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SMART EFFICIENCY ENHANCEMENT OF SOLAR PANELS USING AUTOMATED CLEANING MECHANISM

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ABSTRACT

Dust accumulation on photovoltaic (PV) modules significantly reduces their electrical output and long-term operational efficiency. To address this issue, this work presents a smart automated water-based cleaning system for improving the performance of solar panels under varying environmental conditions. The proposed design integrates an Arduino-based control unit, a relay-driven water pump and wiper motor mechanism, and real-time voltage monitoring using sensor modules. The system periodically activates the cleaning process by spraying water and wiping the panel surface to remove dust, thereby restoring light transmittance and enhancing voltage generation. A regulated power supply is incorporated to ensure stable operation of the control electronics and cleaning actuators. Experimental observations confirm that the automated cleaning method results in a noticeable increase in panel voltage output compared to uncleaned modules exposed to identical irradiation. The study demonstrates that the presented solution is cost-effective, technically feasible, and suitable for small-scale solar installations, offering improved energy harvesting efficiency and reduced manual maintenance requirements.

KEYWORDS: Solar Panel Cleaning, Arduino, Automated Water Spray System, Efficiency Enhancement, Voltage Monitoring

INTRODUCTION

Solar energy is one of the most abundant, clean, and freely available sources of renewable power. Unlike wind, hydel, or biomass systems - which require high installation costs, specific geographic conditions, and continuous maintenance - solar energy can be harnessed easily with minimal operational expense. This makes photovoltaic (PV) technology one of the most practical and scalable solutions for sustainable electricity generation. However, despite its advantages, the performance of solar panels is highly affected by environmental factors, especially dust accumulation on the panel surface. Dust forms an opaque layer over the glass, blocking sunlight and significantly reducing the voltage output and overall energy conversion efficiency. To study and overcome this problem, the proposed system compares the output of two identical solar panels. Solar Panel 1 is kept clean and serves as a reference panel, representing the maximum possible voltage under the available sunlight. Solar Panel 2, exposed to natural dust deposition, produces a comparatively lower voltage when dust builds up. An Arduino-based monitoring unit continuously measures the voltages from both panels. When the voltage of Panel 2 drops notably below that of the clean reference panel, the system identifies this as an efficiency loss due to dust. To restore performance, an automated cleaning mechanism is activated. This mechanism uses a water-spray pump and a wiper motor to wash and wipe the dusty panel surface. Once cleaned, the panel is allowed to dry, and the voltage is again compared to ensure that efficiency has been recovered. This

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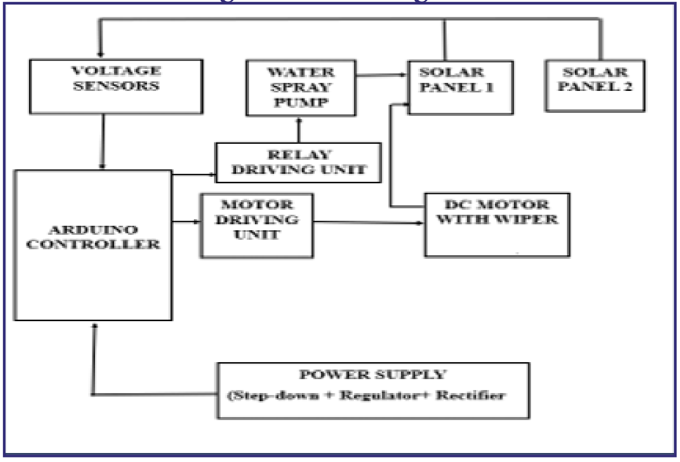
automated method reduces manual effort, maintains consistent power output, and ensures that solar energy can be harnessed effectively without frequent human intervention.

1. LITERATURE SURVEY

The paper proposes an IoT-enabled autonomous robot for cleaning dust from solar panels. It uses sensors and real-time data to detect dust accumulation and schedule cleaning automatically. Remote monitoring through IoT helps maintain consistent panel performance and improve energy efficiency [1]. The paper proposes a time-scheduled automated cleaning system for solar panels using a brush-based robotic mechanism. The system periodically removes dust accumulation from the panel surface, reducing soiling losses. Experimental results show a noticeable improvement in solar panel efficiency and power output after cleaning [2]. This study examines the effect of dust (soil) accumulation on photovoltaic panel performance. Laboratory experiments show that increasing dust levels significantly reduce power output and efficiency [3]. The paper explains that cooling solar panels reduces temperature and increases efficiency. Among different methods, water cooling gives better performance than air cooling, leading to higher power output. [4]. This paper studies the effect of temperature and dust on solar panel performance. It shows that higher temperatures reduce efficiency and power output. Dust accumulation blocks sunlight and further decreases performance. The study highlights the importance of cooling and regular cleaning [5]. This paper experimentally studies how aging factors such as dust, discoloration, delamination, and cracks affect the output power of photovoltaic modules. The results show that aging significantly reduces PV performance, while cleaning can partially restore power output [6].

2. METHODOLOGY

Fig. 1: Block Diagram



1. Solar Panel (6V, 3W DC): The solar panel is the primary power source of the system. It converts sunlight into direct current (DC) electricity, which not only powers the entire project but also provides the voltage data that indicates the panel's efficiency. Any reduction in voltage due to dust or debris signals the need for cleaning, making the solar panel both the energy source and the monitored element in the system.
2. Voltage Sensor (0–25V DC): The voltage sensor is used to continuously monitor the output of the solar panel. It measures the DC voltage and sends the readings to the Arduino controller. When the voltage drops below a certain threshold, it indicates that dust or dirt is reducing the panel's efficiency, prompting the Arduino to initiate the cleaning process.
3. Arduino Controller (5V DC): The Arduino acts as the brain of the project. It receives voltage readings from the sensor, processes the data, and makes decisions about when to start the cleaning process. The Arduino also controls the movement of the servo motor, turns the water pump ON or OFF via the relay, and provides signals to LEDs for visual indications, ensuring the system operates automatically and efficiently.
4. Servo Motor (5V DC): The servo motor is responsible for moving the cleaning mechanism across the surface of the solar panel. It allows precise angular control, ensuring that the brush or spray arm covers the entire panel evenly. This ensures that all dust and debris are removed, helping the panel maintain its maximum efficiency.
5. Water Pump (5V, 0.15A): The water pump sprays

water onto the solar panel during the cleaning operation. It is controlled by the Arduino through the relay and operates only when cleaning is required. Its proper functioning is crucial to remove stubborn dust and dirt, ensuring the panel is clean without wasting excessive water.

6. Electromagnetic Relay (5V, 10A): The relay acts as a switch to control high-power devices like the water pump using the low-power signal from the Arduino. It allows the Arduino to safely turn the pump ON and OFF without drawing high current directly, protecting the controller and other sensitive components.
7. Transistor (100mA): The transistor functions as an electronic switch or amplifier in the circuit. It controls the flow of current to the relay or motor, allowing the Arduino to handle devices that require more current than it can supply directly. This ensures safe operation of higher-power components.
8. Diode (1A, 1000V): The diode protects the system from back EMF generated by the relay or motor. It allows current to flow in only one direction and prevents voltage spikes from damaging sensitive components like the Arduino, ensuring long-term reliability of the system.
9. LED (5mm, 5V): LEDs provide a simple visual indication of the system status. They can show whether the system is ON, whether cleaning is in progress, or alert the user to any faults. This helps in monitoring and troubleshooting the system easily.
10. Step-Down Transformer (230V AC to 9V AC, 500–750mA): The transformer reduces high-voltage AC mains supply to a lower AC voltage suitable for rectification and conversion to DC. This ensures the system receives a safe and manageable voltage for powering the Arduino and other DC components.
11. Filter Capacitor (1000µF, 25V): The filter capacitor smooths out ripples in the rectified DC voltage, providing a stable and clean DC output. This is important for ensuring that the voltage regulator and Arduino receive consistent power, preventing malfunction or erratic behaviour of the system.
12. Voltage Regulator (7805): The 7805voltage regulator provides a constant 5V DC output regardless of variations in input voltage. It powers the Arduino, sensors, and other 5V components, ensuring stable operation of the system and protecting sensitive electronics from voltage fluctuations.

Fig. 2: Circuit Diagram

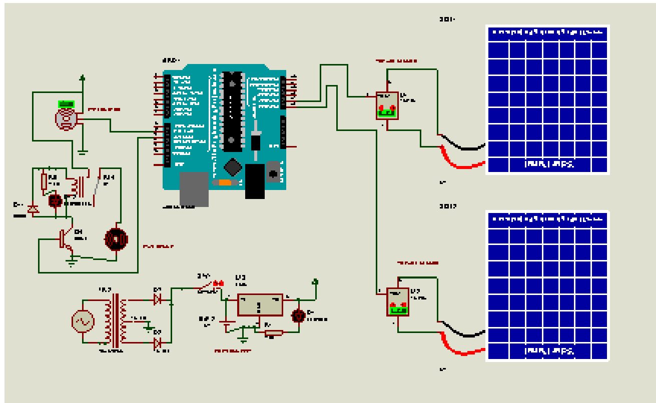
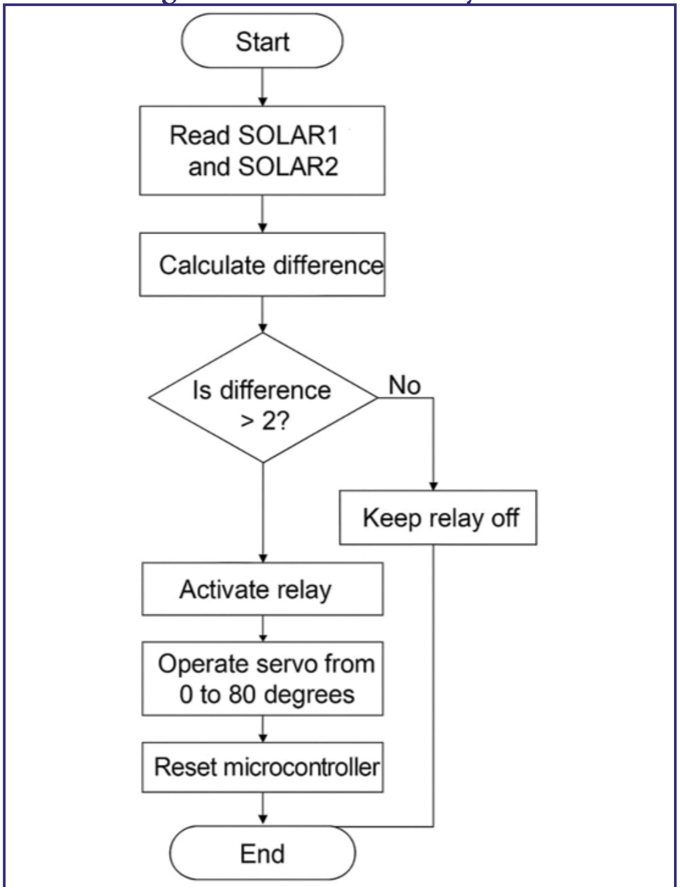


Fig. 3: Flowchart of the System



3. RESULTS AND DISCUSSION

Fig. 4: Prototype

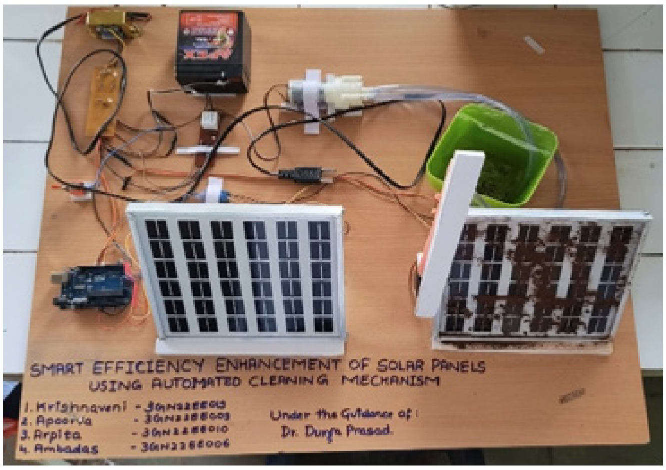


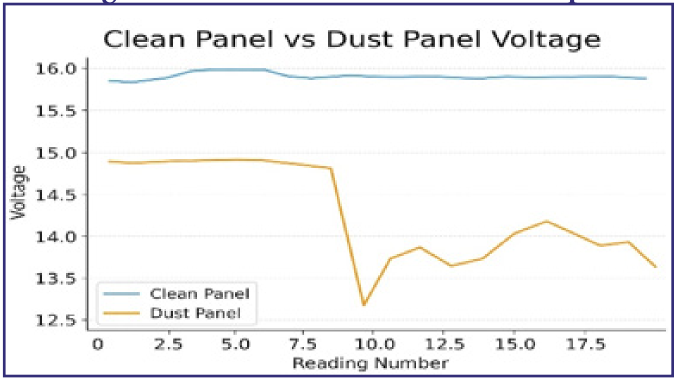
Table 5.1: Voltage Readings of Clean Panel and Dust Panel

Reading No.	CleanPanel Voltage (V)	DustPanel Voltage(V)	Voltage Difference(V)
1	16.21	14.7	1.51
2	16.11	14.67	1.44
3	16.21	14.7	1.51
4	16.24	14.72	1.51
5	16.21	14.72	1.49
6	16.21	14.75	1.46
7	16.21	14.72	1.49
8	16.21	14.67	1.54
9	16.11	14.62	1.49
10	16.19	12.60	3.59
11	16.11	13.40	2.71
12	16.14	13.50	2.64
13	16.16	13.35	2.81
14	16.14	13.43	2.73
15	16.16	13.7	2.47
16	16.14	13.75	2.39
17	16.14	13.6	2.54
18	16.16	13.65	2.51

- Voltage measurements were recorded for clean and dust-covered solar panels under identical environmental conditions.
- The clean panel consistently delivers a stable voltage in the range of 16.11–16.24 V.
- The dust-covered panel shows reduced voltage output, varying between 12.60–14.7V.
- The observed voltage difference ranges from 1.44 V to 3.59V, indicating a significant performance degradation due to dust accumulation.

Clean Panel vs Dust Panel Graph

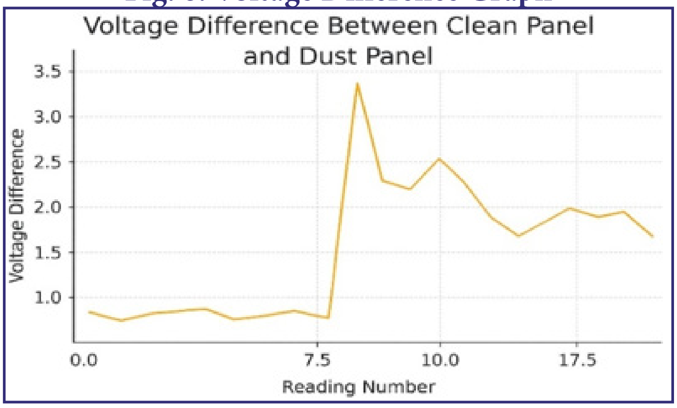
Fig. 5: Clean Panel vs Dust Panel Graph



- The clean panel voltage curve remains nearly constant around 15.8–16.2 V, demonstrating stable and efficient operation.
- The dust panel voltage curve remains consistently lower and exhibits higher fluctuations.
- A sharp voltage drop is observed at reading 8–9, where the dust panel voltage decreases to approximately 12.7 V.
- Even after partial recovery (≈ 13.8–14.0 V), the dust panel output never reaches the clean panel voltage.
- The maximum voltage difference (~3.4–3.6 V) occurs at the point of sudden dust accumulation.

Voltage Difference Graph

Fig. 6: Voltage Difference Graph



- Voltage difference shows dusty panel output drop compared to clean panel.
- Initially, difference is small due to equal sunlight.
- Dust causes sharp voltage drop, increasing the difference.
- Maximum difference occurs when dust is applied.
- Difference then moderates but stays above initial

values.
- Confirms dust reduces solar panel efficiency.

4. CONCLUSION

The project "Smart Efficiency Enhancement of Solar Panels" effectively improves solar panel performance by addressing dust accumulation and heat-related losses through automated monitoring and cleaning. The system maintains higher and more stable voltage output compared to dusty panels, proving that automation enhances energy generation while reducing manual effort and maintenance. Its simple, low-cost design using readily available components makes it reliable, scalable, and suitable for residential, commercial, and large-scale solar applications, contributing to sustainable and efficient solar energy utilization.

5. FUTURE SCOPE

In the future, the system can be miniaturized and made more cost-effective for easier installation and wider adoption. Integration of IoT and AI can enable remote monitoring, intelligent cleaning schedules, predictive maintenance, and multi-service features such as temperature control and performance diagnostics, further improving solar panel efficiency and system intelligence.

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