Electrostatic Cleaning System for Removal of Sand from Solar Panels

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***Abstract* — A unique cleaning system has been developed utilizing an electrostatic force to remove sand from solar panels. A single-phase voltage is applied to parallel wire electrodes embedded in a cover glass plate of a solar panel. It was demonstrated that more than 80% of the adhering sand was repelled from the surface of the slightly inclined panel, and the output power generated by the solar panel was recovered up to 80% after the cleaning operation. The power consumption of this system is virtually zero. This technology is expected to increase the efficiency of mega solar power plants constructed in deserts at low latitudes.**

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

I. INTRODUCTION

Many mega solar power generation plants are being planned and constructed in deserts at low altitudes where the sun shines the brightest. However, sand storms occur frequently in deserts, and solar panels can get covered by stirred-up sand, causing a drastic decrease in the output power of a photovoltaic power generation plant. Because sand on the panel is not cleaned by rain over a long period of time in an arid region, the capacity utilization of the power plant is reduced if the panels are not cleaned.

In order to mitigate this problem, we have developed an automatic cleaning system that does not need scarce cleaning water but instead utilizes an alternating electrostatic force. It consists of a sand-repelling glass plate that consists of parallel wire electrodes embedded in a cover glass plate of a solar panel and a high-voltage power supply to generate a single-phase rectangular voltage. An alternating electrostatic field causes the flip-flop motion of sand particles on the device, and the airborne sand particles are transported downward of the panels by virtue of gravity. The power consumption of this system is extremely low. This technology is expected to increase the efficiency of mega solar power generation plants constructed in deserts at low latitudes.

II. SYSTEM CONFIGURATION

The concept of transporting particles using electrostatic force was first proposed by Masuda et al. [1] and many investigations have since then been conducted on this technology, mainly as a toner supplier for electrophotography [2] and recently as a cleaner of lunar dust on solar panels and optical elements during lunar exploration missions [3]. It was demonstrated that more than 98% of the dust could be removed using electrostatic traveling waves generated by a four-phase rectangular voltage applied to a transparent conveyer consisting of transparent indium tin oxide (ITO) electrodes printed on a glass substrate. However, this technology is not suitable for a commercial mega solar system because it requires expensive ITO electrodes, the ends of the electrodes must be three-dimensional to prevent the intersection of phases, and the power supply and interconnections are relatively complicated for large-scale commercial plants.

The first issue is overcome by adopting parallel wire electrodes embedded in the cover glass plate of the solar panel. Although the wire electrodes create a shadow and disturb the absorption of light, this is minimized by adopting a fine wire and wide pitch configuration. The diameter of the wire electrodes and the pitch between the electrodes were adopted to be 0.3 mm and 7 mm, respectively.

In order to mitigate the last two issues, we adopted a standing wave instead of a traveling wave [4]-[5]. That is, a single-phase rectangular voltage was applied to parallel wire electrodes. Because a traveling wave is not generated by the application of a single-phase voltage, particles are not transported in one direction but rather repelled from the plate, and the airborne sand particles are transported downward of the panels by virtue of gravity. We generated a single-phase rectangular voltage by using a set of positive and negative amplifiers switched by semiconductor relays that were controlled by a microcomputer. Because a high slew-rate is not required for this system, we adopted conventional low-capacity onboard amplifiers (HUR30-6, Matsusada Precision).

Fig. 1 shows the schematic diagram of the system. If the system is operated intermittently, the sand adhering to the cover glass of the solar panels is removed. On the other hand, if the system is operated continuously, the sand that approaches the cover glass is repelled, and thus, the system can protect solar panels against the adhesion of sand.

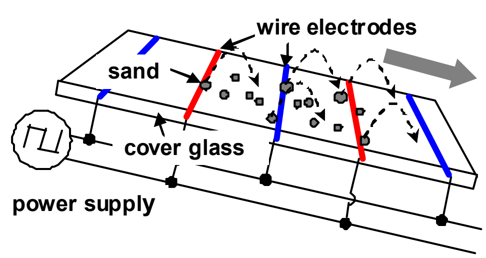

Fig. 1. Schematic diagram of the electrostatic cleaning system for removing sand from the solar panel.

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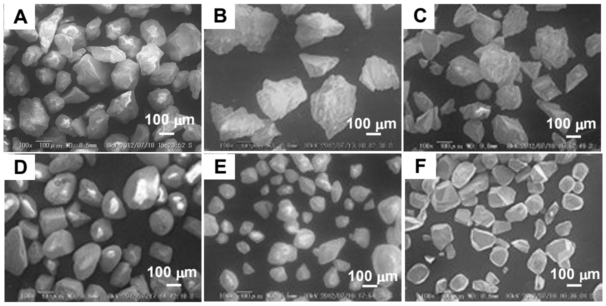

Fig. 2. Six kinds of sand used for experiments.

TABLE I SPECIFICATION OF SAND USED FOR EXPERIMENTS

item	unit	A	B	C	D	E	F
area	–	Namib	Japan	Eurasia	Ocean-ia	North America	Africa
relative permittivity	–	4.2	2.2	3.2	4.3	4.0	5.3
elongation	–	0.72	0.53	0.76	0.83	0.81	0.71
angle of repose	deg	36	38	39	31	34	35
bulk density	g/cm^2	1.5	1.4	1.4	3.0	1.7	3.0

Six kinds of sand, which are collected from the dessert areas in the world, were used for evaluation. The photographs of the sand particles are shown in Fig. 2, and these specifications are summarized in TABLE I. Sand A was commonly used in experiments otherwise specified.

II. RESULTS AND DISCUSSION

A. Effect of Plate Inclination

We manufactured a small device for the basic investigation of the system. Dimension of the substrate glass plate was 100 ×100 ×3 mm. After 0.3 mm copper wires are arranged on the plate, a thin glass plate, 0.1 mm thickness, was adhered using transparent adhesive to make the surface smooth and to prevent insulation breakdown.

The device was inclined, and the sand was uniformly scattered on the cover glass. Then a single-phase rectangular voltage was applied to the parallel electrodes. As shown in Fig. 3, it was confirmed that sand particles on the glass plate were repelled and transported downward of an inclined glass plate by the direct observation of particle motion using a high-speed microscope camera (Fastcam-max 120K model 1, Photoron) [3]-[5] and a numerical calculation based on the distinct element method (DEM) [2]-[6]. The numerical calculations were on the basis of a 3D hard-sphere model using the distinct element method. Details of the numerical method are reported in the literature [2]-[5]. The electrostatic field that determines the Coulomb force and the dielectrophoresis force applied to sand particles is calculated by a two-dimensional differential element method in a cyclic domain. Although the dynamic motion of particles cannot be conveyed from the still images, the calculated and observed movies are in qualitative agreement. As described in the later sections, the calculated performance agrees well with the measured result not only qualitatively but also quantitatively.

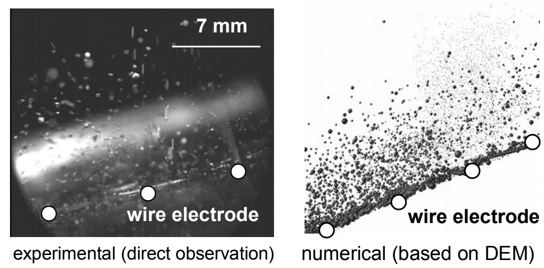

Fig. 3. Observed and calculated motion of dust particles under operation (20°inclination, 100-g/m^2 initial surface loading, 0.8 kVp-p/mm, 1 Hz).

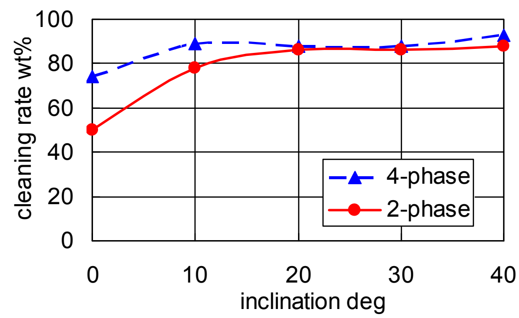

Fig. 4. Relationship between inclination of panel and cleaning rate (100-g/m^2 initial surface loading, 0.86 kVp-p/mm, 1 Hz).

Fig. 4 shows the cleaning rate, the ratio between the power of the photovoltaic cell with and without the system, versus the inclination of the plate. A cleaning experiment using a four-phase traveling wave was also conducted for comparison with single-phase cleaning. High performance was achieved even when the plate was slightly inclined, and the performance is almost the same as that attained for traveling wave cleaning when the inclination is larger than 20 degrees. This suggests that the system is effective at low altitudes where solar panels are installed in low inclination.

B. Effects of Pitch, Applied Voltage, and Frequency

Figs. 5 and 6 show the cleaning rate versus the averaged electrostatic field strength determined by the applied voltage divided by the pitch of the parallel electrodes and the frequency of the applied voltage, respectively. The solid curves in Figs. 5 and 6 show the calculated result. It is confirmed that the calculated results agree well to the measured results. We observed that producing a high field strength realized high performance; however, saturation occurred at a high value. Because the applied voltage is limited by the insulation breakdown, which is determined by the electrostatic field, the system performance is almost independent of the electrode pitch at the threshold voltage. The threshold voltage was 9.8 kVp-p for the 10-mm-pitch device and 8.4 kVp-p for the 7-mm-pitch device. The maximum cleaning rate was approximately 80% at a low frequency of less than 20 Hz.

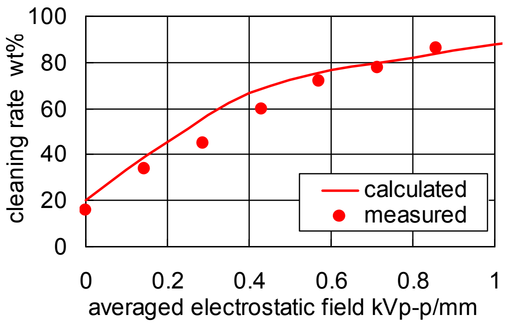

Fig. 5. Relationships between applied voltage (electrostatic field) and cleaning rate (20° inclination, 100-g/m^2 initial surface loading, 1 Hz).

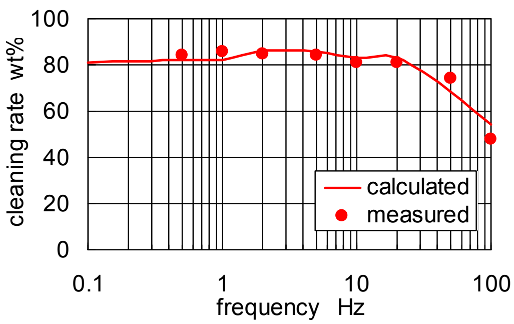

Fig. 6. Relationships between frequency of applied voltage and cleaning rate (20° inclination, 100-g/m^2 initial surface loading, 0.86 kVp-p/mm).

C. Effect of Initial Surface Loading of Sand

Fig. 7 shows the effect of the initial surface loading of the sand. If an amount of sand greater than 300 g/m^2 accumulates on the cover glass, the cleaning performance is decreased due to the aggregation of sand that bridges the adjacent electrodes as shown in the attached photograph in Fig. 7 [7]; however, high performance is realized when the surface loading is less than 300 g/m^2, which corresponds to an approximately 0.3-mm-thick sand layer. Although the cleaning performance was reduced in case of the high surface loading condition, it was experimentally confirmed that the cleaning performance recovered when weak wind, higher than 0.1 m/s, flowed on the plate in the inclined direction parallel to the plate concurrently at the operation of the electrostatic cleaner. Based on this investigation, we are developing an optional technology to enhance the cleaning by utilizing natural wind or by applying forced convection using a plasma actuator that generates electrostatic wind [8,9].

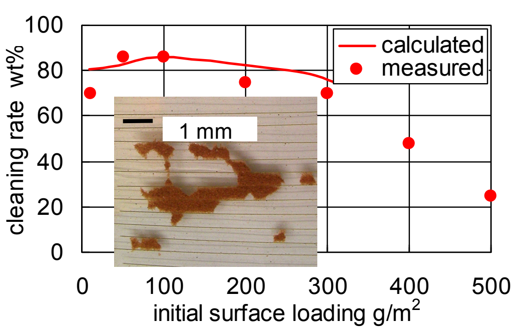

Fig. 7. Relationships between initial surface loading of sand and cleaning rate (20°inclination, 0.86 kVp-p/mm, 1 Hz). Attached photograph shows aggregated sand on the panel after operation. Sand bridges adjacent electrodes, and locks on the plate.

D. Effect of Particle Diameter

In order to investigate the sizes of the particles that can be cleaned by this system, the sand particles were classified into five groups according to the particle size using sieves, and the cleaning experiment was conducted using each classified sand size. Fig. 8 shows the cleaning rate versus the particle size. Particles smaller than 25 μm and larger than 300 μm were not cleaned efficiently. The reasons for the problems with small and large particles are different. Because the electrostatic image force and adhesion force are relatively greater than the Coulomb and electrophoresis driving forces for small particles, these particles adhere to the surface of the glass plate, which causes a reduction in the cleaning performance. On the other hand, the large gravitational force on the large particles hinders their bounding and transport.

E. Effect of Sand Characteristics

Six kinds of sand, shown in Fig. 2 and summarized in TABLE I, were evaluated to confirm the validity of this system for variety in characteristics of sand. Fig. 9 shows a comparison of the cleaning performance. Because many factors affect the cleaning performance, it is difficult to clarify the cause of difference of the cleaning performance; however, it was dem-

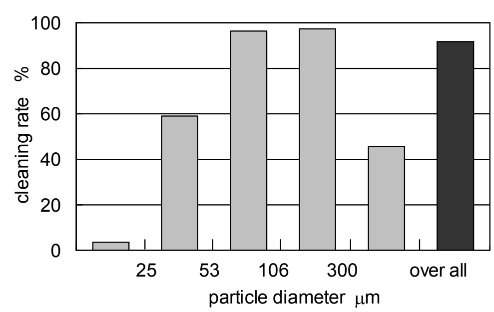

Fig. 8 Cleaning rate for the classified particle sizes (100-g/m^2 initial surface loading, 20° inclination, 0.7 kVp-p/mm, 0.2 Hz).

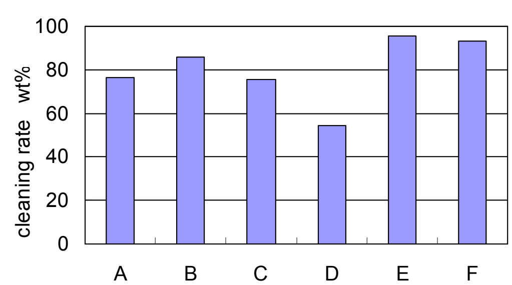

Fig. 9 Cleaning rate for six kinds of sand (300-g/m^2 initial surface loading, 20° inclination, 0.86 kVp-p/mm, 0.2 Hz).

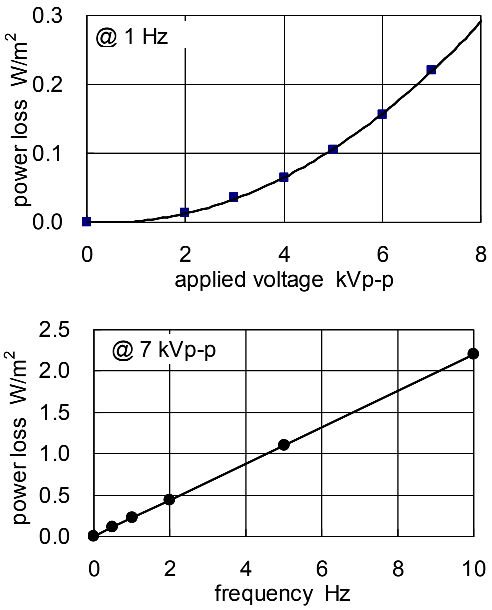

Fig. 10. Power consumption of electrostatic cleaning system.

onstrated that the electrostatic cleaning system is valid for sands with a variable feature.

F. Power Consumption

The power consumption of the cleaning system is shown in Fig. 10. The ordinate of the figures represents the power loss (input to the device) per unit area of the cleaning plate under the assumption that the power loss is proportional to the area of the plate. Because the transient current flowed immediately after the application of the voltage, the power loss is proportional to the frequency. On the other hand, power loss is proportional to the square of the applied voltage if insulation breakdown does not occur [3]. Because the voltage limit for insulation breakdown is 8.4 kVp-p for the 7-mm-pitch electrodes, and the optimal frequency is less than 10 Hz, the power consumption is only 0.2 W/m^2 under operational condition of 7 kVp-p and 1 Hz; the power consumption of this system is extremely low compared to the typical output power of the solar cell.

G. Demonstration

The performance of this system was demonstrated using an actual large solar panel (560 mm × 320 mm). The left-hand side of Fig. 11 shows the sand accumulated on the panel, and the right-hand side shows the panel after the cleaning operation was applied for 3 min. The cleaning system was applied to the left half of the solar panel. It is clearly seen that the presented system is effective for the cleaning of accumulated sand on a solar panel. Another experiment was conducted to demonstrate that the sand that approaches the cover glass is repelled if the system is operated continuously. This experiment also shows the effectiveness of this system. Field experiment

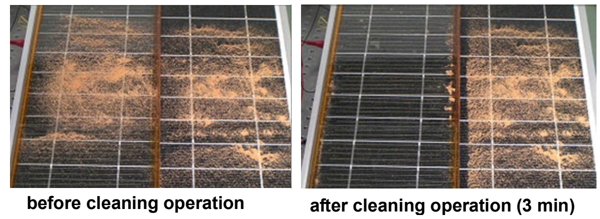

Fig. 11 Demonstration of electrostatic cleaning system (150-g/m^2 initial surface loading, 20° inclination, 0.7 kVp-p/mm, 0.2 Hz).

at a dessert must be conducted to investigate an optimum operational scheme.

After the surface of the plate gets wet due to rainfall or dewfall, or when sandstorm and rainfall occur simultaneously, the accumulated sand strongly adheres to the plate due to liquid bridging force. The cleaning experiments at these conditions confirmed that high performance was realized after the plate was parched.

III. Concluding Remarks

A unique cleaning system for removing the sand that accumulated on the solar panels has been developed; this system utilizes the electrostatic force. The device will be suitable for mega solar power plants constructed in deserts at low latitudes because it is potentially inexpensive, needs virtually no power, and operates automatically without water and other consumables.

The author would like to express his gratitude to Haruna Takahashi (Waseda University) who helped to carried out the experiments. This work is supported by a Grant-in-Aid for Scientific Research (B) from the Japan Society for the Promotion of Science.

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