

Article

Unlocking Efficiency: Parametric Optimization of an Affordable PCB Electrodynamic Screen for Self-Cleaning Solar Panels

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Abstract

Dust accumulation on photovoltaic (PV) module surfaces significantly reduces energy yield in arid environments, yet traditional water-based cleaning techniques are unsustainable. This study presents a complete evaluation of electrodynamic screen (EDS) technology as a waterless cleaning solution, with a focus on dust removal efficiency and the critical trade-offs between energy gains and losses. Using printed circuit board (PCB) technology, a three-phase EDS system was designed and constructed, and its performance was simulated on COMSOL Multiphysics. Under optimal conditions of 50 Hz and a 66% duty cycle, the system achieves 52% dust removal efficiency while consuming less than one watt-hour per square meter during operation. The novelty of this study lies not merely in the hardware, but in the analytical lens applied and the holistic loss–gain methodology that quantitatively assesses, over a seven-day cycle, the reduction in dust-induced optical loss, the intrinsic optical transmission loss introduced by the EDS layer itself, and the operational energy cost of running the system. Rather than focusing on removal efficiency in isolation, this study enables a site-specific evaluation of whether, and when, EDS technology delivers a net energy benefit. By integrating material properties, local soiling conditions, and all major loss mechanisms, this study provides a low-cost and analytical tool for researchers and solar farm operators to assess the real-world feasibility of EDS cleaning before deployment. While the proposed PCB technology is not itself suitable for field deployment, it serves as a low-cost development platform for optimizing electrode geometry and excitation parameters prior to investment in transparent materials.

Keywords: solar PV; dust accumulation; electrodynamic screens; cleaning techniques; non-invasive cleaning



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1. Introduction

Dust accumulation on photovoltaic (PV) module surfaces is a well-known issue that can reduce energy output. In desert and arid regions, where many large solar installations are located, soiling losses can range from 10–30% under moderate dust conditions [1–6] and have been reported up to 40–60% over a few months if panels are left uncleaned [1,7]. Even a thin dust layer (on the order of micrometers) can cause a significant drop in efficiency by blocking and scattering sunlight. Empirical studies indicate that dust deposition can decrease PV output by up to 30% within a single month [8]. This not only diminishes the production of renewable energy but also incurs significant expenses. A 1% decline in efficiency for a 150 MW solar facility is estimated to result in around \$200,000 annually in

lost revenue [8]. Consequently, cleaning is essential; nevertheless, conventional approaches present significant issues. Utilizing water for cleaning consumes substantial resources, amounting to approximately 10 billion liters annually worldwide, rendering the practice unsustainable in regions where water is already limited. Furthermore, cleaning with water or brushes, whether manually or automatically, necessitates significant effort and expense. For instance, water cleaning constitutes approximately 10% of the expenses associated with the operation and maintenance of a solar facility [9]. These operations may also damage the edges of solar cells, potentially resulting in a permanent reduction in light transmission. Consequently, there is an increased demand for dry and automated cleaning solutions that can maintain PV systems effectively without the use of water or abrasive materials [10,11].

Extensive research has been conducted on electrostatic cleaning systems as potential methods to prevent dust accumulation on PV surfaces. Among these, electrodynamic screens (EDSs) appear to be the most promising alternative since they cleanse surfaces without the utilization of water [12,13]. The electrodes on the surface of an EDS are generally arranged in a specific pattern. Oscillating electric fields are generated by activating and deactivating these electrodes by alternating voltage patterns. These fields displace and eliminate dust particles by applying electric forces, without the need for wipers or cleaning chemicals [12,14,15]. The concept was originally devised for application in space to mitigate dust adherence on Mars and the Moon. Since then, it has been utilized to enhance the reliability of PV modules by facilitating self-cleaning [15].

Low energy consumption is a major benefit of EDSs. In order to operate, only a small fraction of the PV module's output is needed. According to experiments, EDS films can restore over 95% of the original PV output after a cleaning cycle, all while using less than 0.2 Wh/m² of energy [12,16]. Given that an EDS eliminates the need for water and uses orders-of-magnitude less energy than conventional cleaning, it is advantageous from a sustainability standpoint [17,18]. In addition to reducing the water footprint of PV power systems, this technology enables more frequent cleaning cycles (e.g., daily or weekly) and eliminates the need for water-based washing, all while maintaining stable performance.

Researchers have determined that transparent EDS layers may reinstate both optical transmittance and electrical output, achieving success rates of 90–95% in controlled laboratory experiments [12,13,19,20]. Despite this advancement, transforming these designs from laboratory experiments into economically viable solutions for large-scale deployment remains challenging. Using indium tin oxide (ITO) coatings on flexible glass substrates complicates manufacturing and raises costs. To address these issues, researchers have developed solutions such as flexible films [4,13], transparent conductive polymers, and printed or embedded electrode configurations utilizing printed circuit boards (PCBs). Achieving an equilibrium of optical transparency, electrical performance, and fabrication simplicity remains a focus for research and advancement.

In this regard, this study proposes a PCB-based electrodynamic screen system, which was designed, simulated, and built while utilizing materials that are now commercially available. In addition to interdigitated electrodes that are patterned directly onto a PCB substrate [21,22], the system comprises a waveform generator powered by a microcontroller and a custom-built high-voltage DC flyback converter followed by an AC inversion stage using solid-state relays. Experiments were conducted to assess the performance of the device over a variety of excitation frequencies and duty cycles. The experiments involved the use of samples of desert dust. The EDS electrode array was fabricated on a standard FR-4 epoxy fiberglass PCB substrate. FR-4 was chosen for its low cost, mechanical rigidity, and ease of prototyping, despite its non-transparent nature and moderate dielectric constant.

The key contribution of this research is the development of a printed PCB-based electrostatic dust removal system capable of achieving effective dust removal from PV surfaces. This is achieved through COMSOL simulations of the electric field distribution, as well as measurements of power consumption and empirically validated cleaning efficiency of the system. Generally, the results of this study demonstrate that electrostatic cleaning is a viable method for handling dust accumulation on PV systems, especially in areas where conventional cleaning procedures are rendered impractical due to the lack of water. The novelty of this study lies not only in the unprecedented efficiency or an entirely new concept, but in the systematic optimization of a low-cost, PCB-based three-phase EDS prototype including detailed efficiency mapping across frequency (1–100 Hz) and duty cycle (40–70%) combined with a quantitative loss–gain framework that accounts for dust-induced optical loss, fixed EDS transmission loss, and operational energy loss.

The prototype is a PCB-based apparatus utilizing a conventional FR-4 epoxy substrate with copper electrodes. It is non-transparent and used exclusively as an economic development platform for parametric optimization. The COMSOL simulation model was developed to replicate the geometry and material characteristics of this PCB prototype (FR-4 substrate, copper electrodes, solder mask layer), facilitating the examination of electric field distribution and qualitative verification of the travelling wave mechanism. A hypothetical discussion of a future transparent design is presented, referencing research on layered constructions using borosilicate glass, optically clear adhesive, transparent conducting electrodes (ITO or silver nanowires), and Willow Glass cover layers. This design serves as a benchmark for future development and is not included in the experimental work discussed herein. Subsequent sections are described as follows: Section 2 shows recent developments in EDS technology. Section 3 is the EDS System Design, Materials and Testing, while Sections 4 and 5 shows the results and discussion.

2. Recent Developments in EDS Technology for PV Applications

Recent developments in EDS for PV applications are increasingly characterized by a synergistic combination of computational modeling and experimental validation. Researchers have extensively utilized finite element models, especially through platforms like COMSOL Multiphysics, to optimize critical design parameters, including electric field distribution, electrode configuration, and operational frequency. These simulations are generally enhanced by empirical testing in controlled environmental chambers, where variables such as humidity, particle size distribution, and dust composition are carefully altered. This dual methodology enhances EDS performance in optimal circumstances and offers essential insights into the system's resilience across various climatic and soiling environments.

Guo et al. [23] conducted comprehensive outdoor experiments to evaluate EDS outside the lab. Their investigation used a two-phase standing-wave setup at 1 Hz and 9 kV to measure cleaning performance with outdoor soiling microscopy. Parallel high-voltage electrodes protected by a transparent protective layer generated traveling electrostatic waves that removed dust via surface tension and electrostatic effects. After four days of hourly activations, the system's clearance effectiveness dropped from 40% to 14%. This performance decrease was caused by cementation effects, where soluble salts and ambient moisture increased particle adherence to PV surfaces. In humid conditions, the authors suggested more frequent and shorter activation cycles to reduce adhesion. Based on these observations, Bernard et al. [13,17] created an advanced three-phase EDS configuration tailored for arid and high-soiling environments. Their iterative design method commenced with comprehensive simulations to enhance dust removal efficiency via better electrode configuration. Subsequent to the simulation-based technique, a functioning prototype was constructed and underwent extensive testing in both laboratory and real-world en-

vironments. The EDS film architecture features interdigitated electrodes configured in a three-phase arrangement, with conventional dimensions of 80 μm for electrode width and 700 μm for inter-electrode spacing [9,15]. The selection of materials is crucial in this design; electrodes are constructed from transparent conductors like ITO or silver nanowire inks, applied on flexible substrates such as ultra-thin Willow Glass or polyethylene terephthalate (PET) films. This combination guarantees mechanical adaptability to both flat and curved PV modules while preserving high optical transmittance. To improve long-term durability, the multilayer assembly is frequently sealed at the edges to avert environmental infiltration.

In a similar study by Bernard et al. [12,13], ITO electrodes on Willow Glass were activated by a three-phase AC signal, resulting in dynamic electric fields that created traveling wave patterns throughout the surface. These fields generated homogeneous Coulombic and dielectrophoretic forces that effectively removed dust particles across a wide size range, from submicron to larger aggregates. The efficiency after cleaning surpassed 95%, while the operational energy consumption remained under 1 Wh/m² every cycle. Notwithstanding these encouraging results, practical obstacles remain, such as scalability for utility-scale PV farms, performance decrease in high humidity (30–40% decreases), and material deterioration from extended ultraviolet exposure [13,23]. Research on alternate conductive materials, like aluminum-doped zinc oxide (AZO), has identified compromises among optical clarity, electrical conductivity, and environmental durability, highlighting the necessity for ongoing material innovation.

Although EDS technology and related flexible film systems indicate a substantial advancement in non-contact, waterless photovoltaic cleaning, their practical implementation is still limited by environmental factors and material constraints. Continued research is crucial to improve the durability, efficiency, and economic viability of EDSs, hence reinforcing its contribution to sustainable solar energy production in dust-affected areas globally.

Notwithstanding these advancements, several gaps exist. The majority of high-efficiency systems (exceeding 90%) employ transparent conductive oxides on rigid or flexible glass substrates, which are expensive and difficult to scale. Inexpensive alternatives like PCB-based electrodes have been investigated [21,22], although they exhibit a deficiency in systematic parametric optimization and quantitative loss–gain assessment. Moreover, little research explicitly considers the intrinsic optical loss caused by the EDS layer, which may partially or entirely negate the benefits of dust removal. This study fills existing gaps by systematically optimizing a low-cost, PCB-based three-phase EDS and presenting a mathematical approach that balances dust recovery with fixed losses.

3. EDS System Design, Materials and Testing

Modeling the EDS with COMSOL Multiphysics

The first stage in developing our EDS model involved the selection of a suitable simulation platform that could precisely depict the system's physical behavior. COMSOL Multiphysics v6.4 was selected from the available software tools due to its capacity to fulfill several essential criteria: accurate representation of electric fields produced by the electrode array, simulation of dust particle interactions with these fields, and facilitation of the optimization of operational and design parameters. The application of finite element modeling (FEM) platforms, such as COMSOL, for EDS analysis is well-established in the literature [24,25]. In this study, the authors designed their own model adhering to known approaches, incorporating unique shape, materials, and excitation conditions customized for our PCB-based prototype.

The modeling process in COMSOL follows a systematic workflow: first, the geometry is defined; second, material properties are assigned; third, the physics are specified; fourth,

this study is configured; and finally, the outputs are analyzed. Figure 1 shows the 3D design of the EDS with its prototype in CAD (Figure 2).

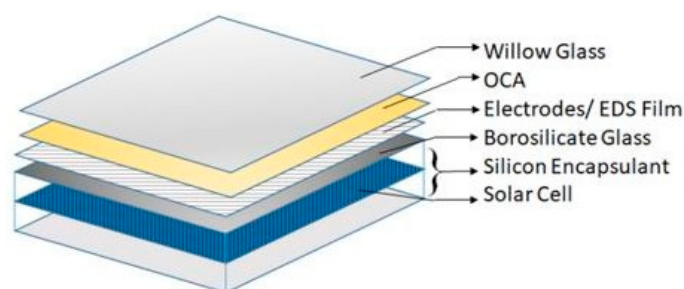


Figure 1. 3D EDS design with layers.

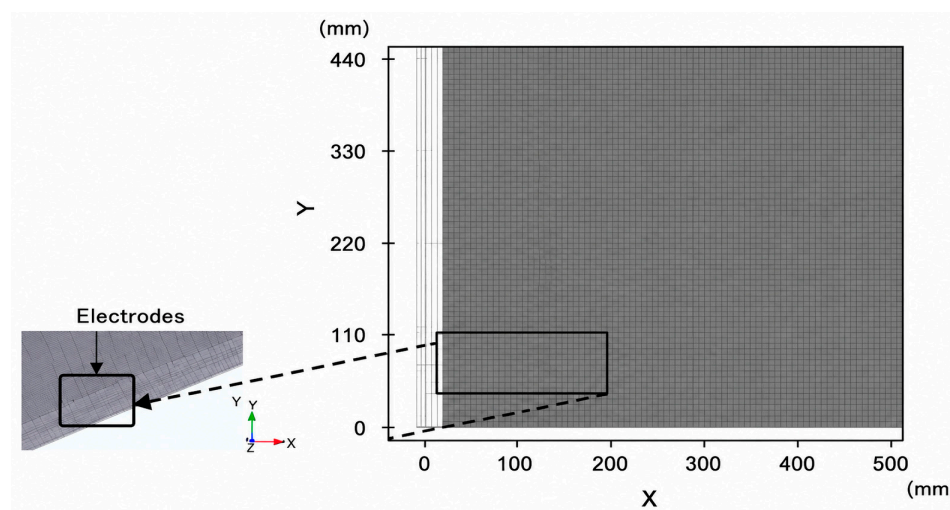


Figure 2. Our EDS prototype in CAD.

Each layer in the model serves a specific function. The parameters used in the simulation are listed in Table 1. These values were selected based on design constraints and prior experimental studies to ensure realistic performance expectations [18].

Table 1. Model parameters during simulation.

Model Parameter	Parameter Value	Model Parameter	Parameter Value
Electrode number	576 electrodes	OCA height	75 μm
System width **	490,000 μm	Willow Glass height	100 μm
Electrode width	80 μm	Electrode spacing	700 μm
Electrode height	3 μm		

** The “system width” listed (490,000 μm) is the physical prototype width. The COMSOL simulation used a smaller representative domain (2.2 mm) with periodic boundaries.

Figure 2 shows the CAD model of the three-phase EDS prototype, illustrating the configuration of the interdigitated electrodes. The design has 576 rectangular electrodes organized in a recurring three-phase configuration (Phase 1, Phase 2, Phase 3). Each electrode measures 80 μm in width, with a center-to-center spacing of 700 μm between neighboring electrodes. This design was chosen based on COMSOL simulations to optimize electric field strength, fabrication feasibility using PCB technology, and the clearance of dust particles, which typically vary from 10 to 300 μm in diameter. The electrodes are connected to three bus bars situated at the edges of the PCB, linking each phase to external solid-state relays. The substrate is an FR-4 PCB material (opaque for this prototype), enabling swift

iterative testing of electrode shapes and electrical parameters prior to the shift to transparent substrates in subsequent designs. Thus, this PCB-based approach is intentionally a low-cost development platform, not a final deployable product.

The initial layer in electrode manufacturing is composed of borosilicate glass. This material is preferred due to its stiffness, high optical transparency, resistance to environmental stress, and ease of manufacturing, despite the theoretical possibility of using any electrically insulating substrate [4]. The electrode printing procedure on borosilicate glass for electrodynamic screens predominantly adheres to one of two methodologies. Subtractive processing is the first and most common method used for ITO and similar materials. It begins by creating a homogeneous, thin coating of the conductive substance across the entire glass surface using a process like sputtering. A light-sensitive photoresist is subsequently applied to this uncoated layer. The resist is subjected to ultraviolet light via a patterned photomask that delineates the prospective electrode configuration. The exposed conductive material is then etched off leaving behind only the desired electrode tracks. The residual photoresist is removed, and the glass is subjected to high-temperature annealing to solidify the electrodes and guarantee robust adhesion to the borosilicate glass. The second method is an additive process, commonly employed for conductive inks such as silver nanowire pastes. Here, the electrode material is formulated into a printable ink. This ink is then directly deposited onto the pristine glass surface in the exact electrode pattern using printing techniques like inkjet or screen printing. The final step involves curing or sintering the printed pattern with heat or light to evaporate the solvents and fuse the conductive particles together, forming continuous, conductive pathways.

The optically clear adhesive (OCA) comprising the second layer of the device serves to bond the structural and functional layers while also preserving a high degree of transparency [4]. The electrodes printed with conductive inks are situated in the third layer. Various types of ink are applicable based on the specific production method employed. This prototype utilized either copper or silver [4]. However, in this study, the prototype differs from that in [4]. This study utilized similar conductive materials while employing a novel PCB-based electrode design, power circuit, and fabrication methodology. The final layer consists of Corning Willow Glass, an ultra-thin cover glass that safeguards the electrode array against oxidation and environmental exposure while ensuring flexibility and durability [4]. Figure 3 shows the electrodes and their component layers.

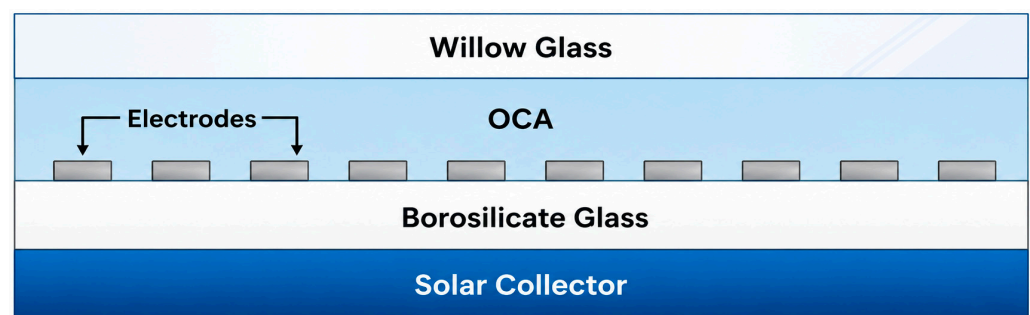


Figure 3. Generic multilayer EDS structure from the literature [4] (not fabricated in this study). This figure is included for conceptual illustration of EDS layering principles, showing a transparent design with borosilicate glass substrate, OCA bonding layer, ITO or silver nanowire electrodes, and Willow Glass cover layer. The prototype fabricated in this study uses an FR-4 PCB substrate with copper electrodes (see Figures 1 and 2). Generic multilayer EDS structure from the literature [4].

It is essential to understand the difference between the actual prototype dimensions and the COMSOL simulation domain. The constructed PCB prototype has a total width of 490 mm (490,000 μm); however, directly modeling the complete domain would be

computationally expensive due to the extremely fine mesh necessary to resolve the 80 μm electrode features. As a result, the COMSOL model was developed utilizing a reduced-order unit cell technique. A portion with three electrodes (one full cycle of the three-phase pattern) and a width of around 2.2 mm (2200 μm) was simulated. Periodic boundary conditions were applied to the left and right boundaries to simulate an infinite array of electrodes. The 490,000 μm value in Table 1 represents the actual prototype width, not the simulation domain. Table 1 has a footnote that clarifies this issue.

In this study, the model specifically utilizes the electrode geometry (80 μm width, 700 μm spacing, three-phase interdigitated pattern) established by Bernard et al. [13], the boundary conditions and meshing strategy (fine mesh at electrode edges, coarser mesh in bulk regions) from Baqraf et al. [26], and the quasi-electrostatic Laplace formulation ($\nabla^2 V = 0$) in accordance with standard EDS modeling practices [24,26]. The authors integrate these methodologies to achieve a balance of geometric precision, computational efficiency, and alignment with published findings while diverging by replacing glass/ITO with FR-4 and copper and including a solder mask layer to reflect our unique PCB-based prototype. The electrostatic interface of the AC/DC module resolved Laplace's equation ($\nabla^2 V = 0$) in the quasi-electrostatic domain by a time-dependent analysis employing sinusoidal three-phase voltages (1.2 kV amplitude, 5 Hz frequency) at the electrode boundaries. The mesh has more than 120,000 triangular elements, including a maximum dimension of 2 μm at the edges and corners of the electrodes, where significant field gradients are anticipated, and progressively coarsening to 50 μm in the bulk substrate and air regions. Mesh convergence was assessed by augmenting the element count to 240,000, yielding a variation of less than 2% in the peak electric field amplitude. The relative tolerance for the iterative solution was established at 10^{-6} .

The COMSOL model was designed to match the dimensions and material characteristics of the actual PCB prototype used in this investigation, which included a FR-4 substrate, copper electrodes, and a solder mask layer. This model does not depict the transparent glass/ITO/Willow Glass structures described in the literature [4], which are only mentioned theoretically in Section 5.

4. Results

4.1. Results in COMSOL Multiphysics

The electric field E is generated by the electrical potential V , and its value is equivalent to the negative gradient of the potential, or $E = -\nabla V$. The charged dust particles are subjected to forces exerted by this electric field. Electrostatic forces, which have the capacity to repel charged particles, and dielectrophoretic forces, which have the ability to move neutral particles by producing a dipole moment in them as a result of the non-uniform electric field, are two of the forces that are involved.

Extremely fine-tuned mesh features, with high-density elements tailored to accurately capture the fast changes in electric potential, characterize the areas immediately surrounding the electrodes. Lowering the computing burden is achieved by gradually shifting to a coarser mesh in the upper parts of the model while keeping the accuracy of computations in parts where fine-grained detail is unnecessary.

This study utilized a COMSOL simulation using a three-phase AC excitation with sinusoidal waveforms of 1.2 kV peak amplitude and a frequency of 5 Hz, incorporating 120° phase changes. The resultant electric field distribution is seen in Figure 4. Sinusoidal excitation is the conventional assumption in traveling wave EDS modeling [12,27], facilitating direct comparison with existing literature.

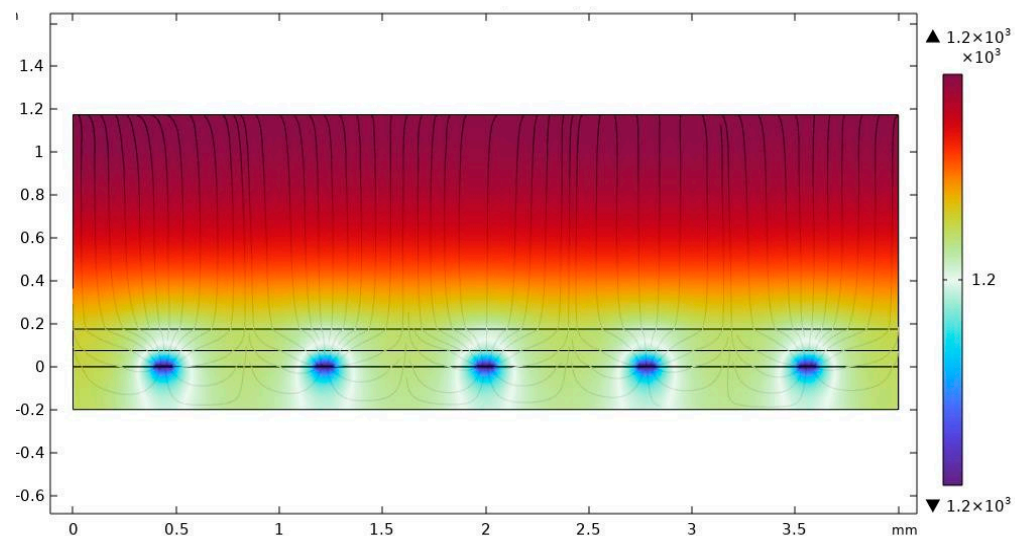


Figure 4. Electric field norm distribution from COMSOL simulation (1.2 kV, 5 Hz, three-phase sinusoidal). Color bar: $0\text{--}2.5 \times 10^6$ V/m.

The physical prototype outlined in Section 4.5 employs square wave excitation owing to the practical limitations of producing high-voltage AC from a DC flyback converter utilizing solid-state relays. Square waves generate a propagating field whose basic Fourier component corresponds to that of a sinusoidal wave; higher harmonics introduce localized field gradients but do not impede efficient dust removal. Prior research [21,22] has demonstrated that square-wave excitation attains cleaning effectiveness equivalent to that of sinusoidal excitation in EDS systems. The experimental optimization of frequency (1–100 Hz) and duty cycle (40–70%) was undertaken using square waves.

In the present study, maintaining a constant applied voltage of 1.2 kV while raising the substrate permittivity (ϵ_r) from 1 to 4 results in a reduction in the surface electric field by around 30–40%, assuming all other factors remain constant. This trade-off must be evaluated when choosing EDS materials: an increased ϵ_r enhances mechanical stability and manufacturability (as seen with FR-4) but diminishes surface field strength. Upcoming transparent designs utilizing glass ($\epsilon_r \approx 4\text{--}6$) will demonstrate comparable field magnitudes to our FR-4 prototype, therefore affirming the significance of our results.

4.2. Field Distribution and Mesh Refinement—Governing Equations for Electric Potential and Field

In the dust-cleaning EDS model, the electric potential $V(x,y)$ in regions without free charge obeys Laplace's equation: $\nabla^2 V = 0$ [26]. This means the potential is a harmonic function, and there are no volume charges; so, the field is determined purely by boundary conditions (the electrodes). Physically, this indicates that E points from high-potential to low-potential regions, and its magnitude is proportional to how fast V changes in space (the spatial gradient). In this simulation, COMSOL solves Laplace's equation with appropriate boundary conditions to find $V(x,y)$, and then computes $E(x,y)$. This approach is standard for EDS analyses [26] since analytic formulas are not available for complex electrode layouts. Notably, solving Laplace's equation with finite elements requires a mesh (discretization) of the domain.

To actively transport dust, the EDS uses a three-phase AC voltage drive applied to interdigitated electrodes [26]. Adjacent electrodes are fed with phase-shifted sinusoidal voltages, producing a traveling electric field wave across the surface. In this case, we apply voltages: $V_1(t) = V_0 \sin(\omega t)$, $V_2(t) = V_0 \sin(\omega t + 120^\circ)$ and $V_3(t) = V_0 \sin(\omega t + 240^\circ)$.

In this case, $V_0 = 1.2$ kV is the amplitude and $f = 5$ Hz is the frequency. Thus, 120° phase-staggered AC drive creates a traveling wave field sweeping across the electrode array [28]. Such three-phase EDS activation (often 1–2 kV in the low Hz range) has been used in experiments to achieve efficient dust removal (for example, Mazumder et al. used a 1.2 kV, 5 Hz three-phase drive in EDS prototypes [12,28]). In this simulation, at any given time, the electrodes have different instantaneous potentials according to the above equations, which sets up a time-varying non-uniform electric field across the surface. However, since the frequency is low (5 Hz), the field distribution in space at any instant resembles a static solution of Laplace's equation (quasi-electrostatic regime). Essentially, the phase difference causes the “high”-potential electrodes to shift in position over time, resulting in a traveling electric field pattern that can drag dust particles toward one end of the PV surface [28].

The traveling high-field zones act as a conveyor belt, transporting dust toward the edges of PV modules. The validity of this mechanism is confirmed through simulation results, which clearly show intense field gradients at electrode boundaries and successful field propagation. The accuracy of these simulations is ensured by the mesh design, which prioritizes field resolution near critical regions [12].

The interdigitated three-phase electrode layout, combined with high-resolution FEM modeling, successfully generates dynamic electric field patterns that facilitate efficient dust removal from PV surfaces using both electrostatic and dielectrophoretic principles [5]. The resulting electric field distribution, which is critical for particle removal, is visualized in Figure 4, showing the intense field gradients around the electrodes.

4.3. Final Design

Based on preliminary modeling and a trade-off analysis of manufacturability, projected field uniformity, and power requirements, two candidate PCB designs for the integrated EDS and power circuit were selected for prototyping and experimental testing. These candidates represent two fundamental operational principles: a single-phase AC excitation (Figure 5) and a three-phase AC excitation (Figure 6). These testing procedures compare the real-world cleaning performance of each configuration to identify the optimal one. The EDS underwent comprehensive modeling and enhancement with Altium Designer. This technique facilitated the selection of two configurations that were highly efficient and met the design specifications. This method, executed with meticulous attention to detail, involved iterative evaluations of circuit configurations, signal integrity, and thermal performance. The evaluations were conducted to verify that the designs adhered to project criteria and industry norms. The power-circuit design underwent empirical testing to confirm its validity. This experiment employed available resources to evaluate critical parameters such as voltage stability, current, and efficiency. The conducted trials only demonstrated the reliability of the chosen design. Furthermore, they provided valuable information that could enhance the design optimization.

To validate the suggested methodology, two printed circuit board (PCB) prototypes were conceived and produced, each with a distinct power supply configuration for the EDS (Figures 5 and 6): a single-phase AC supply and a three-phase AC supply. The single-phase configuration employs a solitary alternating voltage, generating an oscillating electric field. Conversely, the three-phase design, energized by three AC impulses phase-shifted by 120° , produces a traveling wave that sweeps across the surface, resulting in more uniform and efficient dust movement [15].

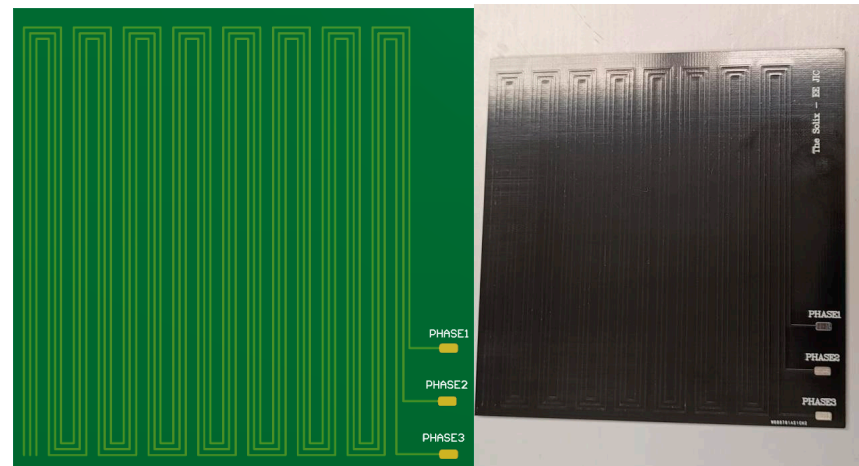


Figure 5. PCB design of the three-phase EDS, powered by three AC signals phase-shifted by 120° .

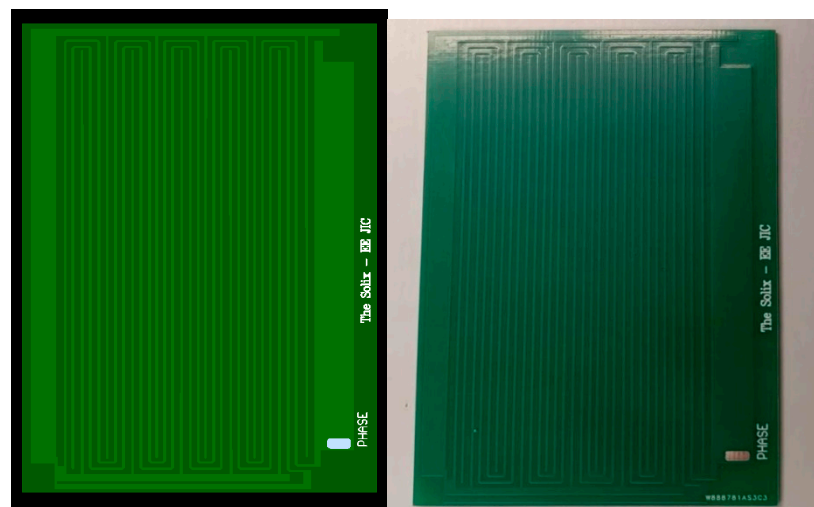


Figure 6. PCB design of the single-phase EDS, powered by a single AC signal.

4.4. Power Circuit Design

The optimal power circuit design is shown in Figure 7. This design uses a flyback converter to boost the 12 V DC input to 1.2 kV DC. However, boosting the voltage before inverting it to AC presented a challenge, as the available MOSFETs could not handle such high voltages. Instead, the authors opted to use optical solid-state relays (SSRs) for the inversion stage. Since the SSRs require a low-voltage switching signal of 1.5 V, a voltage divider circuit was added to reduce the control signal voltage. The selection of optical SSRs, which consist of an LED-driven optocoupler and a pair of back-to-back MOSFETs, as opposed to separate high-voltage MOSFETs with specialized gate drivers, was influenced by two factors. First, discrete high-voltage MOSFETs (e.g., rated at 1.5 kV) necessitate specialized gate driver circuits with galvanic isolation, floating power supply, and meticulous slew rate regulation. The use of three such drivers for three-phase output would have considerably heightened circuit complexity and expanded board size. Second, SSRs with ratings up to 1.5 kV are commercially accessible as integrated, enclosed modules. Discrete MOSFETs with drain-source breakdown voltages over 1.2 kV are infrequently found in through-hole packages appropriate for prototyping and typically need intricate heat-sinking solutions. The corresponding MATLAB/SIMULINK (R2023a) simulation circuit for the power supply is shown in Figure 8, and the control code is provided in Appendix A.



Figure 7. Block diagram of the power circuit for the EDS.

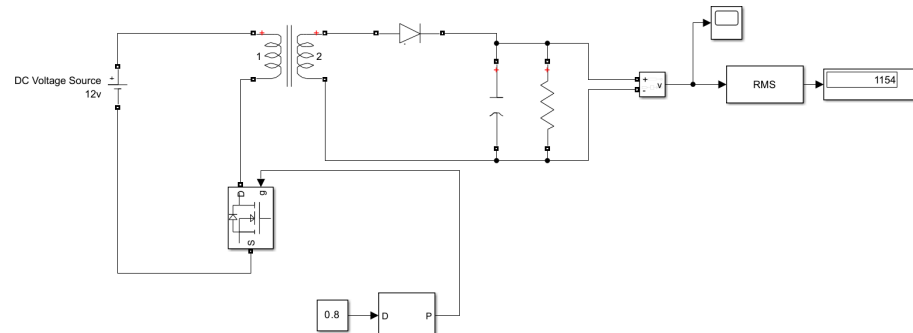


Figure 8. MATLAB/Simulink model of the power supply and inversion stage.

The approach was validated by boosting the DC voltage and then inverting it. This method allows for flexible output, as the inverted AC can easily be configured as either single-phase or three-phase. Initially, we considered using a boost chopper circuit, which comprises a MOSFET, an inductor, a diode, and a capacitor. The voltage output of the boost chopper can be calculated from the equation $V_o = \frac{V_i}{1-D}$; as such, we can calculate the required duty cycle (D) to achieve 1.2 kV with the equation $D = 1 - \frac{V_i}{V_o}$. In this case, our desired D is 0.99 but operating a boost chopper with such a high duty cycle could lead to instability [16].

Figure 8 shows MATLAB/Simulink (R2023a) model of the power supply and inversion stage. The model includes a 12 V DC source, a flyback converter (inductor L , MOSFET switch, diode D , capacitor C), a resistive voltage divider for control signal conditioning, and three solid-state relay (SSR) blocks configured with 120° phase shifts. The output shows the three-phase square wave voltages (1.2 kV peak) delivered to the EDS electrodes (resistive load).

The electrical circuit was built around the simulated design containing a DC power supply, a flyback converter, solid-state relays, an Arduino UNO, resistors and a breadboard with some wires to connect the designed circuit, as shown in Figure 9.

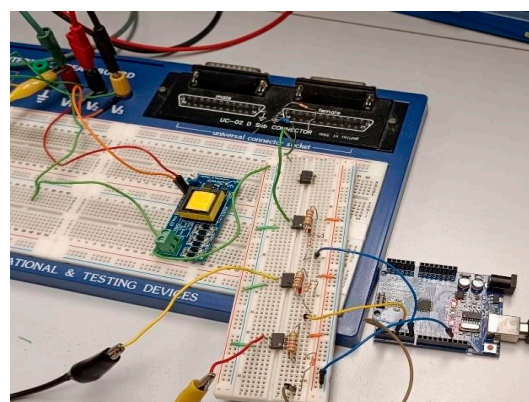


Figure 9. Power circuit comprising a flyback converter, a board with optocouplers and an Arduino module.

4.5. Testing Procedure

The electrical circuit was validated by measuring two key parameters: the boosted DC voltage from the flyback converter and the Arduino-generated signal driving the SSRs. These tests ensured the EDS received the correct power and that the circuit's output met specifications. The successful output was a three-phase AC square wave, shown in Figure 10.

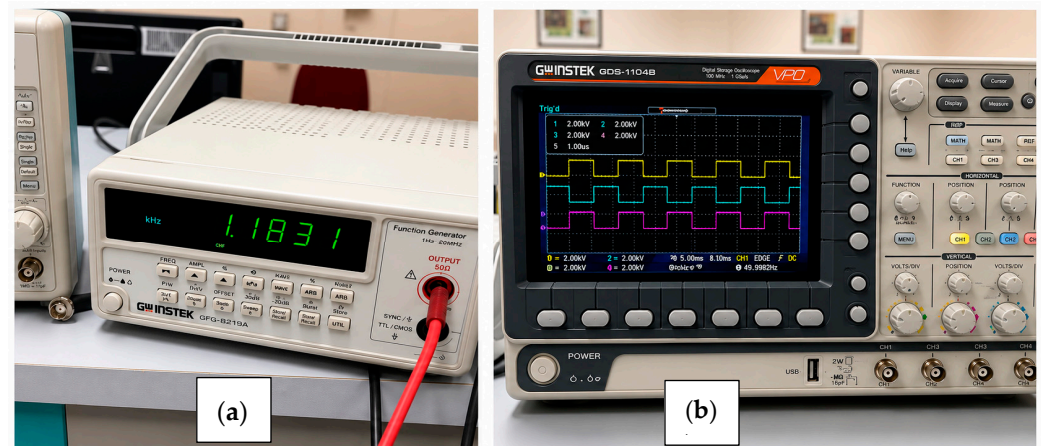


Figure 10. (a): Function generator reading showing the high DC voltage (~1.2 kV) supplied to the solid-state relay array from the flyback converter. (b): Oscilloscope capture showing the resulting three-phase AC square wave signals (Channel 1: Phase 1, Channel 2: Phase 2) generated by the SSRs and supplied to the EDS electrodes.

The testing technique that represents the effectiveness of our EDS as accurately as possible is to use several samples of sand taken from our local desert and then sieved by different sieves each with a differently sized mesh, followed by mixing the different produced samples equally by weight to ensure that the local sandstorms are simulated. To accurately measure the system's effectiveness, the sand portions are weighed on the EDS both before and after operation. This procedure was repeated for different frequencies to quantify the effect of frequency on performance, with all results tabulated. The test also included recording the effect of different duty cycles on the EDS's effectiveness. The significant range of frequencies measured was from 1 Hz up to 100 Hz, and the significant duty cycle is in the range of 40% to 70%. All experiments were conducted with ambient temperature maintained at 23 ± 2 °C and relative humidity at $48 \pm 5\%$, as measured by a calibrated digital hygrometer. These conditions represent typical indoor arid-climate laboratory environments. Each combination of frequency (1–100 Hz in 13 increments) and duty cycle (40–70%) underwent five repetitions ($n = 5$) of the dust removal test to ensure statistical reliability. Between repeats, the EDS surface was meticulously cleaned using compressed air and isopropanol before the reapplication of dust. For each test, a new 5.0 g/m^2 dust sample was uniformly applied to the active EDS surface using a calibrated sieve shaker to guarantee uniform starting dispersion. The EDS was thereafter engaged for 60 s at the set frequency and duty cycle. Afterwards, the efficiency of dust removal was determined.

4.6. Testing Results

The test dust was created from indigenous desert sand to replicate local soiling conditions. The sand was initially subjected to sieving through a series of conventional test sieves (e.g., $75 \mu\text{m}$, $150 \mu\text{m}$, $300 \mu\text{m}$) to achieve a dispersion of particle sizes. The gathered fractions were subsequently combined in similar weight proportions to provide a realistic

polydisperse sample, emulating the diverse particle sizes prevalent in natural sandstorms. Although this mixture serves as a realistic approximation, we recognize the absence of a standardized dust formulation; hence, we utilized particle size distribution data from a published Saudi Aramco study to guarantee that our mixture accurately represents regional dust characteristics.

Both PCB designs were experimentally tested, and their corresponding results are illustrated in the figures below, showing the OFF and ON states (before and after the cleaning process) to demonstrate the cleaning efficiency. Figure 11 presents the results for the single-phase PCB, while Figure 12 depicts those for the three-phase PCB.

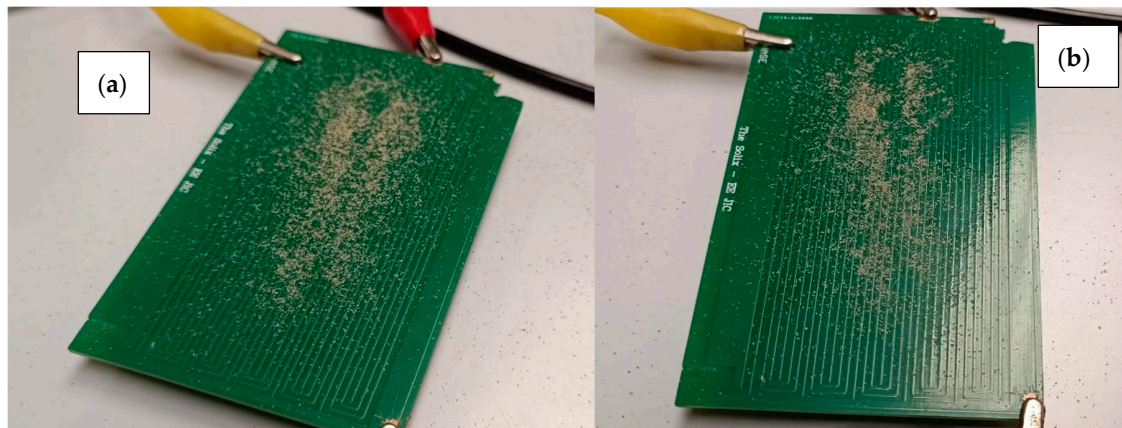


Figure 11. Illustrative images showing (a) dust deposition and (b) the surface after activation, demonstrating negligible cleaning under the tested conditions.

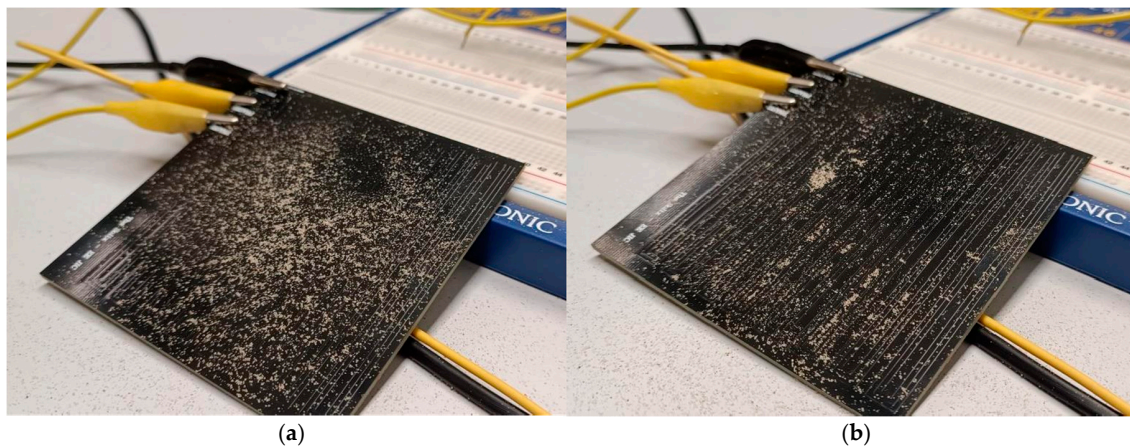


Figure 12. (a) EDS before operation and (b) EDS after operation (three-phase).

The removal efficiency was calculated as $\frac{W_{\text{initial}} - W_{\text{final}}}{W_{\text{initial}}} \times 100\%$, where W is the weight of dust on the PV module surface. For each data point, a fixed initial dust load of 5.0 g/m^2 was applied uniformly across the active surface.

Preliminary testing indicated that the single-phase configuration yielded negligible cleaning efficacy. Therefore, the subsequent comprehensive parametric study to optimize frequency and duty cycle was conducted solely on the three-phase prototype. The three-phase EDS prototype demonstrated peak dust removal efficiency of 52% under optimal operating conditions (50 Hz frequency, 66% duty cycle), as shown in Figure 13 and Table 2. The vertical axis represents the dust removal efficiency, while the horizontal axis is the frequency. The parametric study revealed a clear relationship between electrical parameters and cleaning performance, with efficiency peaking at mid-range frequencies

(40–60 Hz) and declining at higher frequencies due to reduced particle displacement per cycle. The EDS consumed 0.85 ± 0.12 Wh/m² per cleaning cycle (Figure 12). This represents approximately 0.024% of the daily energy yield from a typical PV module surface in Saudi Arabia (assuming 5.5 kWh/m²/day), confirming the energy efficiency of the EDS approach compared to conventional cleaning techniques.

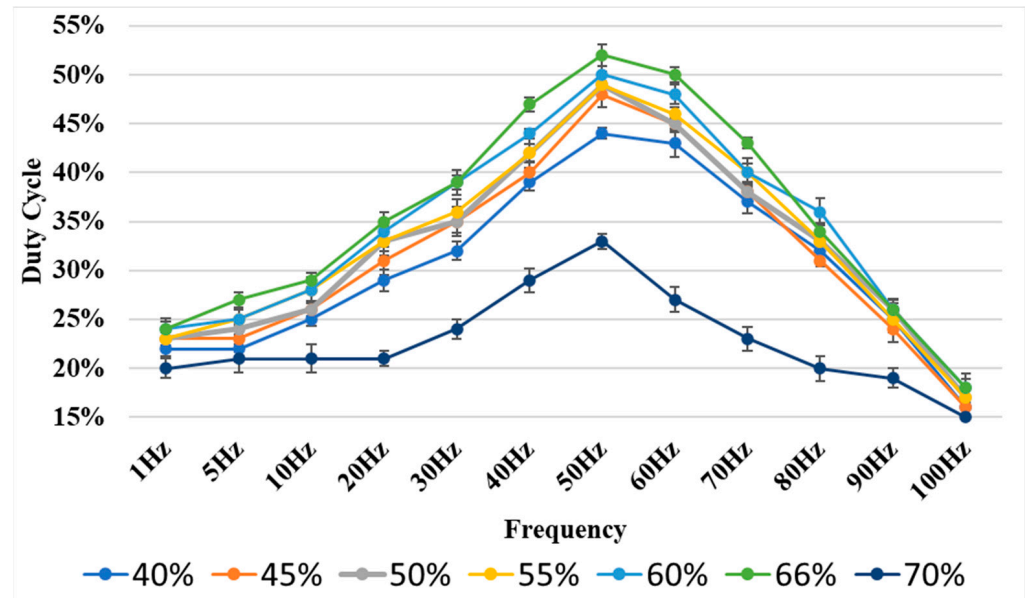


Figure 13. Dust removal efficiency (frequency/duty cycle) for the three phase EDS System.

Table 2. Dust removal efficiency (%) for the three-phase EDS prototype across different frequencies and duty cycles.

Frequency/Duty Cycle	1 Hz	5 Hz	10 Hz	20 Hz	30 Hz	40 Hz	50 Hz	60 Hz	70 Hz	80 Hz	90 Hz	100 Hz
40%	22%	22%	25%	29%	32%	39%	44%	43%	37%	32%	25%	16%
45%	23%	23%	26%	31%	35%	40%	48%	45%	38%	31%	24%	16%
50%	23%	24%	26%	33%	35%	42%	49%	45%	38%	33%	26%	17%
55%	23%	25%	28%	33%	36%	42%	49%	46%	40%	33%	25%	17%
60%	24%	25%	28%	34%	39%	44%	50%	48%	40%	36%	26%	18%
66%	24%	27%	29%	35%	39%	47%	52%	50%	43%	34%	26%	18%
70%	20%	21%	21%	21%	24%	29%	33%	27%	23%	20%	19%	15%

Each data point in Table 2 represents the average of five independent repeats, with standard deviations shown in brackets. The highest recorded efficiency of 52% was reached at 50 Hz with a 66% duty cycle, with a 95% confidence interval of $52\% \pm 1.8\%$. To evaluate if this optimum is statistically significant, two-tailed paired t-tests were performed on the 50 Hz/66% condition and surrounding operating points. The differences between 50 Hz/60% (52% vs. 50%, $p = 0.031$) and 60 Hz/66% (52% vs. 50%, $p = 0.047$) were both statistically significant at the $\alpha = 0.05$ level. This suggests that the 66% duty cycle at 50 Hz provides a minor but reliable improvement over neighboring situations. Significant declines were seen at higher frequencies (e.g., 70 Hz/66%: 43%, $p < 0.001$ compared to the optimum) and at 70% duty cycle across all frequencies ($p < 0.01$). These statistical results show that the observed peak is not due to random experimental fluctuation.

The maximum removal efficiency of 52% is derived from experimental results rather than the COMSOL simulation. The simulation predicts the electric field distribution and qualitatively validates the travelling wave process; nevertheless, it does not directly

calculate removal efficiency. The simulation results validate the final design by demonstrating that our three-phase electrode configuration produces adequate field gradients (approximately 10^6 V/m) to induce particle-repelling forces, elucidating the failure of the single-phase design due to the lack of a directional travelling wave, and informing our choice of electrode geometry as a balance between field strength and manufacturability. A quantitative model for predicting efficiency necessitates integration with particle dynamics, which is beyond the scope of this study; however, the COMSOL model served as an effective screening instrument for refining the selection of electrode designs before the experimental phase. It is important to clarify that the reported peak removal efficiency of 52% is derived from experimental measurements, not from the COMSOL simulation.

4.7. Optical Performance and Loss–Gain Analysis

A comprehensive assessment of EDS viability must consider both the advantages of dust removal and the intrinsic limitations posed by the technology. This section determines the optical and energy trade-offs with a comprehensive loss–gain approach.

The fundamental optical loss resulting from dust formation was assessed by a soiling study carried out over a 7-day duration in a realistic dry environment (i.e., Jubail Industrial City, Saudi Arabia). A clean, bare solar glass specimen comparable to commercial PV cover glass underwent outdoor exposure testing. Any initial cleaning routine was intentionally skipped, letting ambient conditions act on the surface without interference. Dust deposition was quantified daily with a gravimetric and optical transmittance techniques. A spectrophotometer (Ocean Insight FLAME-S-VIS-NIR) was utilized to measure the glass's initial clean-state transmittance, $T_o(\lambda)$, across the full solar range from 300 to 1100 nm. Each day, the samples were placed outdoors and later weighed on a clean Sartorius CPA225D balance to calculate the surface dust density ρ_d (g/m²) in grams per square meter.

The daily transmittance spectra $T_d(\lambda)$ were collected carefully so that the dust film remained untouched. The total optical transmittance loss L_d was determined by comparing the integrated solar-weighted values (weighted by AM1.5, $G(\lambda)$) to the clean reference as follows:

$$L_d = \left(1 - \frac{\int_{300}^{1100} T_d(\lambda) \cdot G(\lambda) d\lambda}{\int_{300}^{1100} T_o(\lambda) \cdot G(\lambda) d\lambda} \right) \times 100\% \quad (1)$$

4.7.1. Dust-Induced Optical Loss Without EDS

Under the investigated soiling conditions, accumulation of dust over a 7-day duration led to an average optical transmission reduction of 8.62% compared to a clean PV surface. This loss shows the performance decrease that would occur without any cleaning action.

4.7.2. Dust Removal Gain with EDS

The three-phase EDS system proposed in this study attained a maximum dust removal efficiency of 52% under optimal operating conditions (50 Hz, 66% duty cycle). This is equivalent to an optical loss of 4.48%.

$$\text{Mitigated Loss} = 8.62\% \times 0.52 = 4.48\%$$

Therefore, the net optical gain from the dust removal is:

$$\Delta_{dust} = 8.62\% - 4.48\% = 4.14\%$$

This value represents the fraction of soiling loss recovered by EDS activation. The residual 4.14% is the optical loss that persists after the EDS removes 52% of the dust; it is not a net gain.

4.7.3. Inherent Optical Loss of the EDS Layer

Due to the non-transparent nature of the PCB substrate and electrode materials, the EDS layer has a fixed optical transmission loss. It can be shown that EDS assembly introduces a substantial and fixed optical transmission loss across the solar spectrum, quantified as 7.9%. This value is derived by comparing the average transmittance of the Reference Glass (96.2%) with that of the EDS assembly (88.3%). This loss is independent of cleaning cycles and represents a permanent reduction in incident irradiance when the EDS is installed. The results of optical transmittance indicated considerable performance constraints in the PCB-based solution. The bare PCB has significantly more attenuation (48.7%), highlighting that the PCB substrate is the main factor contributing to the optical loss. Figure 14 illustrates that the whole EDS assembly demonstrates significant absorption relative to conventional solar glass, especially within the visible spectrum (380–700 nm). The measurements in Figure 14 were obtained using a UV-Vis-NIR spectrophotometer with an integrating sphere. Three samples were measured: reference solar glass, bare PCB electrodes (FR-4 + copper), and the complete PCB-based EDS assembly (FR-4 + copper + solder mask).

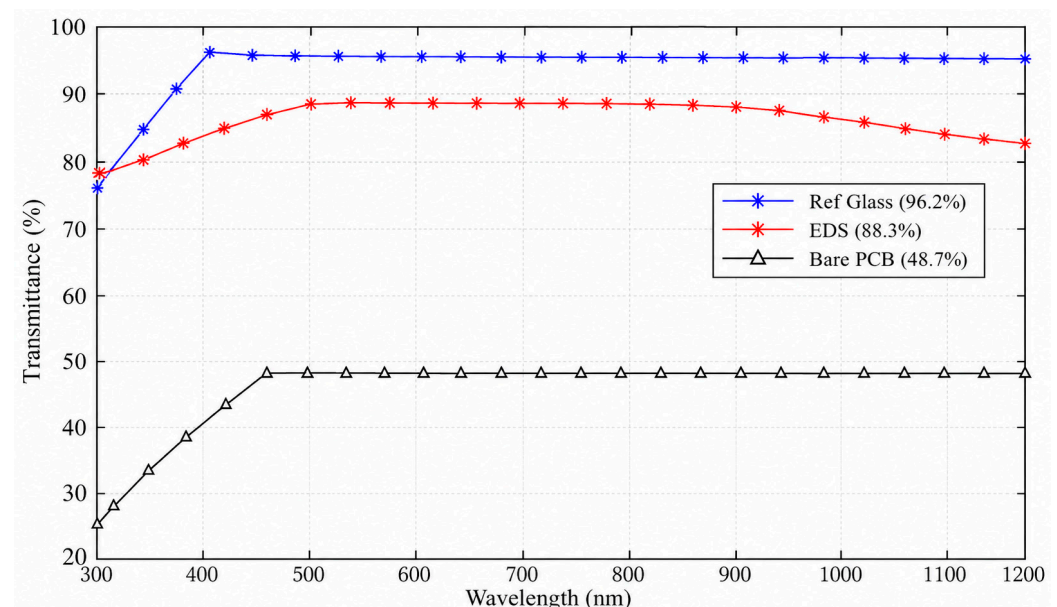


Figure 14. Spectral transmittance comparison of reference solar glass, bare PCB electrodes, and an EDS assembly across the sun's spectrum.

4.7.4. Operational Energy Loss

For a typical PV module in Saudi Arabia with a daily energy yield of 5.5 kWh/m², this is equivalent to an energy loss of 0.0155% per cycle. When expressed as an optical loss equivalent, this is negligible (0.024%) and does not significantly affect the net energy balance.

4.7.5. Net Optical Performance After One Week

The cumulative optical change following one week of EDS operation is computed as follows:

$$\text{Net Gain} = \Delta_{\text{dust}} - \text{EDS loss} = 4.14\% - 7.9\% = -3.76\%$$

This study shows the significance of site-specific soiling rates and EDS material transparency in determining system viability. In areas with heavier dust deposition, the dust removal advantage will quickly overcome the fixed EDS loss, increasing the economic and energy return.

5. Discussion

Through the use of modeling, simulation, and experiments, a thorough evaluation of the performance and viability of EDSs was conducted in order to determine whether they could function as a sustainable alternative to the traditional ways of cleaning PV module surfaces. The results of this study are consistent with and build upon recent studies and provide practical insights into the limitations of using EDSs in real-world contexts.

5.1. Alignment with Previous Research

This study corroborates the fundamental principles that have been described in previous literature, in particular the studies of Bernard et al. [17] and Guo et al., [27] and highlights the fact that multi-phase EDS setups are an effective method of increasing dust removal efficiency when operating under low-power environments. With a frequency of 50 Hz and a duty cycle of 66%, the three-phase EDS design was able to reach its peak performance. At this point, the design was able to achieve a dust removal efficiency of roughly 52%. The results of this study are in close agreement with those of Guo et al. (2019) [27], who conducted field experiments and reported similar trends. In particular, they noted that cleaning efficiency declined over time as a result of dust cementation, which is a limitation that we also observed. However, we were able to minimize the impact of this limitation by optimizing the parameters of the EDS control circuit. Table 3 provides a table of comparison of the present study with the literature.

Table 3. Comparison of the present study with the literature.

Feature	Bernard et al. [13,17]	Guo et al. [27]	Kawamoto [5,11]	Present Study
Electrode material	ITO	ITO	Copper	Copper
Substrate	Willow Glass (flexible)	Glass	Glass/PCB	FR-4 PCB
Transparency	High (around 85%)	High (around 85%)	Low to moderate	Low (<20% bare PCB)
Electrode width (μm)	80	-	100–200	80
Electrode spacing (μm)	700	-	500–1000	700
Number of phases	3	2	2 or 3	3
Excitation waveform	Sinusoidal/Square	Sinusoidal	Square	Square
Peak voltage (kV)	1.0–1.5	9	2–5	1.2
Optimal frequency (Hz)	0.1–10	1	1–10	50
Dust removal efficiency	95%	40%	50–70%	52%
EDS optical loss	5%	5–10%	Not reported	7.9%
Power consumption (Wh/m^2)	<0.2	Not reported	~1–2	0.85
Test environment	Lab (controlled)	Outdoor (humid)	Lab	Lab (48% RH)
Repetitions (n)	Not specified	Not specified	Not specified	5

The comparison table (Table 3) demonstrates a significant difference in performance: our PCB-based prototype achieves 52% dust removal efficiency, whereas transparent EDS systems in the literature regularly achieve above 90% [12,13,17]. This disparity must be accounted for methodically. Our system's poor performance can be attributed to a variety of design choices and real-world limitations of the low-cost PCB development that we adopted. In summary, 52% efficiency is a reasonable performance for a low-cost built PCB-based system that operates with natural desert dust and mild humidity.

5.2. Comparison of Simulation and Experimental Results

The COMSOL simulations forecasted significant electric field gradients (1.2 kV) capable of generating particle-repelling forces, hence validating the theoretical viability of our electrode design. Nonetheless, a direct quantitative comparison with experimental cleaning efficiency is intricate, as the simulation models the field, while the experiment assesses the macroscopic result of particle removal, influenced by factors such as particle adhesion and

inter-particle cohesion, which are not represented in the electrostatic model. The simulation qualitatively confirmed that our three-phase design could generate a traveling wave, which was empirically demonstrated to be significantly more successful than the single-phase design. This study's sub-optimal cleaning efficiency relative to the 90% documented in certain research [13] can be ascribed to practical constraints absent in the ideal simulation, including the increased electrode spacing required by our PCB manufacturing process and possible non-ideal field distribution resulting from substrate characteristics.

5.3. Key Insights and Interpretation

The single-phase system's preliminary performance was minimal, demonstrating the vital significance of creating a moving electric field for successful dust removal. This qualitative observation is consistent with established theory: a single-phase, oscillating field primarily agitates particles in place, whereas the three-phase system's traveling wave generates a uniform, directional force that acts as a conveyor belt, systematically transporting dust off the PV module surface.

The COMSOL Multiphysics simulations validated the three-phase technique, demonstrating that an electric field gradient of ~ 1.2 kV can create repulsive electrostatic and dielectrophoretic forces on particles. These models were critical for refining operational factors including phase sequencing, voltage amplitude, and electrode spacing before physical prototyping. The experimental efficiency illustrates the impact of real production constraints. The prototype's maximum efficiency was most likely constrained by design tradeoffs, such as the increased electrode pitch required by our PCB fabrication process, which reduces field strength and gradient relative to the ideal computed model. Electric field performance in humid conditions will be lower than that predicted by the COMSOL model, and the simulation should be viewed as an idealized upper-bound representation valid only in dry conditions. This emphasizes the need for field validation and adaptive management strategies to mitigate the environmental implications.

The loss–gain study presented in this study shows that the present PCB-based prototype has a net negative optical change of -3.76% throughout a seven-day cleaning cycle under measured soiling circumstances (8.62% weekly loss). The fixed EDS optical loss surpasses the recovered soiling loss. This negative conclusion is this study's main finding: rather than establishing feasibility, this study presents a mathematical framework for determining the conditions under which EDS becomes net-positive. Specifically, the system produces a positive energy return only when the soiling loss per cleaning interval surpasses about 15% for the present prototype, or when the EDS optical loss is lower than approximately 4.8% for the tested soiling rate. The parametric optimization technique and loss–gain analytical tool, which allow for site-specific feasibility assessments prior to deployment, are therefore this study's main strengths.

Multiple EDS units in utility-scale PV farms may influence its power injection profile. The risk is minimal due to low power usage of the EDS, short cleaning cycles (60 s), and scheduling during low grid congestion (e.g., early morning or late afternoon). Even large farms' cumulative EDS power use is orders-of-magnitude lower than their output. To smooth load profiles, inverter cluster activation times may be staggered. While EDS operation is unlikely to affect grid export, large installations may benefit from coordinated scheduling.

5.4. Broader Implications

This study emphasizes the effectiveness of EDS as a low-maintenance, waterless cleaning option that supports global sustainability goals, particularly in regions with limited water resources. It acknowledges the limitations of the method. EDS technology

has the potential to significantly lower the total cost of operation by rendering solar farms water-independent and minimizing operational downtime. The results indicate potential applications in arid regions prone to sandstorms, which diminish the efficiency and longevity of the PV module surface.

EDS aligns with the UN Sustainable Development Goals, specifically SDG 6 (clean water and sanitation) and SDG 7 (affordable and clean energy) by promoting water conservation and enhancing the reliability of solar energy.

A key observation is that the fixed optical loss of the PCB-based EDS may outweigh the cleaning gain in low-soiling regions, as evidenced by this study's net negative optical change after seven days. Viability requires that the recovered transmission from dust removal surpasses the total of the fixed EDS loss and operational energy cost, which is typically met only when soiling losses exceed 15% every cleaning interval. Adopting high-transmittance materials such as ITO, AZO, or silver nanowires, all of which have been shown in the literature to have optical losses of less than 5%, is the path to widespread deployment. Our loss–gain approach provides a quantitative instrument for site-specific assessment: for example, an EDS with a 4% fixed loss and 70% efficiency would result in a net gain in locations with weekly soiling levels above 6%, but would be ineffective where soiling levels were lower. It is much better to prioritize transparent EDS variants with less than 5% optical loss since these would generate net-positive returns under mild soiling and significantly broaden the technology's geographic applicability.

5.5. Limitations of This Study

The opaque FR-4 PCB substrate facilitates rapid prototyping but incurs an optical loss. Consequently, the prototype functions as a development platform, with optimized parameters intended for future transfer to transparent substrates. All investigations were conducted under controlled laboratory circumstances utilizing artificially produced desert dust, which may not entirely replicate the intricacies of field soiling, including cementation, humidity influences, etc. Also, the loss–gain methodology employs a single location, seven-day soiling analysis, and necessitates site-specific input data to yield precise projections for alternative locations. The scalability to utility-scale PV farms and the long-term endurance of electrodes have not yet been investigated.

A significant limitation of this study is that all experiments were carried out in controlled laboratory conditions, with artificially manufactured desert dust. In fact, soiling of solar modules in arid areas is caused by a complex combination of climatic factors, which can have a considerable impact on EDS performance. The dust removal efficiency reported in this study is an upper bound estimate for ideal laboratory conditions. In actual outdoor circumstances, we anticipate decreasing efficiency due to humidity influences, dust cementation, dynamic soiling processes, and long-term material deterioration.

6. Conclusions and Recommendations for Future Work

This study has successfully designed a low-cost, PCB-based EDS for dust removal from PV module surfaces. The three-phase excitation configuration demonstrated superior performance compared to single-phase designs, achieving a peak dust removal efficiency of 52% under optimized operating conditions of 50 Hz frequency and 66% duty cycle while maintaining a low operational energy consumption of 0.85 Wh/m² per cleaning cycle.

The key contribution of this study is the establishment of a holistic loss–gain framework that quantitatively evaluates the essential trade-offs in EDS viability. This framework accounts for the optical loss due to dust accumulation, measured at 8.62% over seven days without cleaning; the inherent optical transmission loss of the EDS material, which was

7.9%; and the minimal operational energy loss, equivalent to approximately 0.0155% of daily PV yield.

Although the 7.9% optical loss of the PCB-based prototype would undermine any economic advantage in a practical PV system, the loss–gain framework indicates that transparent EDS designs with less than 5% loss could attain a net-positive energy yield under moderate soiling. Furthermore, the low-cost PCB platform functions solely as a development tool to refine electrode geometry and drive parameters prior to investing in costly transparent materials.

As justified in this study, the PCB prototype is useful for low-cost parametric optimization, but practical deployment requires a transparent substrate/electrode design with substantially lower optical loss and outdoor durability validation. For future real-world deployment, the optimized design parameters, such as electrode geometry and signal characteristics, must be adapted to scalable, transparent, and durable substrates. Materials such as ITO- or AZO-coated flexible polymers should be employed to substantially reduce the inherent optical penalty. Subsequent research should focus on long-term environmental durability, encapsulation methods suited for harsh climates, and extended field trials under varying soiling and humidity conditions. Additionally, integrating EDS activation with soiling sensors and predictive cleaning algorithms could further enhance energy savings and operational reliability. This study lays a necessary foundation for the development of economical, sustainable, and effective EDS solutions to support solar energy efficiency in dust-affected regions globally. Closed-loop control, in which EDS parameters are modified in real time based on dust observations and using soiling sensors, is one potential future research direction. This would result in cleaning only when needed, adjusting for dust type, and coordinating many units to avoid load spikes, reducing energy consumption and electrode deterioration.

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Conflicts of Interest: The authors declare no conflict of interest

Abbreviations

PV	Photovoltaic
EDS	Electrodynamic Screens (or Electrodynamic Screen)
PCB	Printed Circuit Board
ITO	Indium Tin Oxide
OCA	Optically Clear Adhesive
AC	Alternating Current
DC	Direct Current
SSR	Solid-State Relay
CAD	Computer-Aided Design
FEM	Finite Element Method (or Modeling)
UV	Ultraviolet
NASA	National Aeronautics and Space Administration
OSM	Outdoor Soiling Microscopy

AZO	Aluminum-doped Zinc Oxide
PET	Polyethylene Terephthalate
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
UN	United Nations
SDG	Sustainable Development Goals

Appendix A

Arduino Code used for power circuit:

```
// Pin definitions
const int pins[] = {2, 4, 7}; // Phase 1, Phase 2, Phase 3
// Frequency and duty cycle control int freq = 50; // Frequency in Hz
int duty = 66; // Duty cycle in percentage (default: 66%)
unsigned long period; // Period in microseconds unsigned long onTime; // ON time
in microseconds unsigned long start;
void setup() {
  for (int i = 0; i < 3; i++) {
    pinMode(pins[i], OUTPUT); // Initialize all pins as OUTPUT digitalWrite(pins[i],
LOW); // Set all pins to LOW initially
  }
  period = 1,000,000/freq; // Calculate period in microseconds
  onTime = (period * duty)/100; // Calculate ON time based on duty cycle start
= micros(); // Record the starting time
}
void loop() {
  unsigned long elapsed = micros() – start;
  // Calculate phase based on elapsed time int phase = (elapsed/(period/3)) % 3;
  // Determine ON/OFF state based on duty cycle for (int i = 0; i < 3; i++) {
  if (i == phase) {
    digitalWrite(pins[i], LOW); // OFF phase
  } else {
    // Check if the ON time is within the duty cycle window unsigned long phaseElapsed
= (elapsed % (period/3)); if (phaseElapsed < onTime) {
      digitalWrite(pins[i], HIGH); // ON within the duty cycle
    } else {
      digitalWrite(pins[i], LOW); // OFF outside the duty cycle
    }
  }
  // Reset the start time to avoid overflow if (elapsed >= period) {
  start += period;
  }
}
```

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