



Experimental Development of a PIC-Based Intelligent Energy Management Controller for Voltage Regulation and Load Prioritization in Standalone Photovoltaic Home Systems

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ABSTRACT– This paper presents the experimental development and evaluation of a PIC16F877A-based intelligent controller for voltage regulation and load prioritization in standalone photovoltaic (PV) home energy systems. The proposed system integrates a photovoltaic panel, battery storage, inverter, and embedded controller into a unified platform for efficient energy management. The controller continuously monitors battery voltage using an analog-to-digital converter and implements a threshold-based control strategy to disconnect non-critical loads when the voltage drops below 11.7 V. Experimental results show that the PV system maintains stable voltage characteristics within approximately $\pm 3\%$, while the output current varies significantly with solar irradiance, exhibiting fluctuations of more than 60% under varying environmental conditions. The proposed controller effectively regulates system operation by dynamically managing load distribution, thereby preventing deep battery discharge and improving overall system reliability. In addition, the integration of auxiliary subsystems, such as automatic lighting and motion detection, enhances energy efficiency by reducing unnecessary power consumption. The findings demonstrate that the proposed low-cost PIC-based controller provides a practical and effective solution for intelligent energy management in standalone PV systems, particularly in off-grid residential applications.

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Introduction

The increasing global demand for electrical energy, combined with the depletion of fossil fuel resources and growing environmental concerns, has accelerated the adoption of renewable energy technologies, particularly photovoltaic (PV) systems. PV-based energy systems are widely recognized as a sustainable solution for electricity generation due to their clean, abundant, and environmentally friendly characteristics. The continuous improvement of solar cell efficiency has further strengthened the practical potential of PV technology for modern energy applications [1]. However, PV systems inherently exhibit intermittent and nonlinear behavior caused by fluctuations in solar irradiance, temperature, and partial shading conditions, which can lead to variations in output voltage and power generation [2]–[4].

In residential applications, especially in off-grid or rural areas, standalone PV systems are often used as the primary source of electricity. In such systems, effective energy management is essential to ensure reliable operation. Batteries serve as the main energy storage component and require proper charge–discharge regulation to maintain system performance and extend operational lifetime. Without

appropriate control strategies, unstable PV output and improper energy regulation may reduce system efficiency and reliability [4], [5]. Therefore, the development of intelligent control systems for voltage regulation, battery protection, and load management has become a crucial aspect of standalone PV system design.

Microcontroller-based control systems have been widely implemented as cost-effective and flexible solutions for PV energy management. Previous studies have demonstrated the effectiveness of PIC-based and digital controllers in implementing maximum power point tracking (MPPT) techniques and regulating PV power conversion to improve energy harvesting efficiency [6]–[8]. In addition, digital control platforms and simulation-based approaches have been used to support the development, testing, and monitoring of PV control systems before practical implementation [9], [10].

Various supporting technologies have also been explored to enhance PV system performance under different operating conditions. For example, solar tracking systems have been developed to improve solar energy capture by adjusting the panel orientation toward the sun [11]. Similar PV-based applications, such as photovoltaic systems for traffic light operation, have shown the feasibility of PV technology for

small-scale and standalone electrical loads [12]. In addition, low-cost single-phase photovoltaic systems have been investigated to improve the practicality and efficiency of PV implementation in real applications [13]. These studies indicate that PV system performance depends not only on energy conversion efficiency but also on the effectiveness of the control strategy, system configuration, and load-side management.

In addition to energy conversion efficiency, load management has become an important aspect of standalone PV systems, particularly under limited energy availability. Intelligent energy management strategies allow the system to regulate the distribution of available energy and maintain voltage stability when the supplied power is insufficient. This approach is particularly beneficial for remote and standalone applications, where energy resources are constrained and system reliability is critical [5]. Therefore, integrating voltage regulation, battery protection, and load control into a single embedded system is important for improving the reliability of PV-based home energy systems.

Recent developments in PV control systems have focused primarily on improving efficiency through advanced MPPT techniques, such as perturb and observe (P&O) and incremental conductance methods [2], [14], [15]. Furthermore, the integration of embedded controllers with power electronic components, including DC–DC converters and digital command control systems, has enabled more responsive and efficient PV control mechanisms [9], [13]. However, many existing studies mainly emphasize energy harvesting optimization, MPPT performance, solar tracking, or PV output regulation, while fewer studies address the integration of load prioritization and voltage protection within a single low-cost embedded control framework [5]–[13].

Unlike previous studies that primarily focus on MPPT optimization, PV power conversion, solar tracking, or battery charging control [6]–[13], this study integrates voltage regulation and load prioritization within a single low-cost embedded controller. This integration enables not only efficient energy harvesting but also intelligent energy utilization, which remains relatively underexplored in standalone PV home systems. By combining real-time voltage monitoring, relay-based load control, and decision-making algorithms in a unified system, the proposed approach addresses both energy supply and demand management simultaneously.

Therefore, this paper presents the experimental development of a PIC-based intelligent energy management controller for voltage regulation and load prioritization in standalone photovoltaic home systems. The proposed system utilizes a PIC16F877A microcontroller to monitor battery voltage, regulate system operation, and automatically manage load switching based on predefined thresholds. The main contribution of this work lies in the development of a low-cost integrated controller capable of enhancing system reliability, protecting battery life, and optimizing energy utilization in standalone PV applications.

Material and Methods

The proposed system is developed as a standalone photovoltaic (PV)-based smart home energy system that integrates power generation, storage, and intelligent control into a unified platform. The design follows a mechatronics approach that combines electrical, electronic, and embedded system integration to ensure reliable operation under varying environmental conditions. The overall system development process is illustrated in Figure 1, which outlines the workflow from conceptual design to system implementation and experimental validation.

A. System Configuration

The electrical subsystem consists of a photovoltaic module, battery storage, inverter, and load units. In this study, a monocrystalline PV panel with a nominal capacity of 100 W is used as the primary energy source. The generated DC power is stored in a 12 V battery rated 7 Ah, which serves as the main energy storage unit. A single-phase inverter rated at 650 VA (approximately 390–450 W) is employed to convert DC energy into 240 VAC for household applications.

The overall electrical configuration and interconnection between system components are shown in Figure 2, while the internal configuration of the inverter is presented in Figure 3. These figures illustrate the energy flow from the PV panel to the battery and subsequently to the load.

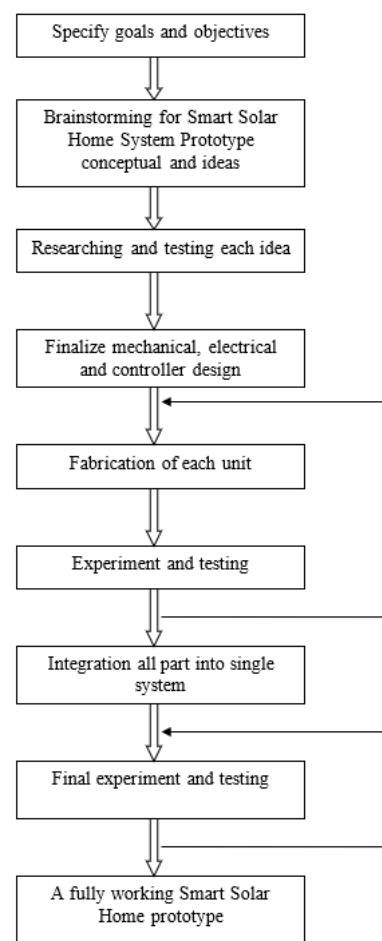


Figure 1. System design and development process of the proposed PV home system.

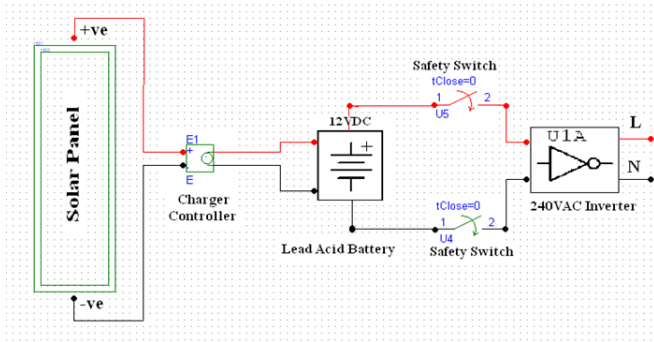


Figure 2. Electrical Circuit Configuration of the Proposed PV Home System

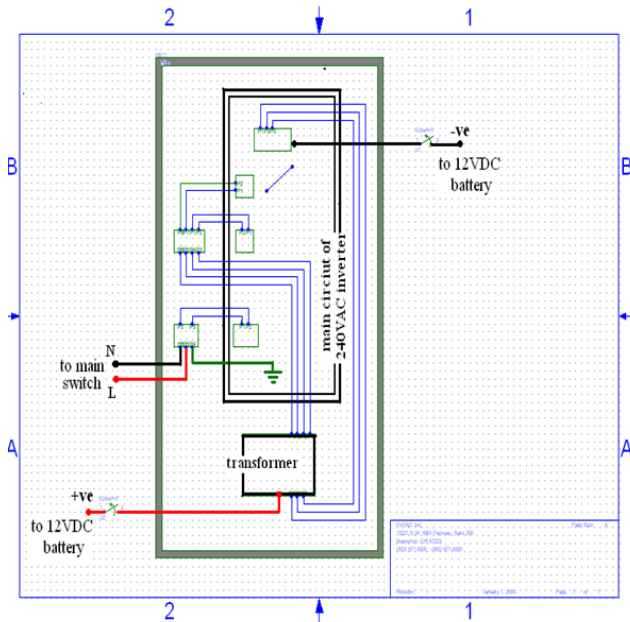


Figure 3. Internal Configuration of 240VAC Inverter for DC-AC Conversion

B. Embedded Controller Design

The core of the system is an embedded controller based on the PIC16F877A microcontroller. This microcontroller is selected due to its built-in analog-to-digital converter (ADC), low power consumption, and suitability for real-time control applications. The internal architecture and interfacing capability of the microcontroller are shown in Figure 5.

The controller continuously monitors the battery voltage through an ADC channel and executes a control algorithm for load prioritization. The system flowchart is presented in Figure 4, which describes the decision-making process based on battery voltage levels.

The controller continuously monitors the battery voltage through an ADC channel and executes a control algorithm for battery protection and load prioritization. The system flowchart, presented in Figure 4, illustrates the decision-making process based on predefined battery voltage levels. Under normal operating conditions, when the battery voltage remains equal to or above 11.7 V, the load connected through input 3 with a 20 A fuse remains active, while the LED indicator is turned off. However, when the battery voltage drops below 11.7 V, the controller detects a low-voltage

condition and automatically disconnects the load by switching input 3 off. At the same time, the LED indicator is turned on to signal that the battery protection mode has been activated. This threshold-based control strategy prevents excessive battery discharge, protects the battery from deep-discharge conditions, and ensures more reliable operation of the standalone photovoltaic system under limited energy availability.

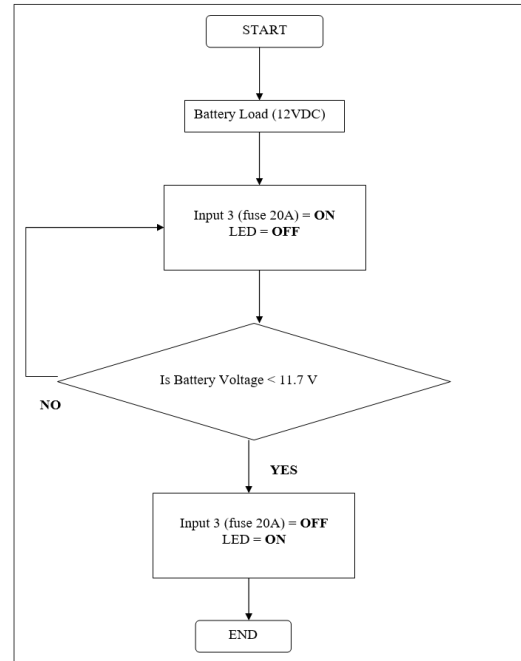


Figure 4. Control Algorithm Flowchart for Battery Protection and Load Prioritization

C. Voltage Sensing and Signal Conditioning

To ensure accurate voltage measurement, a voltage divider circuit is implemented, as shown in Figure 6. The circuit consists of two resistors ($R1 = 10 \text{ k Ohm}$ and $R2 = 10 \text{ k Ohm}$), which scale the battery voltage (0–12 V) to a safe input range (0–5 V) compatible with the microcontroller ADC.

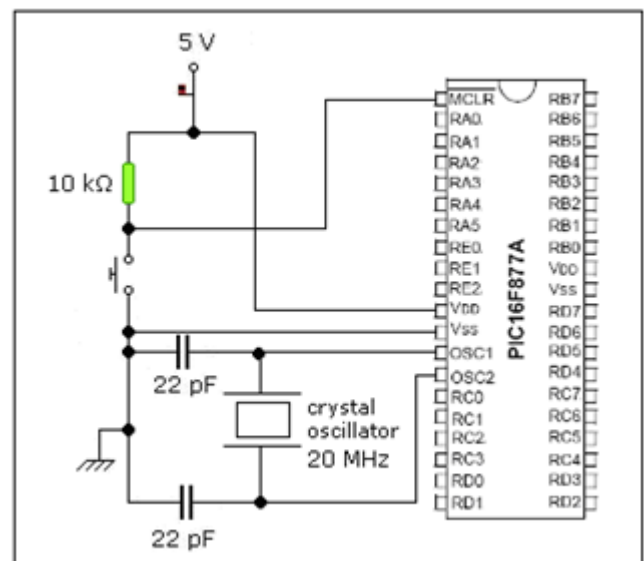


Figure 5. Architecture of PIC16F877A Microcontroller

A voltage regulator (LM7805) is used to provide a stable 5 V supply for the microcontroller and associated control circuitry. This ensures reliable system operation and protects sensitive electronic components from voltage fluctuations.

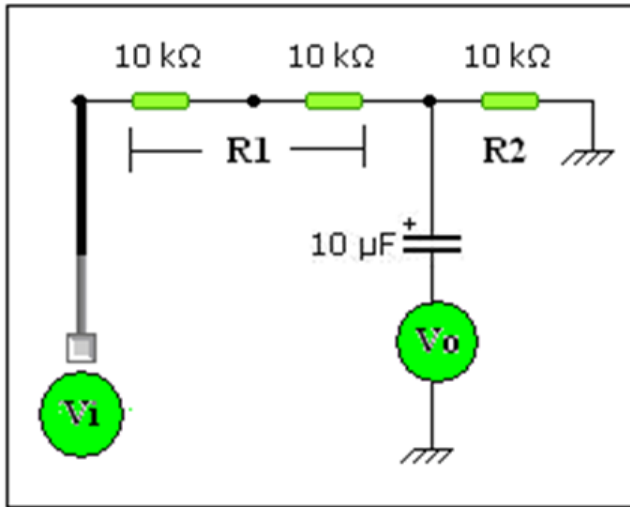


Figure 6. Voltage Divider Circuit for Battery Voltage Sensing

D. Load Control Mechanism

Load control is implemented using a relay-based switching system. A 5 V single-pole double-throw (SPDT) relay with a current rating of 10A at 250V AC or 10A at 30V DC is used to control the connection and disconnection of loads. Since the output current of the microcontroller is insufficient to directly drive the relay, a transistor-based driver circuit is employed, as illustrated in Figure 7. The transistor acts as a switching amplifier, enabling the microcontroller to control high-power loads effectively.

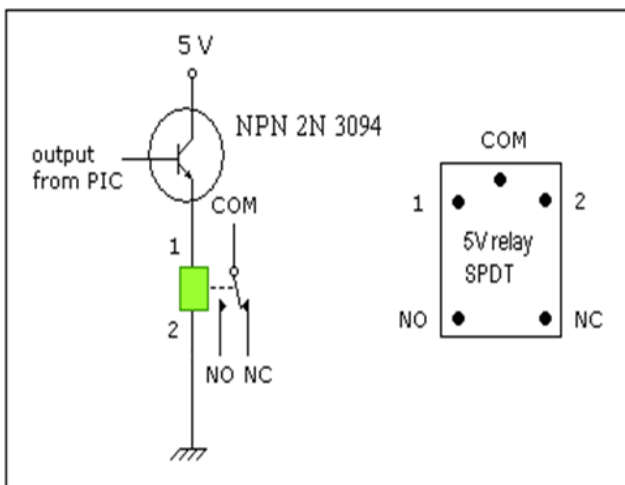


Figure 7. Transistor-Based Relay Driver Circuit for Load Control

E. Control Algorithm and Hysteresis Strategy

The control strategy is based on real-time battery voltage monitoring and threshold-based load prioritization. When the battery voltage drops below 11.7 V, non-critical loads are automatically disconnected to prevent deep discharge. To avoid frequent switching (chattering), a hysteresis mechanism is implemented. Loads are reconnected only

when the battery voltage rises above 12.5 V. This hysteresis control ensures stable operation and prolongs battery lifespan.

F. Experimental Procedure

The complete hardware implementation of the proposed system is shown in Figure 8, which presents the assembled prototype including the controller unit, sensing circuits, relay module, and power system components.

Experimental testing is conducted under natural sunlight conditions. Voltage and current data are measured using a digital multimeter and recorded at 10-minute intervals. The measurements are performed during two observation periods: morning (09:00–12:00) and afternoon (14:00–17:00), to capture variations in solar irradiance and environmental conditions.

The collected data are analyzed to evaluate system performance in terms of voltage stability, current variation, and the effectiveness of the load prioritization mechanism. These results are used to validate the functionality and reliability of the proposed controller in real operating conditions.

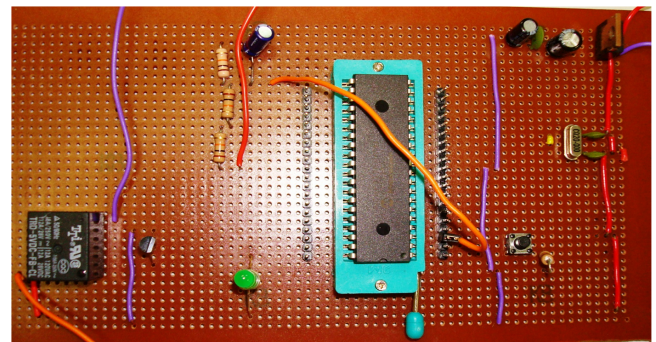


Figure 8. Hardware Implementation of PIC-Based Controller System

Results and Discussion

The performance of the proposed photovoltaic (PV)-based smart home energy system is evaluated through experimental measurements of voltage and current under real environmental conditions. The experiments are conducted during two observation periods, namely the morning session (09:00–12:00) and the afternoon session (14:00–17:00), to capture the effects of solar irradiance variation on system behavior. The variation of PV output voltage and current during the morning period is presented in Figure 9 and Figure 10, respectively.

The results indicate that the output voltage remains relatively stable within the range of approximately 9.2 V to 9.8 V, corresponding to a variation of about $\pm 3\%$, which demonstrates that the system maintains a consistent voltage profile under low-to-moderate irradiance conditions. In contrast, the output current increases significantly from approximately 1.7 A to 3.7 A, representing a variation of more than 100%. This behavior confirms that the PV current is highly dependent on solar irradiance, while the voltage

remains relatively stable due to the inherent characteristics of the PV module and the influence of the connected load. The estimated output power during this period increases from approximately 15.6 W to 36.3 W, indicating a substantial improvement in energy availability as irradiance increases.

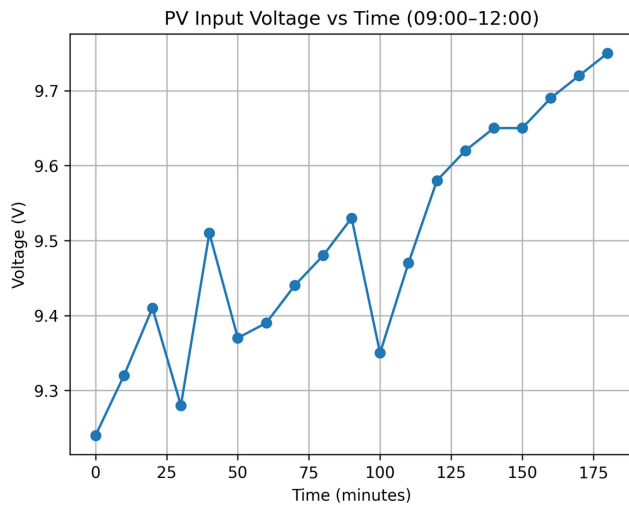


Figure 9. PV Output Voltage Variation During Morning Session

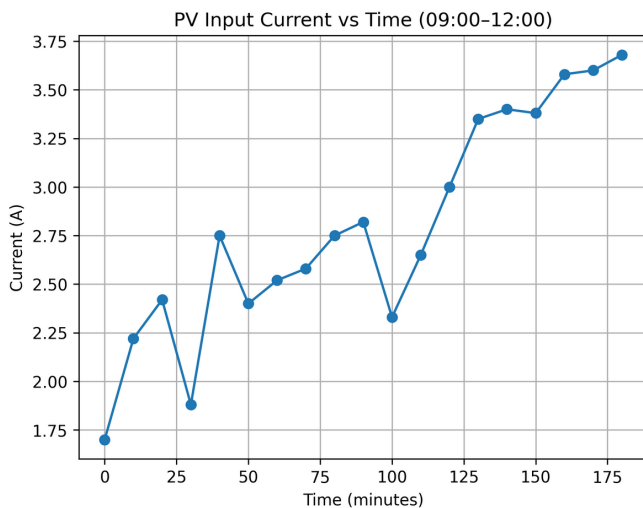


Figure 10. PV Output Current Variation During Morning Session

During the afternoon session, the PV output characteristics exhibit different behavior due to higher irradiance levels and environmental variations such as temperature rise and intermittent cloud coverage. The results presented in Figure 11 and Figure 12 show that the voltage remains within a relatively narrow range of approximately 9.1 V to 9.7 V, indicating that the system maintains voltage stability even under varying environmental conditions. However, the output current decreases significantly from approximately 3.5 A to 1.3 A toward the late afternoon, representing a reduction of more than 60%. This decrease is primarily caused by reduced solar irradiance and increased thermal effects on the PV panel, which negatively impact system efficiency. Consequently, the estimated output power also decreases significantly, highlighting the need for effective energy management under low-energy conditions.

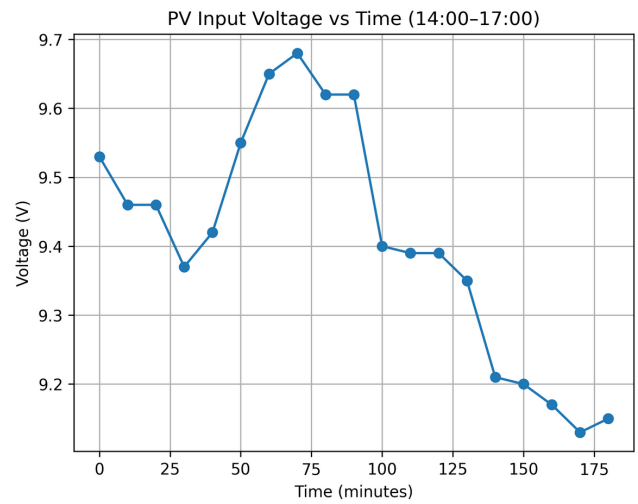


Figure 11. PV Output Voltage Variation During Afternoon Session

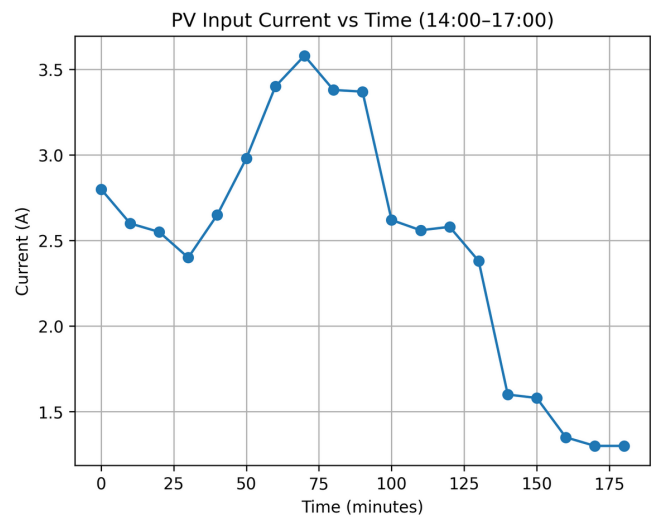


Figure 12. PV Output Current Variation During Afternoon Session

The effectiveness of the proposed PIC16F877A-based controller is demonstrated through its ability to maintain stable system operation under fluctuating environmental conditions. By continuously monitoring battery voltage, the controller activates the load prioritization mechanism when the voltage falls below the predefined threshold of 11.7 V, automatically disconnecting non-critical loads to prevent deep battery discharge. This ensures that essential loads remain operational and enhances overall system reliability. Without such a control mechanism, all loads would remain connected, leading to faster battery depletion and potential system failure. Furthermore, the implementation of a hysteresis strategy, with disconnection at 11.7 V and reconnection at 12.5 V, prevents rapid switching (chattering) and ensures stable system operation.

Compared to conventional PV systems without intelligent control, the proposed system demonstrates improved energy utilization and enhanced operational stability. The ability to dynamically manage load distribution based on available energy allows the system to adapt to varying environmental conditions more effectively. Although a direct experimental comparison with an uncontrolled system is not performed, the observed voltage stability and controlled load behavior

indicate that the proposed controller successfully mitigates the impact of energy fluctuations. In addition, the integration of auxiliary subsystems, such as automatic lighting and motion detection, contributes to improved energy efficiency by reducing unnecessary power consumption.

Despite the promising results, several limitations are identified in this study. The system does not incorporate maximum power point tracking (MPPT), which may limit optimal energy harvesting performance. Furthermore, the experimental validation is conducted on a prototype-scale system, and scalability to larger systems requires further investigation. Future work should focus on integrating advanced MPPT algorithms, implementing IoT-based monitoring for real-time system supervision, and conducting comparative performance analysis with alternative control strategies to further enhance system performance.

Conclusion

This study presents the experimental development and evaluation of a PIC16F877A-based intelligent energy management controller for voltage regulation and load prioritization in standalone photovoltaic (PV) home systems. The proposed system successfully integrates energy generation, storage, and embedded control into a unified platform, enabling reliable operation under varying environmental conditions. The experimental results demonstrate that the system maintains stable voltage characteristics within approximately $\pm 3\%$, while the output current exhibits significant dependence on solar irradiance, with variations exceeding 60% between morning and afternoon conditions. These findings confirm the nonlinear behavior of PV systems and highlight the importance of adaptive control strategies in maintaining system stability.

The implementation of the proposed controller effectively enhances system performance by dynamically managing load distribution based on real-time battery voltage conditions. The integration of a threshold-based control strategy combined with hysteresis (11.7 V for load disconnection and 12.5 V for reconnection) ensures stable operation, prevents rapid switching, and protects the battery from deep discharge. This approach improves energy utilization and enhances the overall reliability of the system, particularly in off-grid environments where energy availability is limited.

Compared to conventional standalone PV systems without intelligent control, the proposed system provides improved operational stability and more efficient energy management. The ability to prioritize loads based on available energy represents a practical and low-cost solution that addresses both energy supply and demand within a single embedded controller framework. This integration constitutes the main contribution of the study, distinguishing it from previous works that primarily focus on energy harvesting or battery charging independently.

Despite the promising results, this study has several limitations, including the absence of maximum power point tracking (MPPT) for optimal energy harvesting and the use of

a prototype-scale system for validation. Future research should focus on integrating advanced MPPT algorithms, incorporating Internet of Things (IoT)-based monitoring for real-time system supervision, and evaluating system performance under larger-scale and more diverse operating conditions. Overall, the proposed PIC-based controller demonstrates strong potential as a practical, low-cost solution for intelligent energy management in standalone photovoltaic systems.

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