A Review on Cleaning Mechanism of Solar Photovoltaic Panel

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***Abstract*— Accumulation of dust (also known as soiling) on the surface of solar panels decreases the amount of sunlight reaching the solar cells underneath and thus the efficiency of the solar panel is severely impacted. To harness their designed capacity to its fullest, they need to be cleaned periodically, usually with water. Due to water scarcity in some area, cleaning becomes difficult, challenging and subsequently costly. Solar Photovoltaic conversion technique of is largely used as a pioneer and efficient conversion of solar energy. Many factors govern Solar Photovoltaic energy conversions efficiency like solar intensity, the area of the module, semiconductor, tracking mechanisms, dust, and dirt etc. Nowadays among these factors dust and dirt has become crucial for research since they have a significant effect on conversion efficiency. If proper cleaning mechanisms are used then, it may show about 25% improvement in output energy or about 15 to 20% enhancement in conversion efficiency. Hence, rigorous study of SPVC automated cleaning mechanism is vital. This paper discusses a comprehensive overview of dust problem and the recent developments made on automated cleaning system of solar photovoltaic modules which gives a brief overview of techniques like electrical, mechanical, chemical and electrostatic. The main objective of the study is to review the literature on solar photovoltaic module automated cleaning techniques for identifying research gaps in the automated cleaning systems.**

***Keywords*— Solar panel cleaning, Automated solar cleaning.**

1. Introduction

Now a day, energy-related aspects are becoming extremely important. They involve, for instance, a rational use of resources, the environmental impact related to the pollutants emission and the consumption of non-renewable resources. For these reasons, there is an increasing worldwide interest in sustainable energy production and energy saving. The research activity and development in PV field have usually been focused on solar radiation analysis, efficient operating strategies, design, and sizing of these systems. Effect of dust on the power reduction and efficient reduction of PV module was quantified. [1]

Growing interest in renewable energy has led the solar photovoltaic (PV) industry to expand notably in the last decade. In the year 2016, a staggering 95 terawatt-hours of electricity [13] was produced in the European Union hence covering 3 percent of the total electricity demand. Because Photovoltaic energy is an accessible technology it has become a popular investment for companies as well as for residential users. Consequently, this demand has stimulated the research for increasing the overall output power of PV systems causing laboratories all over the globe to work hard on making the technology both more efficient and cost effective. [12]

Regardless of the effort of the industry to shorten the payback time, a preventable loss namely soiling is often overlooked. As a result, a layer of dirt piles up on top of the glass reducing its transmittance and therefore decreasing the power output of the entire system. Besides the material and design parameters, there are several omnipresent factors such as dust, humidity and air velocity that can influence the PV cell's performance. By increased wind velocity more heat can be removed from the PV cell surface. In the same vein, higher air velocity lowers the relative humidity of the atmospheric air in the surroundings which in turn leads to better efficiency. [2] Electricity generated using solar photovoltaic (SPV) technology can only be economical if the PV modules operate reliably for 25– 30 years under field conditions. [3]

Seeing that precipitation plays a considerable role in the cleaning capability it must be said that rainfall often does not suffice because of some types of soil cement and stick. The same counts for bird droppings which don't flush away either. However cleaning solar panels is not always as straightforward. To begin with, there is the issue of accessibility. Due to the fact that PV panels often are situated on dangerous and difficult to reach places, it might be hard to clean them manually and it takes the time to do it safely. However, leaving panels uncleaned might not be wise either since soiling can lead to permanent damage of the glass limiting the lifespan of the installation. The logical solution is to clean them automatically and autonomously.

The electrical parameter of the solar panel is sensitive to the dust density so it is very essential to provide auto-cleaning mechanism to remove the dust particles from the surface of the panel in order to ensure high performance.

2. Automated solar panel systems

A) The Boston University Study reported the costs and benefits of three current methods of cleaning solar panels. These methods include natural cleaning through rain and snowfall, manual cleaning, and cleaning by an electrodynamics system (EDS). An emerging technology, called an EDS, consists of interdigitated Electrodes (made of

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indium oxide) in the transparent dielectric film. The cleaning process is orchestrated by low power, three phase pulsed voltages (from 5 to 20 Hz). An electro-dynamic screen (EDS) or multi-phase electric curtain-based system requires a high-voltage external power source for its operation, but the EDS can be made self-sustainable with the power output from the PV cell itself. It incorporates a transparent EDS with a PV array as its power source to make itself sustainable. This process led to a reflectivity restoration of 90% after only a few minutes [4]

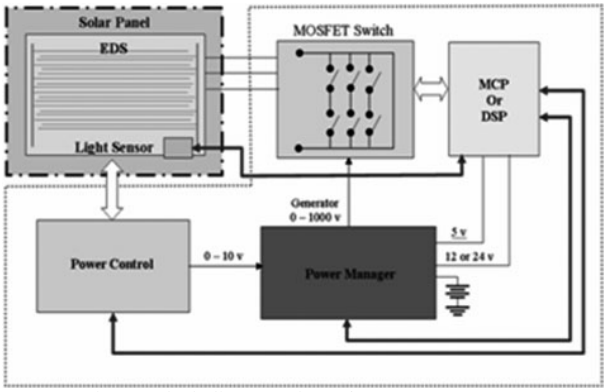

Fig. 1 - Block diagram of EDS/PV array system [5]

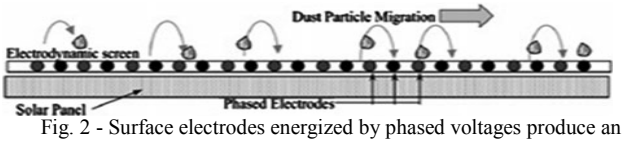

Fig. 2 - Surface electrodes energized by phased voltages produce an electrostatic traveling wave for lifting and transporting dust particles [6]

B) Manual cleaning technically is not a robot but as this is one of the most used ways of cleaning residential solar panels today it, therefore, important to mention as well. Standing on ladders or climbing on roofs, this is often a job for a professional as it is risky and requires the right material. However, this method might have little or no influence on the yearly yield unless it gets done regularly. Especially if the job is done by a contractor this might be very bad investment there the labor costs will exceed the profitable return. [14]

C) Sprinkler systems are often used in dry areas to keep panels clean. It has the same cleaning effect as rainfall and will clean panels at a relatively low cost. Like most systems, the one found on the website of Heliotex [15], exist out of a water filtration system and soap dispensing system. They also mention that water hardness has to be tested to and optionally a water treatment is advised for locations with hard water. Although this is a relatively good working system, there are a couple of drawbacks to it. This system is suitable for very dry sandy areas where sand stacks up very fast but will not clean as thorough as a brush system.

D) An Italian company called 'Wash Panel' produces robots 'solar panel cleaning robot' [16] that clean arrays of PV panels by moving a vertical brush horizontally over a row of panels. Having a length of 1 to 16 meters and containing a 12V battery it can be deployed automatically. Also, a water hose is attached for wetting the panels while cleaning. Wash panel's system is fully autonomous, it has a double programmable functioning through a rain sensor and by use of water jets. It provides a constant and uniform cleaning. This system is modular, with possible supervision and management from a remote site. It doesn't require any extra frame, support and additional guides. It can be installed on ground systems, buildings, peaked roof or shed roof. For continuous monitoring, it sends text messages to mobiles, allowing command control from remote sites as shown in Fig. 3

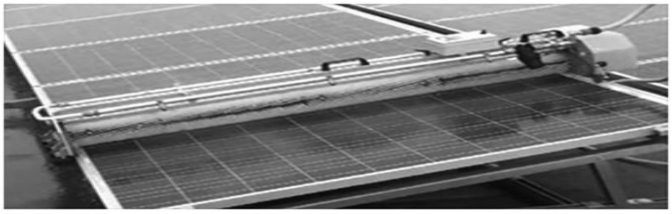

Fig. 3 - Wash panel cleaning over SPV [16]

E) In addition, robotic cleaning mechanisms such as 'Gekko Solar' [17] and 'Gekko Solar Farm' [18] from Sabot Swiss Innovations developed for mobile deployment onto SPV panels as shown in Figure 3. Gekko solar has a cleaning capacity of up to 400m^2 per hour. Its cleaning is through a rotating brush and demineralized water. It is supported by a mobile lifting platform. The operator controls the robot by use of a joystick. It is supplied from a support trolley over a 50m long supply hose. Its movement is based on feet, with vacuum technology, which is rotating on two trapezoid-shaped geared belt drives, enabling the robot to astonishing flexible movement in every chosen direction. It can be radio controlled with a joystick.

Fig. 4 - Cleaning using Gekko solar and Gekko solar farm [13]

F) The GEKKO Solar Farm was developed specifically for the cleaning of large free-field solar parks. The challenge lies in the dimensions. The rows of panels are miles long, which makes an efficient use of cleaning tools a must. With a cleaning capacity of up to 2000m^2 per hour, GEKKO Solar Farm fulfills this requirement. The GEKKO Solar Farm can be used up to an incline of 30° and can traverse gaps of up to 60 cm. The operator controls the robot over radio control using a joystick. This is supported by an integrated crane arm.[17][18]

G) Module cleaning devices have long consisted of telescopic rods with cleaning brushes affixed to the top. The PvSpin is the first of its kind a consistently effective, easy-to-handle module cleaning system powered by water pressure. PvSpin works on the basis of two durable rubber brushes rotating in opposite directions, removing dirt and other contaminants from the module surface. Lightweight and easy to handle, it

can be guided from the ridge of the roof and safely operated by one person. Tough dirt, bird droppings, and other debris are easily removed by the rotation of the durable rubber brushes and filtered water. [19]

Fig. 5 - Pv- Spin Module cleaning device [19]

H) Sinfonia's robot Resola [20] has a distinction in being "autonomous" in that, rather than tethered to rails, the robot is able to move from panel to panel, to tackle the panels' dirt and debris. The robot is equipped with scrub brush, wiper, and detergent and also sprinkles water stored in its tank. The robot can work in the dark. It has LEDs, having wavelengths in the infrared range Fig 6.

I) 'HECTOR' [21] is a robotic cleaning system for Heliostat's, which can be used for Solar PV panel cleaning also, as shown in Figure 11. It is wireless, rechargeable and carries water solution tank with itself. HECTOR robots only require an operator's intervention for refilling its water tank, changing the battery and distributing it within the plant Fig 6. It is fused with various sensors which permit it to navigate autonomously without any human supervision. It requires no external power or water supply for its operation; it carries its own batteries and water tank. HECTOR is designed for night and day operation. Its performance is very slow and the weight of HECTOR is over the panel. HECTOR performs a thorough, uniform, brush cleaning action.

Fig. 6 – Sinfonia Robot [20]

Fig.7 – Hector Robot [21]

J) The Ecoppia E4 [22] is a fully autonomous robot that uses microfiber brushes to sweep the dust off of panels. It's designed for large rows of panels situated in dry and sandy environments. By making use of gravity the brushes move downwards spinning, creating an airflow that helps to blow off the dust. The robot makes use of an onboard solar panel and battery to store energy that allows the robot for cleaning at night. Another interesting feature is the positioning of the solar panel on the bottom of the rail, allowing it to be cleaned by the brushes as well. Both horizontal and vertical translation happens using a guide rail and wheels.

Removing 99% of dust daily, the E4 cleaning solution keeps solar panels at top production levels and use even in the harshest desert conditions. Eliminating manual labor and water waste, a fleet of E4 cleaning robots is remotely managed from a dashboard or mobile app. The water-free E4 robots use a self-cleaning mechanism during and after cleaning routines. It has an Eco-hybrid system which helps significantly extends battery life time. [22]

Fig. 8 – Ecoppia E4 robot [17]

K) The Solarbrush [23] is a light-weight, autonomous robot for dry cleaning solar panels or glass in dry environments. Using tracks made o suction cups, it moves over the panels making it possible to cross gaps up to 30mm and working on surfaces tilted up to 35 degrees. Different kind of brushes can be attached to the front of the robot in order to brush away dust, sand, and dirt. Power comes from a rechargeable battery. It is wireless and rechargeable. It is having a cleaning brush which swipes the dust. Solarbrush is light weight of 2.5 kg.

Fig.9 - Solarbrush robot for solar panel cleaning [23]

L) Miraikikai Inc. designs lightweight, battery□powered robots [19] that can autonomously clean large-scale solar panel arrays. A robot cleaner with small wheels that utilize state of the art sensor technology to deftly navigate entire solar arrays using rotating brushes to flick away dust and sand. The smaller prototype SMR□640AD model, weighing just 17kg, runs on a Li□ion battery cartridge that provides approximately 1.5 hours of usable time per 3□hour battery charge. The robot changes direction to move to the next line of modules when it reaches the edge of the solar PV array and signals the end of cleaning when it arrives at the "goal" point. On□site engineers need only replace batteries and monitor the progress of the robot as it cleans. These robots reduce cleaning costs by 80 percent compared with manual cleaning. These robots would be used exclusively in countries with high amounts of sunlight and low rainfall.

Fig 10- Jetro robot solar cleaning system [24]

M) The NOMADD (NO Water Mechanical Automated Dusting Device) [20] is a desert solar panel cleaning system, which embodies the ultimate combination of solutions to the desert cleaning challenge. The device has eight patents pending that relate to the unique mechanical actions of the system, that allow it to have just three moving parts while removing 99.6% of dust with a cost effective daily clean. The NOMADD achieves its fully automated status, by deploying one dedicated system per row of panels, with onboard power and control system. Each row can be up to 200m long, and 5m wide, with plans to expand to 300m as the product develops to meet customer needs. The unique and cost effective guiding rail system is cost-effective, and ensures that no pressure is applied to panel surfaces and that the system translates smoothly across the array for the lifetime of the array. Maintenance can be performed by unskilled labor, by removing the cover and replacing cheap, simple parts on a two and five yearly maintenance cycle, in under 20 minutes per machine, with a single tool. [25]

Fig. 11 – Nomadd solar cleaning robot [25]

N) Automated microcontroller PIC based cleaning system [7] that reduces the effect of shading on the output power of the PV panels. This design was built and tested for a short period of time. Due to the system's location, the research had to take into consideration several constraints such as lack of power supply, availability of distilled water, maintenance and available space. Microcontroller technology was used as the electrical basis for the design because of its many advantages especially due to its low power consumption. Power losses were calculated and found to be minimal because of the implementation of the microcontroller technology in this design.

Fig. 12 - The cleaning process where the wiper is pulled upwards by two motors attached to the rails. It also shows the electric circuit designed to power and control the mechanical section [7]

O) The PLC microcontroller based automatic cleaning device [8] used to enhance the output power of PV modules especially for offshore applications where efficiency and reliability are critical issues. The system is powered and controlled by means of a programmable logic controller (PLC) which has the ability of program upgrading and low power consumption. The model was built and tested. The main component of this system is the PLC which controls and powers both the mechanical and electrical parts of the design. PLC program is an efficient method to make the system fully automated without any human interface except for initial activation and maintenance issues. The system is successful in removing dust and bird droppings on the PV panels which led the PV to have better output hence, more efficient and more reliable for offshore application.

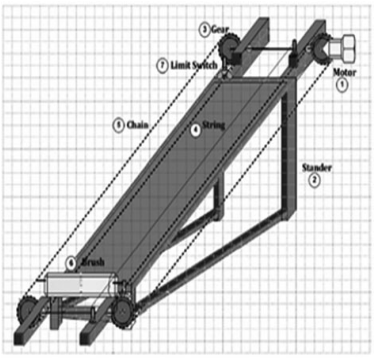

Fig. 13 – PLC based mechanical design for cleaning [8]

P) A novel four-stage automated 'dry cleaning' [9] method is reported for solar panels. The proposed cleaning process is carried out in four stages with no involvement of liquids. The cleaning process involves compressed air spray, followed by cleaning through a foam roller and a poly wool synthetic duster. An electronically controlled mechanical assembly holds the rollers and guides them along the solar panels. The system is very useful for small and large installations alike, especially in dry areas where there is little or no rain throughout the year. The system consists of the onboard compressor which sprays jet air on the panel. It is followed by

a panel cleaning using a spinning foam roller and synthetic duster roller. The system is controlled by an on-board microcontroller and very low electrical power requirements can be met directly using the panel itself. Since it involves no supply of liquids at all, it is very cost effective and efficient for the dry and hot environmental conditions as these of Saudi Arabia, Qatar and the Middle East countries. The detachable rollers and readily available components, which make the maintenance easy and very cheap. All these features make this system user-friendly. It is not to be confined to large industrial plants, and can equally be used at the small scale for home and buildings PVs and solar panels.

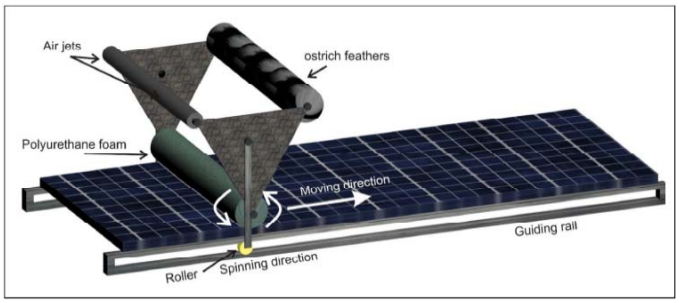

Fig. 14 – Novel dry cleaning assembly for cleaning [9]

Q) Mechatronics drive system for cleaning machine[10] is the structure of the cleaning machine, hydraulic scheme and the mechatronic system based on a unit with a microcontroller. The cleaning machine combines washing system with low-pressure water jet (~2 bars) with brushing the photovoltaic panel. The mechanics and kinematics of the machine were developed by the R&D institute ICTCM Bucharest. It has a Hydraulic tank of 100 l with return filter and oil cooling system. Automating of the installation is based on a microcontroller unit that receives information from sensors, from contacts limiter, thermostat and the pressure switches and gives commands to the valves coils for making various movements. Electrical commands are given through high side switches IC's. The project is very complex and required design in terms of kinematics, hydraulics, and mechatronic systems. The washing machine for solar photovoltaic panels is the first of its kind being developed in the country and is in the prototype stage.

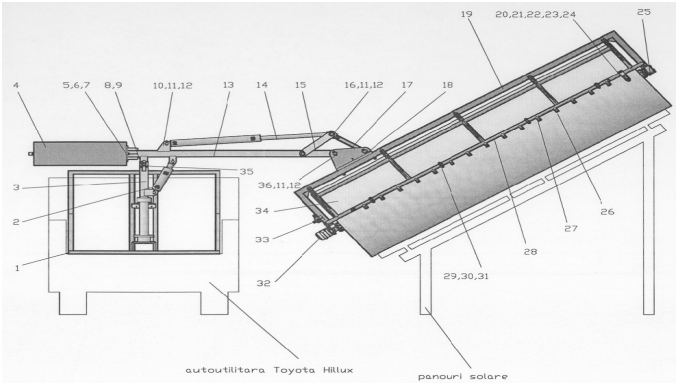

Fig. 15 – Mechatronics drive system for cleaning [10]

3. *Discussions*

The developments in automated cleaning systems have emerged in recent years. There are some natural things which can reduce the frequency and cleaning cost. This can be achieved by the following ways:

(1) By over sizing, the initial PV array installation to ensure any power reduction would not affect the expected system performance.

(2) By discouraging birds from nesting and landing on PV panels.

(3) By deterrence and surface modification (treatments, coatings, and films), so that dirt will not be settled or not been able to form strong bonding with the surface.

(4) By Electrostatic biasing, in which thousands of volts with normal electric field reject the particles.

(5) By designing the panel aerodynamically, the panel should swipe the dust.

(6) By avoiding the effect of irradiance on the solar panel, the life of solar panel should be more.

Dust settlement mainly relies on the dust properties (chemical properties, size, shape, weight, etc.) as well as on the environmental conditions (site-specific factors, environmental features and weather conditions). The surface finish, tilt angle, humidity and wind speed also affect the dust settlement. A framework to understand the various factors that govern the settling/assimilation of dust is illustrated in Fig. 21 [11]. It is easy to discern that the phenomenon of dust settlement is extremely complex and challenging to practically handle/comprehend given all the factors that influence dust settlement.

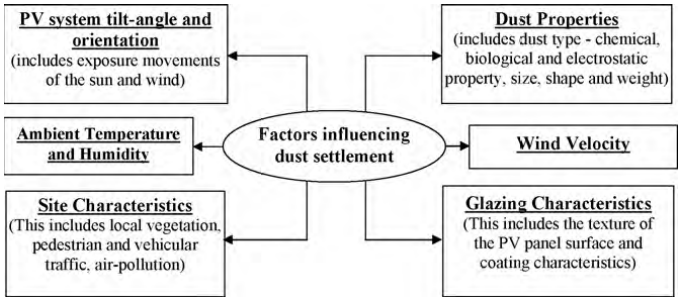

Fig. 16 - Factor influencing dust settlement [11]

The EDS cleaning system is efficient and can be used to remove dust from a variety of surfaces. It has no mechanical movement to scratch the protective surface. It is efficient with and without the use of external power supply.

The manual cleaning is a method that might have little or no influence on the yearly yield unless it gets done regularly. Especially if the job is done by a contractor this might be very bad investment there the labor costs will exceed the profitable return.

Heliotex's Sprinkler systems have lots of advantages that water reaches to every part of solar PV modules. It helps in cooling of solar PV modules, which increases the efficiency

of the plant. Although this is a relatively good working system, there are a couple of drawbacks to it. First, of, there is a large amount of water it uses as it cleanses the panels multiple times a day dependant on the scheduling. Secondly both filters and soap level have to monitored and taken care of both taking time and money. Lastly, there is the fact that wet panels make dirt stick to the panels causing the panels to get dirtier in the long run. It has the limitation that Treated water required & Filter has to be changed periodically also huge wastage of water.

Wash Panel having a length of 1 to 16 meters and containing a 12V battery it can be deployed automatically. Also, a water hose is attached for wetting the panels while cleaning. However, the robot rather doesn't need a track like most panels have. But it has Human intervention is required to start the operation and while moving from one row to another.

Gekko solar & Gekko solar farm are the important invention in solar cleaning mechanism. It has Self-regulating and flexible un interrupted cleaning operations. It reduces manpower in operation and does exactness in operation. Gekko solar has the limitation of inclination up to 45 degrees and gives additional stresses on the surface due to gear, belt, and vacuum system, while Gekko solar farm has the limitation of inclination up to 30 degrees. Also, this robot has complex gear, belt system.

Some other robots like HECTOR, PvSpin, Sinfonia rosola robot are compatible, integrated with all Supplies and can operational day and night also. The PvSpin cleaned 20kW per hour. The device follows the module frames, ensuring that each panel is cleaned completely and effectively. Lightweight and easy to handle, it can be guided from the ridge of the roof and safely operated by one person. Tough dirt, bird droppings, and other debris are easily removed by the rotation of the durable rubber brushes and filtered water. The sinfonia rosola robot is equipped with scrub brush, wiper, and detergent and also sprinkles water stored in its tank. The robot can work in the dark. It has LEDs, having wavelengths in the infrared range. HECTOR robots only require an operator's intervention for refilling its water tank. All this robot has limitations of slow performance in operating and it feeding has to be done regularly.

The Ecoppia E4 is a fully autonomous robot that uses microfiber brushes to sweep the dust off of panels. It's designed for large rows of panels situated in dry and sandy environments. It also recovers energy when the robot descends. Another interesting feature is the positioning of the solar panel on the bottom of the rail, allowing it to be cleaned by the brushes as well. Both horizontal and vertical translation happens using a guide rail and wheels. This technique suitable for only for large arrays and it is highly autonomous so its need lot of construction needed.

The solarbrush is the first robot which includes the drone technique in it. It is automated robot and works up to an inclination of 35 degrees. It is the wirelessly controlled system and can be rechargeable. Miraikikai Inc. design weighing just 17 kg, runs on a Li□ion battery cartridge that provides approximately 1.5 hours of usable time per 3□hour battery charge. The robot changes direction to move to the next line of modules when it reaches the edge of the solar PV array and signals the end of cleaning when it arrives at the "goal" point.
The NOMADD (NO Water Mechanical Automated Dusting Device) is the unique and cost effective guiding rail system, and ensures that no pressure is applied to panel surfaces and that the system translates smoothly across the array for the lifetime of the array. It removes 99.6 % of dust. Its Maintenance can be performed by unskilled labor, by removing the cover and replacing cheap, simple parts on a two and five yearly maintenance cycle, in under 20 minutes per machine, with a single tool. It has the limitation that it is costly and doesn't suitable for the unique panel and low maintenance plant.

The microcontroller based techniques have Self-regulating and flexible uninterrupted cleaning operations. By using microcontroller the system is fully automated and can be used for the unique panel. The system is successful in removing dust and bird droppings on the PV panels which led the PV to have better output hence, more efficient and more reliable for offshore application. The limitation of this technique that it has a complex chain, sprocket-based structure. It has an only single panel-based design.

The novel dry cleaning system with foam used in the design is a polyurethane foam, it is widely and cheaply available in the market. Low-density flexible foam is best suited for the dry cleaning application. The guiding rails are made longer on each side to ensure that the shadow of cleaning structure does not reduce the efficiency of the panel. The rails are extendable like railway tracks so a large number of panels can be attached in a line to use the cleaning structure in an optimum way. The assembly can be programmed with different routines, like in the case of humid weather the foam and synthetic duster roller will not be deployed and instead the whole panel is blown with jet air only. The complete assembly can be realized using lightweight aluminum or composite materials to reduce the energy requirements.

The mechatronics drive system for cleaning is very vast, and design in terms of kinematics, hydraulics, and mechatronic systems is needed. Automating of the installation is based on a microcontroller unit that receives information from sensors. It is costly and suitable only for big plants.

The literature survey shows that the accumulation of dust on the solar panel considerably affects the performance of solar PV panels. The study of different locations data shows that the amount of reduction in power varies from some 30 to 50 %. So the cleaning of PV panels is one of the necessary steps improving the efficiency of the panel. However, market available and general cleaning techniques are used but each of it having some limitations along with its uniqueness too. All these techniques have one common goal that is to improve the efficiency of PV panel. Some methods used roller brush cleaning techniques, water spraying with brushes, compressed air, and advance techniques like electrostatic cleaning with vacuum systems. All try to do best of them.

4. Conclusion

The study presented in this chapter shows the timeline of concepts and projects that have been established to date. These systems were either constructed for research purposes or for commercial use.

Considering the different exiting methods of solar panel cleaning as above and advantages and limitations of each it is felt that a brush type solar panel cleaning could be ideal as it requires no water or a little water for removal of dust. Also, it is low cost and can be indigenously developed. It also operates and considered as an auxiliary unit of the exiting solar PV system. However the total power consumes for removal of dust, the percentage of dust removal, frequency of operations, the speed of the dust removing mechanism, economics, durability, reliability, etc of the dust removal mechanism and its components is required to be tested.

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