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Design and Operational Evaluation of Off-Grid Solar Power Plants with Integrated Automatic Cleaning Systems for Enhanced Performance

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ABSTRACT

This study details the design and experimental evaluation of an off-grid photovoltaic (PV) system equipped with an automatic solar panel cleaning mechanism to address performance degradation due to dust accumulation. The system integrates a mechanical wiper-based cleaning unit, solar charge controller (SCC), inverter, and low-voltage disconnect (LVD) to maintain reliable and stable operation in stand-alone settings. Experimental tests were performed on a 50 Wp PV module under actual outdoor conditions in Padang, Indonesia. System performance was assessed before and after panel cleaning using key electrical parameters, such as output voltage, current, output power, and relative efficiency improvement. Results show that the automatic cleaning mechanism increased the average PV output power from 0.88 W to 1.71 W, representing an efficiency improvement of approximately 11.89% compared to the uncleaned state. In contrast to previous studies that focus on grid-connected systems or manual cleaning methods, this research introduces a low-cost, self-operating cleaning solution tailored for small-scale off-grid PV applications in tropical environments. The proposed system offers practical benefits for enhancing energy yield, system reliability, and maintenance efficiency in remote solar installations.

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1. INTRODUCTION

Renewable energy is a sustainable and eco-friendly source of power that can decrease reliance on fossil fuels, thereby contributing to a reduction in greenhouse gas emission. Additionally, renewable energy power plants can provide electricity to remote regions that lack accsess to teh electical grid. A potential renewable energy source in Indonesia is solar energy which has an average solar radiation intensity of around 4.8 kWh/m2 per day throughout Indonesia[1][2]. Solar photovoltaic (PV) technology converts solar radiation into electrical energy through the photovoltaic effect, in which photons excite charge carriers in semiconductor materials, generating direct current electricity[3][4][5]. The more energy absorbed by the solar panel, the more electrical energy is generated. However, this does not apply if the surface of the solar panel is not clean because it is caused by several factors that can reduce the efficiency of the solar panel [6].

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Off-grid solar PV systems face critical challenges related to system reliability, energy availability, and strong dependence on battery storage[7]. Variations in solar irradiance can cause unstable power supply, while limited battery capacity and charging efficiency directly affect load continuity and system reliability[8]. Any reduction in PV generation efficiency shortens battery autonomy and increases the risk of load disconnection, thereby degrading overall system performance.

One of the major factors that degrades PV performance is surface soiling caused by dust, dirt, water stains, leaves, and other particles [9], [10], [11], [12], . In addition, there are other factors, namely the implementation of unscheduled cleaning causing the accumulation of dust or dirt or objects on the surface of the solar panel and human error when cleaning the surface of the solar panel which has the potential to damage one of the cells on the solar panel [13] .

Previous studies report that dust accumulation can reduce PV output by approximately 10% in mild conditions and over 40% in arid environments [14]. In off-grid systems, such losses directly degrade battery charging performance and supply reliability, making panel cleanliness critical for stable energy availability and system operation. Automatic cleaning systems provide an effective solution by enabling regular maintenance, reducing human error, and minimizing the risk of surface damage compared to manual cleaning [15], [16]. This approach is particularly beneficial for remote off-grid installations, as it helps sustain energy production, extend battery lifetime, and improve overall system reliability.

Although many studies have examined the effects of dust accumulation and cleaning methods on PV performance, most focus on grid-connected or laboratory-scale systems. Comprehensive investigations that integrate the design and operational performance evaluation of automatic cleaning systems in real off-grid PV applications, including their interaction with energy management components, remain limited. This gap restricts practical understanding of the long-term reliability and energy sustainability of off-grid PV systems.

This study aims to design and evaluate an off-grid PV system integrated with an automatic cleaning mechanism. The objectives are to assess system performance before and after cleaning and to analyze the impact of panel cleanliness on energy generation, battery charging, and system reliability. The main contributions of this study include the development of an integrated off-grid PV system with automatic cleaning and an experimental evaluation of its operational performance under real environmental conditions, providing practical insights for off-grid PV deployment.

2. RESEARCH METHOD

2.1. Design

The proposed off-grid PV system consists of a 50 Wp solar panel, a solar charge controller (SCC), a 12 V 8 Ah battery, a low voltage disconnect (LVD), an inverter, and an AC load in the form of a 5 W LED lamp. The SCC regulates the battery charging process to prevent overcharging and deep discharge, while the LVD protects the battery by disconnecting the load when the voltage drops below a predefined threshold. The design of the tool can be seen in Figure 1 and Figure 2.

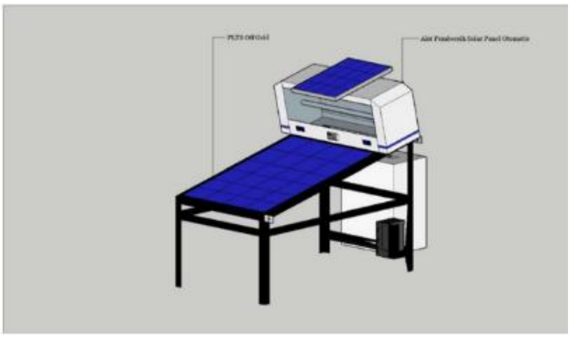

Figure 1. Design tools

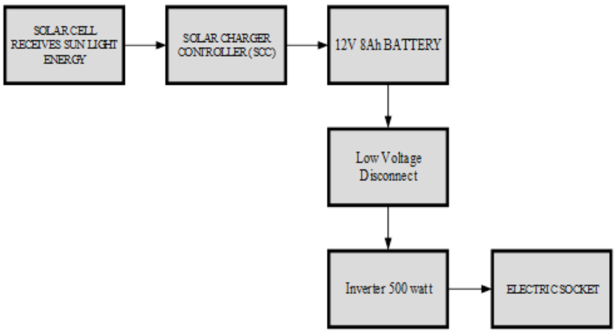

Figure 2. Schematic for off-grid solar power plant planning

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Based on the Figure 2 illustrates the operational configuration of the proposed system. The system utilizes a 50 Wp solar panel as the primary power source. The solar panel converts solar irradiance into electrical energy, which is subsequently stored in a 12 V, 8 Ah battery. The battery charging process is regulated by a solar charge controller (SCC) to control the charging voltage, prevent overcharging, and provide protection during the charging process. The battery output is connected to a low voltage disconnect (LVD), which manages load connection and disconnection based on the battery voltage level. The output of the LVD is then connected to a 12 V DC relay coil, which activates the inverter through the relay contacts. The inverter converts direct current (DC) into alternating current (AC), and the AC output is finally supplied to the electrical socket to power the load, that can see in Figure 3.

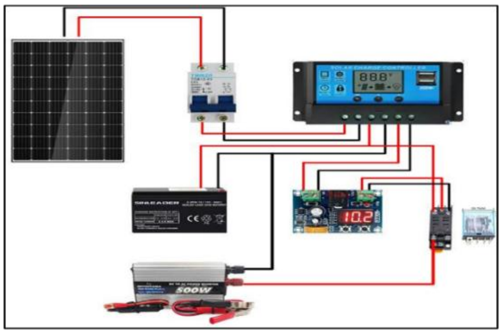

Figure 3. PLTS wiring diagram

The wiring diagram in Figure 3 presents the wiring configuration of the off-grid PV system. The battery is connected first to the solar charge controller (SCC) to enable automatic voltage detection and prevent controller damage. The PV module is then connected to the low voltage disconnect (LVD), which regulates the battery–load connection based on battery voltage. Finally, the battery output is supplied to the inverter to provide AC power to the load.

2.2. Flowchart

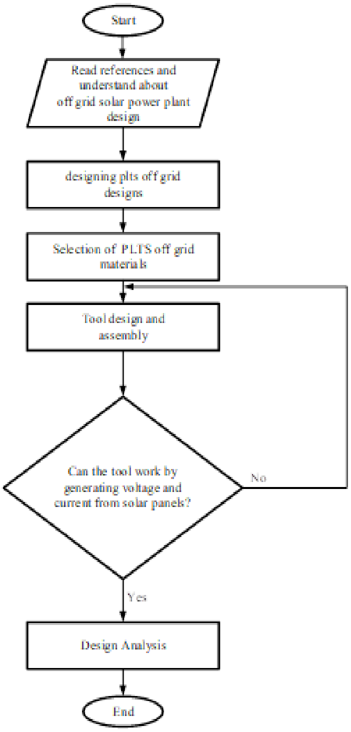

Figure 4. Flowchart

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The automatic cleaning mechanism employs a mechanical wiper driven by a DC motor powered by the system battery. The wiper moves linearly across the surface of the solar panel to remove dust and dirt without using water, thereby minimizing energy consumption and maintenance requirements. Cleaning is activated at predetermined intervals to ensure consistent panel cleanliness while avoiding excessive mechanical wear. This design prioritizes simplicity, reliability, and suitability for off-grid applicationsThe flowchart in Figure 4 explains how the automatic solar panel cleaning tool works concisely and efficiently.

3. RESULTS AND DISCUSSION

3.1. Solar Panel Device Analysis

The tool's overall form, which includes the off-grid PLTS design, is shown in Figure 5. After putting this instrument through its paces, testing revealed that it functions as intended and that each of its parts is functional and appropriate for use.

Figure 1. Overall Structure of the Tool

3.2. Solar Panel Device Analysis

Solar panels convert solar radiation into electrical energy through the photovoltaic effect. The electrical output depends on solar irradiance, where higher irradiance results in higher voltage and current. The generated energy is used to charge the battery, and the charging process is influenced by weather conditions and solar intensity.The solar charge controller (SCC) regulates the battery charging process by preventing overcharging and deep discharge, thereby extending battery lifetime. In addition, the SCC provides protection and ensures safe and stable battery operation during charging.

3.3. Testing on Solar Panels (Solar Cells)

Experimental testing was conducted under outdoor conditions with varying solar irradiance and weather conditions. Measurements were taken at 30-minute intervals over a 4.5-hour period. The evaluated parameters included output voltage (V), output current (A), and output power (W), calculated as the product of voltage and current. Relative efficiency improvement was determined by comparing the electrical output before and after panel cleaning. Environmental conditions such as solar irradiance (lux) and weather conditions were recorded to support result interpretation. The testing and measurement of the solar panel before and after cleaned up can be seen in Figure 6 and Figure 7.

Figure 6. Testing and measuring solar panels before cleaned up

Figure 7. Testing and measuring solar panels after cleaned up

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3.4. Solar Panel Test Data

1) Solar panel test data before cleaning Tuesday/July 23, 2024

Based on the test data results obtained from testing before the panel was cleaned on Tuesday, July 23, 2024, which can be seen in Table 1. The results of the voltage and current produced can also be seen in Figure 8.

Table 1. Solar panel testing before cleaned up Tuesday / July 23 , 2024

NO	Time	LUX (x100)	Weather Condition	Digital VoltmeterAmmeter			Volt SCC	PV Module Voltage (V)
				V	I	W		
1	11:00	314	Sunny and Cloudy	12,4	0,06	0,74	12,5	18,50
2	11.30	216	Sunny and Cloudy	12,2	0,05	0,61	12,5	17,80
3	12.00	901	Sunny	12,6	0,10	2,15	12,6	19,67
4	12.30	118	Cloudy	12	0	0	12,4	17,4

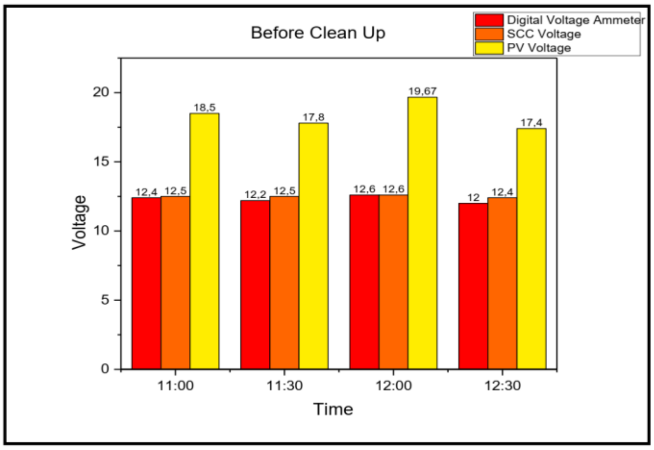

Figure 2. Voltage and current on Solar Charger Controller and digital voltamper meter

Find the average voltage using the following equation:

$$\text{Average}=\frac{Vtotal}{h} \tag{1}$$

Where :
$V_{average}$ = Average charging voltage (V)
V_{total} = Total charging voltage from 11.00 – 12.30 (V)
h = Test duration (per- 30 minutes)
Average Voltage of Solar Panels

$$\text{Average} = \frac{Vtotal}{h}$$
$$=\frac{18{,}50+17{,}80+19{,}67+17{,}4}{4} = 18.34 \text{ V}$$

Finding the average current on a digital ammeter can be done using the following equation:

$$\text{I average} = \frac{\text{Itotal}}{h} \tag{2}$$

Where :
I average = Average charging current (A)
I tot = Total charging current from 11.00- 12.30(A)
h = Test duration (Per 30 minutes)

Based on the equation above, the average battery charging current can be calculated using data from the test table. The following is the calculation for finding the average current:

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$$\text{Average} = \frac{\text{Itotal}}{h}$$

$$= \frac{0{,}06+0{,}05+0{,}10+0}{4} = 0.052 \text{ A}$$

2) Solar panel test data during charging after cleaning on Tuesday/23 July 2024

Based on the test data results obtained from testing after the panel was cleaned on Tuesday, July 23, 2024, which can be seen in Table 2. The results of the voltage and current produced can also be seen in Figure 9.

Table 2. Solar panel testing after cleaned up Tuesday / July 23 , 2024

NO	Time	LUX (x100)	Weather Condition	Digital Voltmeter Ammeter			Volt SCC	PV Module Voltage (V)
				V	I	W		
1	13:00	700	Sunny	12,6	0,16	2,01	12,6	20,52
2	13.30	684	Cloudy	12,5	0,12	1,5	12,5	20,3
3	14.00	912	Sunny	12,7	0,19	2,41	12,5	21,6
4	14.30	211	Cloudy	12,4	0,08	0,9	12,5	18,58

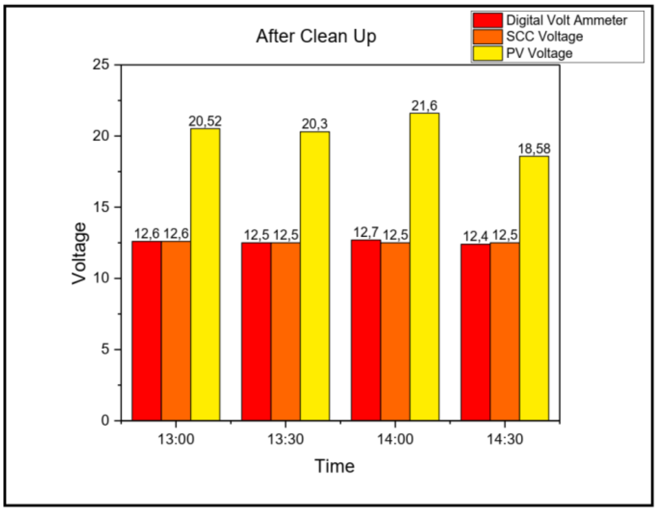

Figure 3. Voltage and current on *the* Solar Charger Controller and digital voltampere meter

Find the average voltage using the following equation (1):

Average Voltage of Solar Panels

$$\text{Average} = \frac{\text{Vtotal}}{h}$$

$$= \frac{20{,}52+20{,}3+21{,}6+18{,}58}{4} = 20.52 \text{ V}$$

Based on the equation (2) above, the average battery charging current can be calculated using data from the test table. The following is the calculation for finding the average current:

$$\text{Average} = \frac{\text{Itotal}}{h}$$

$$= \frac{0{,}16+0{,}12+0{,}19+0{,}08}{4} = 0.13 \text{ A}$$

3) Effect of Panel Cleaning on PV Output Power

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As a representative indicator of photovoltaic system performance, the output power was used to assess the effectiveness of the proposed cleaning mechanism. Accordingly, the output power of the photovoltaic module was calculated using the basic electrical relationship:

$$P = V \, X \, \mathrm{I} \quad (3)$$

where:
P is the output power of the photovoltaic module (W), V is the measured output voltage of the PV module (V), and I is the measured output current of the PV module (A).

Therefore, the average output power before cleaning was calculated as:

$$P_{\text{before}} = V_{\text{before}} \times I_{\text{before}}$$
$$P_{\text{before}} = 18.34 \times 0.052 \approx 0.88 \text{ W}$$

After the panel cleaning process, the average output voltage and current were measured as:

$$V_{\text{after}} = 20.52 \text{ V}$$
$$I_{\text{after}} = 0.13 \text{ A}$$

Thus, the average output power after cleaning was calculated as:

$$P_{\text{after}} = V_{\text{after}} \times I_{\text{after}}$$
$$P_{\text{after}} = 20.52 \times 0.13 \approx 1.71 \text{ W}$$

The relative performance improvement of the photovoltaic module due to the panel cleaning process was quantified based on the output power using the following expression:

$$\eta_{\text{improvement}}(\%) = \frac{P_{\text{after}} - P_{\text{before}}}{P_{\text{before}}} \times 100\% \quad (4)$$

where:
$\eta_{\text{improvement}}$ is the relative performance improvement (%), P_{before} is the average output power before cleaning (W), P_{after} is the average output power after cleaning (W)

Therefore, the relative performance improvement is calculated as follows:

$$\eta_{\text{improvement}} = \frac{1.71 - 0.88}{0.88} \times 100\%$$
$$\eta_{\text{improvement}} = \frac{0.83}{0.88} \times 100\% \approx 94.32\%$$

This result indicates that the output power of the photovoltaic module increased by approximately 94.32% after the application of the automatic cleaning mechanism. The relatively high percentage improvement is attributed to the low initial output power under soiled panel conditions and moderate solar irradiance during the experimental period, which makes the relative increase more pronounced after cleaning.

4) Solar Panel Cleaning Efficiency

To calculate the efficiency of solar panel cleaning, we can compare the voltage (V) produced by the solar panel before and after cleaning using the following equation:

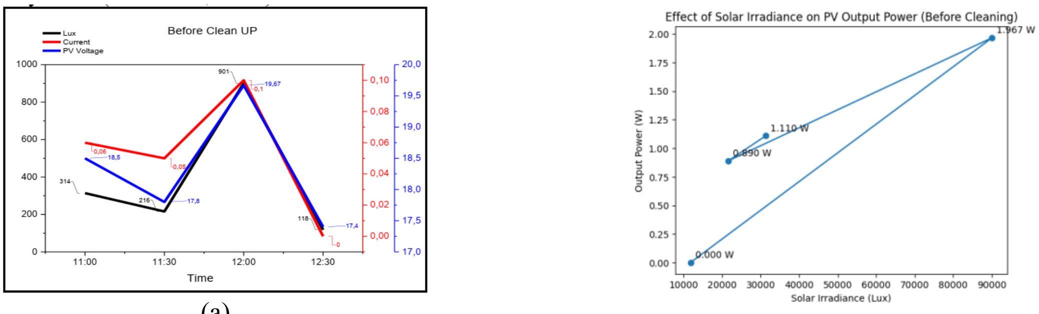
$$Efisiensi = \frac{\overline{V}_{After} - \overline{V}_{Before}}{\overline{V}_{before}} \, x \, 100\% \quad (5)$$

$$Efisiensi = \frac{20{,}52 - 18{,}34}{18{,}34} \, x \, 100\% = 11.89\%$$

Based on the calculation above, the result of the increase in solar panel efficiency is 11.89%. This means that after cleaning, the solar panel produces a voltage of about 11.89% compared to before cleaning.

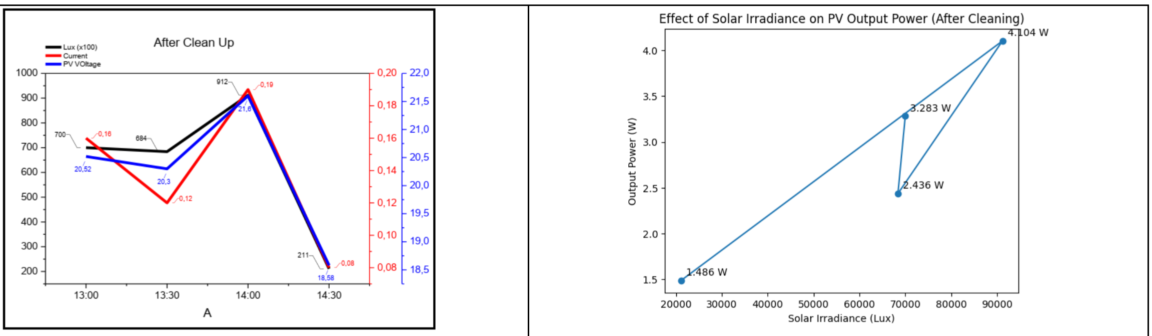
3.5. The Effect of Light Intensity on Current, Voltage, and Power Output

Graph of the effect of solar irradiance on the output current and power of the PV module before cleaning. Under the pre-cleaning condition, solar irradiance increased from 11,800 lux to 90,100 lux, resulting in an increase in output voltage from 17.4 V to 19.67 V, output current from 0 A to 0.10 A, and output power from 0 W to 1.97 W., can also be seen in Figure 10.



(a) (b)

Figure 10. Graph influence intense i bag sunlight to (a) current and voltage, (b) power output before cleaned up



(a) (b)

Figure 11. Graph influence intense i bag sunlight to (a) current and voltage, (b) power output after cleaned up

Figure 11 illustrates the effect of solar irradiance on the PV module output power after the panel cleaning process. Following cleaning, an increase in solar irradiance from 21,100 lux to 91,200 lux resulted in a corresponding rise in output power from 1.49 W to 4.10 W. The results indicate that higher solar irradiance leads to greater power generation; however, for similar irradiance levels, the post-cleaning condition yields significantly higher output power compared to the pre-cleaning condition. This improvement demonstrates that the removal of surface soiling effectively enhances light absorption by the PV module, thereby improving energy conversion efficiency and overall system performance.

3.6. Battery Calculation

1. Calculating battery charging time

To calculate the charging time and battery usage time, we use an efficiency of 80%. Since the battery capacity used is 8Ah, the battery capacity used is:
Used capacity = 80% x 8 Ah = 6.4 Ah.
Based on the equation above, the battery charging time can be calculated as follows:

$$Charging\ Time\ (h) = \frac{Battery\ Capacity \times \eta battery}{Charging\ Current \times \eta charger} \tag{6}$$

where:

Charging Time (h) is the required time to fully charge the battery (hours), *Battery Capacity* is the rated battery capacity (Ah), Charging Current is the average charging current (A), $\eta_{battery}$ is the battery efficiency, and $\eta_{charger}$ is the efficiency of the charging system (e.g., solar charge controller).

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Based on the equation presented above, the charging current generated by the photovoltaic module can be calculated as follows:

$$I_{\text{charge}} = \frac{P_{\text{in}} \times \eta}{V_{\text{battery}}} \tag{7}$$

where:

I_{charge} is the charging current (A), P_{in} is the input power from the solar panel (W), η is the charging system efficiency, and V_{battery} is the nominal battery voltage (V).

By substituting the measured values into Eq. (7), the charging current is obtained as:

$$I_{\text{charge}} = \frac{50 \times 0.80}{12} = 3.33 \text{ A}$$

Once the charging current is determined, the required charging time can be estimated using:

$$t_{\text{charge}} = \frac{C_{\text{battery}}}{I_{\text{charge}} \times \eta} \tag{8}$$

where:

t_{charge} is the charging time (h), and C_{battery} is the battery capacity (Ah).

Thus, for a 12 V battery with a capacity of 6.4 Ah, the estimated charging time is:

$$t_{\text{charge}} = \frac{6.4}{3.33 \times 0.80} \approx 2.40 \text{ h}$$

Based on the calculation results, a 12 V battery with a nominal capacity of 6.4 Ah charged at an average current of 3.33 A requires approximately 2.40 h to reach full charge, assuming a charging system efficiency of 80%.

2. Calculating battery discharge time

Battery capacity utilization can be evaluated through analytical calculation. The duration for which the battery can supply the load (discharge time) can be estimated using the following equation:

$$t_{\text{discharge}} = \frac{C_{\text{battery}} \times \eta_{\text{battery}}}{I_{\text{DC}}} \tag{9}$$

where:

$t_{\text{discharge}}$ is the battery discharge time (h), C_{battery} is the battery capacity (Ah), η_{battery} is the battery efficiency, and I_{DC} is the DC current drawn from the battery (A).

To determine the DC current drawn from the battery when supplying an AC load through an inverter, the DC input power to the inverter is first calculated as:

$$P_{\text{DC}} = \frac{P_{\text{AC}}}{\eta_{\text{inv}}} \tag{10}$$

where:

P_{DC} is the DC input power to the inverter (W), P_{AC} is the AC load power (W), and η_{inv} is the inverter efficiency.

For a 5 W LED lamp supplied through an inverter with an efficiency of 85%, the required DC input power is:

$$P_{\text{DC}} = \frac{5}{0.85} = 5.88 \text{ W}$$

The corresponding DC current drawn from a 12 V battery is then calculated as:

$$I_{\text{DC}} = \frac{P_{\text{DC}}}{V_{\text{battery}}} \tag{11}$$

$$I_{\text{DC}} = \frac{5.88}{12} = 0.49 \text{ A}$$

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Once the DC current is obtained, the battery discharge time can be estimated as:

$$t_{\text{discharge}} = \frac{6.4}{0.49} \approx 13.06\,\text{h}$$

Based on the calculation results, a 12 V battery with a nominal capacity of 6.4 Ah can supply a 5 W AC load through an inverter with 85% efficiency for approximately 13 h under the assumed operating conditions.

4. CONCLUSION

This study demonstrates that integrating an automatic solar panel cleaning mechanism into a small-scale off-grid photovoltaic system can significantly enhance electrical performance and operational reliability. Experimental results show that panel cleaning increased the average output power from 0.88 W to 1.71 W, corresponding to a relative performance improvement of approximately 94.32% under the tested operating conditions. This substantial increase confirms that surface soiling imposes significant optical losses on photovoltaic modules and that the proposed cleaning mechanism effectively restores light transmittance, thereby improving power generation. The integration of a solar charge controller, inverter, and low voltage disconnect further enhances battery protection and overall system stability.

The primary contribution of this work lies in the development of a practical, low-cost, and easily implementable automatic cleaning solution to enhance off-grid PV system performance in tropical environments. Although the results are promising, this study is limited by the relatively short testing duration and the specific environmental conditions considered. Therefore, future research should focus on long-term performance evaluation across different seasons, optimization of cleaning frequency, assessment of the energy consumption of the cleaning mechanism, and comparative analysis with alternative automatic cleaning technologies to further strengthen the scientific contribution and practical applicability of the proposed system.

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