INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN SCIENCE AND ENGINEERING, VOL.6., NO.04., APRIL 2025.

Electrostatic Precipitation for Solar Panel Optimization

Devananda V S[1], Mellow Elizabeth Reji[1], Muhammed Isham[1], Nithin K S[1], Veena Mathew[2], Mohitha Thomas[3]

[1]*Student, Department of Electrical and Electronics Engineering, Mar Athanasius College of Engineering, Kerala, India*
[2]*Associate Professor, Department of Electrical and Electronics Engineering, Mar Athanasius College of Engineering, Kerala, India*
[3]*Professor, Department of Electrical and Electronics Engineering, Mar Athanasius College of Engineering, Kerala, India*
Corresponding Author: devanandavs02@gmail.com

***Abstract*: Solar energy is a vital component of sustainable energy solutions, offering a renewable and eco-friendly alternative to fossil fuels. However, the efficiency of solar panels is significantly affected by dust accumulation, commonly referred to as soiling, which can reduce energy output by up to 40 This paper proposes an innovative, waterless dust removal system utilizing electrostatic forces to enhance the performance and durability of solar panels. The system operates by generating a high-voltage electrostatic field that induces charge in dust particles. These charged particles are then repelled and dislodged from the panel surface using two vertically spaced electrodes—one transparent and fixed, and the other a moving non-transparent electrode. By eliminating direct contact with the solar panels, this approach significantly reduces wear and extends the lifespan of the panels. Moreover, the system does not rely on water, making it particularly advantageous in arid and water-scarce regions. Unlike traditional mechanical systems, the electrostatic method is energy-efficient and minimizes maintenance costs over time. The proposed system offers a transformative solution for maintaining solar panel efficiency and longevity, providing a sustainable, cost-effective, and scalable alternative to existing cleaning technologies. Future work will focus on optimizing power consumption, improving system robustness, and assessing large-scale implementation for commercial solar farms.**

***Keywords*: Solar Panel Efficiency, Sustainable Energy, High voltage, Electrostatic Dust Removal, Water less cleaning.**

1. Introduction

HE rising global demand for electricity has increased dependence on non-renewable energy sources like coal and natural gas, leading to severe environmental consequences. Fossil fuel combustion releases greenhouse gases (GHGs), with fossil fuels contributing to approximately 80% of global CO emissions in 2022 [1]. This has accelerated the transition towards renewable energy sources, with solar power emerging as a key solution. The global share of renewable energy in electricity production rose from 20% to 28% between 2011 and 2021, with solar energy showing the highest growth. India, for instance, generated 46.3% of its electricity from renewables in 2024 and aims to reach 500 GW of renewable capacity by 2030 [2].

Despite its advantages, solar energy faces efficiency challenges, primarily due to soiling, where dust accumulation on photovoltaic (PV) panels reduce energy output by up to 21.57% [3]. Conventional cleaning methods, including manual and automated water-based cleaning, are labor-intensive, water-consuming, and may damage panels over time. Although robotic cleaning systems offer some improvements, they remain costly and mechanically intrusive.

This work proposes an electrostatic dust removal system that utilizes Coulomb's force to dislodge dust particles without physical contact. The system employs a high-voltage field across two vertically spaced electrodes to charge and remove dust, eliminating water use and minimizing panel wear. With negligible power consumption, this approach offers a sustainable, efficient, and non-invasive alternative for maintaining PV performance, making it ideal for large-scale industrial solar farms.

2. Existing Technologies

1) *Manual Cleaning*: Manual cleaning is a simple and cost-effective solution, particularly for small-scale solar installations. Since it does not require any additional power source, it remains a widely used method for maintaining solar panel efficiency. However, this approach has several drawbacks. It is labor intensive and impractical for large solar farms and requires significant efforts from the workforce. In addition, frequent physical scrubbing can cause panel damage over time, reducing their longevity. Another major disadvantage is its high-water consumption, which makes it unsuitable for regions facing water scarcity.
2) *Robotic Cleaning*: Robotic cleaning offers an automated solution that significantly reduces labor costs while improving efficiency, particularly for large-scale solar installations. These systems can be programmed to clean panels systematically, ensuring consistent maintenance. Despite these advantages, robotic cleaning comes with notable limitations. The initial investment and maintenance costs are considerably high, making it a less viable option for small businesses or residential setups. In addition, robotic cleaning systems still involve some mechanical contact with the surface of the panel, which can lead to gradual wear and tear. In addition, these systems may

require additional power for their operation, which can affect the overall energy efficiency of the solar setup.

3) *Waterless Brrush Cleaning*: Waterless brush cleaning is an effective alternative to traditional water-based methods, significantly reducing water consumption. This method can also be automated, making it suitable for large-scale solar farms. However, there are some drawbacks to consider. The physical brushes used in this method may cause gradual wear and tear on the panels, potentially leading to a loss of long-term efficiency. In addition, regular maintenance of the brushes is required to ensure that they remain effective, increasing operational costs and complexity.

Given the limitations of traditional cleaning methods, the need for a contactless and waterless alternative has become evident. The proposed electrostatic dust removal system addresses these challenges by utilizing an electrostatic field to repel dust particles without mechanical contact. This method not only preserves the integrity of the panel, but also eliminates the need for water, making it a viable solution for arid regions.

The proposed electrostatic dust removal system presents a revolutionary, contactless approach to cleaning solar panels. By utilizing an electrostatic field to repel dust particles, this method eliminates physical contact, reducing the risk of panel degradation. One of its most significant advantages is the absence of water usage, making it an ideal choice for dry and arid environments. Additionally, the system is energy-efficient, minimizing operational costs over time. However, there are some challenges associated with its implementation. The system requires high-voltage components, which may pose safety concerns if not properly managed. Furthermore, the initial setup cost can be higher compared to manual cleaning methods, potentially limiting its adoption for smaller-scale installations.

3. Objective

The primary objective is to develop an efficient and non-invasive method for removing a substantial percentage of dust and sand particles from the surface of a Photovoltaic (PV) panel. The accumulation of dust on PV panels significantly reduces their efficiency by obstructing sunlight and lowering energy conversion rates. Therefore, this work focuses on designing a cleaning system that ensures minimal to no direct contact between the PV panel surface and the cleaning mechanism, thereby preventing physical damage such as scratches and eliminating the need for water-based cleaning methods.

To achieve this, three key aspects are addressed. Firstly, a high-voltage power source will be constructed to facilitate dust removal using electrostatic or electromagnetic principles. Secondly, a system will be developed to effectively extract and repel dust and sand particles from the surface of the solar panel, thereby maintaining optimal energy generation efficiency. Lastly, an integrated monitoring system will be designed to measure essential environmental parameters such as temperature and humidity, providing real-time data that can aid in optimizing the panel's performance and assessing the impact of environmental conditions on dust accumulation.

By addressing these objectives, this study aims to contribute to the advancement of sustainable and maintenance-free solar energy solutions, particularly in arid and dusty environments where frequent manual cleaning is impractical and water resources are scarce.

4. System Architecture and Working Principle

The contactless dust removal system for solar panels utilizes electrostatic cleaning combined with precise linear movement to maintain panel efficiency without physical contact. The system comprises a high-voltage power source, a linear guide actuator, a sensing unit, and a measuring unit, each playing a crucial role in the cleaning process.

The sensing unit, responsible for detecting dust accumulation, consists of a Light Dependent Resistor (LDR) Module and a Laser Module. The LDR monitors the light intensity falling on the panel surface, where a reduction in detected light due to dust accumulation signals the need for cleaning. The Laser Module enhances detection accuracy by scattering light in the presence of dust, aiding in precise monitoring.

The high-voltage power source, essential for electrostatic dust removal, includes a Flyback Transformer and Driver Circuitry. The microcontroller regulates the high-voltage circuit as needed. When activated, the Flyback Transformer steps up the voltage to generate an electrostatic field, which is applied to an electrode on the Transparent Conductive Surface of the solar panel. This field lifts dust particles off the surface without abrasion or water usage.

The measuring unit provides real-time environmental data to optimize the cleaning process. It includes a Humidity Sensor, which monitors ambient humidity levels that may affect electrostatic cleaning efficiency, and an LCD screen that displays critical parameters such as humidity and light intensity for user monitoring and troubleshooting.

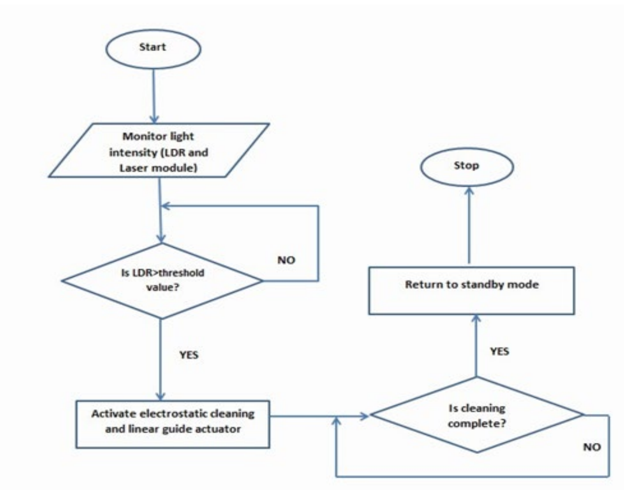

Fig. 1. Flow chart of the contactless dust removal system

The linear guide actuator ensures thorough cleaning by precisely moving the electrostatic cleaning mechanism across the panel surface. A servo motor, controlled by the microcontroller, drives the actuator, converting rotational motion into linear displacement. The servo motor allows for precise control over the actuator's position, ensuring effective and uniform dust removal across the panel.

The system operates in a structured sequence: the sensing unit detects dust accumulation by monitoring light levels. When the detected intensity falls below a preset threshold, the microcontroller activates the high-voltage source, generating an electrostatic field to lift dust from the panel. Simultane- ously, the servo motor moves the actuator to ensure uniform coverage. The LCD screen continuously displays key readings, providing real-time feedback for easy monitoring.

5. Design Concept and Criteria

The contactless dust removal system for solar panels integrates an electrostatic cleaning mechanism with a linear guide actuator for precise movement. This design prevents physical abrasion, minimizes maintenance requirements, and enhances the efficiency and lifespan of solar panels. The system relies on a high-voltage source to generate an electrostatic field that lifts and repels dust particles without direct contact.

A. High-Voltage Generation for Electrostatic Cleaning

A crucial component of the system is the high-voltage power source, which generates the electrostatic force required for dust removal. Several methods were considered, including the Cockcroft-Walton multiplier, ignition coils, magnetic leakage transformers, Marx generators, and flyback transformers. The voltage source needed to meet key criteria:

i. Stable High-Voltage Output – Maintain voltage between 10kV and 50kV.
ii. Thermal Management – Operate continuously without overheating.
iii. Cost and Portability – Be cost-effective and lightweight for practical implementation. After evaluating these factors, a flyback transformer (BSC25-1010A) was selected due to its ability to deliver a consistent high-voltage output while ensuring efficiency and portability. The design calculations for the high-voltage generation are based on this transformer's specifications.

Assume:

- Inductance, $L = 1$ mH
- Switching frequency, $f_s = 12$ kHz
- Current across resistor, $I_r = 1$ mA

The analysis provides insights into the design and operation of a high-voltage step-up converter with an assumed output of 10 kV.

$$\text{Turns Ratio} = \frac{V_s}{V_p} = \frac{10000}{5} = 2000 \qquad (1)$$

$$\text{Duty cycle} = \frac{D}{1-D} = \frac{V_o \cdot N_p}{V_{in} \cdot N_s} = \frac{10000 \cdot 2000}{5} = 1 \qquad (1)$$

Solving for D:

$$D = 0.5 \qquad (2)$$

$$\text{Resistance, } R = \frac{V_{out}}{I_{out}} = \frac{10000}{1 \times 10^{-3}} = 10\,\text{M}\Omega \qquad (3)$$

Assuming the energy stored across the capacitor, $E = 1$ mJ.

$$\text{Capacitance, } C = \frac{2 \cdot E}{V_{out}^2 \cdot \text{ripple}} = \frac{2 \cdot 1 \times 10^{-3}}{(1 \times 10^3)^2 \cdot 0.05} = 4\,\text{nF} \qquad (4)$$

$$\text{Primary current, } I_p = \frac{V_{in} \cdot D}{L_p \cdot f_s} = \frac{5 \cdot 0.5}{1 \times 10^{-3} \cdot 12 \times 10^3} = 0.05\,\text{A} \qquad (5)$$

The calculated duty cycle ensures efficient energy transfer, maintaining stable operation at the given switching frequency. The high output resistance supports low current flow, ensuring controlled power delivery. The required capacitance is determined to maintain voltage stability while minimizing ripple effects. Additionally, the primary current remains within safe operating limits, preventing excessive power dissipation. These calculations aid in optimizing the converter's performance, ensuring reliable and efficient high-voltage generation.

6. Simulation Model with Results

In the high-voltage MATLAB simulation, a 5V input is stepped up to approximately 10 kV using a high-frequency switching circuit. This simulation serves to verify the feasibility of achieving the required output rather than modeling a specific flyback transformer setup. A diode blocks reverse current, maintaining voltage stability with a minimal drop of about 0.8V. Due to high series resistance, the current remains low (1 mA), ensuring safety while generating a strong electric field for dust repulsion. The results confirm the expected high voltage with minimal power consumption, aligning with the intended application.

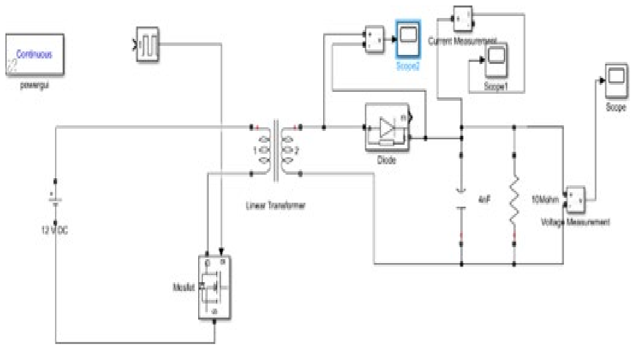

Fig. 2. Simulation circuit for high voltage generation

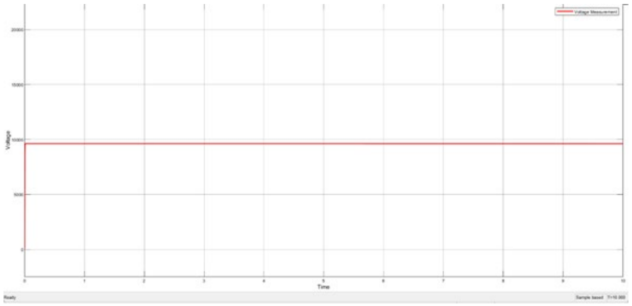

Fig. 3. Simulated high voltage output waveform

7. Experimental Setup

A. Gate Driver Circuit

The MOSFET driver circuit plays a crucial role in controlling the high-voltage source. It utilizes an IRF9540 P-channel MOSFET, which functions as a switch to regulate current flow through the load. The gate of the MOSFET is connected to the collector of a BC548 NPN transistor via a 1k pull-up resistor, ensuring the MOSFET remains OFF when the transistor is inactive. When the BC548 transistor turns ON, it pulls the MOSFET gate to ground, turning it ON and allowing current to flow. The transistor itself is driven by a PWM signal from a microcontroller, which ensures efficient switching of the MOSFET.

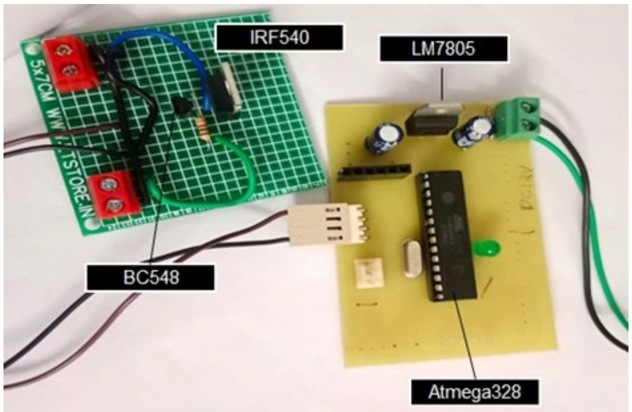

Fig. 4. Gate driver circuit

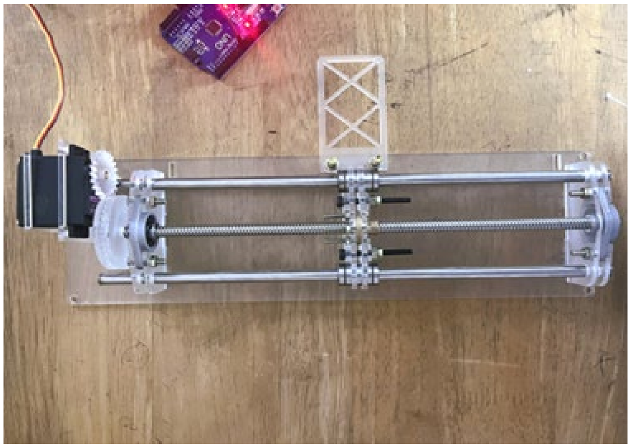

Fig. 5. Linear actuator

The driver circuit is designed to operate at high frequen- cies using Pulse Width Modulation (PWM) signals, enabling precise control of the MOSFETs. The switching mechanism allows current to flow intermittently through the primary wind- ing of a flyback transformer, creating a fluctuating magnetic field. This process steps up the input voltage to a much higher level, which is then rectified and applied to the electrodes to generate a strong electrostatic field. This high-voltage field ef- fectively facilitates dust removal by electrostatic precipitation, ensuring a clean solar panel surface for optimal efficiency.

B. Linear Actuator

The cleaning mechanism moves across the solar panel using a linear actuator controlled by a servo motor. A microcontroller governs the servo motor, which converts rotational motion into linear displacement via a screw rod and coupler mechanism. The motor driver regulates the motor's speed and direction based on programmed control logic. The system operates on pre-programmed movement sequences to ensure precise coverage of the solar panel.

C. Integration and Testing

The overall system was tested for seamless integration, with the gate driver circuit ensuring stable high-voltage generation.

The inclusion of a linear actuator system enables precise movement of the cleaning mechanism across the solar panel, ensuring even coverage. The actuator, driven by a servo motor, operates in a controlled manner based on microcontroller input, preventing over-travel and ensuring effective cleaning.

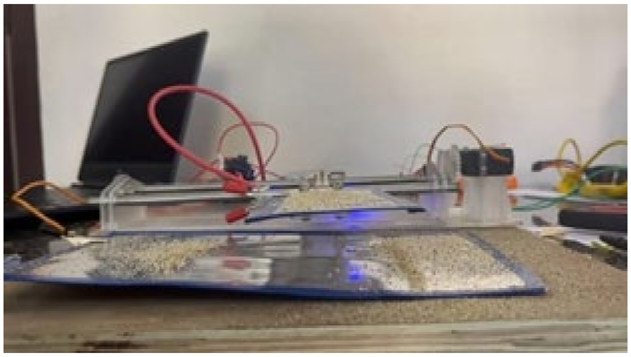

Fig. 6. Removal of sand particles using electrostatic precipitation

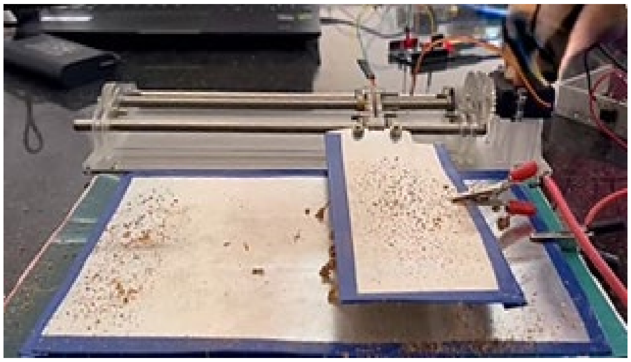

Fig. 7. Removal of sawdust using electrostatic precipitation

The optimized hardware system, featuring a robust MOSFET driver circuit and an integrated cleaning mechanism, significantly enhances the reliability and functionality of the electrostatic dust removal system. Using high-voltage generation and automated cleaning, this system improves the long-term efficiency and sustainability of solar energy harvesting.

8. Conclusion and Future Scope

The system successfully generated an output exceeding 10kV from an input of approximately 5V, effectively charging and removing particles from the electrode plates. During testing, sand particles were repelled, while sawdust tended to clump together. The accumulated sawdust can be redirected to a designated area through programmed control if required. The system demonstrated an overall efficiency of approximately 90%. Electrostatic cleaning is best suited for dry and dusty environments where fine dust is the primary issue. Studies suggest it can restore up to 95% of efficiency lost due to dust, making it comparable or even superior to conventional methods in certain conditions. However, its effectiveness may be limited against sticky or oil-based contaminants, requiring hybrid solutions such as occasional water cleaning for optimal performance.

Applying high voltage to solar panels presents potential risks, including insulation breakdown, photovoltaic cell degradation, and long-term efficiency reduction. Inadequate insulation or poor design can also cause arcing and localized heating, potentially damaging the panel surface and reducing its lifespan. Additionally, environmental factors such as humidity and airborne particle composition influence system performance, necessitating further optimization.

Future research should focus on refining voltage levels to ensure safe operation while maintaining cleaning effectiveness. Advancements in insulation techniques, alternative electrode materials, and improved circuit designs could help mitigate high-voltage risks. Studying real-world environmental conditions and long-term impacts will be crucial for enhancing system reliability. Furthermore, integrating adaptive control mechanisms and real-time monitoring could improve both safety and efficiency, making the system more suitable for large-scale solar panel maintenance applications.

9. Acknowledgment

The authors would like to thank Dr. Veena Mathew for her invaluable guidance and support throughout this research. The authors would also like to thank Mar Athanasius College of Engineering for providing the necessary resources and facilities to conduct this study. Finally, the authors acknowledge the contributions of their peers for their insightful discussions and constructive feedback, which have helped refine this work.

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