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# A comprehensive analysis of the electric field distribution in an electrodynamic screen

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ABSTRACT

The electrodynamic screen, or EDS, has shown promising results in mitigation of dust accumulation losses in solar energy harvesting systems. In this paper, the electric field distributions in two EDS configurations have been thoroughly investigated. The analytical solutions for the electric potential and electric field distribution in the first EDS configuration have been provided and corroborated numerically using finite element analysis (FEA) software. The electrostatic model of second EDS configuration has been developed in the FEA software and its electric field distribution has been analyzed numerically. A comparison has been made between the two configurations regarding dust removal efficiency.



## Introduction

Dust accumulation on the optical surfaces of solar energy harvesting devices such as flat-plate photovoltaic (PV) panels, concentrated solar mirrors, and concentrated photovoltaics (CPV) systems has an adverse impact on their performance by scattering and absorption of the incident sunlight. A literature survey on the dust accumulation problem by Sayyah et al. [1] has shown that dust deposition can cause up to 1% loss in the daily output power in flat-plate PV installations located in arid and semi-arid areas of the world, where the average of annual solar insolation is more than 4.5 kWh/m$^2$/day. Accumulation of carbon particulates, caused by incomplete combustion of fuels in motor vehicles and industrial plants, also deteriorates the performance of the PV installation in urban areas [2,3]. The dust accumulation problem is more detrimental for the performance of concentrated solar-energy harvesting systems, as they are sensitive to direct normal irradiance (DNI), while flat-plate PV panels are capable of using scattered sunlight in power generation [4].

In order to restore the efficiency of the solar energy harvesting systems, use of high-pressure water jets, sometimes mixed with detergents, is the most commonly-practiced manual cleaning method in large-scale solar plants. This method, however, requires significant amounts of distilled or demineralized water which is scant in arid zones and also is labor-intensive, as it requires a team of trained personnel to perform the cleaning task. Furthermore, water cleaning use is not scalable, i.e., lack of it will impede growth of CSP and PV plants. Recently, there have been some advancements in utilizing robotic devices in cleaning flat-plate PV panels [5], yet they are still in the developmental stage, require water resources for cleaning, and their scalability in large-scale solar plants has not been well established.

In order to cope with the shortcomings of commonly-practiced cleaning methods, the concept of automatic dust removal using electrostatic forces is in developmental stages and on a commercialization path. The general idea of automatic dust removal was initially introduced by Tatom et al. [6] at NASA and then developed by Masuda et al. [7,8] at the University of Tokyo in the 1970s for transporting charged aerosol particles. Although the concept has found a niche application for dust removal on solar modules to be used in Mars exploration missions [9–12], there have been significant endeavors to adopt this technology to mitigate dust accumulation losses in solar-energy harvesting plants [13,14]. Electrodynamic screen (EDS) technology represents a viable, promising solution as it does not require water resources or mechanical movement in removing dust particles, and it is an extremely low-power technology that can be fed from the harvesting device itself and does not need an external power source. The EDS consists of inter-digitated electrodes deposited on a glass substrate, encapsulated by one or more transparent dielectric

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coating(s) that protect the electrodes from direct exposure to the outdoor environment. The EDS can be easily integrated onto a PV panel or a reflecting mirror in concentrated solar power (CSP) applications. The electrodes are connected to a single-phase or multi-phase power supply that energizes the electrodes with a specified waveform pattern and frequency. Once the deposited dust particles are charged sufficiently, they are removed by the Coulomb force from the EDS surface.

Electric field distribution model plays a decisive role in performance evaluation of the EDS and in how to increase its dust removal efficiency by manipulating the design parameters as well as material selection. This paper deals with the analysis of electric field distributions in two EDS configurations. The organization of this paper is as follows: the analytical solutions for the electric potential and electric field components for the first EDS configuration are presented in the next section, followed by the corroboration of analytical solutions. Thereafter we provide the simulation results for the electric field distribution in the second EDS configuration and a comparison between two configurations. Finally, the last section provides the conclusions of the paper.

## Analytical solution for the electric field

In this section, we provide closed-form solutions for the electric field and electric potential in the first EDS configuration. The analytical solutions show explicitly how various design parameters play a role in the electric field distribution and provide valuable insight through the physical model of the problem. The solutions can be easily implemented for dust-particle trajectory studies.

### *First EDS configuration*

Fig. 1 depicts the configuration of an EDS in the $xy$-plane. The electrodes are deposited on a glass substrate; their height is neglected in the calculations. In Fig. 1, the width of the electrodes and inter-electrode spacing are denoted as $w$ and $g$, respectively. The electrodes are encapsulated by two layers of transparent dielectric materials 1 and 2, with relative permittivities of $\varepsilon_{d1}$ and $\varepsilon_{d2}$, respectively. As an example in the practice, dielectric 1 is optically clear adhesive (OCA) and dielectric 2 is a very thin borosilicate glass. The electrodes have the same size and inter-electrode spacing and are connected to a three-phase power supply that provides traveling-waves to repel and convey dust particles. As the output of the power supply for energizing the electrodes is known at any given time $t$, regardless of the type of waveform, the electrode voltages are known at each time instant and are represented as a function of time.

Since the electrodes are connected to a three-phase power supply, the fundamental spatial period, denoted as $T_s$, is expressed as

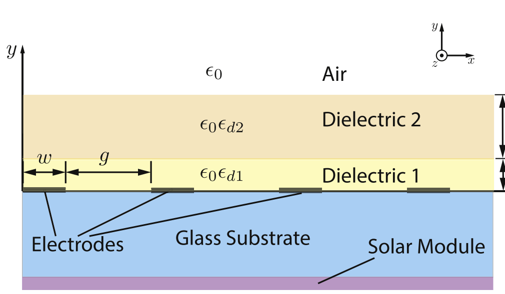


**Fig. 1.** Schematic of the EDS configuration with two stacked layers of transparent dielectric coatings. The solar module could be a photovoltaic cell or a reflecting mirror film in a concentrated solar power application. The dust particles, not depicted in the sketch, deposit on the dielectric layer 2. The electrodes are connected to a three-phase power supply. The problem is assumed to be infinite in the $z$ direction (normal to the page).

$$T_s = 3(w+g). \tag{1}$$

We assume that the electric field distribution is not affected by the charge of deposited dust particles on the EDS surface, i.e., they carry no net charge. Hence, in the absence of net electric charge in the region above the EDS surface, we can write Laplace's equation for the electric potential in the air, denoted as $\phi_a(x,y)$ as follows:

$$\frac{\partial \phi_a^2(x,y)}{\partial x^2} + \frac{\partial \phi_a^2(x,y)}{\partial y^2} = 0, \quad 0 \le x \le T_s, \quad \delta_1+\delta_2 \le y < \infty \tag{2}$$

We have added the subscript "$a$" that highlights the electric potential in the air. Similarly, the subscripts "$d1$" and "$d2$" denote the potentials in the dielectric layers 1 and 2, respectively. The goal is to find the electric potential and the electric field components in the two layers of the dielectric materials and air. The electric field components in the air are the ones exerted on the dust particles and effect the dust removal process. However, the electric field solutions within two dielectric layers can be used for further analysis of electric stress and dielectric breakdown.

### *Electric potential*

The electric potentials at $y=0$, $y=\delta_1$, and $y=\delta_1+\delta_2$ (air/dielectric 2 boundary) in Fig. 1 are functions of $x$ and are respectively expressed as:

$$v_m(x) = \sum_{k=0}^{\infty} a_k \cos(k\Omega_0 x) + b_k \sin(k\Omega_0 x), \tag{3}$$

$$u_m(x) = \sum_{k=0}^{\infty} g_k \cos(k\Omega_0 x) + h_k \sin(k\Omega_0 x), \tag{4}$$

$$w_m(x) = \sum_{k=0}^{\infty} p_k \cos(k\Omega_0 x) + q_k \sin(k\Omega_0 x), \tag{5}$$

where $a_k$, $b_k$, $g_k$, $h_k$, $p_k$, and $q_k$ are the Fourier coefficients, and $\Omega_0 = \frac{2\pi}{T_s}$. The Fourier coefficients $a_k$ and $b_k$ are known at each time instant, as the electric potential applied to the electrodes is known, and $g_k, h_k, p_k$, and $q_k$ are unknown Fourier coefficients that need to be calculated. We can assume that the electric potential varies approximately linearly between adjacent electrodes at $y=0$. Because applied voltages are time varying, the introduced Fourier coefficients are also functions of time; for instance $a_k(t)$ and $b_k(t)$. For the ease of representation, however, we drop the dependency upon "$t$". We may write the electric potential inside the dielectric materials in such a way that both boundary conditions at their boundaries are satisfied. We assume the potential inside the first dielectric is a summation of two functions, one a function of $v_m$ and the other a function of $u_m$, as defined in Eqs. (3) and (4), respectively:

$$\phi_{d1}(x,y) = f_1(v_m) + f_2(u_m), \quad 0 \le x \le T_s, \quad 0 \le y \le \delta_1 \tag{6}$$

in which the functions $f_1$ and $f_2$ are variables of both $x$ and $y$. The function $f_1(v_m)$ is written as:

$$f_1(v_m) = v_m\left(A_1 e^{-k\Omega_0 y} + A_2 e^{k\Omega_0 y}\right), \tag{7}$$

where the constants $A_1$ and $A_2$ need to be obtained. Since we must have the boundary conditions at $y=0$ and $y=\delta_1$ satisfied, we must have $f_1(v_m)=v_m$ and $f_1(v_m)=0$, respectively. Hence,

$$\begin{cases} A_1 + A_2 = 1, & \text{if } y = 0 \\ A_1 e^{-k\Omega_0\delta_1} + A_2 e^{k\Omega_0\delta_1} = 0 & \text{if } y = \delta_1 \end{cases} \tag{8}$$

The constants $A_1$ and $A_2$ in the Eq. (8) are obtained as: