Smart solar maintenance: IoT-enabled automated cleaning for enhanced photovoltaic efficiency

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ABSTRACT

This innovative project aims to increase the effectiveness and user experience of solar panel systems by introducing a state-of-the-art dust and speck removal system. Leveraging cutting-edge technology, the system demonstrates a remarkable 32% increase in power output compared to dirty solar panels. The approach is characterized by its reliance on the universe as the system controller, reducing the need for manual intervention and minimizing the workforce required for panel cleaning. The proposed timed system utilizes water and wipers, facilitated by internet of things (IoT) technology, microcontrollers, and sensor modules for efficient and automated operation. An Android application provides user control and notifications about ongoing processes. The system's adaptability for various settings is emphasized, offering a portable solution. The smart IoT based automatic solar panel cleaning ensures reliable performance, underscoring the project's commitment to improve scalability, cost-efficiency, performance, integrity, and consistency.

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1. INTRODUCTION

The global deployment of photovoltaic arrays has seen a recent surge, with each solar park designed for a 20-25 year lifespan. Maximizing electricity generation is imperative throughout their operational life. Several factors, including ambient conditions, component performance, and intrinsic system characteristics, influence the efficiency of solar photovoltaic modules [1]–[3]. The correlation between energy generation and the amount of accessible sun radiation and spectrum content is crucial. However, dust buildup and other debris on PV panels poses a challenge, as traditional cleaning methods with commercial detergents are inefficient and can potentially damage the panels. This issue is particularly pronounced in large ground-based solar arrays, such as those comprising up to 22,000 panels, necessitating the implementation of automated cleaning systems covering expansive areas [4]–[7].

In many developing countries, electricity generation is a critical concern, driven by the growing demands of the manufacturing and retail sectors. To address this, there is a pressing need to promote the adoption of renewable energy sources like solar photovoltaic. This method is gaining popularity due to its widespread availability, affordability, ease of installation, and minimal maintenance requirements [8]–[11].

The internet of things (IoT) emerges as a transformative technology, enhancing the functionality of everyday objects by networking them through a common protocol and utilizing cloud-based storage and processing systems. Real-time solar monitoring systems, enabled by IoT, become essential in optimizing PV panel performance. Monitoring parameters such as PV voltage, temperature, and humidity in real-time allows for data-driven decision-making and proactive measures to maintain peak efficiency, contributing to the long-term reduction of harmful emissions and the preservation of the ozone layer [12], [13].

Several studies have focused on developing and enhancing automated cleaning systems for solar panels to address efficiency challenges caused by dust accumulation. Mondal *et al.* [14] provided an overview of dust-related challenges and recent developments in automated cleaning systems, including electrical, mechanical, chemical, and electrostatic techniques. Habib *et al.* [15] proposed a system consisting of an light dependent resistors (LDR) sensor, wiper unit, and sprayer for detecting and cleaning dust on solar panels. In a study by Manju *et al.* [16], an Arduino-controlled cleaning system was designed to remove dust from solar PV modules, particularly relevant in dusty environments like those in tropical countries. The system aimed to improve power efficiency by preventing up to a 50% reduction in power output if panels were not cleaned monthly [17]. Khadka *et al.* [18] presented a smart solar photovoltaic panel cleaning system featuring a cleaning robot and cloud interface. The researchers developed an automated solar panel cleaning system using IoT, providing transparency and control through a mobile application. This system demonstrated a 32% increase in energy output compared to dusty solar panels, offering a cost-effective and scalable solution with reduced manpower requirements [19]. Integration with IoT applications allows for real-time monitoring and activation of cleaning instructions when needed, reducing external impedance and enhancing solar panel performance by up to 22% [20]. Malhan *et al.* [21] presented a flexible cleaning system that travels the length of solar panels. This system not only removes debris but also monitors electrical power generation. Derakhshandeh *et al.* [22] conducted a thorough investigation. of existing automatic cleaning systems, categorizing them into active and passive types. The efficiency of the solar panel was affected by dust particles, and the proposed system aimed to maintain optimal power generation even in dusty environments.

The system included sensors for monitoring and predicting the suitable time for cleaning actions, offering a potential solution for large-scale solar farms. Overall, these studies emphasize the importance of automated cleaning systems in maintaining the efficiency of solar panels, particularly in regions with challenging environmental conditions. The integration of IoT and advanced technologies further enhances the monitoring and effectiveness of these systems [23]–[25].

2. METHOD

In the development of virtually implemented solar panels, the project employs a sophisticated system designed to monitor and optimize the performance of each panel array. The hardware components chosen for this purpose include voltage sensors and temperature sensors. The integration of a DHT11 sensor further enhances the system's capabilities by providing precise temperature and humidity measurements in the surrounding environment, allowing for more comprehensive data analysis. These sensors are instrumental in ascertaining the quantity of voltage and current generated by specific types of solar panels. To facilitate data acquisition and processing, software programmers employ languages supported by the Arduino integrated development environment, such as C and C++, with the resulting code uploaded onto the ESP32 microcontroller featuring integrated Wi-Fi. This enables the transmission of data to cloud storage, emphasizing the integration of the IoT in solar power plant management.

Figure 1 shows the Block diagram of IoT based solar panel cleaning system. A pivotal feature of the solar panel system involves the incorporation of two LDRs strategically positioned on the panel periphery. These LDRs play a crucial role in the solar tracker's operation, optimizing the panel's orientation to maximize exposure to sunlight throughout the day. The Arduino, programmed in C, acts as the controller for the stepper motor, adjusting the solar panel based on information received from the LDRs. Moreover, the system includes a water pump under Arduino control, facilitating the dispersion of water onto the solar panel that generates enough pressure to clear its surface. The primary objective is to achieve maximum solar exposure, with the resultant power output stored in a 12-volt DC battery. The LDRs play a dual role in detecting and measuring solar irradiance, ensuring optimal orientation for solar tracking and helping the solar tracker capture the highest intensity of available sunlight. The on/off control of the water pump, integrated into the system, contributes to the cleaning process, removing dirt and dust particles and maintaining the efficiency of the solar panels. In essence, this solar panel system leverages cutting-edge technology, including IoT connectivity, sensors, and a solar tracker, to create a comprehensive and automated solution. By seamlessly integrating hardware and software components, the system not only monitors and optimizes solar panel performance but also ensures the efficient cleaning of panels, ultimately maximizing the overall efficiency of solar energy capture.

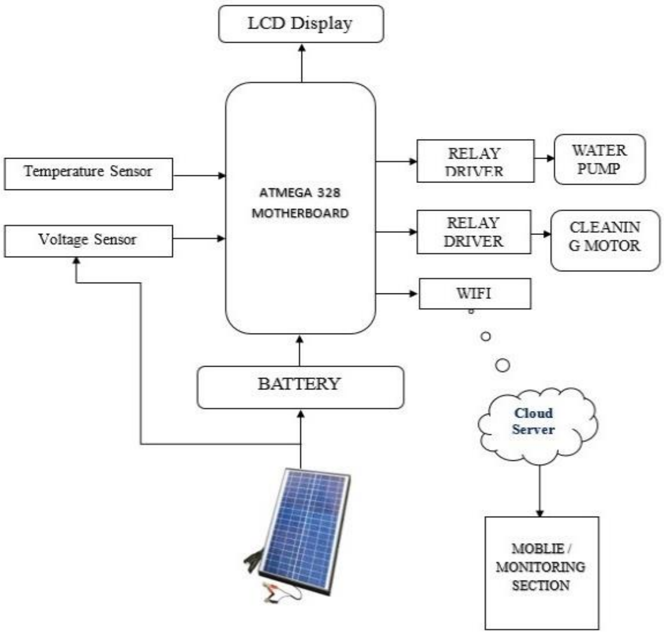

Figure 1. Block diagram of IoT based solar panel cleaning system

3. RESULTS AND DISCUSSION

Figure 2 shows the circuit diagram of IoT based solar panel cleaning system. The collected data is systematically presented in Table 1, encapsulating the measured parameters, while Table 2 compiles the computed power and efficiencies derived from the measured voltage and current. Figure 3 shows the protype model of proposed method and the visual representation of these findings is depicted in Figure 4, illustrating the current versus voltage (I-V) characteristics of the solar panel in undusted, dusty, and cleaned conditions. Notably, the data in Table 1 reveals a significant reduction in current by almost 20% when the solar panel is covered by dust, leading to a linear decrease in real power. The subsequent cleaning process, executed by the developed robot, results in a nearly 20% increase in current, as evidenced in Table 1 and Figure 4. Figure 5 visually demonstrates the enhanced efficiency of the solar panel post-cleaning.

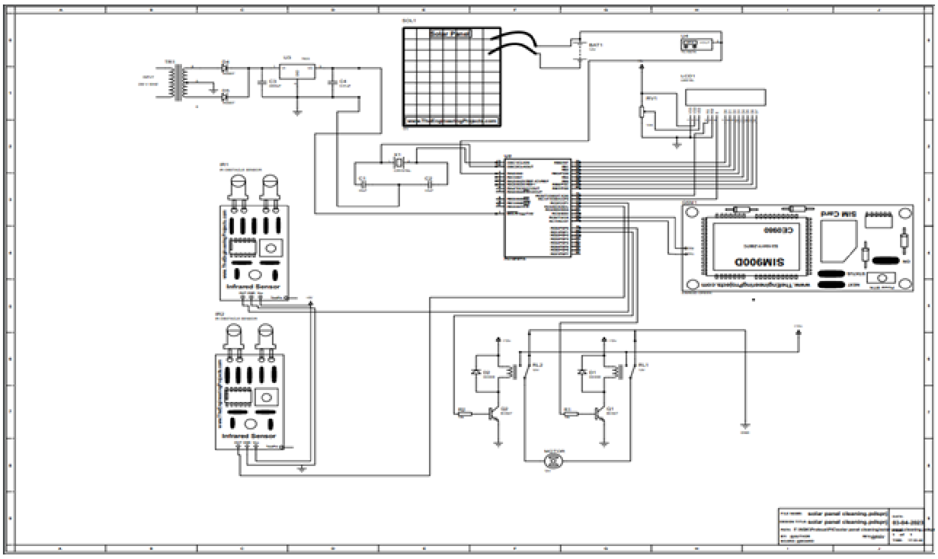

Figure 2. Circuit diagram of IoT based solar panel cleaning system

Table 1. Measured voltage and current of tested solar panel

Time	Before dust		During dust		After cleaning	
	Voltage (v)	Current (A)	Voltage (v)	Current (A)	Voltage (v)	Current (A)
11.00 AM	17.80	4.80	14.24	3.84	17.44	4.70
12.00 PM	18.80	4.82	15.04	3.85	18.42	4.72
01.00 PM	18.00	4.70	14.04	3.76	17.64	4.60
02.00 PM	17.10	4.60	13.68	3.68	16.75	4.50

Table 2. Calculated real power and efficiency of tested solar panel

Time	Before dust		During dust		After dust	
	Voltage (v)	Current (A)	Voltage (v)	Current (A)	Voltage (v)	Current (A)
11.00 AM	17.80	4.80	14.24	3.84	17.44	4.70
12.00 PM	18.80	4.82	15.04	3.85	18.42	4.72
01.00 PM	18.00	4.70	14.04	3.76	17.64	4.60
02.00 PM	17.10	4.60	13.68	3.68	16.75	4.50

Figure 3. Protype model of proposed method

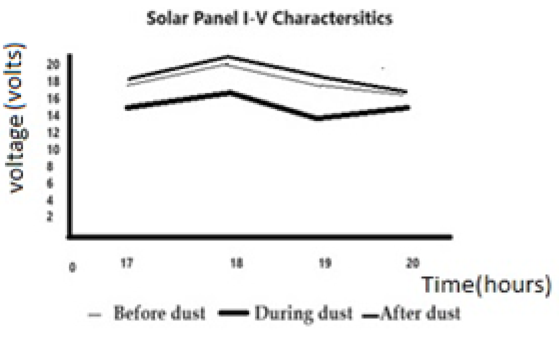

Figure 4. Solar panel V-I characteristics

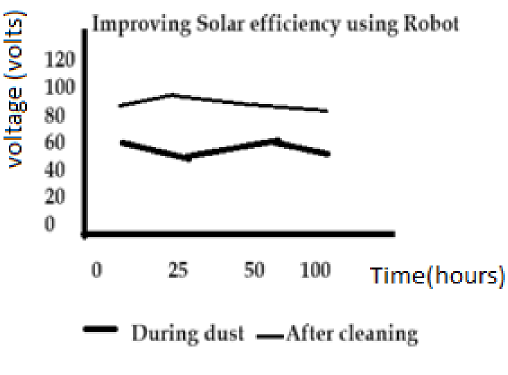

Figure 5. Improved efficiency of solar panel system

The solar panel under examination is a 180 W 36-cell 12 V nominal solar panel, boasting specifications such as a maximum power output of 180 watts and a maximum voltage of 18.95 volts. The robust experimental data, provided in Tables 1 and 2, clearly showcases the impact of dust accumulation on the solar panel's performance and the subsequent improvement achieved through the developed robot-assisted cleaning process. These findings underscore thepractical significance of employing innovative cleaning solutions to maximize the efficiency and overall output of solar energy systems.

4. CONCLUSION

In conclusion, the comprehensive evaluation of a 180 W 36-cell 12 V solar panel revealed significant insights into the impact of dust accumulation on its performance and the effectiveness of a developed robot-assisted cleaning process. The measured data, meticulously presented a notable decrease in current by approximately 20% when the solar panel was covered with dust, leading to a linear reduction in real power. The subsequent implementation of the robotic cleaning system proved highly effective, restoring the current almost by 20% and showcasing an improved efficiency. These findings underscore the critical role of regular cleaning in maintaining optimal solar panel efficiency. The developed robot not only successfully addressed the negative impact of dust accumulation but also showcased its potential to enhance the overall performance of solar energy systems. This study provides valuable insights for the solar energy industry, emphasizing the importance of proactive maintenance measures to ensure sustained efficiency and power output. As solar energy continues to be a crucial player in renewable energy sources, innovations such as robotic cleaning solutions contribute to the reliability and long-term viability of solar panel installations.

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