Electrostatic Cleaning Equipment for Dust Removal from Solar Panels of Mega Solar Power Generation Plants

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***Abstract* — Electrostatic cleaning equipment has been developed to remove dust from the surface of solar panels. When a high ac voltage is applied to the parallel screen electrodes placed on a solar panel, the resultant electrostatic force acts on the particles near the electrodes. The reciprocatory motion of the particles between the electrodes is due to the alternating electrostatic force, where some particles pass through the openings of the upper screen electrode and fall downward along the inclined panel owing to the gravitational force. We demonstrated that the dust is removed efficiently from the panel surface. The power consumption of this system is negligibly low. This technology is expected to increase the effective efficiency of mega solar power plants constructed in deserts.**

***Index Terms* — cleaner, dust, electrostatic force, mega solar, sand, solar panel.**

I. Introduction

Large-scale photovoltaic (PV) power generation plants, also known as mega and giga solar power plants, are being constructed worldwide because they do not emit carbon dioxide and are becoming economically compatible with other power generation systems [1]. However, one of the most serious problems in PV power plants constructed in deserts is the soiling of PV panels [2-8]. In places where rain is abundant (e.g., Japan), dust accumulated on the panels is cleaned automatically by rainfall and the decrease in output power is acceptably small; however, as shown in Fig. 1, the panels placed in deserts degrade drastically owing to the stirred-up dust, and the output power of a plant is decreases with time without cleaning. For example, a soiled PV panel in Doha will only be able to provide approximately 85% of the electricity if it is not cleaned for one month [8].

The most primitive and secure countermeasure is manual cleaning with a brush and water. Robotic cleaning has also been put to practical use. However, manual operation is hard in the harsh desert environments, water and its transportation to the sites where the power plants are installed are costly, and the future labor cost is indefinite. An alternative cleaning system [9-11] that uses an electrostatic traveling wave for cleaning dust is under development based on the novel concept first proposed by Masuda et al. [12] because it can be operated automatically, requires no consumables, has no mechanical moving parts, and has extremely low energy consumption. In this system, multi-phase high voltage is applied to a transparent conveyer plate consisting of parallel indium tin oxide (ITO) electrodes printed on a glass substrate to generate the electrostatic traveling wave on the glass plate, and the resultant electrostatic force moves small dust particles on the plate in one direction. Nevertheless, one of the authors is developing a simplified electrostatic cleaning system that utilizes the standing-wave instead of the traveling-wave [13,14] generated by a single-phase rectangular voltage applied to the parallel electrodes to mitigate the complexity of the electrode wiring, power supply, and interconnections. Because a traveling wave is not generated by the application of a single-phase voltage, the particles are not transported in one direction but rather repelled from the plate and flip-flopped on the plate; further, when airborne, the dust particles are transported downward by gravity along the inclined panel. Parallel wire electrodes embedded in the cover glass plate of the solar panel was employed instead of ITO electrodes to reduce the manufacturing cost of the cleaning plate. Although the wire electrodes create a shadow and disturb the absorption of light, this is minimized by using a fine wire and a wide pitch configuration. However, in both systems, the initial cost will be substantial, because all of the PV panels must be covered by electrode-embedded glass plates and long wiring is necessary. The output power of the PV panel is slightly decreased owing to the light shielding effect in both the ITO and wire electrode systems. Moreover, these systems cannot be applied to existing mega solar plants.

Fig.1. Soiled PV panels installed in Doha, Qatar. (Courtesy Bing Guo, Texas A&M University at Qatar)

Therefore, we are developing detachable electrostatic cleaning equipment that can be realized with a low initial cost, does not reduce the output power of the PV panel, and is applicable for the existing plants. In this system, a high alternating voltage is applied between the parallel screen electrodes set in a flame. The dust particles on the panel surface are agitated by the alternating electrostatic field in the vicinity of the elec-

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trodes and ejected by passing them through the openings in the upper screen electrode. The ejected dust then falls downward along the inclined panel owing to the gravitational force. We investigated the fundamental performance and demonstrated the operation of this system for the dust collected from the deposited dust on the solar panel installed in Doha, Qatar [14].

II. System Configuration

The configuration of the proposed electrostatic cleaning system is shown in Fig. 2 (a). This system was developed originally for removing lunar dust adhered to spacesuits [15] and for the sampling of lunar, Martian, and asteroid regolith [16-19]. When a high ac voltage is applied between the parallel screen electrodes of the device, the resultant Coulomb and dielectrophoresis forces [20] act on the dust particles in the vicinity of the electrodes. The dust particles are agitated by the alternating electrostatic field in the vicinity of the electrodes, and some particles pass through the opening in the upper screen electrode owing to their inertia force as observed (shown in Fig. 2 (b)) using a high-speed microscope camera (Fastcam max 120 K model 1, Photoron, Tokyo) [16].

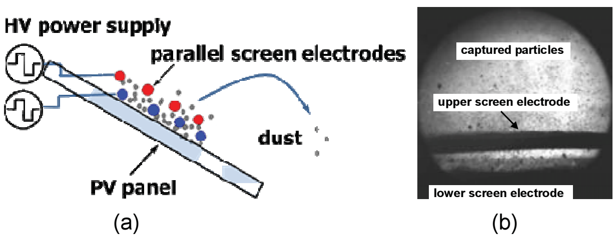


Fig. 2. Electrostatic cleaning equipment of dust accumulated on PV panels. (a) Schematic illustration of the system and (b) snapshot of particles captured at the screen electrodes (Adapted from the reference [16] with permission from ASCE.)

We manufactured small, wide, and long cleaning devices as shown in Fig. 3. The small device is used to investigate the basic performance of this system, and the wide and long devices are used to demonstrate the practical performance for the actual PV panel. The screen electrodes are attached to the plastic frames of the devices. The inner width and length of the small frame are both 50 mm, those of the wide frames are both 50×4 mm (active area), whereas those of the long frames are 50×5 mm and 50×1 mm (active area), respectively. The electrodes are composed of a metal wire, 1 mm in diameter, and coated with a polyester film. The pitch between the wires of the screen electrode is 5 mm and the gap between the screen electrodes is 5 mm in all devices.

A single-phase rectangular voltage is generated using a set of small positive and negative on-board-type amplifiers (HRU20-4P and HRU20-4N, max. ±5 kV, 6 mA, 30 W, W75.4×D38.1×H19.1 mm, Matsusada Precision Inc., Tokyo) that are switched by semiconductor relays controlled by a microprocessor [13-19].

The device is placed on a dust-deposited glass plate inclined at 30° such that the lower screen electrode was in contact with the deposited dust. It is reported that a considerable amount of dust can be captured when the lower screen electrode is in contact with the dust; however, almost no dust is captured when the device is not in contact with the dust [16], because the Coulombic force is inversely proportional to the gap between the electrode and particle and the dielectrophoresis attracting force is inversely proportional to the square of the gap [20]. The device was then moved in the vertical and lateral directions by hand as shown in Fig. 4 such that all areas of the glass plate were cleaned. The cleaning efficiency was evaluated by the ratio of the dust weight initially deposited onto the glass plate to the residual dust after the cleaning operation. The experiment was conducted in an air-conditioned laboratory (20–25 ℃, 40–60% relative humidity).

Small Doha dust particles collected from the deposited dust on the solar panel installed in Doha, Qatar were used for our experiments. The typical particle size is approximately 6–10 μm in diameter, and the primary component is calcium carbonate. The physical, chemical, and dielectric properties of the Doha dust are summarized in the literature [14].

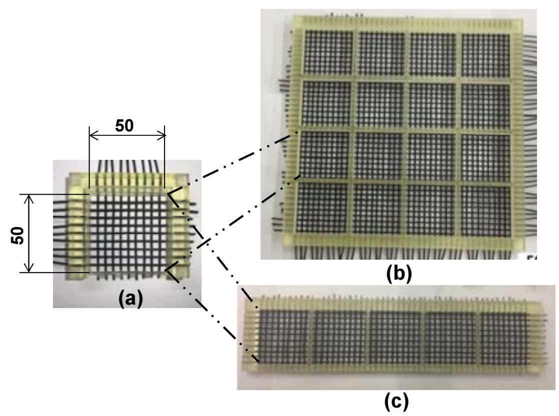


Fig. 3. Cleaning devices. (parallel screen electrodes in lattice geometry) (a) small device: active area 50 mm × 50 mm, (b) wide device: active area 50×4 mm × 50×4 mm, (c) long device: active area 50×5 mm × 50 mm.

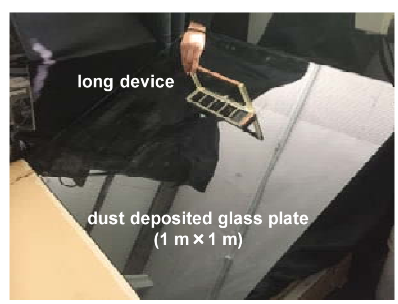
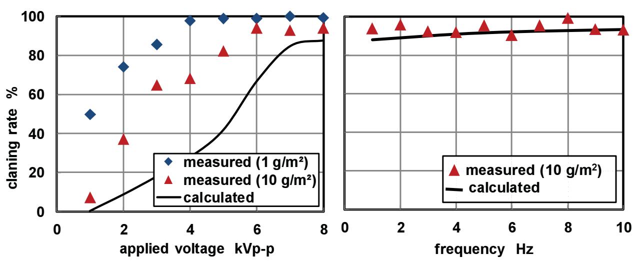


Fig. 4. Cleaning operation of equipment. The long device is operated on an inclined large glass plate (1 m × 1 m) on which Doha dust is uniformly deposited.

III. Results and Discussion

Fig. 5 shows the cleaning efficiency attained by the small device versus the applied voltage and the frequency. A small target glass plate (100 mm × 100 mm) was cleaned in the experiments. We observed that a high performance was achieved by applying a high voltage; however, saturation occurred at a high value. The applied voltage was limited by the insulation breakdown. The threshold voltage was approximately 9.0 $kV_{p\text{-}p}$. The maximum cleaning efficiency was almost 100%, when the initial loading of dust was 1 g/m^2, which corresponds to the dust accumulated for three days. The dust accumulation rate on the PV panels in the Middle East and North Africa regions is approximately 0.3 g/m^2/day [8]. Because the performance is slightly deteriorated when the initial loading is high, it is suggested that a frequent operation is preferable.

The cleaning performance is almost irrelevant to the frequency if the frequency is less than 10 Hz. A high-frequency operation is preferable for rapid cleaning; however, the cleaning performance will deteriorate at higher frequencies because the particles' motions cannot follow the high-speed change in polarity, thus limiting the operational frequency.



(a) (b)

Fig. 5. Cleaning efficiency attained by the small device versus (a) applied voltage (1 Hz) and (b) frequency (8 $kV_{p\text{-}p}$).

The solid curves in the figures show the calculated results based on the modified discrete element method [21]. The electrostatic field that determines the Coulombic force and the dielectrophoresis force applied to the particles is calculated by a three-dimensional differential element method. The calculated conditions are the following; number of particles: 25,000; particle diameter: randomly assigned based on the measured distribution of the particle diameter; relative density of particles: 2.2; and relative permittivity of particles: 2.5. Fig. 6 shows a snapshot of the calculated particle motion. The cleaning rate is determined by the weight of the collected particles below the device after a 5-s operation divided by the weight of the initially settled particles on the plate. Although a large discrepancy exists between the calculated and measured results when the applied voltage is low probably because the adhesion force is not properly evaluated in the calculation, the calculated results agree fairly well at high voltages.

The effects of the panel inclination and particle diameter are calculated based on this numerical method. As shown in Fig. 7 (a), the cleaning performance is deteriorated when the inclination is low. However, a separate experiment suggests that the low performance at low inclination can be improved by operating the system synchronized with the occurrence of natural wind [14]. Regarding the effect of particle diameter, medium size particles, approximately 100 μm, are most efficiently removed as shown in Fig. 7 (b). The relatively large adhesion force prevents the release of small particles from the glass plate [13,22], and the large gravitational force on the large particles hinders their capture and transport.

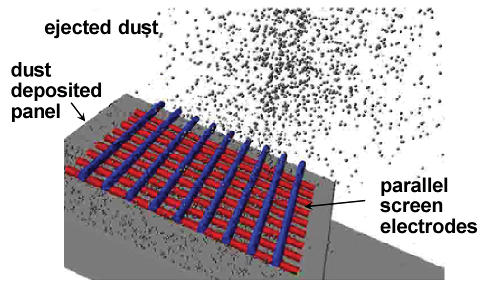
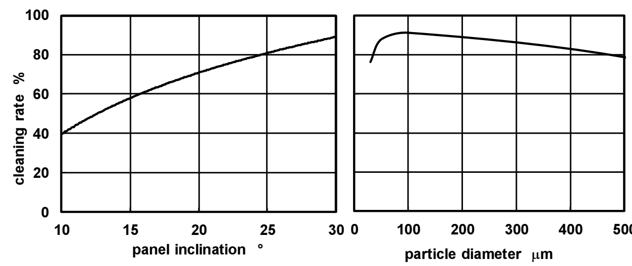


Fig. 6. Snapshot of calculated particle motion.



(a) (b)

Fig. 7. Calculated cleaning efficiency versus (a) panel inclination and (b) particle diameter.

Because the small cleaning device requires a substantially longer time to clean the entire area of a large panel, the wide and long devices were manufactured and a large glass plate (1 m × 1 m), which simulates an actual solar panel, was used for the cleaning experiments. Fig. 8 shows the experimental results. It is clearly shown that the fundamental characteristics were similar to those of the small device, although the cleaning performance with the wide device had slightly deteriorated. The cleaning performance of the wide device deteriorated because some ejected particles from the upper column of the wide device fell down into the lower column. This unfavorable effect is eliminated in the long device, and thus a high performance was realized in the long device.

Another concern is the cleaning of cemented particles. Deposited dust that contains water-soluble components forms a salt solution in a highly humid environment, the precipitated salt adheres to water-insoluble particles, and forms a layer of cemented particles that is strongly fixed on the glass plate. This phenomenon occurs even in the arid area when the dew point is higher than the temperature at night. The adhesion force of the cemented particles is much higher than the electrostatic force, and almost no cemented dust was cleaned by the present equipment. Therefore, the operation before the fixed layer is formed (e.g., daily operation) and/or the combination with a mechanical cleaning will be effective to compensate the issue. A field experiment is indispensable in proposing an effective solution.

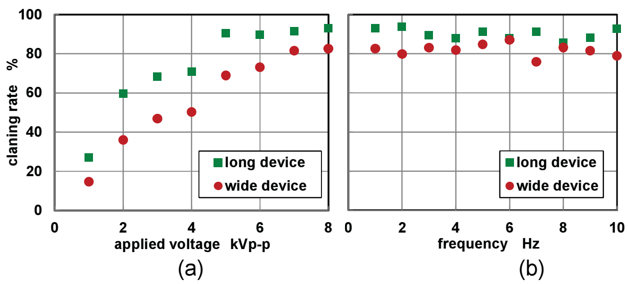


Fig. 8. Cleaning efficiency attained by the wide and long devices versus (a) applied voltage (1 Hz) and (b) frequency (8 kV_{p-p}) (1 g/m^2).

IV. Power Consumption

Fig. 9 shows the measured power consumption (input power to the high voltage source). It was approximately 11 W, which comprises 5 W for idling, 6 W for control, and a negligible amount for the panel, for our high voltage source under operational conditions of 8 kV_{p-p} and 1 Hz [14]. The total energy consumption of this system is extremely low as compared to the typical output energy of a solar panel. For example, if the equipment is operated daily for 10 min/panel, the electricity consumption is approximately 1.8 Wh/day/panel, which is negligibly small compared to the typical output of the PV panel.

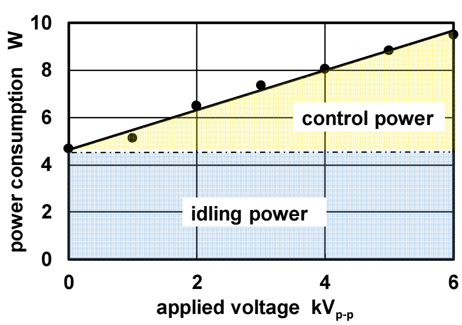


Fig. 9. Power consumption of high voltage source (1 Hz).

IV. Concluding Remarks

Detachable cleaning equipment for the removal of dust that accumulates on PV panels using electrostatic standing wave has been developed, and a high performance was demonstrated. This system is suitable for use in mega solar power plants constructed in deserts at low latitudes because it is potentially inexpensive, and requires virtually no power, water, or any other consumables. However, because this system is not fully operated automatically, its combination with the proposed cleaning equipment and a robotic system will be required to compensate for this disadvantage.

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References

[1] K. Komoto, E. Cunow, C. Breyer, D. Faiman, K. Megherbi, P. van der Vleuten, "IEA PVPS Task8: Study on Very Large Scale Photovoltaic (VLS-PV) Systems," *38th IEEE Photovoltaic Specialists Conference (PVSC)*, 2012, pp.001778–001782.

[2] M. Mani, R. Pillai, "Impact of dust on solar photovoltaic (PV) performance: research status, challenges and recommendations," *Renewable & Sustainable Energy Reviews*, vol. 14, 2010, pp.3124–3131.

[3] A.O. Mohamed, A. Hasan, "Effect of dust accumulation on performance of photovoltaic solar modules in Sahara environment," *J. Basic Appl. Sci. Res.,* vol. 2, 2012, pp.11030–11036.

[4] H.A. Kazem, T. Khatib, K. Sopian, F. Buttinger, W. Elmenreich, A.S. Albusaidi, "Effect of dust deposition on the performance of multi-crystalline photovoltaic modules based on experimental measurements," *Int. J. Renew. Energy Res.*, vol. 3, 2013, pp.850–853.

[5] D.S. Rajput, K. Sudhakar, "Effect of dust on the performance of solar PV panel," *Int. J. Chem. Technol. Res.*, vol. 5, 2013, pp.1083–1086.

[6] A. Ndiaye, C.M.F. Kebe, P.A. Ndiaye, A. Charki, A. Kobi, V. Sambou, "Impact of dust on the photovoltaic (PV) modules characteristics after an exposition year in Sahelian environment: the case of Senegal," *Int. J. Phys. Sci.*, vol. 8, 2013, pp.1166–1173.

[7] T. Sarver, A. Al-Qaraghuli, L. L. Kazmerski, "A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches," *Renewable & Sustainable Energy Reviews*, vol. 22, 2013, pp.698–733.

[8] B. Guo, W. Javed, B. W. Figgis, T. Mirza, "Effect of dust and weather conditions on photovoltaic performance in Doha, Qatar," *First Workshop on Smart Grid and Renewable Energy*, QD-002658, 2015.

[9] M. Mazumder, R. Sharma, A. Biris, J. Zhang, C. Calle, M. Zahn, "Self-cleaning transparent dust shields for protecting solar panels and other devices," *Particulate Science and Technology*, vol. 25, 2007, pp.5–20.

[10] M. Mazumder, M.N. Horenstein, J.W. Stark, P. Girouard, R. Sumner, B. Henderson, O. Sadder, H. Ishihara, A.S. Biris, R. Sharma, "Characterization of electrodynamic screen performance for dust removal from solar panels and solar hydrogen generators," *IEEE Trans. Ind. Appl.* Vol. 49, 2013, pp.1793–1800.

[11] M. K. Mazumder, et al, "Mitigation of Dust Impact on Solar Collectors by Water-Free Cleaning with Transparent Electrodynamic Films: Progress and Challenges," *IEEE J. Photovoltaics*, vol. 7, 2017, pp.1342–1353.
[12] S. Masuda, K. Fujibayashi, K. Ishida, H. Inaba, "Confinement and transportation of charged aerosol clouds via electric curtain," *Trans. Inst. Electr. Eng. Jpn.*, vol. 92, 1972, pp. 9–18.
[13] H. Kawamoto, T. Shibata, "Electrostatic Cleaning System for Removal of Sand from Solar Panels," *J. Electrostat*, vol. 73, 2014, pp.65–70.
[14] H. Kawamoto, B. Guo, "Improvement of an electrostatic cleaning system for removal of dust from solar panels," *J. Electrostatics*, vol. 91, 2018, pp.28–33.
[15] H. Kawamoto, "Electrostatic Cleaning Device for Removing Lunar Dust Adhered to Spacesuits," *J. Aerosp. Eng*, vol. 25, 2012, pp.470–473.
[16] H. Kawamoto, "Sampling of Small Regolith Particles from Asteroids Utilizing Alternative Electrostatic Field and Electrostatic Traveling Wave," *J. Aerosp. Eng*, vol. 27, 2014, pp.631–635.
[17] H. Kawamoto, A. Shigeta, M. Adachi, "Utilizing Electrostatic Force and Mechanical Vibration to Obtain Regolith Sample from the Moon and Mars," *J. Aerosp. Eng*, vol. 29, 2016, 04015031-1–6.
[18] M. Adachi, H. Maezono, H. Kawamoto, "Sampling of Regolith on Asteroids Using Electrostatic Force," *J. Aerosp. Eng*, vol. 29, 2016, pp.04015081-1–9.
[19] M. Adachi, T. Kojima, H. Kawamoto, "Electrostatic Sampler for Large Regolith Particles on Asteroids," *J. Aerospace Engineering*, vol. 30, 2017, pp.04016098-1–9.
[20] T.B. Jones, Electromechanics of Particles, Cambridge University Press, New York, 1995.
[21] M. Adachi, H. Kawamoto, "Electrostatic dust shield system used for Lunar and Mars exploration equipment," *Trans. JSME* (in Japanese), vol. 81, 2015.
[22] B. Guo, W. Javed, "Efficiency of Electrodynamic Dust Shield at Dust Loading Levels Relevant to Solar Energy Applications," *IEEE J. Photovoltaics*, vol. 8, 2017, pp.196–202.