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Electrostatic cleaning equipment for dust removal from soiled solar panels

Hiroyuki Kawamoto

Dept. of Applied Mechanics and Aerospace Engineering, Waseda University, 3-4-1, Okubo, Shinjuku, Tokyo, 169-8555, Japan

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ABSTRACT

Electrostatic cleaning equipment has been developed to remove dust from the surface of soiled 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 arises 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 how dust is removed efficiently from the panel surface. High cleaning performance is realized by the application of low frequency high voltage, and high inclination of the panel and low initial dust loading are preferable. Although residual dust accumulates after repeated cleaning operations, the amount of accumulated dust is much smaller than that without cleaning. The power consumption of this system is negligibly low. This technology is expected to significantly increase the efficiency of mega solar power plants constructed in deserts.

1. 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]. Deserts in low altitudes have a tremendous potential for deployment of solar power generation plants because of the high solar irradiation levels and the ample availability of land. However, one of the most serious problems in PV power plants constructed in deserts is the soiling of PV panels [2–11]. 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 decreases rapidly with time without cleaning. For example, a soiled PV panel in Doha, Qatar, will only be able to provide approximately 85% of the electricity provided initially if it is not cleaned for one month [9].

The most primitive and secure countermeasure is manual cleaning of the PV panels with a brush and water. Robotic cleaning has also been put to practical use [12,13]. However, manual operation is hard in the harsh desert environments, labor cost is indefinite, and the transportation cost of water to the power plants is costly. Another possible method is to apply a transparent super hydrophobic coating on the panels for reducing adhesion of dust particles to improve the cleaning performance [14,15]. Although this passive method, the so-called anti-dust coating, is simple and economical, water is still needed for its cleaning and its outdoor lifetime is very limited.

An alternative cleaning system that uses an electrostatic traveling wave for cleaning dust is under development [16–19] based on the novel concept first proposed by Masuda et al. [20] The system is considered futuristic because it can be operated automatically, requires no consumables, has no mechanical moving parts, and has extremely low energy consumption [21]. The system was originally developed for space applications [21–24]. In this system, multi-phase high voltage is applied to a transparent conveyor 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 drives 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 [25–33] generated by a single-phase rectangular voltage applied to the parallel electrodes to mitigate the complexities of the electrode wiring, power supply, and interconnections [25,33]. 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. This simplified system was also originally developed for space applications [34], and it is modified for the mega solar system, i.e., parallel metal wire electrodes embedded in the cover glass plate of the solar panel were employed instead of transparent ITO electrodes to reduce the manufacturing cost of the cleaning plate. Although the wire electrodes create a shadow and disturb the absorption of light, the unfavorable effect is

E-mail address: kawa@waseda.jp.

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

minimized by using a fine wire and a wide pitch configuration [25,33]. 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 ITO and wire electrode systems. Another limitation of the systems is that they cannot be applied to the existing mega solar plants.

Therefore, we are developing detachable electrostatic cleaning equipment that can be implemented with a low initial cost, does not reduce the output power of the PV panel, and is applicable to the existing plants. In this system, a high alternating voltage is applied between the parallel screen electrodes set in a frame [35]. The dust particles on the panel surface are agitated by the alternating electrostatic field in the vicinity of the electrodes and are 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. The equipment is placed on the PV panel only when the panel is soiled, and it is moved side to side and up and down on the panel to clean the whole surface of the PV panel. 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 [10,33].

2. 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 [36] and for the sampling of lunar, Martian, and asteroid regolith [37–40]. When a high AC voltage is applied between the parallel screen electrodes of the device, the resultant Coulomb and dielectrophoresis forces [41] act on the dust particles near the electrodes. The dust particles are agitated by the alternating electrostatic field near the electrodes, and some particles pass through the opening in the upper screen electrode owing to their own inertia force as observed (shown in Fig. 2 (b)) using a high-speed microscope camera (Fastcam max 120 K model 1, Photoron, Tokyo) [37]. Although the averaged charge density of the dust particles is almost

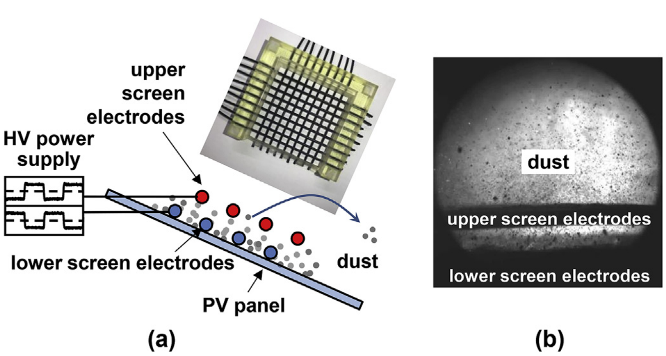

Fig. 2. Electrostatic cleaning equipment of dust accumulated on PV panels. (a) Schematic illustration of the system and (b) snapshot of particles captured at the parallel screen electrodes observed from the lateral side of the device (Adapted from reference [37] with permission from ASCE.).

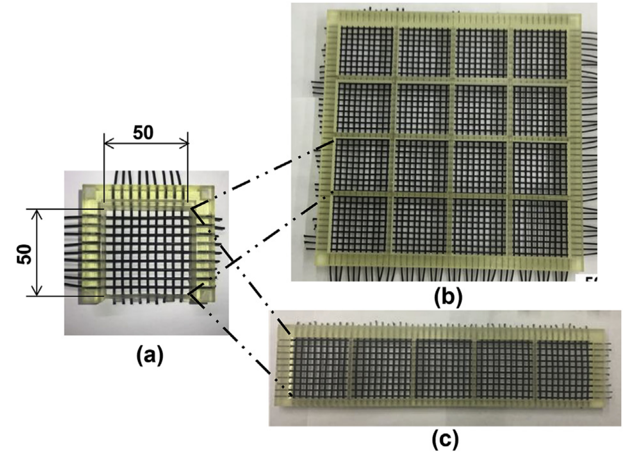

Fig. 3. Cleaning devices. Parallel screen electrodes are attached in plastic frames in lattice geometry. (a) small device: active area 50 × 50 mm^2, (b) wide device: active area 200 × 200 mm^2, (c) long device: active area 250 × 50 mm^2.

zero, there is a wide charge distribution of both positive and negative charges as observed in the actual deposited dust [33]. Thus, Coulomb force is effective to remove the dust. Mechanical collision between particle-particle and particle-electrodes causes the tribocharging, and this increases the charge density [33]. Because the polarity changes by the application of AC voltage, dielectrophoresis force is also effective to agitate the dust particles. The mechanism is the same as that in the electrostatic dust cleaner utilizing the traveling wave [42].

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 large panel. The screen electrodes are attached to the plastic frames molded by a 3D printer. The inner width and length of the small frame are both 50 mm, those of the wide frame are both 200 mm (active area: 200 × 200 mm^2), whereas those of the long frame are 250 mm and 50 mm (active area: 250 × 50 mm^2), respectively. The electrodes are composed of a copper wire which is 1 mm in diameter and coated with a polyester film in 0.15 mm thickness. 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. The wires were inserted in grooves installed in the flames.

A single-phase rectangular voltage, shown in the left side of Fig. 2 (a), was 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 were switched by photo-MOS relays (AQV258, Panasonic) controlled by a microprocessor (MPU, PIC16F1623/1938, Microchip) [25,33,36,37]. Although the voltage is high, strict safety measures are not necessary because the maximum current is low.

The device was placed on a dust-deposited inclined glass plate 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 [37], 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 [41]. Then the dust was deposited manually on the plate as uniformly as possible. The device was then moved in the vertical and lateral directions by hand, as shown in Fig. 4, such that all the areas of the glass plate were cleaned. The inclination of the panel and initial dust loading were experimental parameters. The cleaning efficiency was evaluated by the ratio of the weight of the cleaned dust after the cleaning operation to the weight of the dust initially deposited on the glass plate. The effectiveness of the cleaning system for improving PV performance can be evaluated by

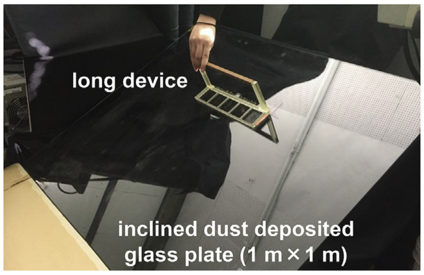

Fig. 4. Cleaning operation of equipment. The long device is operated on an inclined large glass plate (1 m × 1 m) on which dust is uniformly deposited.

using the relation between dust mass loading and PV performance loss [10]. The experiment was conducted in an air-conditioned laboratory (20–25 °C, 40–60% relative humidity).

Small dust particles collected from the deposited dust on the actual 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 dust are summarized in the literature [33]. In addition to the Doha dust, Namib sand, collected from the Namib Desert in Africa, was used for experiment. High performance was demonstrated for relatively large Namib sand (200–300 μm in diameter, main composition; SiO_2); however, it is not realistic because the dust deposited on the panel is very small. Small particles such as Doha dust are hard to clean owing the high adhesion force [33]. Therefore, evaluation of the cleaning system using the Doha dust is a conservative approach. The experimental results using six types of sand collected from deserts around the world suggested that the electrostatic system is effective for a variety of sands [25].

3. Results and discussion

3.1. Effects of applied voltage and frequency

Fig. 5 shows the cleaning efficiency attained by the small device versus the applied voltage and frequency. A small target glass plate (100 mm × 100 mm) was cleaned in the experiment. We observed that 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 kVp-p. The insulation strength of the device must be improved to apply high voltage. 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 [9].

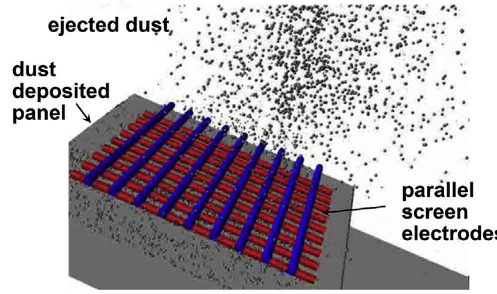

Fig. 6. Snapshot of calculated particle motion.

The cleaning performance is almost irrelevant to the frequency if the frequency is less than 10 Hz as shown in Fig. 5 (b). 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 [23,24].

The solid curves in the figures show the calculated results based on the modified discrete element method [43]. The electrostatic field that determines the Coulombic and dielectrophoresis forces applied to the particles is calculated by a three-dimensional differential element method. The calculated conditions are as follows: 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. 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. Another possible reason of the discrepancy at low applied voltage is that ejected dust particles fell from the small glass plate not only in the downward direction but also to the lateral sides, and thus, high cleaning rate was attained. However, in the numerical calculation, the device was not moved, and particles that fell to the lateral sides were not counted to determine the cleaning efficiency. Nevertheless, the calculated results agree fairly well at high voltages. A large glass plate (1 m × 1 m) was used for subsequent experiments to avoid the unreasonable effect in the small plate.

3.2. Effects of configuration and size of device

Because the small cleaning device requires a substantially longer time to clean the entire area of a large panel, 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. It

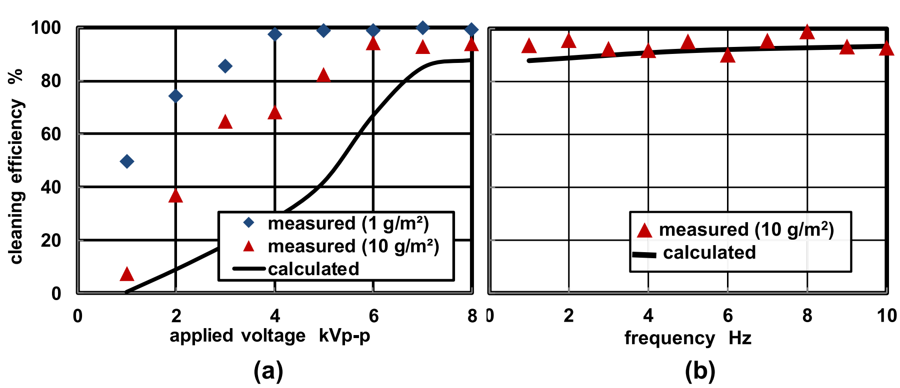

Fig. 5. Cleaning efficiency attained by the small device versus (a) applied voltage (@1 Hz) and (b) frequency (@8 kVp-p). Target glass plate: 100 mm × 100 mm, panel inclination: 30°, parameter: initial dust loading (g/m^2).

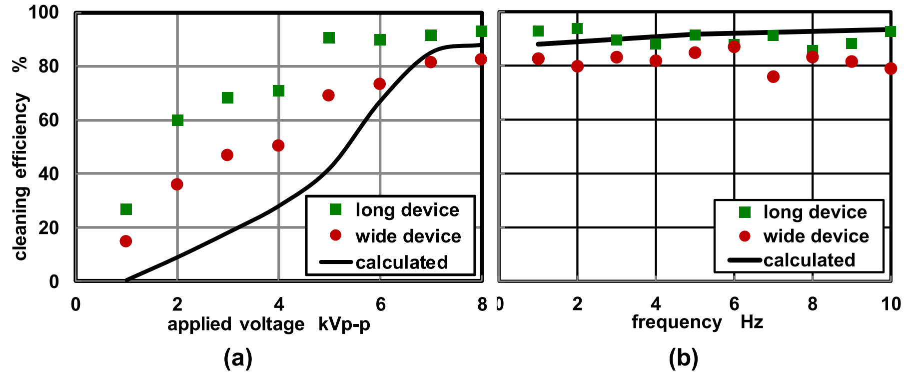

Fig. 7. Cleaning efficiency attained by the wide and long devices versus (a) applied voltage (@1 Hz) and (b) frequency (@8 kVp-p). Target glass plate: 1 m × 1 m, panel inclination: 30°, initial dust loading: 1 g/m^2.

took approximately 5 min to clean the whole area of the large panel with the long device at 8 kVp-p (1 Hz) voltage application. Fig. 7 shows the experimental results on the cleaning performance. It is clearly shown that the fundamental characteristics were similar to those of the small device, i.e., the cleaning performance was increased by applying a high voltage, but it saturated at a high value, and it was almost irrelevant to the frequency if it was less than 10 Hz.

The cleaning performance for the large glass plate deteriorated slightly compared with that for the small glass plate because, as stated in the preceding section, the amount of dust that fell from the lateral sides of the large plate was relatively small compared with those of the small plate, and a cleaning operation must be repeated for the deposited particles on the upper part of the large plate. Cleaning of large plate is realistic for evaluating the system performance. The cleaning performance of the wide device deteriorated compared with that of the long device because some ejected particles from the upper column of the wide device fell down into the lower column. It was observed that sweeping the device from top to bottom was most efficient than that from bottom to top or from left and right. The unfavorable effect in the wide device is eliminated in the long device, and thus, a relatively high performance was realized in the long device.

3.3. Effects of panel inclination and initial dust loading

The effects of the panel inclination and the initial dust loading were investigated. As shown in Fig. 8 (a), the cleaning performance deteriorated when the inclination was low because the cleaning is assisted by gravity. When the target panel was small (100 mm × 100 mm), the deterioration was little even when the inclination is low because ejected dust particles from the small glass fell out not only in the downward direction but also to the lateral sides. In case of the full-scale large plate (1 m × 1 m), the cleaning performance slightly decreased when the inclination was low; however, approximately 80% of the adhered dust was cleaned even at 20°, which is the typical inclination angle of solar panels installed in the Middle East. The cleaning performance was as high as 70% even at the 10° inclination. The effect of inclination in this system is consistent with the build-in type cleaning system [25]. Because the optimal inclination is determined by the latitude where the PV power generation plant is installed, it is not possible to alter it. Nevertheless, a separate experiment suggests that the low performance at low inclination can be improved if the operation of the system is synchronized with the occurrence of natural wind [34].

Regarding the effect of initial dust loading, low dust loading is preferable as shown in Fig. 8 (b). However, the deterioration is low when the initial dust loading is less than approximately 5 g/m^2, which corresponds to the dust accumulated in approximately 17 days in Doha, Qatar. It is suggested that the system must be operated before the accumulated dust loading is 5 g/m^2.

3.4. Effect of repeated operation

Because the cleaning rate is less than 100%, a small amount of dust remains on the panel after the cleaning operation and accumulates on the panel. The residual cumulative weight of the dust was measured after cumulative cleaning times as shown in Fig. 9. An amount of 1.25 g/m^2 dust was deposited on the soiled panel after each cleaning operation. It is clearly seen that the residual dust increased with cleaning times, but the cumulative residual dust is much smaller than that without cleaning (solid line in Fig. 9). Small dust particles are apt to remain on the panel, because adhesion force for small particles is relatively large as compared with the Coulomb and dielectrophoretic driving forces [25].

Another concern is the cleaning of cemented particles. Deposited dust that contains water-soluble components forms a salt solution in a

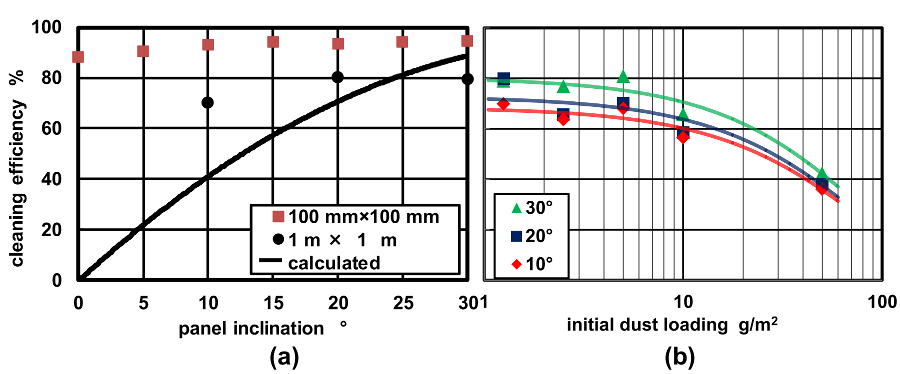

Fig. 8. Cleaning efficiency versus (a) panel inclination (initial dust loading: 1 g/m^2) and (b) initial dust loading (target plate: 1 m × 1 m). long device, @8 kVp-p, 1 Hz.

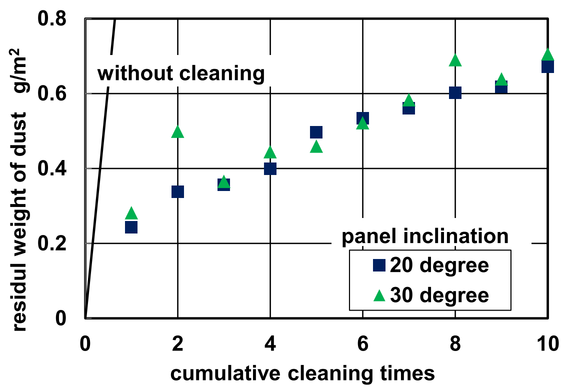

Fig. 9. Residual weight of dust after cumulative cleaning times. An amount of 1.25 g/m^2 dust was deposited on the soiled panel after each cleaning operation. Target glass plate: 1 m × 1 m, long device, @8 kVp-p, 1 Hz.

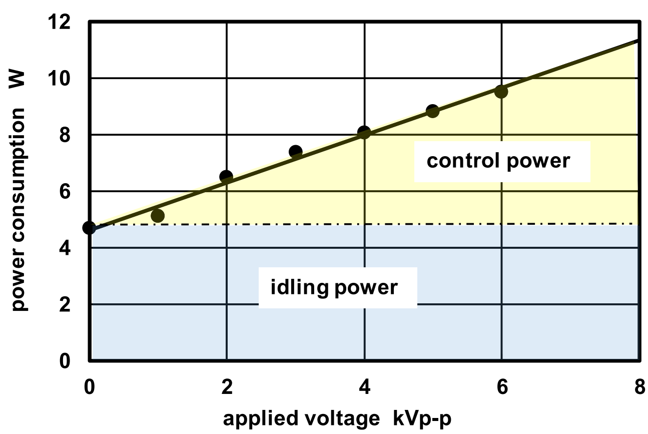

Fig. 10. Power consumption of high voltage source (@1 Hz).

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 [44]. This phenomenon occurs even in the arid area when the dew point is higher than the ambient 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, cleaning the panel before the fixed layer is formed and/or the combination with a mechanical cleaning will be effective to compensate for the issue. To propose an effective solution, a field experiment is indispensable.

4. Power consumption

Fig. 10 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 kVp-p and 1 Hz rectangular voltage [33]. The total energy consumption of this system is extremely low as compared to the typical output energy of a solar panel. Because it takes approximately 5 min to clean the entire area of the 1 m × 1 m panel, the electricity consumption is approximately 0.9 Wh/panel at each cleaning cycle, which is negligibly small compared with the typical output of the PV panel.

5. Concluding remarks

Detachable cleaning equipment for the removal of dust that accumulates on the PV panels using electrostatic standing wave has been developed, and high performance was demonstrated. High cleaning performance is realized by the application of low frequency high rectangular voltage. The applied voltage is limited by the insulation breakdown. High inclination of the panel is preferable, but approximately 80% of the accumulated dust is cleaned when the inclination is higher than 20°. It is better to operate the system before the accumulated dust is more than 5 g/m^2. Although residual small particles are not efficiently cleaned and are accumulated after repeated cleaning operations, the amount of the accumulated dust is much smaller than that without cleaning. The power consumption of this system is negligibly low. 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 the operation of this system is not fully automatic, integrating it with the proposed cleaning equipment and a robotic system will be required to compensate for this disadvantage. The robotic system that can sweep automatically all over PV array has been commercially available [45].

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