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Optimizing sun-tracking angle for higher irradiance collection of PV panels using a particle-based dust accumulation model with gravity effect

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ABSTRACT

Dust accumulation on a solar panel surface can significantly hinder optical to electrical energy conversion and leads to photovoltaic energy degradation. In clean conditions, maximum absorption efficiency is achieved when the solar panel is orthogonal to the incident light (i.e., dual-axis solar tracker). However, when natural pollutants accumulate on the surface, panel position needs to be adjusted in order to increase the amount of sunlight energy absorbed by the solar panel. A numerical model is proposed in this study to estimate dust accumulation on the surface of a two-dimensional panel, in which the adsorption/desorption rate of airborne dust under the effect of gravity and other dust-panel interaction (i.e., Van der Waals and electrostatic effects) can be calculated. The model is developed through precise attachment/detachment force and momentum analyses, where the time-varying dust coverage is formulated via a first-order differential equation which includes the gravitational desorption rate. Although there is a diverse composition of natural soiling, only dry dust particles are considered at this stage. The model is first validated with experimental data, and then the steady-state solution of this model is obtained to search for the optimal tilt angle for maximum absorption efficiency when the cell is subject to AM1.5 solar irradiance at different solar zenith angles. The extra required tilt angle is an increasing function of panel length and friction coefficient. The optimized tilt angle panel is able to provide better daily performance depending on panel length and surface friction coefficient. Optimization results show that by applying the proposed optimal tilt angle adjustment protocol, the daily absorption efficiency of a silicon solar panel can be improved by up to 24% depending on the friction coefficient compared to the dual-axis solar tracking system.

1. Introduction

Despite the fact that the majority of today's global energy demand is satisfied through non-renewable sources such as fossil fuels, coal and natural gas, renewable energy sources are gaining ever-increasing attention due to sustainability and less negative environmental impacts (Energy, 2016). Solar energy technology stands on the top of the list of renewable energy investments, and is expected to constitute a major fraction of power supply for both terrestrial and space applications in the near future.

Photovoltaic (PV) solar cells are the main components of solar energy generation that convert sunlight irradiation to electricity. Generally, the performance of a solar cell can be affected by both deterministic and stochastic factors. Deterministic factors consist of the material of solar panel, cell design style and geographical location in stationary earth applications. These factors determine the long term average efficiency of the cell and can be optimally engineered. Stochastic factors on the other hand include variable environmental conditions such as local solar intensity, dust, temperature, humidity, wind, rain, shading and soiling losses (Ahmed et al., 2013; Maghami et al., 2016). Among these factors, dust accumulation on the surface of the cell is one of the most important and common causes of efficiency degradation. Normally, airborne dust is generated from multiple sources, such as pollutants in wind, volcanic eruptions and vehicle movements (Maghami et al., 2016). Dust particles deposit on the panel surface and gradually form an opaque area that prevents the sunlight from reaching the absorbing layer. Rather, it parasitically absorbs the radiated energy or reflects it back to earth. Since the output current of a PV cell is directly related to the absorbed radiation in silicon, less absorption due to dusty surface means less overall efficiency. Performance degradation due to dust accumulation has been formally studied and measured in numerous previous studies (Hottel and Woertz, 1942; Garg, 1974; Salim et al., 1988; Kazem et al., 2014; Kaldellis and Kapsali, 2011). It has been found that the accumulated dust on the solar panel can negatively affect the efficiency of photovoltaic energy harvesting in both short term and long term time scales. Therefore, it is

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Nomenclature

ξ	surface coverage (–)
S_{dust}	area covered by dust particles (m^2)
S_{total}	total solar cell surface area (m^2)
R_{ad}	adsorption rate (s^{-1})
R_{de}	desorption rate (s^{-1})
$R_{de,0}$	natural desorption rate (s^{-1})
$R_{de,g}$	gravitational desorption rate (s^{-1})
c_{ad}	adsorption rate constant (s^{-1})
c_{dep}	deposition constant (s^{-1})
c_{res}	resuspension constant (s^{-1})
S_{ad}	adsorption ratio of dust particles (–)
R	gas constant ($J{\cdot}mol^{-1}{\cdot}K^{-1}$)
T	air temperature (K)
E_{ad}	enthalpy for natural adsorption ($kJ{\cdot}mol^{-1}$)
E_{de}	enthalpy for natural desorption ($kJ{\cdot}mol^{-1}$)
E_g	enthalpy for gravitational desorption ($kJ{\cdot}mol^{-1}$)
F_{at}	attachment force (N)
F_{de}	detachment force (N)
F_{vdw}	Van der Waals force (N)
F_E	electrostatic force (N)
F_{ei}	electrostatic image force (N)
F_{edl}	electrostatic double layer force (N)
F_{ef}	electrical field force (N)
G	gravity of a dust particle (N)
h_{ϖ}	Lifshitz constant (eV)
z_0^*	average distance between molecules of dust and solar panel (m)
Q_{dust}	electric charge of a dust particle (C)
ϵ_0	permittivity of free space ($F{\cdot}m^{-1}$)
U	electric potential difference (V)
σ	surface charge density ($C{\cdot}m^{-2}$)
I	average momentum of dust particles ($kg{\cdot}m{\cdot}s^{-1}$)
m	dust particle Mass (kg)
ρ_d	dust density ($kg{\cdot}m^{-3}$)
r_d	particle radius (m)
μ	surface friction coefficient (-)
g	gravitational acceleration ($m{\cdot}s^{-2}$)
β	surface tilt angle (degree)
$\overline{V}$	average velocity of dust particles ($m{\cdot}s^{-1}$)
$\overline{L}$	length of the solar panel (m)
a	particle acceleration ($m{\cdot}s^{-2}$)
θ	incident angle (degree)
φ	solar zenith angle (degree)
$I(\omega)$	solar irradiance ($W{\cdot}m^{-2}nm^{-1}$)
$R(\omega,\theta)^*$	reflectance of the cell at wavelength ω and incident angle θ (–)
$F(\theta,\beta)^*$	absorption efficiency at incident angle θ and tilt angle β (–)
γ	average transmission of a single dust layer (–)
$AL(\theta)$	angular reflection loss (–)
a_r	angular loss coefficient (–)
n_1	refractive index of air (–)
n_2	refractive index of silicon (–)
n_ω^*	real part of refractive index of silicon at wavelength ω (–)
k_ω^*	imaginary part of refractive index of silicon at wavelength ω (–)
R_s	reflectance of s-polarized light (–)
R_p	reflectance of p-polarized light (–)
E_{loss}	insolation loss (–)
E_{dust}	energy absorbed by the dusty panel (J)
E_{clean}	energy absorbed by the clean panel (J)

imperative to study the dynamics of the dust particles on the panel surface and develop efficient methods to remove them.

At present, existing mechanisms to deal with surface dust include maintenance cleaning (He et al., 2011), induced surface charge (Aoyoma and Masuda, 1971; Calle et al., 2008) and creating mechanical vibration (Williams et al., 2007) in order to shake off the undesirable particles. All of these methods require extra scheduling and installation of additional equipment, and can be quite costly over time. In this paper, we propose an efficient method of controlling performance loss due to surface dust by exploiting the gravity of particles on the tilted surface. Our study revolves around the idea that optimal positioning of a solar panel with respect to sunlight direction and ground surface can reduce accumulated dust by letting the particles slide off the surface, while maintaining a suboptimal absorption of the incident light. In clean conditions, maximum absorptivity can be obtained when the solar panel is orthogonal to the incident light (i.e., solar tracker application). However, when dust accumulates on the surface, additional tilting of the panel increases the detachment force that accelerate the particles to slide off the panel, but it reduces the amount of absorbed energy per area for the clean section of the surface. Early prior experiments studied the effect of tilt angle on the cell performance degradation (Hegazy, 2001; Cano et al., 2014; Gandhi et al., 2014; Negash and Tadiwose, 2015). It has been found that the reduction of the solar cell efficiency declines as tilt angle increases, because fewer dust particles can accumulate on the surface if the panel is positioned at higher tilt angle. Therefore, combined with the experiment data, it is essential to develop a numerical dust accumulation model with gravity effect for better evaluation of the solar cell performance.

In order to simulate the sliding process of dust particles, we first establish a numerical dust accumulation model, where the two-dimensional PV panel is modeled with dual-axis sunlight tracking solution. Although there is a diverse composition of natural soiling (Darwish et al., 2015; El-Shobokshy and Hussein, 1993), only dust particles in dry condition are considered at this stage so that particle agglomeration does not occur due to rainfall or dew. The model is based on the assumption that only monolayer and non-dissociative adsorption/desorption occurs in the dust sliding process. The natural adsorption/desorption process and the effect of particle gravity and other dust-panel interaction (i.e., Van der Waals and electrostatic effects) are modeled in the proposed framework. The physical factors that contribute to these process are identified and formulated. Among those are the major environmental factors such as air temperature and enthalpy, and the physical characteristics of the panel, such as length, surface friction coefficient, etc. The evolution of dust fraction is expressed via a first-order differential equation in this model with two main contributing parameters: adsorption rate and desorption rate. Consequently, by numerically applying the proposed dust accumulation model, the steady-state solution of surface dust fraction can be calculated for every setting of parameters, solar and tilt angles. The model is validated using previously collected and studied experimental data. Based on this framework, the optimal tilt angle is numerically found in order to maximize optical efficiency with respect to standard AM1.5 solar irradiance at different solar zenith angles. The optimal tilt angle is in general higher than the solar zenith angle, meaning that the flat cell should be tilted slightly higher than the solar tracker position in order to achieve maximum absorption efficiency. It is also found that the required extra tilt angle becomes smaller as the solar zenith angle increases. Through the application of the proposed optimization scheme, the absorption efficiency of an optimized solar panel can be improved by a factor of 1.24 and 3.27, compared to the dual-axis PV solar panel and horizontal PV panel, respectively. In summary, the novelty of this work is twofold which can be expressed as follows: