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Design and Simulation of a Self-Powered Electrodynamic Screen (EDS) for Dust Mitigation in Photovoltaic Panels

Ahmed Raouf Abdelhamid El-Mallawany
Mechanical engieneering department
Arab Academy for Science, Technology, and Maritime Transport
Cairo, Egypt
ahmedelmallawany@aast.edu

Osama Ahmed
Department of Electronic and Electrical Engineering, London
Brunel University London
London, UK
Osama.Ahmed@brunel.ac.uk

Mohamed Darwish
Department of Electronic and Electrical Engineering, London
Brunel University London
London, UK
mohamed.darwish@brunel.ac.uk

***Abstract*— Recent advancements in self-cleaning solar panel technologies have significantly enhanced photovoltaic (PV) system efficiency, reduced maintenance requirements, and promoted sustainability. Among these innovations, Electrodynamic Screen (EDS) systems stand out by employing electromagnetic fields to repel dust particles from solar panel surfaces without the need for water or manual intervention. This paper will focus specifically on EDS technology, exploring its operating principles and, critically, examining how high voltage is generated and safely applied to solar panels. Understanding these mechanisms is essential for evaluating the viability and scalability of EDS solutions in real-world solar energy applications, particularly in arid and dust-prone environments.**

Keywords— Electrodynamic Screen (EDS), Self-Cleaning Solar Panels; Dust Removal Technology; Photovoltaic Efficiency Enhancement.

I. Introduction & Related Work

Solar energy plays an increasingly vital role in the global pursuit of sustainable energy solutions. With growing concerns over climate change and finite fossil fuel resources, solar photovoltaics (PV) have become a cornerstone technology in the transition towards a low-carbon economy. According to the International Energy Agency (IEA) [1], solar PV was the leading source of new power capacity additions worldwide in 2022, accounting for nearly 60% of total newly installed electricity generation capacity [1]. Its scalability, declining costs, and environmental benefits make it a preferred choice for governments, industries, and private users alike.

However, despite its many advantages, one persistent operational challenge threatens the efficiency and economic viability of PV systems: the accumulation of dust, sand, pollen, and other airborne particulates on the panel surface. Numerous studies have demonstrated that soiling can reduce energy output by as much as 30% in heavily affected environments [2]. In desert regions, where solar resources are abundant, the problem is even more severe, with energy losses sometimes exceeding 40% if no cleaning is performed for extended periods [3].

Traditionally, PV systems have relied on manual cleaning methods, which involve washing panels with water and sometimes detergents, using brushes or high-pressure sprays. Robotic cleaning systems have also emerged, offering automated solutions that can clean large solar farms with less human labour [4]. However, these conventional approaches present several drawbacks:

- Water Consumption: Manual and robotic washing often require substantial amounts of water—up to 5 liters per panel per cleaning cycle—posing a significant sustainability concern in arid and drought-prone regions [5, 6].
- Labor and Operational Costs: Manual cleaning demands frequent labor, especially in dusty environments, increasing the operational costs and reducing the economic attractiveness of PV installations.
- Physical Damage: Repeated mechanical contact with panel surfaces can introduce micro-scratches, reducing transparency and leading to performance degradation over time.
- Limited Accessibility: Rooftop and remote installations often present logistical challenges, making regular manual cleaning impractical or unsafe.

Given these limitations, there is a pressing need for innovative, waterless, low-maintenance solutions that can ensure sustained PV performance without compromising environmental or economic objectives. The urgency to overcome soiling-related losses has led to the exploration and development of self-cleaning technologies. Several approaches have been investigated, including:

- Hydrophobic and oleophobic coatings, inspired by the lotus effect, to promote water-based cleaning via rainfall.
- Photocatalytic coatings, using materials like titanium dioxide (TiO_2) to break down organic contaminants under ultraviolet light exposure [7].
- Mechanical vibration systems, which use actuators or wind-induced motion to dislodge dust.

While each method offers unique advantages, limitations such as coating degradation over time or dependence on environmental factors (e.g., rain or strong winds) have spurred interest in more active, controllable cleaning technologies.

II. Emergence of Electrodynamic Screen (EDS) Technology

Among the various innovations, Electrodynamic Screen (EDS) technology has emerged as a particularly promising solution for mitigating dust-related energy losses.

EDS systems work by embedding transparent, interdigitated electrodes onto or within the solar panel's surface. When activated, these electrodes generate travelling or oscillating electric fields that impart electrostatic charges to dust particles as illustrated in Fig. 1. The interaction of these charges with the electric field forces the particles to move off the surface, effectively cleaning the panel without requiring water, physical contact, or external mechanical forces [8].

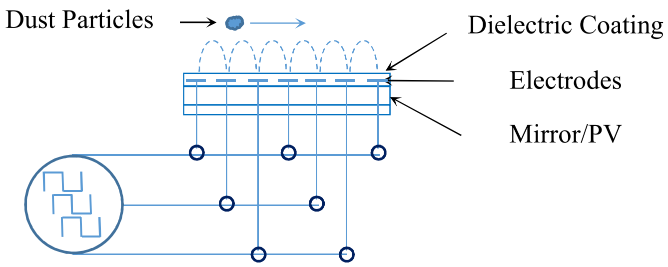

Figure 1: EDS Technology

Laboratory and field tests by companies like Sol Clarity and research institutions like the Daegu Gyeongbuk Institute of Science & Technology (DGIST) have demonstrated the effectiveness of EDS systems. Sol Clarity's EDS™ overlay, for example, achieved the removal of more than 90% of dust accumulation, restoring over 95% of the original power output, while consuming as little as 1 kWh of energy per 500 panels cleaned per day. DGIST's innovation, utilizing wind-driven triboelectric Nano-generators to power EDS screens, further enhances the sustainability credentials of this technology.

III. Working Principles of EDS Technology

Electrodynamic Screen (EDS) technology for dust removal, especially in applications like solar panels in arid environments, relies on high-voltage, time-varying electric fields—often in the form of three-phase high-voltage pulses—to repel or transport dust particles off the surface.

Generating these pulses (as shown in Fig. 1) from solar photovoltaic (PV) sources requires converting the low-voltage DC output of solar panels into high-voltage AC signals. Here's how the process typically works:

- DC Output from PV Panels: PV panels generate low-voltage DC (typically 12–48V or higher depending on configuration). The available voltage is not sufficient to create the high electric fields required for EDS, which often need hundreds to a few thousand volts.
- DC-DC Boost Conversion: A DC-DC boost converter is used to step up the PV voltage to a higher DC voltage level (e.g. 300–1500V depending on EDS design). This converter uses switching elements (e.g. MOSFETs, IGBTs) controlled by a pulse-width modulation (PWM) scheme.
- High-Voltage Three-Phase Pulse Generation: A high-voltage inverter converts the boosted DC into three-phase AC pulses. These are not necessarily sinusoidal but can be square or pulsed waveforms, depending on the EDS driving requirements. Frequency is typically in the range of 1–30 Hz for effective particle transport. Voltage amplitudes are in the range of several hundred to a few thousand volts.
- Phase Control and Timing: A microcontroller or FPGA manages the timing and sequence of the three-phase pulses. The pulses are phase-shifted by 120° to create a travelling electric wave across the screen. This movement of the field carries dust particles off the surface via electrostatic forces.
- Power Management and Synchronisation: To operate autonomously, the system can store excess PV energy in capacitors or batteries to power the EDS during low irradiance periods (e.g. morning or evening), use maximum power point tracking (MPPT) to optimise PV efficiency while simultaneously powering the EDS.

IV. Aplication of High Voltage to Solar Panels

Applying high voltage to the surface of solar panels through Electrodynamic Screen (EDS) systems must be performed with meticulous care to ensure the integrity, performance, and longevity of the photovoltaic (PV) modules. Improper voltage application can lead to several critical issues:

- Electrical breakdown of the encapsulation materials, resulting in permanent damage.
- Optical losses due to degradation or discoloration of transparent conductive layers.
- Compromised structural reliability of the module under varying environmental conditions such as temperature fluctuations and humidity.

Therefore, a carefully engineered high-voltage generation and application system is essential to maintain both the electrical and physical performance of the panels.

Central to this process is the design of a step-up high-voltage converter. The system must be able to boost the relatively low voltage output from the solar panel to the higher voltage levels required for the effective operation of the EDS without introducing significant power penalties. Importantly, the input power for the step-up converter should be sourced directly from the solar panel itself, ensuring a self-sufficient operation without reliance on external energy supplies.

To ensure the economic and operational feasibility of the EDS technology, the power consumption of the high-voltage generation circuit must be strictly limited. It is recommended that the power drawn by the step-up converter should not exceed 5% of the total power generated by the solar panel. This high level of efficiency is critical because excessive energy diversion would undermine the fundamental purpose of maximizing net energy output.

In addition to efficiency, the system should ideally incorporate energy recovery mechanisms. These systems capture and reuse any excess or reactive energy produced during the voltage generation process, further enhancing overall efficiency. Techniques such as regenerative circuits or resonant energy recovery designs can be employed to minimize energy losses.

V. Case Study – Design of EDS System

This case study presents the design and implementation of a photovoltaic-powered Electrodynamic Screen (EDS) system intended for autonomous dust removal on solar panels deployed in arid environments. This case study outlines the step-by-step design process of each subsystem, detailing how the components work together to create a sustainable, low-maintenance solution to a common operational challenge in solar energy deployment. The input and output of the system are:

- Input voltage 48 VDC
- Output voltage: ±1000 V - 3-phase 30 Hz for electrode driving.

A. DC-DC Boost converter Design

The purpose of this stage is to step up the low DC voltage from the photovoltaic source to a high-voltage level of 1500 VDC, suitable for generating the required EDS pulses. The duty cycle of the boost converter can be determined using the standard boost converter equation (equation 1), based on an input voltage of 48 V and an output voltage of 1500 V. This high-voltage DC will subsequently be utilised to produce a pulsating AC waveform with an effective amplitude of approximately 1000 V for driving the electrodynamic screen.

$$V_{out} = \frac{V_{in}}{1-D} \tag{1}$$

From Equation (1), the calculated duty cycle is 0.968. By substituting this value into the boost inductor sizing formula (Equation 2), and assuming a switching frequency of 10 kHz—selected as a trade-off between minimising switching losses and reducing inductor size—along with a 100 Ω load, the minimum required inductance is found to be approximately 4.96 µH

$$L_{\min} = \frac{D(1-D)^2\ R}{2f} \tag{2}$$

Using the boost converter output capacitor equation (Equation 3) and assuming a permissible output voltage ripple of 1%, the required capacitance is calculated to be approximately 96.8 µF.

$$C = \frac{D}{R\ f\left(\frac{\Delta V_{out}}{V_{out}}\right)} \tag{3}$$

B. Three-Phase High-Voltage Inverter

The purpose of this stage is to convert the high-voltage DC into a three-phase pulsed output, operating in the range of approximately 1–30 Hz, for driving the EDS electrodes. Let each phase switching signal be a square wave function:

$$S_A(t) = sgn\ (\sin(\omega t))$$

$$S_B(t) = sgn\ \left[\sin\left(\omega t - \frac{2\pi}{3}\right)\right] \tag{4}$$

$$S_C(t) = sgn\ \left[\sin\left(\omega t + \frac{2\pi}{3}\right)\right] \tag{5}$$

Where $sgn(\ )$ *is the sign function*:

$$sgn\ (x) = \begin{Bmatrix} +1 & if\ x > 0 \\ -1 & if\ x < 0 \\ 0 & if\ x = 0 \end{Bmatrix} \tag{6}$$

Output voltage (e.g., V_{AN}) is:

$$V_{AN} = \frac{V_{dc}}{2}.S_A(t) \tag{7}$$

$$V_{BN} = \frac{V_{dc}}{2}.S_B(t) \tag{8}$$

$$V_{CN} = \frac{V_{dc}}{2}.S_C(t) \tag{9}$$

For 30 Hz output, each electrical cycle ≈ 33.3 ms

C. The control Unit

The control unit serves as the central intelligence of the Electrodynamic Screen (EDS) system, responsible for generating accurate and synchronised timing signals to drive the three-phase high-voltage inverter. These signals are essential for producing the 120° phase-shifted square pulses that enable the travelling electric field across the EDS electrodes, which is critical for effective dust removal.

To achieve this, a high-performance microcontroller—such as the STM32 or Arduino Due—is utilised. These platforms are well-suited due to their ability to handle real-time signal generation, pulse-width modulation (PWM), and precise phase control. The microcontroller generates three distinct PWM signals with 120° phase shifts, each corresponding to one phase of the inverter. This sequencing ensures consistent and balanced operation of the three-phase output, which in turn maintains uniform dust repelling action across the solar panel surface.

In addition to core signal generation, the control unit includes several advanced features to enhance functionality and system reliability. Dynamic frequency adjustment allows the output pulse frequency to be tuned between 1 Hz and 30 Hz, depending on operational needs or environmental conditions such as dust density. The control firmware can also incorporate environmental sensing inputs, such as temperature and ambient light levels, enabling the system to activate or adjust EDS operation only when necessary—thereby reducing energy consumption and extending system lifespan.

To ensure operational safety, the control unit integrates hardware and software-based safety interlocks. These may include overvoltage and overcurrent protection, fault detection, and automatic shutdown in abnormal conditions, safeguarding both the electronic components and the PV panels.

Furthermore, for modern monitoring and remote control requirements, an ESP32 wireless communication module can be embedded within the system. This module enables Wi-Fi or Bluetooth-based connectivity, allowing users to monitor system status, trigger manual cleaning cycles, or adjust parameters remotely through a mobile app or cloud platform.

Such integration transforms the EDS into a smart, autonomous, and user-configurable solution, ideal for deployment in both residential and utility-scale solar installations.

VI. Simulation and Validation

To validate the functionality of the designed EDS system, simulations were conducted for both the DC-DC boost converter and the three-phase inverter stages using PSpice environment. These simulations provide insight into the dynamic behaviour, voltage stability, and phase control required for effective dust removal.

A. Boost Converter Simulation

The boost converter plays a critical role in elevating the low DC voltage (48 V) sourced from the photovoltaic array to a high-voltage level suitable for EDS activation. Figure 2 presents the simulated schematic of the boost converter designed using PSpice. The component values—including an inductance of 4.96 µH and an output capacitor of 96.8 µF—were calculated to optimize performance while maintaining voltage stability and minimizing ripple. A switching frequency of 10 kHz was selected to balance efficiency and size constraints.

The simulation confirms that the converter successfully boosts the input voltage to the required 1500 V DC level with minimal voltage ripple and stable operation, making it suitable for feeding into the subsequent inverter stage. This voltage serves as the input to the high-voltage inverter that drives the EDS electrodes.

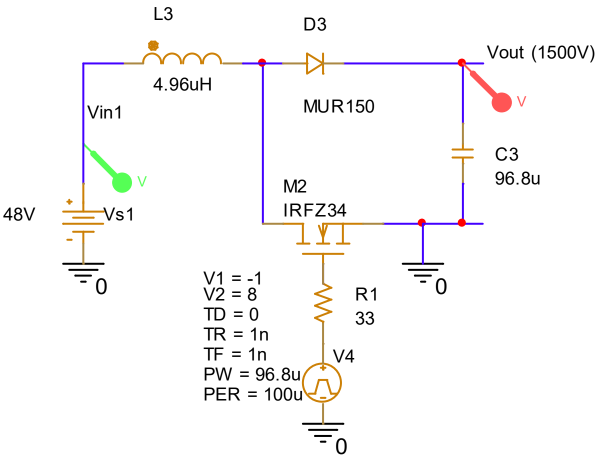

Figure 2: EDS Boost converter

B. 3-Phase Puls Inverter

The three-phase inverter, depicted in Figure 3, converts the high-voltage DC output from the boost converter into a 3-phase pulsed waveform, necessary for creating the electrodynamic sweeping effect across the EDS electrodes. The inverter is implemented using six IRFZ34 MOSFETs arranged in a standard three-leg bridge configuration. Gate driver circuits are used to provide electrical isolation, using optocouplers to ensure safety and prevent feedback into the control system.

The inverter is controlled to output square pulses that are 120° out of phase from one another. This is accomplished using a microcontroller that generates the required timing signals. As shown in Figure 4, the inverter produces clean, synchronised pulses at 30 Hz and ±500 V (for a total swing of 1000 V per phase), which are ideal for generating the travelling wave electric field required to displace dust particles. The system allows frequency variation between 1 and 30 Hz, providing flexibility in tuning the EDS operation based on environmental dust levels.

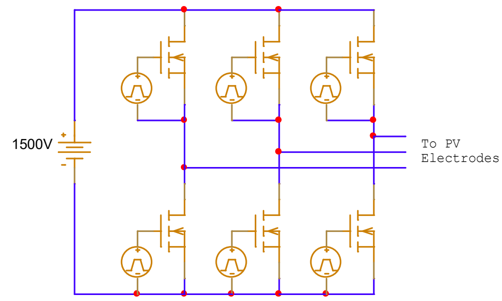

Figure 3: EDS 3-phase inverter configuration

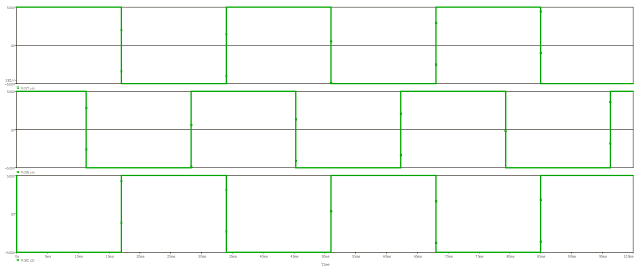

Figure 4: 1000V 30 Hz output applied to the EDS electrodes

VII. Concluions

This paper has presented the comprehensive design, modelling, and simulation of a photovoltaic-powered Electrodynamic Screen (EDS) system tailored for autonomous dust removal in solar energy applications. The proposed system is particularly suited to arid and dust-prone environments where conventional cleaning methods are impractical due to water scarcity, high labour costs, or limited accessibility. By leveraging the inherent benefits of EDS technology—namely, contactless and waterless cleaning—the system addresses a major barrier to maintaining photovoltaic (PV) efficiency over time.

The system architecture integrates two key subsystems: a high-efficiency DC-DC boost converter and a three-phase high-voltage inverter. Simulation results demonstrate that the boost converter reliably steps up the input voltage from 48 V DC (typical of a PV array) to 1500 V DC, ensuring sufficient voltage for dust displacement via electrostatic forces. Additionally, the three-phase inverter successfully generates 30 Hz square pulses with precise 120° phase shifts, delivering the required travelling wave electric field across the EDS electrodes.

The simulation validates that the proposed configuration not only achieves its functional objectives but also does so with a design optimised for autonomy, minimal maintenance, and integration into existing PV systems. The system's simplicity, scalability, and reliance solely on solar power suggest strong potential for deployment in utility-scale solar farms and remote installations.

Looking ahead, future work will focus on physical hardware implementation and experimental validation of the system under real-world environmental conditions. This includes evaluating system performance across varying dust loads, ambient temperatures, and irradiance levels. Additional research will also explore energy optimisation techniques, such as maximum power point tracking (MPPT), dynamic frequency control for EDS activation, and regenerative energy recovery circuits to further reduce system losses. Furthermore, incorporating wireless monitoring and control through embedded IoT modules can enhance system reliability and maintenance scheduling. These enhancements will collectively contribute to a robust, self-sustaining solution for preserving solar panel output and extending the lifecycle of PV infrastructure in challenging environments.

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