Design and Development of Automated Solar PV Module Cleaning Robot

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Abstract:

It has been found that the accumulation of dust on photovoltaic panels can significantly reduce their output resulting in an increase in the cost of the electricity. There are several methods used to clean the solar PV panel. The PV cleaning system presented in this research paper is a straightforward alternative that addresses this issue effectively. This work is aimed to provide a better alternative for maintaining the efficiency of the solar PV panel. In the present study, an automated solar PV module cleaning system has been developed. The proposed design provides a durable, dependable, and automated cleaning mechanism for solar power plants. This research illuminates the advantages of dry-cleaning solar PV modules. This design proposes a cost-effective and automated cleaning solution for PV modules and is equipped with a width-adjustment mechanism to clean solar plants with different-sized PV modules. It has been found that the cleaning of solar PV panels improves the performance efficiency of the solar PV plant by 11 to 18 %. The robotic cleaning system was found less time consuming compared to the manual cleaning of the solar PV panel. It is found to be very difficult for manual cleaning to clean solar plants of higher capacity. Depending upon the size of the solar PV panel, it is found to be difficult to clean all surface area of the solar PV panel at the time of manual cleaning. The robotic cleaning system for a solar PV panel is found to be very effective for the solar PV power plants of higher capacity and located at remote locations. The use of a solar PV cleaning system enhances the overall efficiency of the solar panel thus reducing the cost of the electricity.

Keywords: *Photovoltaic (PV) panel, Solar Energy, Robotic PV cleaning, solar efficiency*

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1. INTRODUCTION

Demand for solar energy has risen because of solar energy's abundance and lack of pollution; huge solar power plants have been installed throughout the world [1]. When installed in desert regions with abundant sunshine, solar power plants produce more energy than usual.

Additionally, solar panels installed on roofs collect more solar radiation than those mounted on the ground [2]. The energy sector's newest technology, photovoltaics (PV), converts the sun's radiant energy directly into electricity. The photovoltaic cells convert the energy contained in the photons that the sun releases into usable energy. The energy sector has undergone a radical transformation due to PV technology, which has made it possible to generate clean power and move toward more environmentally friendly energy practices. This opened the door for the photovoltaic industry to make rapid industrial progress in earlier times, and it continues to do so as technology advances [3-4]. The smallest component for converting solar energy into electrical energy is a photovoltaic cell. Solar cells' ability to convert energy into usable forms depends on the semiconductor technology used in their production. The most widely used technology is silicon-based, and its conversion efficiency is between 5 and 15% [5]. One can witness a great advancement in technology if they follow the development of the PV industry, starting with the creation of prototype models, experimental scale models, and the current real-time operating power plants [6]. To solve the issues with energy demand at the load centres themselves and avoid the need for lengthy transmission and distribution, these photovoltaic technologies have emerged and become a crucial component of many other sectors. Commercial PV technology development also led to the development of large utilities and multi-megawatt power plants [7]. The main issue with solar energy is that it is installed outside where it can be impacted by snow, dust, and bird droppings, which would lower the production efficiency. Another issue is that damage to the inverter, modules and wire connections could reduce capability by 10% to 25%. [8]. At the level of operation and maintenance, dust continues to pose a significant challenge for the solar industry because dust build-up on panels can significantly lower the power output of those panels [9-10]. The presence of climatic factors that promote dust deposition on solar PV panels and areas with the highest levels of solar insolation are strongly correlated. As a result, if the deposition is not reduced, dust deposition is a serious issue that will affect the economic viability of solar power in many regions [11].

Eltayeb et al. [12] designed and developed a water-based robotic cleaning system for dust particle cleaning on the solar photovoltaic (PV) panel. The developed robot uses a rotary brush as well as a water spray to clean the PV panel. The solar tracking system was also integrated to improve the efficiency of the PV panel. Noh et al. [13] developed a water-based fully automated solar PV panel cleaning system. The Arduino controller system was utilized to control the movement of the robot during cleaning. The authors found that the robotic system developed is more effective than manual cleaning. The cleaning of solar PV panels improves the efficiency of the solar panel by 50 %. Khadka et al. [14] studied the various factors affecting the performance of solar PV panels. The author found the soiling of the PV panel as an important problem which affects the performance of the panel. The authors propose a result-making model that makes use of machine learning tools, techniques for data processing, and parameters that are likely to occur. A significant development in the field of renewable energy could come from the incorporation of data science and machine learning in a solar PV panel cleaning system. Chailoet et al. [15] studied the feasibility of the modular robotic cleaning solution for scrubbing the solar panel. The developed water-based robotic cleaning system is useful for solar farms, solar rooftops and floating solar panels. It is found that the intermediate cleaning of the solar panel improves efficiency and increases power generation. Akyazi et al. [16] found muddy rain, snow and soiling as the main reasons to reduce the efficiency of the solar PV panel. The authors developed a robotic cleaning system for solar PV panels using an Arduino Mega microcontroller and tested it in real-time. The Arduino microcontroller is used to control the movement of the robot. The developed system improved the power output of the PV panel. Kumar et al. [17] proposed a concept for the dust cleaning problems on the building integrated photovoltaics (BIPV) and building applied photovoltaics (BAPV). The authors provided a detailed investigation of the effect of the air dust particles on the performance of the PV panel. The effect of ecological dust particles on energy loss in the PV module was assessed by evaluating the electrical performance index such as voltage, current and power. Kangane et al. [18] studied the effect of the orientation of solar panels on dust particle collection and performance efficiency. They found that the vertical alignment of solar panels will reduce dust accumulation but at the same time reduction in solar irradiation reduces the power output. They mentioned reduction in manpower, efficient and proper cleaning, and lessconsumption of water as the main advantages of the robotic cleaning system. Parrott et al. [19] designed an autonomous robot for cleaning the solar PV panel. They found the silicon rubber foam brush as more effective in panel cleaning as it creates less impact on the PV panel surface.Jaradat et al. [20] reported that the dust and dirt particle accumulation on the solar PV panel decreases the efficiency of the PV panel. They suggested the portable robotic cleaning systemfor cleaning the solar PV panel. They concluded that the robotic cleaning system can remove more than 80 % of dust particles on the PV panel surface. In the field of the effect of dust accumulation on PVs, studies have been conducted in controlled environments; few have been conducted outdoors, and the majority of these experiments examine only dust deposition. The dust dispersion is rarely considered in relation to solar energy collection. Lengweiler [21] proposed a mathematical model that describes the dust deposition velocity and the resuspension rate as a function of environmental conditions for the health control of ventilation in buildings. His investigation was conducted in a wind tunnel under laboratory conditions.

The overall efficiency of the solar PV panel is 20 % which is very less compared to the efficiencies of the available power sources. The dust accumulated on the solar PV panel reduces the performance efficiency of the solar PV panel. Intermediate cleaning of the solar panel depending on the level of dust accumulation is recommended by the researchers. This work aims to design and develop a waterless solar PV panel robotic cleaning system. The performance of the developed robot is also studied in the current work. The effect of cleaning on the performance efficiency of the solar PV panel under different environmental conditions is also studied. The comparison of the developed solar PV panel robotic cleaning system with the commercially available systems is also described.

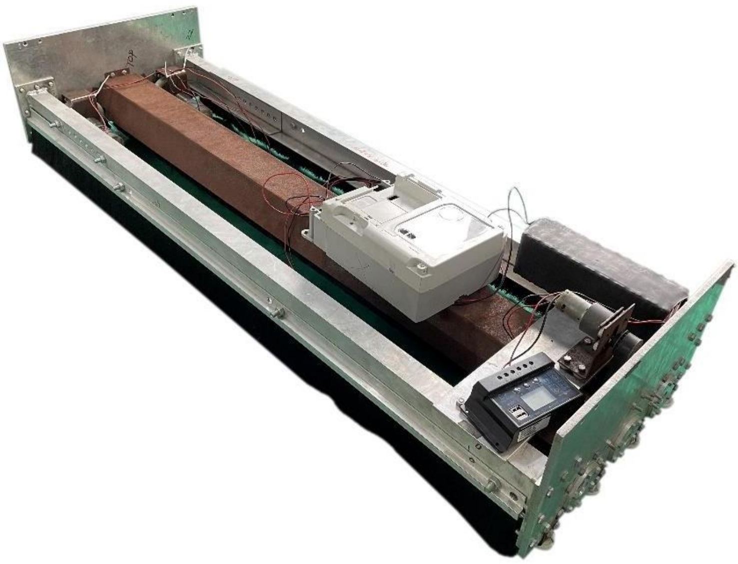
2. MATERIALS AND METHODS

Using a modular design, robots can serve panels of 1-2 metres in length. The primary method for cleaning solar panel arrays involves the rotating of a cleaning brush on the top surface of the panels. The invention comprises a cleaning system for various types of solar panels. The robot's length can be adjusted using a bolt configuration that facilitates disassembly and assembly.

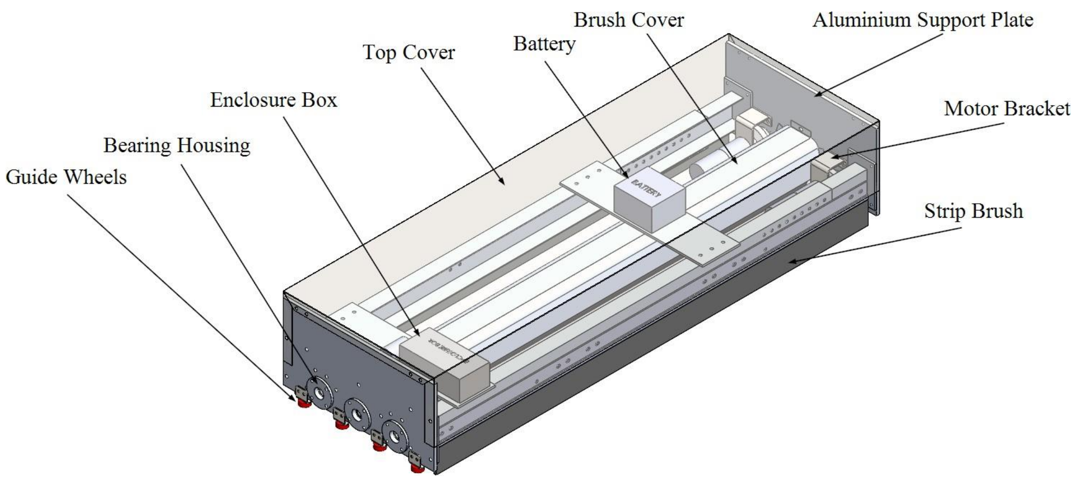
The purpose of the field tests described in this research was to evaluate the effectiveness of employing robotic cleaning equipment (shown in Figure 1 (a) and (b)) in reducing the effects of deposited dust on solar power generation. Fig. 1 (a) shows the photographic view and part details are shown in Fig. 1 (b). In the experiment, two solar PV panel sets each of 5 panels and each panel with 2 kW capacity (with 10 kW of total capacity for one set) were positioned. Each set consists of a 330 W panel with an area of (2 m x 1 m = 2 m^2) 2 m^2. So, a 2 kW panel has a surface area of 12 m^2 while the surface area of the set with a 10 kW capacity is 60 m^2. The solar PV panels were installed at Pune. The solar PV panel was put at an appropriate sun angle of 25 degrees for the Pune (India) region by the installer. The energy generated by the solar PV panels was monitored with the use of an inverter. For the first set of experiments from 25th April to 5th May 2022, both the PV panel were uncleaned over the last 6 months. The system was put into operation in December 2019, and we conducted tests from 25th April to 16th May 2022. Complete data collection was available, yielding accurate results for 22 days. The area where the panels are placed has paved walkways and gravel to reduce the amount of dust generated by the movement of people. The land is located along a road with minimal traffic, and there are no industrial sites nearby. A building site was located around 700 meters northwest of the testing location, with prevailing winds blowing from the southwest.

2.1 Design Overview

This robot was developed to clean a whole solar plant table. While defining the robot's geometry, weather and durability were considered. Provisions have been made to ensure that the robot is weatherproof, and that water and dust do not interfere with its operation. Utilizing sensors has allowed the robot to require minimal human help. Care has been taken to overcome minor flaws that develop during the installation of the solar plant, such as the fact that the tilt angles of the solar panels are not identical, which causes minor alignment concerns. Although the major objective of this robot is to provide an effective method for cleaning PV modules, this design also focuses on optimizing existing systems.



(a)



(b)

Fig. 1. The complete setup of the PV module cleaning robot; (a) Photographic image and (b) Part Details

The robot is fitted with a length-adjustment mechanism so that it can be used to clean panels of varying lengths. It was also found that existing market solutions use one robot per row for cleaning purposes, which dramatically increases cleaning costs. The concept presented in this research offers a cost-effective solution to this issue, employing only one robot per table. After cleaning the first table, the robot returns to the bot assembly adjacent to the table in the walkway and docks. This robot is tasked with transporting the cleaning robot to the next row. Once the robot is placed parallel to the second row, it exits the dock and cleans the second row. This process is repeated until all rows of a specific table have been cleaned. The specification of the developed robot is given in Table 1.

Table 1: Robot Specification

Robot Specification	
Length of Robot	1200mm
Width of Robot	400mm
Battery Capacity	30Ah
Cleaning Capacity	480^2/hr

2.2 Design Details

The PV Cleaner moves in both directions on the PV module. On the cleaning machine, the clockwise rotation of the cylindrical Brush was mounted. The PV Cleaner follows the revolving brush and strip brushes as they travel. It removes dust from the entire table by pushing it away from the borders of the PV module and moving it in the direction of the PV Cleaner's movement. The PV Cleaner returns to the row-changing trolley once it reaches the table's end. As the PV Cleaner approaches the changing trolley, it stops. The position of the PV cleaner row is afterwards altered by the row-changing trolley. After this, the PV Cleaner has activated again, and the procedure continues until the entire table is dust-free.

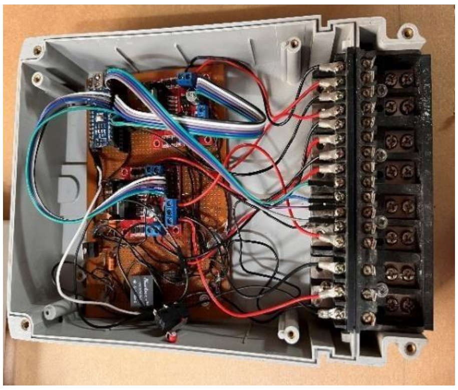
The components used in the automated solar PV cleaning robot for cleaning solar panels are specified as follows:

i. Brush: Rotary brushes are mounted on the side plate structure with a length of 1.2 meters.
ii. Strip Brushes: Strip Brushes are mounted on C-Channels along the length of the cleaningrobot.
iii. Wheels: A set of four wheels with a 70mm diameter are implemented to ensure the robotmoves smoothly.
iv. Guide wheels: A set of eight guide wheels are used to position the robot on the solar panel.This will ensure the robot will not slide and fall on the ground.

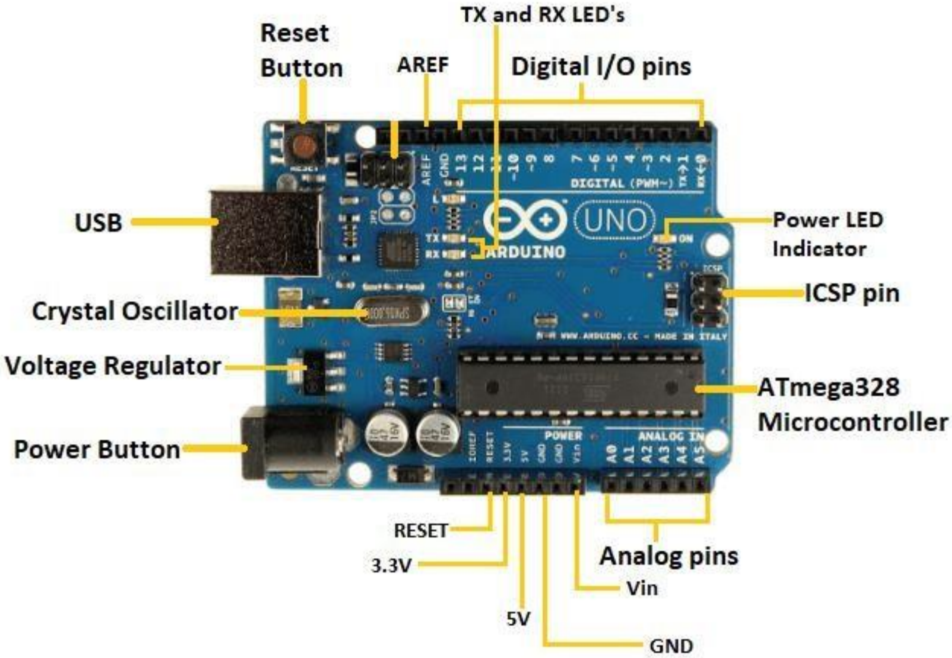
v. Motor for driving brush: A 25 W 12V DC motor with 200 rpm will be used.
vi. Motor for driving wheels: A 88W 12V DC motor with 100 rpm will be used.
vii. Aluminium Side plate support structure used to ensure rigidity of robot.
viii. Ultrasonic sensors: Ultrasonic Sensor HC-SR04 four quantities are used to detect thecorners of solar panels.

2.3 Electronics System Design

The design of this Cleaner's Electronics System was divided into two systems: DC motor drive and solar charge controller. Arduino will be controlling the system (shown in Figure 2 (a) and (b)). Fig. 2 (a) shows the photographic view and part details are shown in Fig. 2 (b). Arduino controls the rotational speed and direction of four 12-volt DC motors.



(a)



(b)

Fig. 2. The control system for PV panel cleaning robot; (a) Photographic image and (b) Part Details

We have created a circuit for the row-changing trolley for the second system. It waspowered by four DC motors for forward and reverse movement.

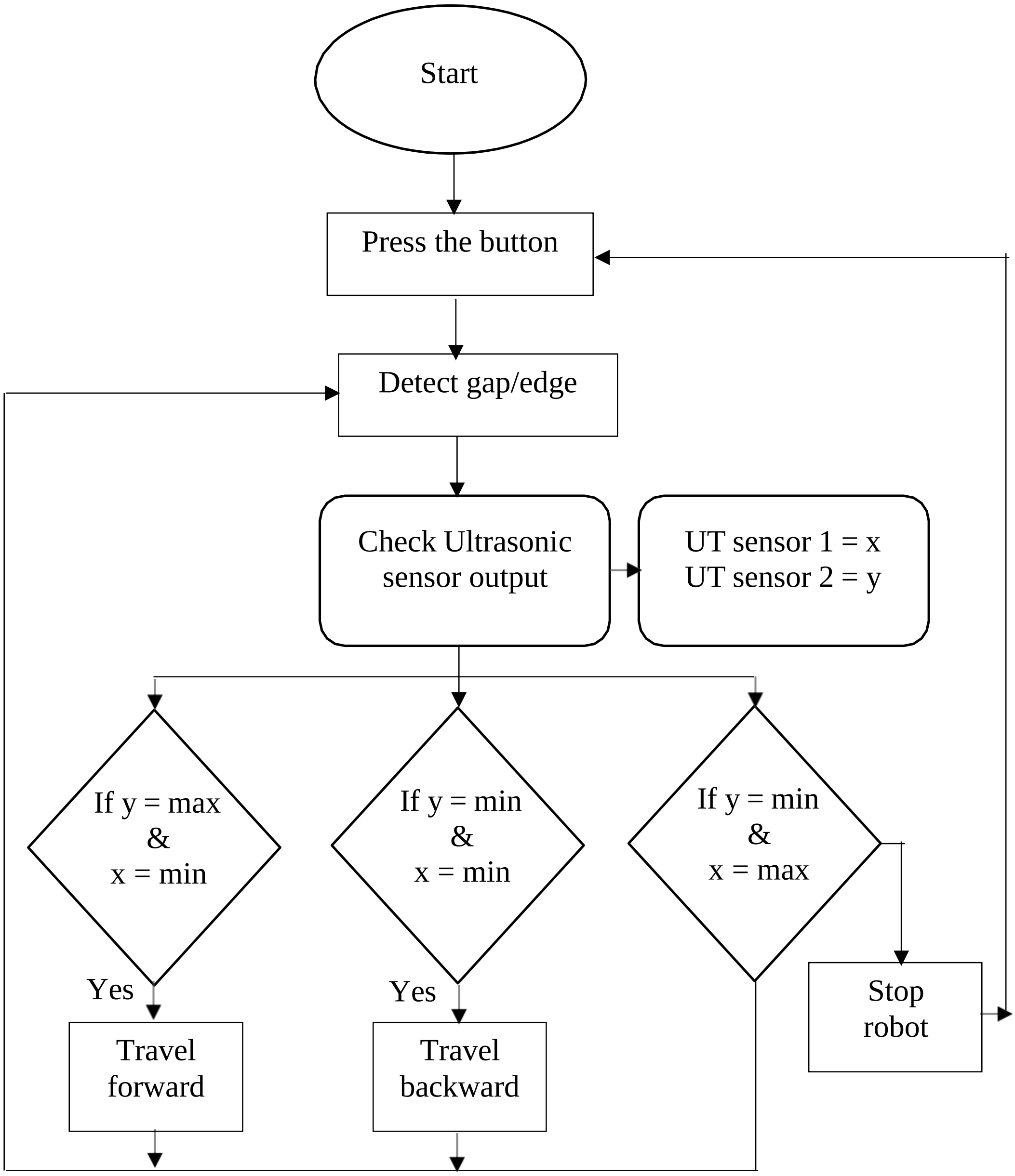


Fig. 3. PV cleaning robot working

The brush-equipped robot cleaner is designed to remove dust and undesirable particles from the surface of PV panels and cleans the panel surface. When the user presses the start button to activate the robot, the DC motor begins rotating the brush, and the robot begins cleaning the panel surface. As depicted in Fig. 3 The Robot will not move forward if the output from the Ultrasonic sensor 1 sensor is maximum. In the code, the Ultrasonic sensor 1 output is assumed to be x and the Ultrasonic sensor 2 output is assumed to be y. Ultrasonic sensor 1 output is connected to Arduino nano pin 5, while Ultrasonic sensor 2 output is connected to Arduino nano pin 6. L298 2A Dual Motor Driver Module pins are connected to Arduino nano pins (7,8,9,10,11,12,13,14).

3 EXPERIMENTAL SET-UP

The testing bed was constructed from durable steel sections and was intended to accommodate the actual site constraints of the project. It could accommodate the PV cleaning robot, battery, and panel.

Fig. 4. Actual prototype for PV cleaner on the test bed

The PV cleaner is a precise assembly of a handful of components. Fig. 3 and Fig. 4 depict a fully operating robot cleaning system. The PV Cleaner robot glides along the length of the PV module while cleaning the entire surface. The central box contains the electronics system that powers the motors. When ultrasonic sensors on both sides of the PV cleaner detect the end panel edge, the robot returns to its starting point and performs a second cleaning run. The actual prototype of the PV cleaner with all components is shown in Fig. 5.

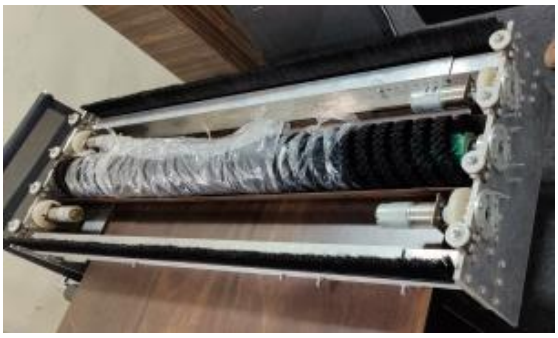


Fig. 5. Actual prototype for a PV cleaner with all components

. The experiments were performed from 25th April 2022 to 16th May 2022. The dimensions of the installed single solar PV panel with a capacity of 330 W are 1 m (Width) × 2 m (Length). The test set-up consists of two sets of a solar PV plant with a capacity of 10 kW and a surface area of 60 m^2. Both the panels were cleaned for the last 6 months before the start of experimentation. One set of the solar PV plant is kept uncleaned throughout the experimentation while the other set is cleaned once a day for the last 11 days of experiments i.e. from 6th May 2022 to 16th May 2022. The uncleaned solar panel is shown in Fig. 6 while the solar panel cleaned using the developed robotic cleaning module is also shown in Fig. 7

Fig. 6. Uncleaned solar PV panel

Fig. 7. Cleaned solar PV panel using the developed robot

4. RESULTS AND DISCUSSIONS

4.1 Comparison of the power generation

To study the performance efficiency of the developed solar PV panel robotic cleaning system, solar power generated using the uncleaned solar power plant is compared with energy generated using a cleaned solar power plant. The power generation is measured for the day from 25th April 2022 to 16th May 2022. The power generated by uncleaned solar PV plants set 1 and set 2 is as shown in Fig. 8. From Fig. 8, the energy generated in both sets of uncleaned solar PV plants for the days of experimentation from 25th April to 5th May 2022 varies from 7.8 kW to 8.05 kW. There is a small difference in the power generated by both uncleaned solar set 1 and set 2 because of the uneven soiling of the solar PV panels. The developed solar PV panel cleaning robot is used to clean the solar PV panel. To study the effect of panel cleaning on energy generation, set 1 is kept uncleaned while set 2 is cleaned using the developed robotic system. The power generated by the cleaned (set 1) and uncleaned (set 2) solar PV plant is measured from 6th May to 16th May 2022. The comparison of the power generation of the uncleaned and cleaned solar PV plant is as shown in Fig. 9. There is no significant difference in power generation by set 2 in 22 days of experiments under uncleaned conditions. After performing the cleaning of the one solar PV plant using the developed robot, the energy generation in the cleaned solar plant varies from 8.95 kW to 9.05 kW.

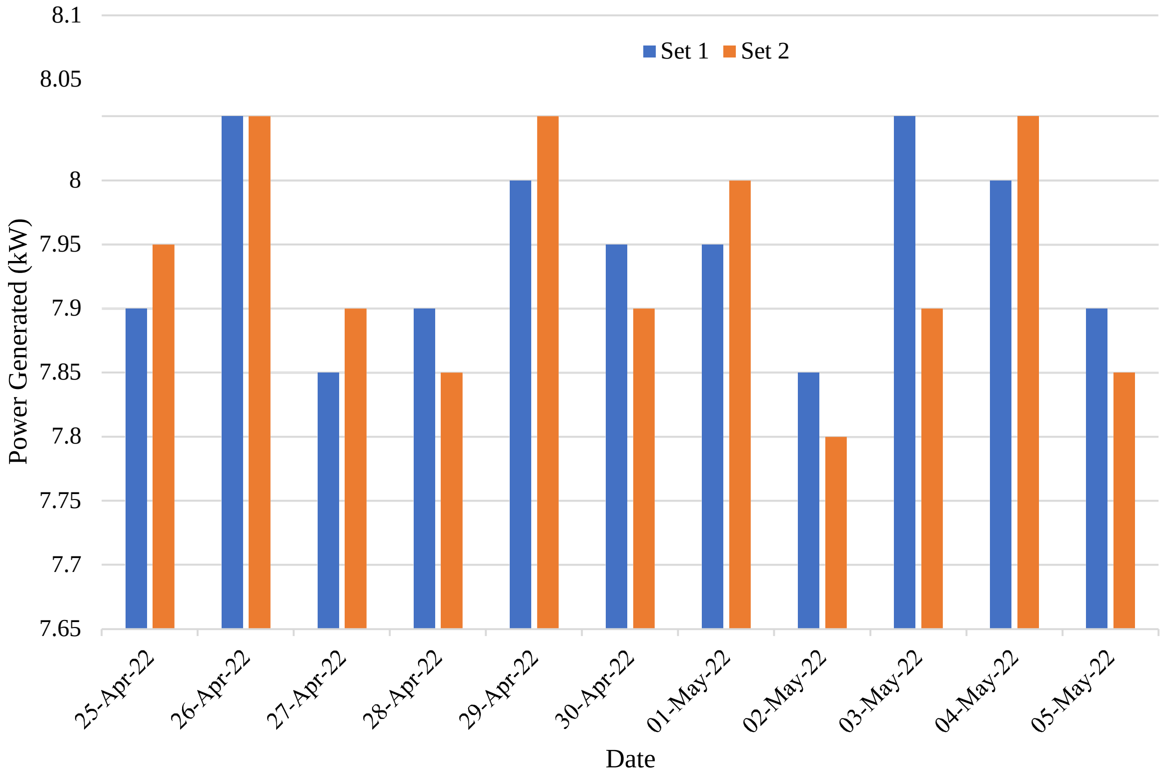


Fig. 8. Power generated in uncleaned solar PV plant

It is seen that, after cleaning the solar panel, the performance efficiency of the solar PV plant increases from 11.8 % to 17.3 %. The improved performance efficiency is calculated as:

$$\%\,\eta = \frac{P_{cleaned} - P_{uncleaned}}{P_{uncleaned}}$$

Where, η is the efficiency, $P_{cleaned}$ energy generated in cleaned solar PV panel plant and $P_{uncleaned}$ energy generated in uncleaned solar PV panel plants. The robotic cleaning of the solar PV panel improves power generation and increases the efficiency of the solar PV plant.

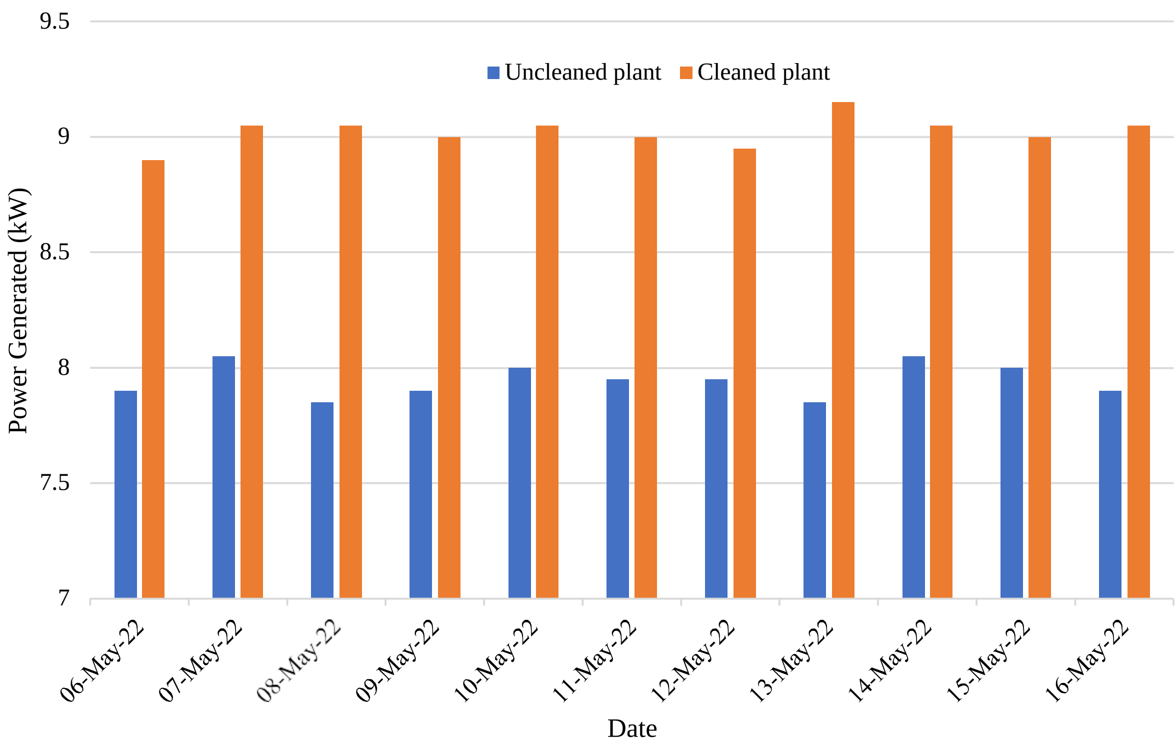


Fig. 9. Power generated in uncleaned and cleaned solar PV plant

4.2 Comparison of the developed system with the existing system

There are several methods such as manual cleaning, surface coating, vibrations and water-based cleaning used for the cleaning of the solar PV panels. It is very difficult to compare each system of solar PV panel cleaning with the developed cleaning system. In this study, for the comparison of the developed robotic cleaning system of the solar PV plant, the manual cleaning system is selected. To compare robotic cleaning with manual cleaning; the solar PV plant set is cleaned manually. Three experiments have been performed for manual cleaning. The time taken for the manual cleaning and the area cleaned is also measured. A mobile stopwatch has been used to measure the time required by the robot as well as the human to clean the solar PV panels. The time taken to clean the solar PV panel set of 10 kW by robotic cleaning method and by manual cleaning is as shown in Fig. 10. For the developed robotic cleaning system, it takes an average of 10 minutes to clean one plant. The manual cleaning takes an average of 15 minutes to clean the maximum possible area of the solar PV panel. It has been found that the time taken by manual cleaning is 50 % more than that of the time taken by the robotic cleaning system. The developed robotic cleaning system is found to be quicker and less time-consuming. The robotic system covers the full area of the solar PV panel while it is found difficult for human cleaning to cover the full panel area because of the size of the solar PV panel.

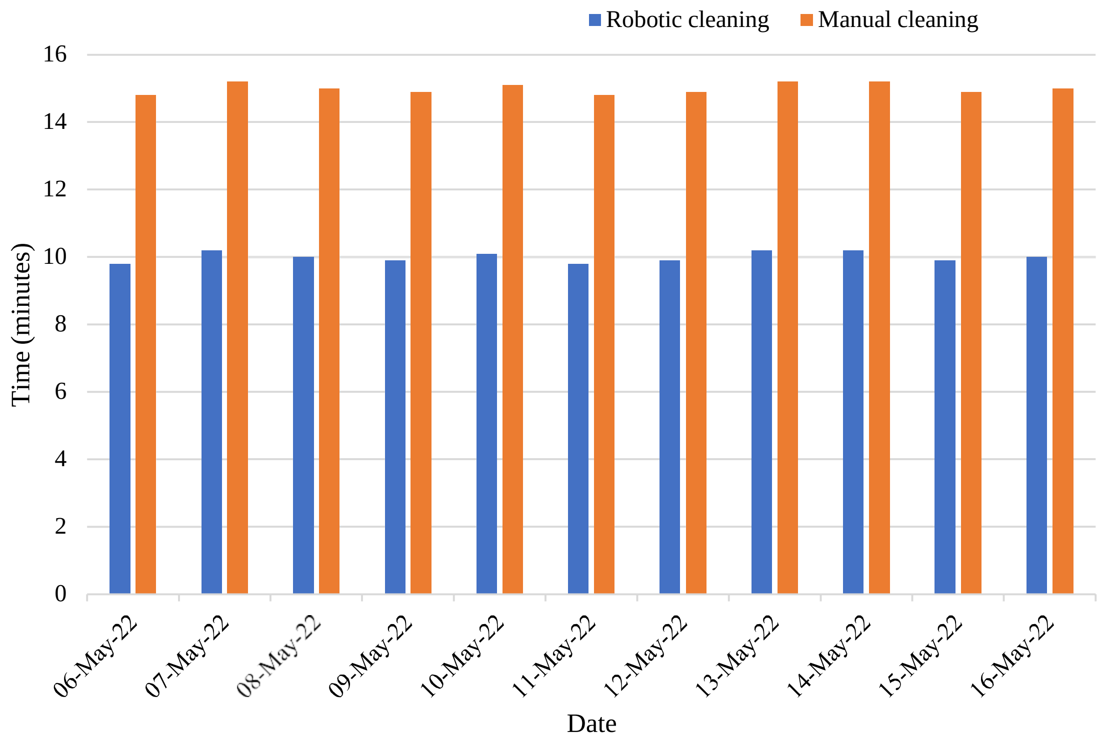


Fig. 10. Time taken for robotic and manual cleaning for solar PV plant

The developed robotic cleaning covers the total area of the solar panel while it is very difficult to clean the whole solar PV panel at the time of manual cleaning. The developed robotic cleaning system can be made automatic to dust sensors so that the cleaning would be done at the time of requirement. The manual cleaning of solar PV panels is very risky in the case of solar PV plants of higher capacity. It is very difficult for humans to reach out to the location of plants situated in a large area, and it is also very difficult to clean the whole panel. The developed robotic cleaning system for solar PV panels would be very effective in solar power plants with higher capacity. The system can be made automatic to minimize human interference. There are chances of the mechanical failure of the robotic cleaning system which can be solved by the technician. The impact of cleaning of solar PV panels on the performance efficiency will be scaled up depending on the capacity of the solar PV plant.

5. CONCLUSION

In the present study, the solar PV panel robotic cleaning system is designed, and one full-scale prototype is developed. Two PV solar power plant sets with a power generation capacity of 10 kW and panel surface area of 60 m^2 located in Pune (Maharashtra, India) have been selected for experimentation. Initially, both sets of solar PV panels were kept uncleaned for six months before experimentation. The power generated by both the plates has been measured in uncleaned conditions. It has been found that there is no significant difference in power generation by both sets of solar PV power plants. Then one solar PV power plant set is kept uncleaned for the next set of the experiment while the other solar PV power plant was cleaned once a day. The power generated by both sets of solar PV power plants (one is uncleaned and the other is cleaned) has been measured. The time taken by the robotic cleaning system and manual cleaning to clean the solar PV plant was recorded.

It has been found that. The accumulation of dust on photovoltaic panels can significantly reduce their output. The PV cleaning system presented in this research paper is a straightforward alternative that addresses this issue effectively. This project is aimed to provide a better alternative for maintaining the efficiency of the solar PV panel. It has been found that the cleaning of solar PV panels improves the performance efficiency of the solar PV plant by 11 to 18 %. The robotic cleaning system was found 50 % less time consuming compared to the manual cleaning of the solar PV panel. It is found to be very difficult for manual cleaning to clean solar plants of higher capacity. Depending upon the size of the solar PV panel, it is found to be difficult to clean all surface area of the solar PV panel at the time of manual cleaning. The robotic cleaning system for a solar PV panel is found to be very effective for the solar PVpower plants of higher capacity and located at remote locations. The use of a solar PV cleaningsystem enhances the overall efficiency of the solar panel thus reducing the cost of theelectricity.

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