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Photovoltaic Array Cleaning System Design and Evaluation

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***Abstract*—**Dust accumulation on the photovoltaic module's surface results in appreciable loss and negatively affects the generated power. Hence, in this paper, the design of a photovoltaic array cleaning system is presented. The cleaning system utilizes one drive motor, two guide rails, and four sweepers during the cleaning process. The cleaning system was experimentally implemented for one month to investigate its efficiency on PV array energy output. The energy capture over a month for PV array cleaned using the proposed cleaning system is compared with that of the energy capture using soiled PV array. The results show a 15% increase in energy generation from PV array with cleaning. From the results, investigating the optimal scheduling of the PV array cleaning could be an interesting research topic.

***Keywords*—**Cleaning system, dust accumulation, PV array, PV module, soiling.

I. Introduction

SINCE the photovoltaic (PV) cell's fundamental role is to absorb as much incoming solar irradiance as possible, the PV cell should always be cleaned and uncovered to avoid power output loss. However, PV module cleaning is a critical challenge during the operation and maintenance stages, especially due to soiling and dust accumulation on the PV module's surface. It has been shown that there is a 15% power generation loss due to the soiling and dust accumulation on the surface of the PV module [1]. Thus, the effect of uncleaned PV modules on the PV power generation system for various fields is an emerging research topic.

The PV module cleaning plays a vital role in the PV power generation system. The operation and maintenance cost can be substantially reduced if the cleaning system is designed and manufactured to be as simple as possible. The cleaning system should also be affordable, easy to install, and easy to maintain as the market solutions are complicated, heavy with large components, which causes difficulties to install and use.

To prevent power output loss due to dust accumulation on the PV module, there is currently a need for an efficient cleaning method to remove the dust from the PV module's surface. In some regions, due to dust accumulation and dust adhesion phenomena that occur after sandstorms followed by rain, cleaning utilizing rainfall is considered a PV module cleaning solution, with no cleaning cost. Although the cleaning solution depends on weather, location, and the PV module tilt angle, in some cases, manual cleaning is regarded as an easy cleaning solution due to the simplicity of the dust cleaning procedure using soft cloths or brushes [2]. Manual cleaning still requires laborers, carried water, and is not a solution for large PV power generation systems. Reference [2] researched a cleaning system to remove soiling from the PV module's surface. The result shows that using a cleaning system could increase the PV module power output by about 10%. Considering fast PV module cleaning for large PV power generation systems, recent studies have developed portable robotics and an automated cleaning system to clean the PV module surface. Authors in [3] conducted a study using an automated robot to clean the PV module and decrease dust accumulation effect on the PV module power output. In [4], a combination of multiple cleaning approaches, including vibration, air, and water jet experiments were conducted in the harsh desert environment of Saudi Arabia to analyze the performance of PV module after cleaning procedure. The results indicate that PV module water-cleaning increased the power output by an average of 27% [4]. The effect of dust on PV module is deference depending on the type of PV module material. Polycrystalline PV module shows more power output loss than the monocrystalline. A reduction of 6% to 13% of the PV module power output was measured [5]. Considering these studies, after many laboratory-based tests leading towards the development of a PV module cleaning system, this paper presents the results of a one-month field study of the cleaning system in Nasukarasuyama city, Japan. The study was conducted to address the effectiveness of the proposed cleaning system, specifically on PV array. This work's primary contribution is to develop a PV array cleaning system with simple and fewer components and investigate its impact on the PV system power output.

II. Experiment Setup and Site Information

A. Experimental PV System Description

The experiment set up is installed at Farm in Nasukarasuyama city in Tochigi prefecture, Japan (36.651949, 140.116528). Tochigi prefecture located in the Kanto region is known for its warm, muggy, wet, and mostly cloudy summer. All PV modules were installed facing south with a tilt angle of 34°. In this study, we have conducted two experiments to investigate the impact of soiling on PV modules energy output for one month (March 2020). Experiment details will be provided in the following sections.

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B. Solar Irradiation

Solar irradiation is the most sensitive parameters for PV module performance. Therefore, we utilized the solar irradiation data acquired from Power Data Access Viewer (PDAV), which is NASA's project for the prediction of worldwide energy resources [6]. The monthly solar irradiation during the monitored period (March 2020) is presented in Fig. 1.

C. Temperature

The ambient temperature and the PV module temperature were measured. The PV module temperature was measured using a digital thermometer (TPM-10). The ambient temperature was acquired from Japan Meteorological Agency [7]. The monthly temperature during the monitored period (March 2020) is presented in Fig. 1.

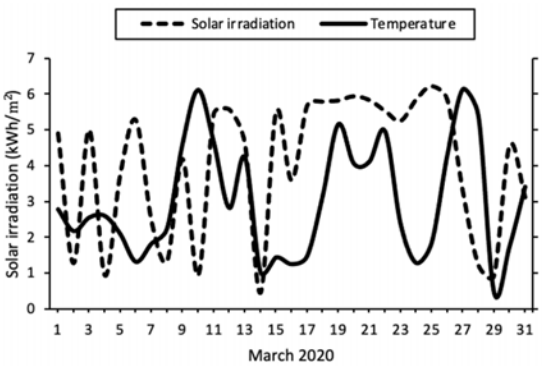

Fig. 1 The monthly temperature and monthly solar irradiation during the monitored period (March 2020)

D. Soling Loss Evaluation

The first experiment was conducted to investigate the soiling loss of the PV module without cleaning using the proposed cleaning system. The experimental setup for evaluation of the soiling loss is consists of two PV modules. PV module-1 is cleaned by the proposed cleaning system. Module-2 remains uncleaned after facing real weather conditions for one month. The PV modules used were manufactured by JinkoSolar, model number (JKM310P-72-J) with a dimension of 1956 × 992 × 40 mm (L × W × D) and a rated power of 310 Wp (V_{oc} = 45.9 V, I_{sc} = 8.96 A, V_{mp} = 37 V, I_{mp} = 8.38 A). The information of the soiling experiment is shown in Table I. A Hioki CM4371 multimeter was used to measure the PV module current, and a Sanwa digital multimeter PM3 was used to measure the PV module voltage. The voltage and current values for Module-1 and Module-2 were recorded simultaneously to minimize the effect of the instant change in the irradiance level. The PV modules were directly connected to the load, i.e., the PV modules did not operate at the maximum power point because of the experiment instrument limitation. The PV module temperature was measured using a digital thermometer (TPM-10)

E. Uncertainty Analysis

The uncertainty of a derived parameter, X, due to the uncertainty in the individual measured variables, x_1, x_2… x_n is referred to as uncertainty propagation. The general form of the total uncertainty in derived parameter X can be calculated using (1) [8]:

$$\omega_x = \sqrt{\left(\frac{\partial X}{\partial x_1}\right)^2 {\omega_{x_1}}^2 + \left(\frac{\partial X}{\partial x_2}\right)^2 {\omega_{x_2}}^2 + \ldots + \left(\frac{\partial X}{\partial x_n}\right)^2 {\omega_{x_n}}^2} \quad (1)$$

where ω_x is the uncertainty of the variable x, ω_{xn} is the uncertainty of parameter x_n , and $\partial X/\partial x_1$ is the partial derivative of X with respect to x_1. The maximum uncertainties in the different measured and evaluated parameters obtained from an experimental error analysis are presented in Table II.

TABLE I
EXPERIMENT 1 INFORMATION

Items	Information
Date	2020/3/26
Time	14:00
Outside Temperature	18 ℃
PV module Type	310 W (72 cells)
Number of PV modules	2
Module Temperature	43.2 °C

TABLE II
ACCURACY OF THE MEASURING DEVICES

Parameters	Information
Current (A)	± 1.3 %
Voltage (V)	± 0.7 %
Module Temperature (°C)	± 1

F. Energy Evaluation

In experiment two, the PV array configuration is a series configuration consist of 168 PV modules. The experimental setup is composed of two sets of PV array: namely: Array-1 and Array-2. The PV array specification is shown in Table III. It is assumed that the solar irradiance received by the two sets of PV arrays is the same throughout the experiment period. This assumption is reasonable because the PV modules connected to Inverter- 1 and Inverter-2 are installed in the same location under the open sky. The first set of 168 PV modules (Array-1) are connected to Inverter-1, and the second set of PV modules (Array-2) connected to Inverter-2. The information of the energy experiment is shown in Table III.

To monitor the PV system's performance under actual weather conditions, measurements of the actual energy values in kWh from inverters were made continuously.

The AC energy E_{output} can be calculated based on (2) [9]:

$$E_{output} = P_{STC} \times PSH \times K_{DEGRADATION} \times \eta_{SUB-SYS} \quad (2)$$

where P_{STC} is the installed capacity power output [kW] of the PV system under STC condition, PSH is peak sunshine hours, $K_{DERATION}$ is the degradation rate of the system, and $\eta_{SUB-SYS}$ is the efficiency of the PV subsystem.

The sunshine peak hour was calculated by (3):

$$PSH = \frac{H}{G_0} \quad (3)$$

where H is the solar irradiation ($\mathrm{kWh/m^2}$) and G_0 is the solar irradiation under STC ($\mathrm{kWh/m^2}$). PV system energy production estimation is done using a variable PSH multiplied by the power output of the PV system in kW. PSH differs from the hours of sunlight, which is the total hours from sunrise to sunset. PSH is the average solar irradiation ($\mathrm{kWh/m^2}$) a certain location receives per day.

TABLE III
EXPERIMENT 3 INFORMATION

Items	Information
Date	March 2020
PV module Type	245 W
Number of PV module (cleaned PV array)	168 (series connection)
Number of PV Module (uncleaned PV array)	168 (series connection)
Number of inverters	2
Average Daily PV Module Temperature	43.2 °C

III. THE PROPOSED PV ARRAY CLEANING SYSTEM

The PV array cleaning system shown in Fig. 2 consists of one drive motor, two guide rails, and four sweepers, one sweeper at the top of each column. The sweepers depend in their work on two guide rails fixed on the left and right sides of the array (the PV module frame) to hold the sweepers and control their movement and sliding on the PV modules and thus on the whole PV Array. The sweeper motor unit is easily fixed to the PV module frame's edge using a special bracket. The motor works in simultaneous operation up to four columns along with the sweepers. The sweeping process begins from the first row where the sweepers at the top of the columns move together to sweep the whole PV modules in the first row, then keeps moving vertically as for the columns and the array as a whole to sweep the second row until they finish their sweeping process at the fourth row. The cleaning system includes three following units used as an anti-deflection to support the driveshaft from a deflection. The following unit is fixed at the top of the cleaning system to avoid shading on the PV array. The system's maintenance frequency can be set long by adopting Ethylene Propylene Dine Monomer (EPDM) wiper with long life, heat resistance, and weather resistance. The power source can be selected from the battery method (automatic charging by mini-PV module) or AC power supply method (AC 100 V to AC 200 V) from outside.

IV. RESULTS

A. Effect of Soiling

To determine the impact of cleaning on PV module output, PV module-1 was subjected to cleaning. PV module-2 was considered as a reference and was not cleaned. From the obtained results, it is quite noticeable that the output power of PV module-1 after being cleaned using the proposed system is higher than the output power of PV module-2 that is exposed to dust. The power output of cleaned PV module-1 was 183.9 W compared to 171.2 W from that of the uncleaned PV module-2. This represents around 6.9% more power from the cleaned PV module compared to the uncleaned PV module. The cleaning system's effect can also be seen from a visual comparison given in Fig. 3, where the lower side of PV module-2 was covered by dust. The image clearly shows that PV module -2 was covered by a considerable amount of dust, whereas PV module-1 in Fig. 4 was significantly clearer after cleaning. The power obtained for the PV module before and after cleaning can be interpreted as the PV module's soiling loss. The power output of each PV module compared to obtain soiling loss as (4) [10]:

$$Soiling_{loss}(\%) = \left(\frac{P^c_{mp} - P^d_{mp}}{I^c_{sc}}\right) \times 100 \quad (4)$$

where P^c_{mp} is the power output of cleaned PV module-1 and P^d_{mp} is uncleaned PV module-2 power output. The soiling loss was calculated as 6.8 %.

Fig. 2 An overview of the PV array cleaning system.

Fig. 3 The PV module before cleaning (PV module-2)

Fig. 4 The PV module after cleaning (PV module-1)

B. Monthly Energy Output

Fig. 5 shows the measured energy of the cleaned and uncleaned PV array-1 and PV array-2 for March 2020. As a result of the comparison made by considering all system components efficiency, the results show a 15% increase in energy generation from the PV array with cleaning. A total monthly of 2758.58 kWh of energy was generated from the PV array with cleaning, while 2348.62 kWh was generated from the PV array without cleaning in March 2020. The difference between energy from the cleaned and uncleaned array is attributed to assumptions of dust and another real-life situation. An example of detailed degradation and losses that affect the performance ratio of the PV system are: inverter losses (4% to 10%), temperature losses (5% to 20%), DC cables losses (1% to 3%), AC cables losses (1% to 3%), shadings (0% to 80%), losses at weak irradiation (3% to 7%), losses due to dust, snow (2%), and loss due to aging of the PV module [11]. These degradations, losses, and inefficiencies usually depend on the PV system site, the PV cell technology, and the system's sizing.

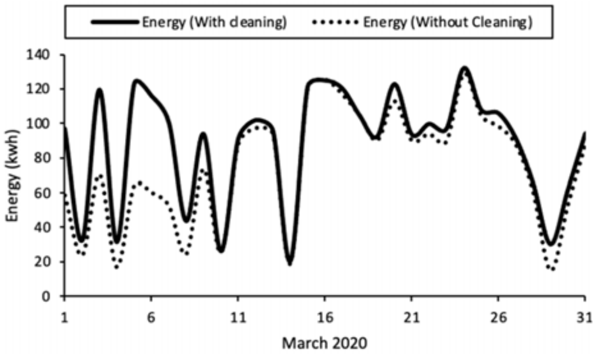

Fig. 5 Measured energy of the cleaned and uncleaned PV array.

C. Correlation Coefficient

As shown in Fig. 6, the correlation coefficient (R^2) between the clean and uncleaned array's energy values was calculated using (5), as 0.7492.

$$R^2 = \frac{\sum(E_{CLD}-E_{CLD\_AVE})(E_{UNCLD}-E_{UNCLD\_AVE})}{\sqrt{\sum(E_{CLD}-E_{CLD\_AVE})^2\sum(E_{UNCLD}-E_{UNCLD\_AVE})^2}} \quad (5)$$

where E_{CLD} is the measured energy from the cleaned PV array, E_{UNCLD} is the measured energy from the uncleaned PV array, E_{CLD_AVE} is the measured average energy from the cleaned PV array, and E_{UNCLD_AVE} is the measured average energy of the uncleaned PV array.

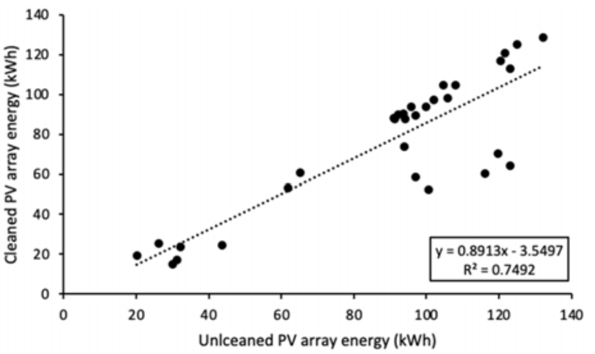

Fig. 6 Correlation between the cleaned PV array energy and uncleaned PV array energy value

V. CONCLUSION

A PV array cleaning system that has low-cost and efficient performance was designed and evaluated. The system used one drive motor, two guide rails, and four sweepers. The proposed system differs from previous systems by being simpler, less complicated. The system is fixed on a PV module or PV array and does not need to be installed in the daytime and removed at night as the approach of previous systems that constitute one of the most serious challenges, especially in hard-to-reach places such as the middle of deserts such as the Middle East region. The system was experimentally implemented to investigate its efficiency and impact on the soiling of PV module and PV array energy output for one month (March 2020). An improvement of 15% in the generated energy from the PV array with cleaning comparing the energy generated from the PV array without cleaning. A natural next step in this area of research would be to investigate optimal scheduling and computing the cleaning rate (for example, how many times per year or how many times per month), as interesting research that could be considered future work to ensure a positive energy balance.

REFERENCES

[1] M. Al-Housani, Y. Bicer, and M. Koç, "Experimental investigations on PV cleaning of large-scale solar power plants in desert climates: Comparison of cleaning techniques for drone retrofitting," *Energy Convers. Manag.*, vol. 185, pp. 800–815, Apr. 2019, doi: 10.1016/j.enconman.2019.01.058.

[2] D. Deb and N. L. Brahmbhatt, "Review of yield increase of solar panels through soiling prevention, and a proposed water-free automated cleaning solution," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 3306–3313, Feb. 2018, doi: 10.1016/j.rser.2017.10.014.

[3] B. Parrott, P. Carrasco Zanini, A. Shehri, K. Kotsovos, and I. Gereige, "Automated, robotic dry-cleaning of solar panels in Thuwal, Saudi Arabia using a silicone rubber brush," *Sol. Energy*, vol. 171, pp. 526–533, Sep. 2018, doi: 10.1016/j.solener.2018.06.104.

[4] Alghamdi, Bahaj, Blunden, and Wu, "Dust Removal from Solar PV Modules by Automated Cleaning Systems," *Energies*, vol. 12, no. 15, p. 2923, Jul. 2019, doi: 10.3390/en12152923.

[5] S. A. Kalogirou, R. Agathokleous, and G. Panayiotou, "On-site PV characterization and the effect of soiling on their performance," *Energy*, vol. 51, pp. 439–446, Mar. 2013, doi: 10.1016/j.energy.2012.12.018.

[6] "POWER Data Access Viewer." https://power.larc.nasa.gov/data-access-viewer/ (accessed Mar. 08, 2021).

[7] "Japan Meteorological Agency." https://www.jma.go.jp/jma/indexe.html (accessed Mar. 11, 2021).

[8] A. Radwan, S. Ookawara, S. Mori, and M. Ahmed, "Uniform cooling for concentrator photovoltaic cells and electronic chips by forced convective boiling in 3D-printed monolithic double-layer microchannel heat sink," *Energy Convers. Manag.*, vol. 166, pp. 356–371, Jun. 2018, doi: 10.1016/j.enconman.2018.04.037.

[9] M. Z. Saleheen, A. A. Salema, S. M. Mominul Islam, C. R. Sarimuthu, and M. Z. Hasan, "A target-oriented performance assessment and model development of a grid-connected solar PV (GCPV) system for a commercial building in Malaysia," *Renew. Energy*, vol. 171, pp. 371–382, Jun. 2021, doi: 10.1016/j.renene.2021.02.108.

[10] S. Bahreini, M. Yaghoubi, and M. Aghaei, "Effect of Dust on Solar Photovoltaic Modules in Shiraz," p. 5.

[11] A. Dobos, "PVWatts Version 5 Manual," NREL/TP-6A20-62641, 1158421, Sep. 2014. doi: 10.2172/1158421.