Renewable Energy 119 (2018) 410–420

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Criteria for particles to be levitated and to move continuously on traveling-wave electric curtain for dust mitigation on solar panels

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ARTICLE INFO

Article history:
Received 11 April 2016
Received in revised form
9 September 2017
Accepted 3 December 2017
Available online 6 December 2017

Keywords:
Continuous motion mode
Dust mitigation
Electric curtain
Particle levitation
Traveling wave
Reciprocating motion

ABSTRACT

Dust accumulation on solar panels reduces power-generation efficiency significantly and even shortens service life of an equipment. Traveling-wave electric curtain technique is effective for removing dust on solar panels. The key issue of removing dust by electric curtain is the directional transport of dust. The continuous motion mode (A new motion mode proposed in this paper. In this mode a particle is transported continuously in one direction) is advantageous to directional transport. The criteria for continuous motion mode are derived by analyzing two jointly sufficient conditions: one is referred to as being continuously levitated from the dielectric surface and the other is being transported continuously in one direction. Levitation and movement analyses indicate that a particle in the "true movable area" can be levitated and transported continuously in one direction if particle acceleration complies with certain conditions; otherwise the particle motion will degenerate into reciprocating motion, but afterward the motion will shift to continuous motion if the x-component of velocity increases to a certain amount.

1. Introduction

Solar Power Generation System (SPGS) is composed of a series of photovoltaic solar cell arrays. As the inexhaustible solar power is not only clean but also noiseless, SPGS is becoming a widely used technology for power-generation [1,2]. However, dust particles, which are susceptible to accumulate on solar panels in wild environment, especially in arid and desert areas (e.g., Xinjiang and Gansu province of Northwest China, etc.), have a strong impact on power-generation efficiency [3,4]. For example, it is likely to be decreased by 40% if the dust accumulation increases to $4 g/m^2$ [2,5].

There are many options available to dust mitigation on solar panels. Among these options, natural cleaning method, mechanical cleaning technique, and self-cleaning nano-film are commonly used for dust removal [1]. However, these methods have some shortcomings for dust mitigation on solar panels in arid/desert areas. Natural cleaning method removes dust only by using natural forces, such as wind, rain, and gravity, etc., which is undoubtedly low in removal efficiency. Mechanical cleaning technique, which is higher in removal efficiency than natural method, removes dust by operating mechanical tool to sweep, blow, or vibrate dust out, and it would inevitably make damages to solar panels. Self-cleaning nano-film method, however, employs self-cleaning film, such as superhydrophilicity and superhydrophobic nano-film, to prevent dust from accumulating on solar panels. High as its removal efficiency is, it is not suitable for widely application in engineering, due to its high cost and immature preparation process.

Compared with the above mentioned methods, electric curtain technique may be a better choice for dust mitigation, as it is not only contactless but also high in removal efficiency with a low power consumption. Electric curtain method employs the electric curtain (EC), consisted of a series of parallel electrode grids powered by a multi-phase AC source that generates an electric field, to repel the particles on the dielectric surface [6–10].

The idea of employing the EC technique for dust mitigation was

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https://doi.org/10.1016/j.renene.2017.12.009

firstly proposed by Tatom et al. [11] in 1967 with a series of testing in space exploration by NASA. But it did not gain widespread interests until Masuda et al. [12] who proved the feasibility of particle manipulation on the traveling-wave EC in air in 1970s. Comparatively speaking, these studies conducted by Masuda et al. [13–16], in terms of theoretical analysis and experimental testing, are much more comprehensive. In these studies, results showed that traveling-wave EC was able to move dust successfully, whereas standing-wave EC was just able to levitate dust from the dielectric surface with no net horizontal transport. Later on, these phenomenon were identified again by Dudzicz [17] in their experiments. Consequently, the research of the EC technology was temporally focused on traveling-wave EC. However, with the development of the EC technology, standing-wave EC was also proved to be able to remove dust successfully, which was validated by Hemstreet [18], Sims et al. [19], and Atten et al. [9] in their research. Recently, similar results were also found by Liu et al. [20] Kawamoto [21] and Sun et al. [22,23].

Many significant results have been obtained both in numerical investigations and experimental research in these studies cited above. In the aspect of numerical investigations, potential and electric field approximations between electrodes were established by Masuda et al. [13] by using substitute charge method on a plane-type periodical electrode system connected to a balanced 3-phase sine wave voltage. Dust removal mechanism was also demonstrated by Masuda et al. [12,16]. On the basis of Masuda's prior works, Schmidlin [24] analyzed three primary motion modes for particles on EC, referred to as curtain mode (CM), hoping mode (HM), and surfing mode (SM). Dudzicz [17], Mazumder et al. [5], and Horenstein et al. [25] modeled the particle trajectory on traveling wave EC. Kawamoto et al. [26], Liu et al. [27,28], and Qian et al. [29] modeled the particle motion by using discrete element method (DEM). Sun et al. [23] simulated the particle dynamics, levitation process, and motion trajectory. After a thorough analysis of the dust removal process, Sun et al. [30] demonstrated a critical voltage criterion and maintained that the influence of Van der Waals force on dust movement can be overcome when the applied voltage is beyond the criterion.

In the aspect of experiments, a series of experiments, both on traveling-wave and standing-wave EC, were employed by Masuda et al. [12–16], Dudzicz [17], Kawamoto et al. [31], R. Sharma et al. [6], and Liu et al. [32]. In these studies, influences of applied voltage, frequency, grid parameters, as well as particle size distribution on removal efficiency, motion mode, power consumption, and transport velocity and height were examined.

In previous studies, three primary motion modes have been identified [20]: the curtain mode (CM), hoping mode (HM), and surfing mode (SM). The current paper, however, attempts to propose a new motion mode called the “continuous motion mode (CMM)” and to derive and test the criteria for a particle to be transported in continuous motion mode on traveling-wave EC. Under continuous motion mode, a particle is transported continuously in one direction rather than reversed and oscillated back and forth in-between electrodes, which is conducive to dust mitigation. To be specific, there are two jointly sufficient conditions for continuous motion mode: one is referred to as being continuously levitated from the dielectric surface and the other is being transported continuously in one direction. By analyzing these conditions in numerical simulations in section 3, the criteria for a particle to be levitated and to move continuously in one direction are derived respectively. Then, testing experiments for the criteria are performed in section 4. Experimental results match well with numerical analysis.

2. Principle

2.1. Electric curtain structure

The traveling-wave EC, as shown in Fig. 1, is composed of a series of parallel electrode grids connected to the three-phase sine wave AC voltage that produces a traveling-wave electric field [11,12]. The electrode grids with grid width a and grid distance b are embedded in the substrate and covered by a strong dielectric material with a thickness of h.

2.2. Potential and electric field

In the coordinate system, shown in Fig. 1, the x-axis is perpendicular to the grid axis and the y-axis is perpendicular to the dielectric surface. In light of Refs. [13] and [16], to a plane-type periodical electrode system connected to a balanced three-phase sine wave voltage in the form $U = u_0\cos(\omega t)$, the potential field between electrodes can be expressed as follows [16]:

$$\varphi(x,y,t) = u_0\left[\varphi(x,y)cos\omega t + \varphi\left(x-\frac{\lambda}{3},y\right)\cos\left(\omega t-\frac{2\pi}{3}\right) + \varphi\left(x-\frac{2\lambda}{3},y\right)\cos\left(\omega t-\frac{4\pi}{3}\right)\right]. \tag{1}$$

The boundary condition is given as follows [16]:

$$\begin{cases} \varphi(x,0) = \sum\limits_{n=0}^{\infty} a_n \cos(n\alpha x) \\ \varphi(x,y) = \sum\limits_{n=0}^{\infty} a_n \cos(n\alpha x) exp(-n\alpha y) \end{cases}, \tag{2}$$

where $\varphi(x,0)$ is defined as such that the potential on electrode U is unity and the electrodes V and W are grounded, a_n is Fourier coefficient, λ is the periodicity of the EC and is given by $\lambda = 3(a+b)$, and α is defined as $\alpha = 2\pi/\lambda$.

Furthermore, the electric field between electrodes can be expressed as follows [16]:

$$E(x,y,t) = -\nabla\varphi(x,y,t) \tag{3}$$

3. Criteria for continuous motion mode

In order to extract the underlying physics of the continuous motion mode, under which a particle is transported continuously in one direction rather than reversed and oscillated back and forth in-between electrodes, the particle movement process is divided into levitation period and transport period, as the forces and motions are not identical before and after being lifted off the dielectric surface. A particle in the levitation period experiences adhesive force, whereas the particle in the transport period experiences air resistance instead.

There are two jointly sufficient conditions for continuous motion mode: one is that a particle is levitated from the dielectric surface and the other is that a particle is transported continuously in one direction rather than reversed and oscillated back and forth. The criteria for a particle to be transported in such mode on the traveling-wave EC are derived by analyzing these two conditions in detail below in levitation period and transport period, respectively.