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Performance Improvement of PV Modules under the Effect of Partial Shading using Bil-Bot Wiping Mechanism

Musa Suleiman[1,2], Prof. Deepak Kumar Joshi[1], Bilyamin Muhammad[3], Isah Bello[2]

[1]*Department of Electrical Engineering, Mewar University, India*
[2]*Department of Electrical and Electronics Engineering,Kaduna Polytechnic, Nigeria*
[3]*Department of Computer Engineering,Kaduna Polytechnic, Nigeria*

Abstract: Photovoltaic (PV) modules are central to the operation and success of solar power systems. The role they play in energy conversion, system efficiency, economic benefits, environmental impact, and technological advancement highlights their importance in driving the growth and adoption of solar energy.Therefore, enhancing the performance efficiency of PV modules under partial shading is paramount, as shading can negatively affectthe energy production process of the solar power systems. To address this challenge, this study presents an innovative technology based on Bil-Bot Wiping Mechanism. The Bil-Bot Wiping Mechanism is a simple and reliable system that automates the cleaning process using a motor-driven wiper mechanism, controlled by an ESP8266 microcontroller. The system integrates an LDR sensor to monitor ambient light, an LM35 sensor to measure the panel surface temperature, and a DSM501A dust sensor to detect dust levels. These sensors provide real-time data displayed on an LCD and are used to trigger the wiping mechanism when necessary, allowing for precise control andmonitoringof the PV module's performance. The ESP8266 microcontroller manages the sensor data and controls the wiper mechanism while also enabling remote monitoring and control via Blynk Internet of Things (IoT) platform. Powered by a 10W solar panel and a 12V battery, the system is designed for continuous operation, even in low-light conditions. Results obtained showed that the system effectively maintains the cleanliness of the PV panel, ensuring optimal energy production. In addition, the IoT functionality allows for real-time monitoring and remote operation, making it a versatile solution for both small and large-scale solar installations.

Keywords: Bil-Bot, Internet of Things (IoT), PV Module, Sensors.

1. Introduction

Photovoltaic (PV) modules are fundamental in solar energy systems, and their importance cannot be overstated. The PV modules play a vital role in the conversion of solar energy into usable electrical power through the photovoltaic effect [1]. This conversion is the first and most critical step in harnessing solar energy, making PV module essential for any solar power system. In addition, it directly influences the efficiency, reliability, and overall performance of solar power installations [2].However, the performance efficiency of PV modules can be significantly reduced by the partial blockage of sunlight, which occurs when one or multiple cells of the PV module are partially or fully shaded due to dirt or dust particles. Thus, reduces current flow, voltage drop, output power, and overall efficiency of the module [3]. To address this issue, PV Cleaning Systems are essential to improve the performance and reliability of PV modules.

The PV cleaning system is designed to maintain the efficiency and performance of solar panels by ensuring they are free from dirt, dust, and other contaminants that can obstruct sunlight and reduce energy output [4]. Clean PV modules help prevent the build-up of grime that can cause long-term damage or degradation of the panels' surfaces and materials. Also, they operate at optimal efficiencyand produces up to 20% more energy compared to dirty ones [5]. Manual andAutomatedcleaning systems are the two main approaches utilized for PV maintenance. The manual approach involves using brushes, sponges, and cleaning solutions to remove dirt and debris from the surface of the panels with the aid of human intervention. However, it requires manual effort and can be time-consuming. Furthermore, in some cases, it may involve climbing onto rooftops or using ladders, which can be hazardous to human life [6].

In this regard, an automated cleaning system was introduced to address the limitations of the manual approach through the deployment of technology. Performance evaluation of various existing automated cleaning system was presented in [7]. The study evaluated different automated cleaning approaches, including autonomous and track-mounted robots, in various environmental conditions. The study concluded that some automated cleaning systems offer significant advantages in terms of cleaning efficiency, operational time, and labour reduction. However, the high initial costs, maintenance needs, and adaptability issues represent notable challenges. To maximize the benefits of automated cleaning systems, it is essential to address these limitations through continued technological advancements, cost reductions, and improved system designs. Therefore, this study presents a simpleand reliable PV cleaning technology using Bil-Bot Wiping Mechanism to mitigate the effects of partial shading caused by dust or dirt particles.

The proposed Bil-Bot is an automated device equipped with smart sensors, Internet of Things (IoT), and wiping technology to clear dirtor dust particles from the surface of PV modules. By maintaining a clean and unobstructed surface, the Bil-Bot helps to maximize light absorption and minimize performance losses caused by shading. Through a series of experimental evaluations and performance assessments, the authors seek to determine the potential benefits of this technology in enhancing the overall energy output and operational reliability of PV systems. The findings will further contribute valuable insights into optimizing PV module efficiency and advancing the development of more resilient and high-performing solar energy solutions.

2. Related Works

Several studies on PV cleaning systems have explored various existing methods and technologies aimed at optimizing the performance and maintenance of solar panels. While these studies provide valuable insights, they also highlighted some limitations.Given this, an ultrasonic sensor based cleaning system was proposed to remove contaminants from solar panels [8]. The panels were first exposed to dust and organic particles. An ultrasonic transducers and tanks were then used to generate high-frequency sound waves and focus it onto the panel surfacesto create microscopic bubbles. These bubbles implode, creating high-impact forces that displace dirt and contaminants from surfaces. Furthermore, a mild detergent solution was utilized to enhance the cleaning process and ensure effective removal of contaminants. The study was found to be highly effective in removing particulate matter and some organic contaminants from the surface of the solar panels, restoring the panels' light transmission and energy conversion efficiency.Furthermore, the study demonstrated a shorter cleaning time compared to manual methods, with reduced labour requirements. However, in addition to high cost of ultrasonic cleaning equipment and the need for specialized maintenance, it was also observed to be less effective at removing certain types of contaminants, particularly those that are sticky or have adhered strongly to the panel surfaces. Hence,limits its adoption, especially for smaller installations.

Wilson et al. [9] investigated the effectiveness of air blowers in removing dust from solar panels. The study measured the amount of dust removed and found that air blowers could effectively clear a significant portion of surface dust, which is crucial for maintaining solar panel efficiency. In addition, air blowers are advantageous in water-scarce regions as they do not use water. This makes them an environmentally friendly option and reduces operational costs related to water usage. Although, higher pressure and flow rates generally improve dust removal but also increase energy consumption and noise levels. Also, air blowers may be less effective against adhered dirt, and has the potential to redistribute the dust than removed entirely, especially if the air blower is not properly placed.An approach based on brush utilization for PV cleaning system was evaluated and presented in [10]. The authors employed different types of brushes, including soft, medium, and stiff bristles. It was observed that soft brushes are less abrasive and suitable for delicate surfaces, while stiffer brushes are more effective for tougher grime. Despite their effectiveness, brush-based systems can cause abrasion or damage to solar panels due to wear and tear. Hence, results to scratching or degrading the panel surface. Furthermore, frequent replacement of brushes due to wear can lead to higher operational costs.

The efficiency and environmental impact of water based cleaning systems for solar PV panels was presented in [11]. The authors subjected the solar panels to various types and levels of contamination, andemployed different water-based cleaning systems, including high-pressure water jets, spray systems, and automated washing rigs to clean the panels as well as evaluate their performance. The experimental findings obtained showed that the water-based cleaning systems were effective in removing a substantial amount of dirt and contaminants, resulting in a notable increase in the panels' light transmission and electrical output by up to 15-20% compared to dirty panels. However, inappropriate utilization of cleaning agents can damage panels or lead to mineral deposits. In addition, this study may not be suitable in arid regions. Another approach for self-cleaning based on sliding mechanism was presented in [12]. The system comprises features such as automated brushes or high-pressure air nozzles integrated into the sliding mechanism. The sliding mechanism is then controlled by an automated system that adjusts the panel positions based on a pre-set schedule or sensor data. This automation helps in ensuring regular cleaning without manual intervention. Although, the system minimizes the need for manual cleaning, reducing labour and maintenance costs. However, the design and integration of the sliding mechanism and cleaning elements add complexity to the PV system, requiring careful engineering and maintenance.

Johnson et al. [13] evaluated the effectiveness, efficiency, and practicality of semi-automated systems designed for cleaning photovoltaic (PV) panels in large solar farms. The system was designed to be water-efficient, incorporating features such as water recycling, making it suitable for deployment in regions with limited water resources. Although, semi-automated systems generally show good reliability but require regular maintenance to ensure continued performance. Furthermore, the systems may require a balance between manual intervention and automation, leading to complexity in operation and management. In another study, the authors reviewed the development of self-cleaning coatings designed to reduce the need for manual or automated cleaning [14].These coatings offer improved cleaning efficiency, durability, and environmental benefits. However, their high initial costs and the need for further long-term effectiveness studies are notable considerations.

Ahmad et al. [15] implemented an automated system for monitoring and cleaning solar panels at Kaduna Polytechnic in Nigeria, where it was tested under local conditions. The authors employed sensors, brushes and data acquisition modules to continuously monitor the performance of the solar panels. The system operates automatically when dirt or dust accumulation reaches a certain threshold in real-time. Parameters such as voltage, current, and temperature are tracked to assess the operational status and efficiency of the panels. Experimental results demonstrated a significant improvement in solar panel efficiency by reducing dust-related power losses. Hence, improving panel performance and reducing manual intervention. However, integration of monitoring and cleaning components adds complexity to the system, requiring careful design and maintenance.

Overall, while existing studies provide valuable insights into various PV cleaning systems, several limitations remain. These include high initial costs, environmental impacts, maintenance challenges, and varying effectiveness depending on the type of dirt particles and installation conditions. Addressing these limitations through the utilization of the proposed Bil-Bot Wiping Mechanism will be crucial for optimizing PV cleaning systems and improving the efficiency and sustainability of solar energy systems.

3. Materials and Method

This section presents the step by step procedure followed for the realization of the proposed study. This entails the use of solar panels with the following specifications presented in Table 1.

Table 1:Solar panel specifications

Specification	Value
Maximum Power (Pmax)	10W
Open-Circuit Voltage (Voc)	18V
Maximum Power Voltage (Vmp)	15V
Short-Circuit Current (Isc)	0.9A
Maximum Power Current (Imp)	0.67A
Dimensions	30 x 20 cm (12 x 8 inches)
Weight	1 kg
Efficiency	16%

The overall experimental procedure to be followed can be summarized in the flowchart presented in Figure 1. An explanation of each block is presented herewith.

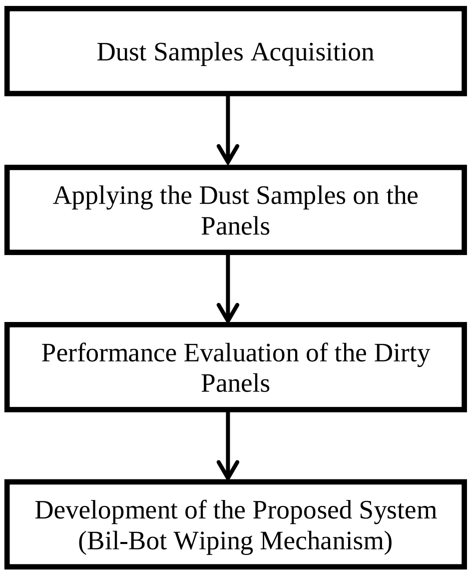


Figure 1:Flowchart of the Proposed Methodology

3.1 Dust Samples Acquisition

Two types of dust samples that are commonly found in our environment were utilizedinthis study, namely; Ashand Sandy soil. These samples are labelled asSample A and Sample B respectively. Figure 2 presents the dust samples acquired.

Sample A Sample B

Figure 2:Dust Samples

3.2 Dust Application

In this study, 10g of Samples A and B each were applied on solar panel separately, so as to determine the effects ofdust accumulation on the performance of the solar panel. This helps in understanding how dust impacts the efficiency of solar panel and how often they might need to be cleaned. Here's a step-by-step procedure carried out on applying the dust samples on the solar panel.

Step 1: The solar panel was thoroughly cleaned before applying the dust samples, in order to ensure accurate testing. A distilled water and soft cloth was used to avoid scratching the panel surface

Step 2: The dust samples were spread evenly across the surface of the solar panel. This was done using a controlled dust-spraying mechanism to ensure consistency.

Step 3: The dusty panel was then exposed to sunlight at its peak hours.

Step 4: The above steps were repeated for each sample

3.3 Performance Evaluation of the Dirty Panels

After applying the dust, the performance of the dusty solar panel was measured as well as recorded in order to compare with that of the cleaned panel based on power output, voltage, current, and efficiency. This evaluation was carried out using Pyranometer and Multimeter. The Pyranometer measures the solar irradiance, providing data on the sunlight hitting the panel before and after dust accumulation, while the Multimeter measures electrical parameters such as voltage, current, and output power in the PV panel to determine the effect of dust on electrical output.

3.4 Bit-Bot Wiping Mechanism

Designing the proposed system involves integrating a Light Dependent Resistor (LDR) sensor, an LM35 temperature sensor, a DSM501A dust sensor, an LCD display, a wiping mechanism, IoT capabilities, and the ESP8266 microcontroller. The goal is to create a system that automatically cleans PV panels based on environmental data. Below is a step-by-step guide followed for the design, including hardware components, and circuit connections.

3.4.1 Hardware Components Selection

Selecting the right hardware components for the Bil-Bot wiping mechanism is crucial for ensuring the system is efficient, reliable, and cost-effective.Below is a detailed selection process for the key components:

(a) ESP8266 Microcontroller

The ESP8266 microcontroller is the central unit that coordinates all activities, processes sensor data, controls the wiping mechanism, and handles IoT communication. The ESP8266 was employed due to its powerful processing capabilities with built-in Wi-Fi for IoT integration, making it ideal for remote monitoring and control.Ithas the following key features;

- Integrated Wi-Fi and Bluetooth
- Multiple GPIO pins
- ADC and DAC support
- Dual-core CPU.

(b) Sensors

The sensors are utilized to collect data on the environmental and operational conditions of the PV panel.An LDR, LM35 temperature sensor, and DSM501A dust sensor were used in the proposed system. The functions and key features of each sensor are presented below.

(1) LDR Sensor

LDRs are simple and effective for detecting changes in light intensity, which is important for determining when the panels may be shaded or covered in dust. Some of the features that make the LDR suitable for this system include wide spectral response, and high sensitivity to light changes.

(2) LM35 Temperature Sensor

The LM35 temperature sensor is easy to use, with an accurate temperature reading directly in Celsius, which is useful for monitoring the operating conditions of the PV panels. Thus, makes it suitable for the system.

(3) DSM501A Dust Sensor

The DSM501A dust sensor was used due to its effectivenessin monitoring air quality and detecting dust levels, which helps in determining when the panels need cleaning.

(c) Wiping Mechanism

The wiping mechanism of the Bil-Bot system is a crucial part of ensuring the cleanliness of PV panels. This unit comprises DC motor, motor driver, wiping blade, and water tank. Below are more detailed components considered for the wiping mechanism:

(1) DC Motor

A 12V DC motor with high torque and low RPM was used to drive the wiper blades across the panel, ensuring thorough cleaning.

(2) Motor Driver

An L298N Dual H-Bridge motor driver was utilized because it can drive two DC motors, supporting up to 46V and 2A per channel. Furthermore, the L298N is a versatile motor driver that can control the direction and speed of the motor, which is critical for the wiping mechanism.

(3) Wiping Blade

A custom wiper blade was locally constructed using silicone rubber, matching the size of the PV panel width. The materials used make the wiping blade durable and effective at removing dust without scratching the surface of the PV panel.

(4) Water Tank

The water is used for the removal of sticky dirt on the surface of the panel. The water spraying is only activated when the ESP senses abnormalities in the output performance of the PV after just been cleaned.

(d) Power Supply

An appropriate and effective power system design is highly required, as it is responsible for powering the entire Bil-Bot system as well as ensuring and efficient and long lasting operation.

(1) Battery Pack

A 12V Li-ion battery pack is a good match for the motor and the ESP8266 (with a voltage regulator for 3.3V), providing a reliable power source. This battery pack will be integrated with the 10W panel, allowing the system to be self-sustaining, especially in remote locationsfor extended periods.

(2) Voltage Regulator

An LM7805 voltage regulator was used in the system to converts higher voltages down to 5V for use with the ESP8266 and sensors, ensuring stable power delivery.

This selection of hardware components provides a balanced approach to creating a reliable and efficient Bil-Bot wiping mechanism. The ESP8266 microcontroller acts as the central hub, integrating sensor data and controlling the motor while also providing IoT capabilities for remote monitoring. The selected sensors offers accurate environmental monitoring, and the motor and driver ensure the wiper mechanism functions smoothly. Furthermore, the power supply, with a solar charging system, supports long-term operation in outdoor environments.

3.4.2 Components Integration

Integrating the hardware components for the Bil-Bot wiping mechanism involves connecting sensors, motors, display, and microcontroller in a way that ensures smooth operation and reliable performance. Below is a step by step procedure followed on integrating the selected hardware components. The

ESP8266microcontroller as the central hub of the entire system was connected to the various units of the Bil-Bot presented herewith.

(a) Sensors Integration with the ESP8266

This section presents how each of the sensors was connected to the microcontroller.

(1) LDR Sensor

One end of the LDR was connected to 3.3V and the other end to a 10kΩ resistor in series to GND. The junction between the LDR and resistor was connected to ananalog input pin on the ESP8266. Figure 3 presents the connection of the LDR sensor with the ESP8266.

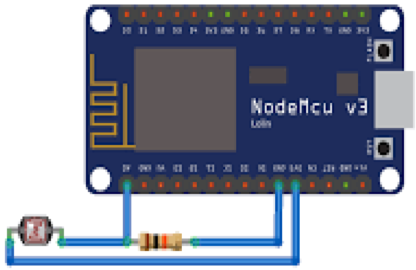


Figure 3: LDR Integration with ESP8266

(2) LM35 Temperature Sensor

The V_{CC} pin of the LM35 was connected to 3.3V, GND to GND, and the V_{OUT} pin to ananalog input pin on the ESP8266.Figure 4 presents the connection of the LM35 sensor with the ESP8266.

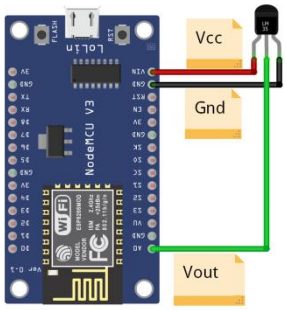


Figure 4: LM35 Integration with ESP8266

(3) DSM501A Dust Sensor

The V_{CC}pin of the sensor was connected to 5V, GND to GND, and the output pin to a digital input pin on the ESP8266. Figure 5 presents the connection of the DSM501A sensor with the ESP8266.

Figure 5: DSM501A Integration with ESP8266

(b) Motor Driver and Wiping Mechanism

This section presents how the DC motor was connected to the L298N motor driver and subsequently to the ESP8266. The L298N's $V_{CC}$was first connected to the battery pack's positive terminal, GND to the negative terminal, and the 5V output to the motor's power input.The IN1 and IN2 pins were then connected toGPIO pinson the ESP8266 for controlling the motor's direction. Finally, the motor terminals were connected to the output pins (OUT1 and OUT2) of the L298N driver.

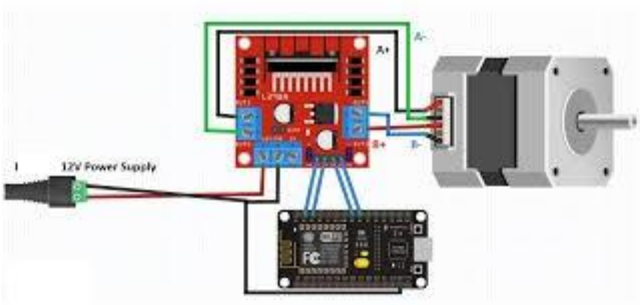


Figure 6: L298N Driver Integration with ESP8266

(c) IoT Integration

The ESP8266's built-in Wi-Fi module was programmed to send data to Blynk IoT platform for remote monitoring. The ESP8266 was programmed to connect to a Wi-Fi network and send sensor data to the Blynk application.

3.4.3 System Enclosure

After integrating all the components together, the system was enclosed in a waterproof casing, protecting the sensitive components from environmental damage. Figure 7 presents the assembled prototype of the Bil-Bot wiping mechanism

Figure 7: Assembled System

4. Experimental Results

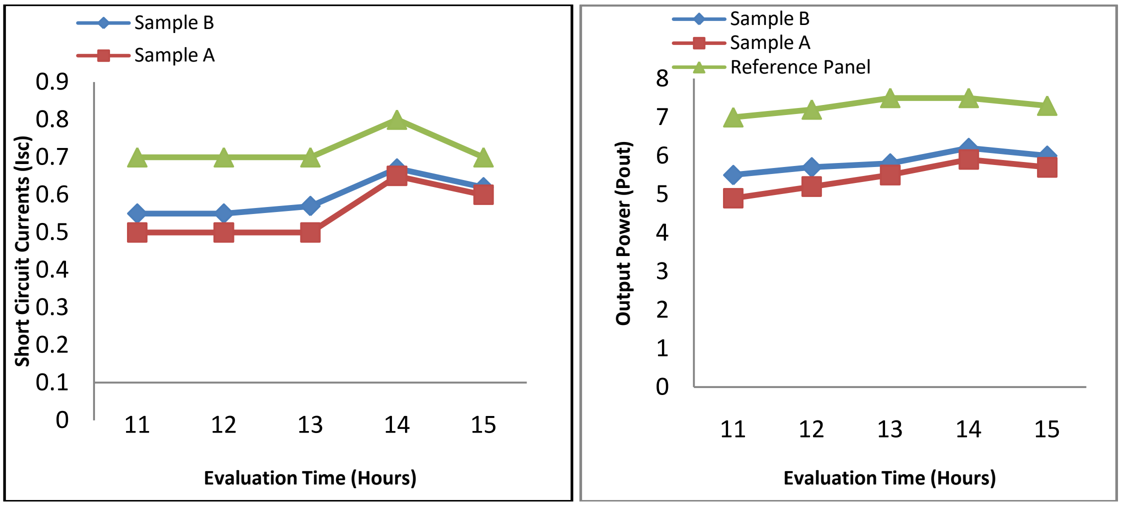
In this section, the experimental resultsobtained after conducting various test are presented. These tests were carried out under peak sun hours of Kaduna state. The peak sun hours in Kaduna state, particularly during the month of August in which this evaluation was conducted, the temperature tends to be relatively mild compared to other months of the year. The average high temperature in August is approximately 27.6°C (81.7°F)**,** with an average low of 21°C (69.8°F), as it experiences the highest rainfall of about 149 mm over 24.9 days.

The performance evaluation test of panels subjected to Samples A and B were first conducted. The results obtained were then recorded and compared with that of a clean panel based on short circuit current and output power. Table 2 presents the results obtained.

Table 2:Performance Evaluation of Dusty Panel

Evaluation Condition			Reference Panel (Clean)		Panel Subjected to:				Percentage Decrement (%)			
					Sample A		Sample B		Sample A		Sample B	
Time (hrs)	Temp. (^oC)	Irrad. (W/m^2)	I_{SC} (A)	P_{OUT} (W)	I_{SC} (A)	P_{OUT} (W)	I_{SC} (A)	P_{OUT} (W)	I_{SC} (A)	P_{OUT} (W)	I_{SC} (A)	P_{OUT} (W)
11	27.0	358	0.7	7.0	0.5	4.9	0.55	5.5	28.5	30.0	21.4	21.4
12	27.3	483	0.7	7.2	0.5	5.2	0.55	5.7	28.5	27.8	21.4	20.8
13	27.5	597	0.7	7.5	0.5	5.5	0.57	5.8	28.5	26.7	18.6	22.7
14	28.0	873	0.8	7.5	0.65	5.9	0.67	6.2	18.7	21.3	16.3	17.3
15	27.6	628	0.7	7.3	0.6	5.7	0.62	6.0	14.3	21.9	11.4	17.8

Table 2 presents the performance evaluation of the 10W panel under the effect of 10g of samples A and B. it can be observed that the percentage decrement of the output power decreases with decrease in the short circuit currents. For 10g of sample A (i.e. Ash), the output power of the panel decreases by 30%, 27.8%, 26.7%, 21.3%, and 21.9% respectively, while the output power of the panel under the effect of 10g of sample B (i.e. Sand) decreases by 21.4%, 20.8%, 22.7%, 17.3%, and 17.8% respectively when compared to the output power of the reference panel. Therefore, it can be concluded that Ash sample affect the output performance of the PV panel more than the Sand sample. Figure 8 shows the effect of the dust samples on I_{SC} and P_{OUT} of the panel.



(a)Iscvs Time for Clean & Dusty Panel (b) P_{OUT}vs Time for Clean & Dusty Panel

Figure 8: Comparative Analysis between Clean and Dusty Panels

Figure 8 presents the comparative analysis between the reference and dusty panels based on I_{SC} and P_{OUT}. To improve the performance efficiency of the dusty panels, the proposed Bil-Bot wiping mechanism was utilized to clean the panels. The cleaning process was conducted at the same peak hours the panel was subjected to the dust samples. After successfully cleaning the dusty panels using the proposed system, measurements were taken and recorded as presented in Table 3.

Table 3: Experimental Results of the Developed Bil-Bot System

Dusty Panels				Developed Bil-Bot Wiping Mechanism				Percentage Improvement (%)			
Sample A		Sample B		Sample A		Sample B		Sample A		Sample B	
I_{SC} (A)	P_{OUT} (W)	I_{SC} (A)	P_{OUT} (W)	I_{SC} (A)	P_{OUT} (W)	I_{SC} (A)	P_{OUT} (W)	I_{SC} (A)	P_{OUT} (W)	I_{SC} (A)	P_{OUT} (W)
0.50	4.9	0.55	5.5	0.65	6.8	0.68	7.0	30	39	24	27
0.50	5.2	0.55	5.7	0.67	6.9	0.69	7.1	34	33	25	25
0.50	5.5	0.57	5.8	0.67	7.2	0.69	7.3	34	31	21	26
0.65	5.9	0.67	6.2	0.75	7.3	0.78	7.5	15	24	16	21
0.60	5.7	0.62	6.0	0.70	7.2	0.70	7.4	17	26	13	23

Table 3 presents the results obtained when the dusty panels are cleaned using the Bil-Bot wiping mechanism. It can be observed that the output power of the panel affected by sample A increases by 39%, 33%, 31%, 24%, and 26% respectively. Also, the output power of the panel affected by sample B was observed to have increase by 27%, 25%, 26%, 21%, and 23% respectively.

5. Conclusion

The Bil-Bot wiping mechanism, integrating various sensors, an ESP8266 microcontroller, and IoT capabilities, proved effective in maintaining the cleanliness and efficiency of a PV panel. The system demonstrated the potential for automated maintenance solutions in solar energy installations, particularly in regions prone to dust and environmental pollutants. The design addresses challenges such as power management, sensor calibration, and environmental durability, offering a scalable and efficient approach to automated PV panel maintenance.With some adjustments and enhancements, this design could be a viable solution for larger solar installations, contributing to increased energy output and reduced manual maintenance efforts.

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