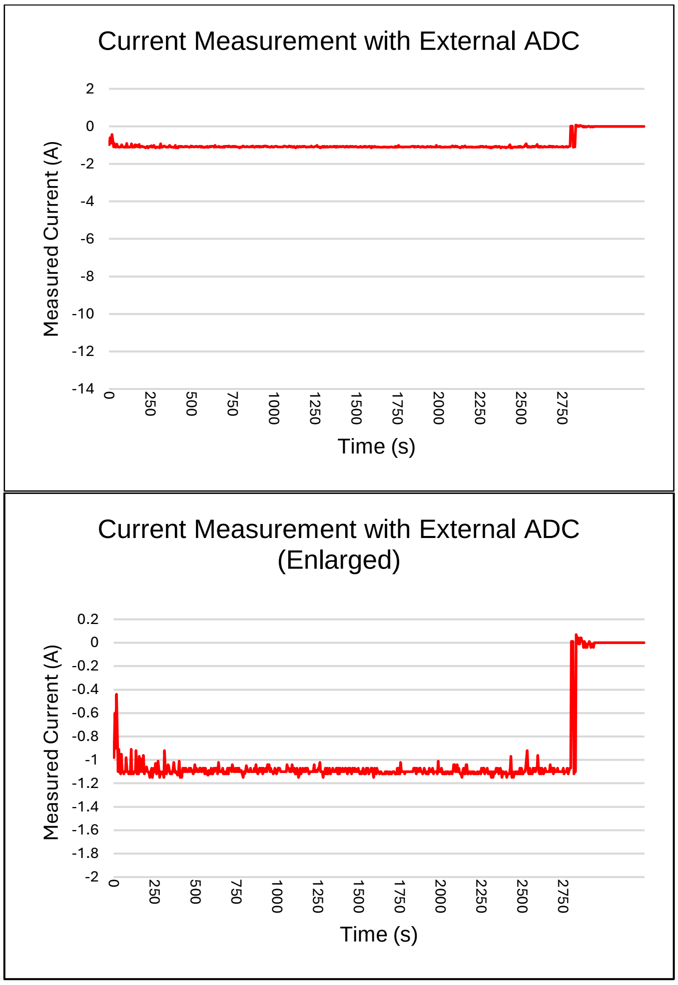

Figure 11. Results of Current Measurement with External ADC

The results shown that the current sensor result is not fluctuates as shown in Figure 10. The graph above shows the current measurement results using an external ADC (Analog-to-Digital Converter) in an enlarged time range to provide more details. In this graph, the Y-axis displays the measured current in amperes (A) with a range from -1.15 A to 0.07 A, while the X-axis shows the time in seconds (s) from 0 to about 2935 seconds. The measurement results show some small fluctuations at the beginning of the measurement, which then the current becomes relatively stable around 0 A offset after the charging cycle is almost done. However, near the end of the measurement period (at the timeframe of 2830 s), there was a significant current spike of up to 0.07 A. This small fluctuation at the beginning of the measurement indicates an initial adjustment or noise which then stabilised with external ADC. The steady current around 0 A indicates the stable condition of the system during most of the measurement period, while the current spike near the end of the period may indicate a change in the system condition, such as the end of the battery charging process. Current measurement using an external ADC shows better stability with a few small fluctuations at the beginning of the measurement and a spike in current near the end of the measurement period. The current fluctuations value using standard deviation formula resulting 0.0868 A (equal to 86.8 mA) based on Figure 11.

The results is better than without using external ADC. The integration of the ADS1115 external ADC enhances the resolution and sensitivity of the current measurements, addressing the limitations of the microcontroller's internal ADC. The higher precision and stability of the current data enable more reliable monitoring and diagnostics of the PV system's performance.

C. Measurement Accuracy Comparison

The benchmark results of current monitoring system is compared to Arefin et al. (2020) and Khwanrit et al. (2018) which is the absence of external ADC can be seen. This section is concerned to current fluctuations measured by two results. The use of external ADC eliminates the extreme fluctuations that happened in Figure 10. This is important because the ACS712 Hall-effect sensor itself has sensitive fluctuation that leads to inaccuracy, and proven in Figure 12. In the range of 0-2 A current measurement, the ACS712 is considerably high than another sensor Khwanrit et al. (2018).

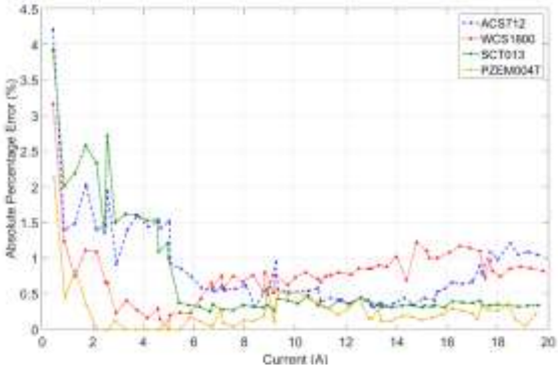

Figure 12. Percentage Error Comparison of Different Sensors Type (Khwanrit et al., 2018)

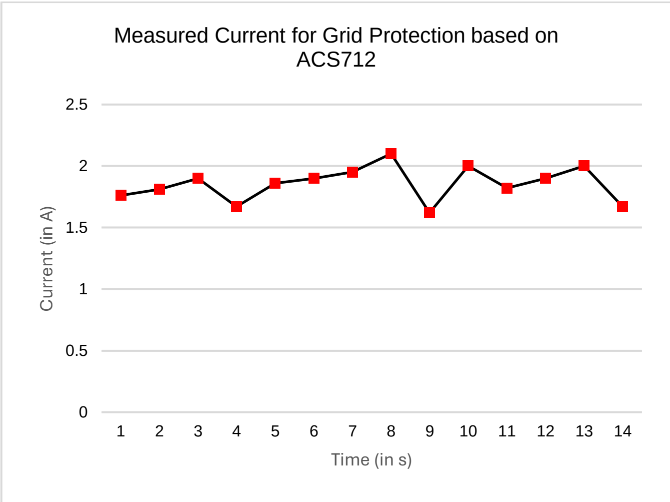

Figure 13. Results of Current Measurement without External ADC in

Grid Protection System (Arefin et al., 2020)

The benchmark results of the current monitoring system in Arefin et al., 2020 resulted in a fluctuation with a deviation error calculated to be around 0.134 A (equal to 134 mA). This has proven that the ACS712 sensor itself cannot be used without calibration and the use of an external ADC to achieve the best measurement accuracy.

The internal ADC of microcontroller itself (such as Arduino UNO and ESP8266 used in Arefin et al., 2020 and Khwanrit et al., 2018 cannot provide the optimum results from the measurement. This is where the external ADC ADS1115 is helpfully improves the results of current measurement according to Figure 11.

CONCLUSION

This paper presents the design and implementation of a current sensing monitoring system for a PWM solar charge controller using the ACS712 current sensor integrated with an external ADC. The primary objective of this system is to provide a cost-effective solution for monitoring the performance and behavior of photovoltaic (PV) charging systems, which is crucial for identifying and addressing any issues that may arise. The key advantage of this system is its ability to continuously monitor the current output from each input terminal of the PWM controller with higher precision, as well as the overall voltage and current, by leveraging the external ADC. This data is made accessible through serial communication with a microcontroller, allowing for comprehensive analysis and diagnostics of the PV system's performance. The integration of the external ADC enhances the accuracy and resolution, and eliminated the data noises produced of the current measurements, providing users with more reliable and detailed data for diagnosing and optimizing the PV system's operation. The findings of this study demonstrate the effectiveness of the ACS712-based current sensing monitoring system, coupled with the external ADC, in accurately tracking the performance of the PWM solar charge controller. Future work should focus on developing the current monitoring system with more reliable current sensors that are resistant to interference. While the ACS712 sensor used in this study provided reasonable performance, there may be opportunities to explore alternative current sensing technologies that offer enhanced accuracy, stability, and immunity to external electromagnetic interference (EMI).

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