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Smart Solar Power System with Load Prioritization for Rural Areas and Islands

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Abstract

Solar energy is a free, renewable, and clean energy source that can be an alternative to diesel generators in rural electrification. But it is highly weather-dependent, making it unreliable, especially without a proper energy management system and uncontrolled load usage. This project proposes a smart solar power system with a load prioritization mechanism that aims to improve reliability by gradually shedding lower-priority loads as the battery's State of Charge (SoC) decreases, preserving power for critical loads. Using a voltage divider circuit, the programmed Arduino UNO safely monitors the State of Charge (SoC) of the battery and smartly controls relays connected to the loads. The system's voltage measuring accuracy and relay response to load prioritization were tested before conducting an experiment to evaluate the efficiency and reliability improvements between the traditional and designed systems. The accuracy of the measured voltage values has been proven high, with each measurement having only a minimal deviation (<1%), and the relays' control also operated as intended. The experiment results concluded that the designed system has reduced the voltage depletion rate by approximately 44.44%, implying an improvement in the efficiency and reliability of the solar energy management system, creating an option for rural electrification.

1. Introduction

Access to reliable electricity remains a significant challenge in many rural and island communities, where extending the national power grid is often not economically viable [1]. As a result, these regions frequently rely on diesel generators, which are expensive, environmentally harmful [2] [3] [4], and unsustainable in the long term. Solar photovoltaic (PV) systems offer a promising alternative due to their renewable nature, low operating costs, and environmentally friendly [5], making it suitable for off-grid applications.

However, the effectiveness of solar energy is limited by its high dependency on weather conditions [6] [7] [8]. Even with battery storage, traditional solar PV systems often struggle to meet increasing energy demands, especially when power is consumed without regulation. Uncontrolled load usage can lead to premature battery depletion, resulting in system failure or blackouts [8], which is a critical issue especially in remote areas where backup power options are limited.

To address this problem, this project proposes a smart solar energy management system with an integrated load prioritization mechanism. The system is designed to monitor the battery's State of Charge (SoC) and intelligently control load connections using a voltage-based threshold algorithm implemented on an Arduino UNO. By prioritizing essential loads and disconnecting non-critical ones during low energy conditions, the

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system aims to enhance energy efficiency and improve the reliability of solar-powered systems for rural and off-grid electrification.

2. Methodology

This section discussed the sizing and selection of hardware components, prototype design and circuit connections, and Arduino program used to achieve the load prioritization.

2.1 Overview of the System

The proposed system integrates the load prioritization mechanism into a conventional solar photovoltaic (PV) system using simple components. The solar panel functions as a generator, converting sunlight into electrical power and storing it in a battery. A solar charge controller is positioned between the solar panel and the battery to regulate and manage the incoming power from the panel to the battery and the outgoing power from the battery to the loads, preventing overcharging or over-discharging. To ensure that the Arduino UNO can safely read the battery voltage, a voltage divider circuit is used to step down the battery's voltage to an appropriate level. The load prioritization algorithm is written in Arduino IDE software and uploaded to Arduino UNO. Based on the predefined threshold in the algorithm, Arduino UNO will control the relays to determine whether to connect or disconnect the battery to the loads. Unlike a typical solar PV system, the inverter is removed since only DC loads are used. The block diagram in Fig.1 illustrates the connections and interactions between the components in the system.

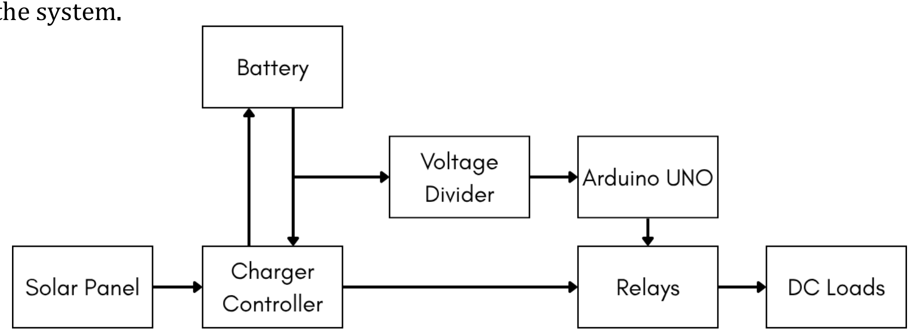

Fig. 1 *Block Diagram of the Proposed System*

Fig.2 shows the process flowchart of the proposed system. The system begins with the Arduino UNO acts as a voltage sensor to measure the battery's Soc. If it will supply power to every available load. Over the time, the battery SoC slowly decreasing, until it falls below the Threshold 1 and the non-essential loads will be cut off from the system. When the battery SoC further dropped below Threshold 2, important load will be cut off, prioritizing the critical loads. Lastly, if the battery SoC reaches the limit where it falls below Threshold 3, all loads will be disconnected.

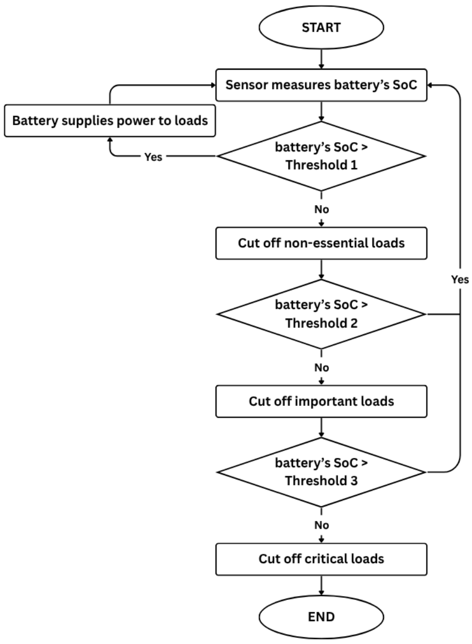

Fig. 2 *Flowchart of the Proposed System*

2.2 Hardware Components Specifications

Selecting the appropriate size and quantity of each component is important to ensure the proposed system functions effectively. For instance, the chosen rating for the solar panel rating must be sufficient to charge the battery efficiently, as well as the battery must provide enough power to meet the demands of all connected loads. Therefore, the calculations should begin from the consumer side [9].

2.2.1 DC Loads

This project only uses DC loads to simplify the system. The selected loads include LEDs, a mini submersible water pump, and a piezo buzzer, reflecting the 3 most common loads in a rural household, Compact Fluorescent Lamp (CFL), water pump, and a television [9] [10] [11]. Each load corresponds to a different priority level. Table 1 shows the calculated total power rating and energy requirements for these loads based on their estimated power rating, quantity, and daily operating hours.

Table 1 *Estimated power for daily loads in a rural household.*

DC Loads	Power Rating (W)	Quantity (nos.)	Total Power Rating (W)	Daily Operating Time (h)	Total Energy (Wh)
LED	0.04	4	0.16	5	0.8
Water Pump	2	1	2	0.5	1
Buzzer	0.15	1	0.15	2	0.3
Total	-	-	2.31		2.1

2.2.2 Battery

According to Table 1, the estimated total power and energy requirements for the loads are 2.31 W and 2.1 Wh per day, respectively. Since the loads operate at low voltage, a 12V 7.2 Ah battery has been selected due to its wide availability in the market. Additionally, the battery has been designed to provide 3 days of autonomy as backup. From the Equation (1), the estimated capacity of the battery is calculated to be 0.53 Ah.

$$C_{battery\,(required)} = \frac{E_{loads\,(received)}}{V_{system}} \times Autonomy\ Days \tag{1}$$

However, it is uncommon to let the battery discharge completely, as doing so will damage it and shorten its lifespan. Therefore, the battery's Depth of Discharge (DoD) is assumed to be 0.5. Using Equation (2), the final battery capacity is calculated to be 1.06 Ah.

$$C_{battery\,(actual)} = \frac{C_{battery\,(required)}}{DoD} \tag{2}$$

By comparing the required Amp-hour (Ah) rating with the selected rating using Equation (3), it is determined that only one battery is necessary for the system.

$$No.of\ batteries = \frac{C_{battery\,(actual)}}{Battery_{Ah-rating}} \tag{3}$$

Assuming a battery efficiency of 85%, the Equation (4) gives 2.47 Wh of energy required by the battery in order to power all daily loads effectively.

$$E_{battery\,(required)} = \frac{E_{battery\,(supplied\ to\ loads)}}{\eta_{battery}} \tag{4}$$

2.2.3 Charger Controller

Similar to the battery, the charger controller is also assumed to operate at 85% of efficiency, resulting in 2.91W energy required by the charger controller after calculating using Equation (5).

$$E_{charger\ controller(required)} = \frac{E_{charger\ controller(supplied\ to\ battery)}}{\eta_{charger\ controller}} \tag{5}$$

2.2.4 Solar Panel

The final step is to determine the size and number of solar panels required by the system. Assuming that daily Peak Sunlight Hours (PSH) is 5 hours, the calculated power required is 0.58W. To match the 12 V of system voltage, one 10W 12 V solar panel is selected for the system.

$$P_{total} = \frac{E_{charger\ controller(required)}}{PSH} \tag{6}$$

2.3 Prototype Model

As shown in Fig. 3, the final prototype was built based on the selected hardware components and connected as proposed in the previous sections. A DC-DC buck converter, LM2596 was added to lower the output voltage of the charger controller to match load voltage.

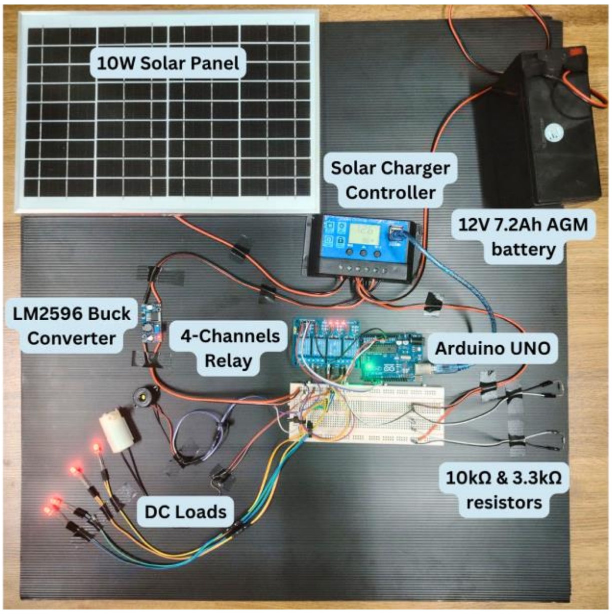

Fig. 3 *Prototype Design*

2.3.1 Voltage Divider

The voltage divider circuit is an important part of the system in this project, ensuring the Arduino UNO can safely and accurately measure the battery voltage. It reduces the battery voltage proportionally based on the ratio of the connected resistors. In the prototype, 10 kΩ and 3.3 kΩ resistors are connected in parallel to the 12 V battery and Arduino UNO analog (A0) and ground (GND) pins, respectively as shown in Fig. 4.

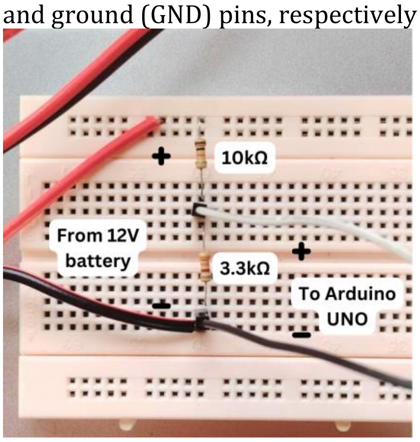

Fig. 4 *Voltage Divider Circuit*

But Arduino UNO will automatically convert the voltage and read the number in ADC value. Thus, a calculation was included in the Arduino coding to convert the ADC value to actual battery voltage as shown in Fig 5.

```
int Vin = analogRead(voltagePin);

// Convert ADC reading to voltage at A0 (Vout)
float Vout = Vin * (5.0 / 1023.0);

// Calculate actual battery voltage using divider ratio
float batteryVoltage = (Vout * (13300) / 3300);
```

Fig. 5 *Coding to convert ADC value to battery voltage*

2.3.2 Load Prioritization Algorithm

The load prioritization is achieved by using Arduino UNO to control the 4-channels relay connected to 3 different types of loads mentioned in section 2.2.1. The voltage measured from the voltage divider will be compared to the predefined threshold values to help Arduino identify the condition of the battery voltage. For this project, the predefined threshold values are 12.6 V, 12.3 V and, 12.0V as shown in Fig. 6.

```
const float THRESH_1 = 12.6;
const float THRESH_2 = 12.3;
const float THRESH_3 = 12.0;
```

Fig. 6 *Load Prioritization threshold values for the system*

Once the threshold values were initialized, the next step is to control the relays for different conditions identified by Arduino UNO. Since there are 3 threshold values serves as boundaries, there will be 4 different relays switching. To easily perform multiple choices switching, 'if…else" function is used. Fig. 7 shows how the load prioritization can be achieved by using "If…else" function. Note that the Arduino will send a LOW signal when "batteryVoltage" is higher than THRESH_1. This is all because of the 4-channels relay used is an active-low relay, which means it will be triggered by a low signal and vice versa.

```
if (batteryVoltage > THRESH_1) {
  digitalWrite(relayLED, LOW);
  digitalWrite(relayMotor, LOW);
  digitalWrite(relayBuzzer, LOW);
}
else if (batteryVoltage > THRESH_2) {
  digitalWrite(relayLED, LOW);
  digitalWrite(relayMotor, LOW);
  digitalWrite(relayBuzzer, HIGH);
}
else if (batteryVoltage > THRESH_3) {
  digitalWrite(relayLED, LOW);
  digitalWrite(relayMotor, HIGH);
  digitalWrite(relayBuzzer, HIGH);
}
else {
  digitalWrite(relayLED, HIGH);
  digitalWrite(relayMotor, HIGH);
  digitalWrite(relayBuzzer, HIGH);
}
```

Fig. 7" If*…else" function with different conditions and statements*

3. Results and Discussions

This section presents the results in data and information collected from prototype testing. It focuses on the system functionality and followed by a performance analysis between proposed system and traditional solar PV system.

3.1 Voltage Measurement Accuracy

Fig. 8 shows three separate readings measured by Arduino, displayed on Serial Monitor in Arduino IDE. The measured values are 12.85 V, 12.93 V, and 12.89 V, taken at a same reference value of 12.9 V, as shown on the charger controller's screen in Fig.1. The accuracy of each measurement is determined by the error or the deviation of the measured value from the reference value. Based on the calculation, the error for each individual reading is 0.05V, 0.03V, and 0.01 V, respectively. When compared to the gap between voltage thresholds used in the system, which is 0.3V, these errors are significantly low and unlikely to cause mis-execution in the load prioritization algorithm. In addition, the readings also are closely grouped within a narrow error range of -0.05 V to +0.03 V, resulting in a total variation of less than 0.1 V. This confirms the high accuracy and precision of the voltage divider circuit and Arduino ADC conversion, making it reliable for continuous monitoring of the battery's State of Charge (SoC) in the system.

(a) **(b)** **(c)**

Fig. 8 *Serial Monitor displays battery voltage of (a) 12.85V; (b) 12.93V; (c) 12.89V*

3.2 Relays Response on Load Prioritization

The load prioritization logic was tested under four different voltage scenarios to observe how the relays responded according to the predefined threshold. Instead of waiting for the battery to deplete by itself, a potentiometer was connected in series to the voltage divider circuit to simulate the voltage. In each case, the Arduino measured the voltage and sent LOW and HIGH output signals through pins 3, 5, and 6 to control the relays. Table 2 summarizes the test results for all cases. In the first case, the Serial Monitor displayed a measured voltage of 12.83 V with all relays activated, which can be verified by the number of indicator lights showing on the relay. This confirms that the system allowed full operation during optimal battery levels. In the next case, the battery voltage is simulated to 12.37 V, which is below THRESH_1, causing only the buzzer's relay to be deactivated. This demonstrated that the system correctly shed the non-essential load to conserve energy while keeping the other important loads. The test continued with the third case, where the battery voltage is 12.13 V. Again, another lower priority load was disconnected, reflecting the system's ability to preserve the remaining power only for the critical load during limited energy conditions. The last case represents the state when the battery voltage is close to its DoD, which is why all relays were turned off to allow the battery fully focus on charging.

Table 2 *Relays status based on measured "batteryVoltage" for each case*

Types of Case	"batteryVoltage" (V)	Relay 1 (LEDs)	Relay 2 (Water Pump)	Relay 3 (Buzzer)
Case 1	12.82	ON	ON	ON
Case 2	12.37	ON	ON	OFF
Case 3	12.13	ON	OFF	OFF
Case 4	11.62	OFF	OFF	OFF

3.3 Performance Comparison Between Traditional and Load Prioritization System

To evaluate the effectiveness of the load prioritization in enhancing the solar energy management system, a performance comparison was conducted against a traditional solar setup without load control. Both systems have the same setup, where they began with the same initial voltage of 12.7 V, and all loads were connected for 5 hours under no sun conditions. The initial and final readings of the battery voltage were recorded in Table 3, as well as the battery voltage of every 1-hour.

Table 3 Voltage Comparison between Traditional and Designed System

Time (h)	Battery Voltage (V)	
	Traditional system	Designed System
0	12.7	12.7
1	12.4	12.5
2	12.2	12.4
3	12.0	12.3
4	11.9	12.2
5	11.8	12.2

Based on the recorded values in Table 3, a graph was plotted for better visualization in comparing and analysing the data as shown in Fig. 9. The rate of voltage depletion, representing by the slope, which was calculated by dividing the difference between initial and final voltage readings to the total time. The battery voltage was found decreases 0.18 V/h in the traditional system, which is approximately 1.8 times of the smart system with load prioritization, with only 0.1 V/h. This suggests that the smart system has improved efficiency and reliability due to the reduction in voltage depletion rate by approximately 44.44% compared to a traditional solar setup.

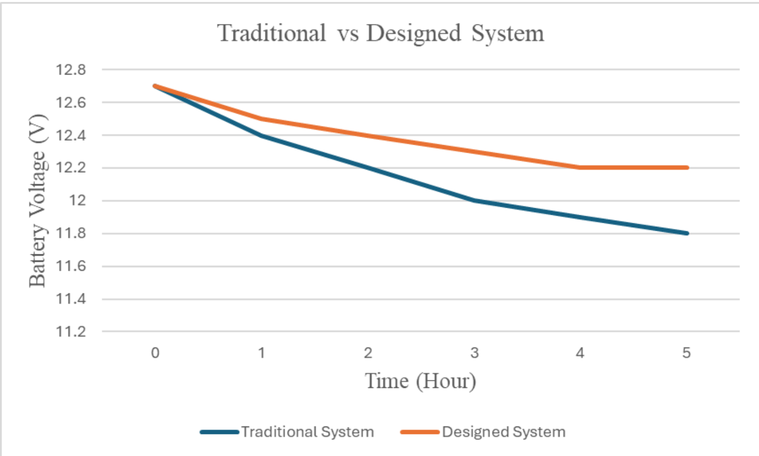

Fig. 9 *Comparison of battery voltage between traditional and designed system*

4. Conclusion

This project successfully developed and demonstrated a smart solar energy management system equipped with load prioritization for rural and off-grid communities. By integrating a simple voltage monitoring technique using a voltage divider and Arduino UNO, the system was able to measure the battery's State of Charge (SoC) and control load distribution accordingly. Through a predefined threshold-based algorithm, the system ensured that essential loads were maintained while non-critical loads were shed during low-energy conditions.

Experimental testing validated the system's performance in both load control accuracy and voltage monitoring reliability, with less than 1% deviation in voltage readings. Furthermore, a five-hour comparative test with a conventional solar system showed a reduction in battery voltage depletion rate by approximately 44.44%, indicating improved energy efficiency and reliability.

The results confirm that the proposed system can enhance solar energy utilization and prolong battery lifespan without relying on costly or complex components. This approach offers a practical, low-cost solution for energy access in underserved communities, supporting sustainable development goals through smarter renewable energy management.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Lim Kian Ann, Dirman Hanafi;* ***data collection:*** *Lim Kian Ann;* ***analysis and interpretation of results:*** *Lim Kian Ann;* ***draft manuscript preparation:*** *Lim Kian Ann, Dirman Hanafi. All authors reviewed the results and approved the final version of the manuscript.*

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