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Design of Wiper based Solar Panel Cleaning System

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Abstract: ***The efficiency of the solar PV module is greatly affected by the environment factors and one of the main factors is dust. In the tropical countries like India, the problem of dust accumulation on the solar panels is severe. The power outputs of the PV modules are reduced by 50-60% in a month in some areas of India because of the dust. So, in order to reduce the loss of efficiency by the dust accumulation, the model of solar panel cleaning system has been proposed. This system consists of two wipers, each arranged at the diagonally opposite corners of the panel, driven by a DC motor through a mechanism. By cleaning the panels using this system daily or weekly, depending upon the rate of dust accumulation, the power loss due to dust can be controlled and kept within 5 to 10% of the output power. This cleaning system is an economical solution to the problem of soiling so, use of this panel cleaning system with the PV panels would reduce the overall payback period of the solar PV system in the areas where the soiling losses are high.***

Keywords: solar panel, cleaning system, wiper system, soiling loss, dust

1. Introduction

The use of solar PV modules as the power source is increasing day by day. This increasing demand of the solar PV modules has encouraged people to work in this field, to increase their efficiency and make them more economically viable. There are several hurdles in making their use affordable for the people, for both the off grid as well as the on grid solar power system. The research related to the characteristics of semiconductors used in solar cells has limited the efficiency of PV systems to 15–20%. There are several losses linked with the power generation using solar panel like shading loss, wiring loss, sun tracking loss and soiling loss. Among all these losses the most critical one for the tropical countries is the soiling loss, which is due to the accumulation of the dust, dirt or other particles on the glass of the PV modules. So, in these areas there is no option other than cleaning the PV modules to maintain the high power output, but as the PV modules are mounted at greater height on the roof for avoiding the shading in the off grid system, their access is difficult and risky. Also, the panel cleaning is required to be done once or twice a day in the dusty areas, which would be cumbersome if done manually. So, there is a necessity of developing a system to clean the solar panel automatically, to reduce the loss of power due to soiling.

2. Effect of Dust on Performance of Solar PV Modules

Although the efficiency of the PV system has augmented through many improvements, there are several environmental and natural factors such as the deposition of soil, snow, bird droppings etc., on the PV module surfaces that can result in inefficiency in the performance of such systems. The amount and type of dust in the air vary at different places, and it depends on presence various factors like industries, automobiles, forest fires, volcanic eruptions etc.

Accumulation of different types of dust particles has different effect on the transmittance of the glass cover. There are 15 different types of dust that are commonly found in the air and some of them are red soil, cement, ash, carbon, limestone, silica, calcium carbonate, sand, sand clay, soil, mud and coarser mode of airborne dust, and Harmattan dust. Out of them ash, limestone, silica, calcium carbonate, sand and soil have greater effect on the PV panel **[1]**. The transmittance of solar radiation through the dust ranges from about 2% to 40% depending on the factors like duration of dust accumulation, size and density of the dust particles, the air pollution level, season and location **[2]**.

The effect of the dust accumulation on the solar panel inclined at different angles is different**.** Garg has measured the normal transmittance of direct radiation through glass and found that over a period of 30 days, the transmittance reduced from 90% to 30% for a horizontal mounting**[3]**. Measurements of similar type were made in Kuwait by Sayigh et al. **[4]**, who observed 64%, 48%, 38%, 30% and 17% reduction in the transmittance of the glass plates after 38 days of exposure to the environment with tilt angles of 0°, 15°, 30°, 45° and 60°, respectively.

The dust deposition density varies with the tilt angle of the PV panel. Its value goes from 15.84 g/m^2 (for glass sample installed at a tilt angle of 0°) to 4.48 g/m^2 (for glass sample installed at a tilt angle of 90° and oriented with 135° deviation from north), the corresponding transmittance diminishes by approximately 52.54–12.38% respectively, as per the test carried out by H.K. Elminir**[5].**

The tests of the effect of the dust on the solar panels were carried by many researchers at several places over the world and the data reveals astonishing values of drop in the power output of the PV modules over dust accumulation. Some of these test results are given in table 2.1.

Table 2.1

Author and/or location	Time duration (months)	Results
Mekhilef et al. [6] Malaysia	(in Lab) 2 months	Investigated effect of dust on PV performance as function of tilt. Study show that average deduction in power output in different reign, for example power output reduce in Saudi 40% in Kuwait round 65%, Egypt 33–65% and in USA 1– 4.7%.
Sulaiman et al.	(in Lab)	Dust accumulation reduces peak

[7] Malaysia		power by around 18%.
Mastec bayeva et al. [8] India	1 month	During one month power output reduces from 87 to 75%.
Nimmo et al. [9] Saudi Arabia	6 months	Efficiency reduces by 26% & 40% from solar collectors and PV module, respectively.
Hassan et al. [10,11] Saudi Arabia	6 months	Efficiency reduces after 1 and 6 month by 33.5% and 65.8% respectively.
Asl-Soleimani et al. [12], Iran	10 months	Energy output reduces around 60% by pollution in Tehran.

3. System Design

3.1 System components and their arrangement

The system designed to clean the solar panel consist of various components, each with their own function to perform. These components are listed below with their function, significance and their location in the system.

3.1.1 Wipers

The most widely used and effective way for cleaning glass surface is wiping it, by using wiper system. The automobiles have been using the wiper system since more than a century and various improvements have been made in the design till now. It is robust in construction, simple in design, cheap to manufacture, quick in operation as compared to the other glass cleaning systems.

Simple wipers clean the surface along the circular path but the solar panel has a rectangular glass surface to be cleaned. So, in order to cover the maximum area under the wiper cleaning system, the arrangement consisting two wipers, each at the diagonally opposite end of the solar panel was used**.** The area of panel surface cleaned, of the total surface area of the panel depends on the length to width ratio of the solar panel. The percentage of the total area of the PV module surface cleaned by the cleaning system increases as the length to width ratio of the PV panel approaches to 1 as shown in table 3.1.1.1.

Table 3.1.1.1

Dimensions of panel(length× width) in mm	Length to width ratio of panel	Total area of panel glass(mm^2)	Area of glass cleaned (mm^2)	Percentage of area cleaned
1667×1000	1.667	1667000	1553766.8	93.20
1590×1053	1.509	1674270	1622050.6	96.88
996×665	1.49	662340	643051.6	97.08
660×520	1.269	343200	342308.4	99.74

The area cleaned by the cleaning system of the solar panel with the dimensions 1660×1000mm is as shown in the Figure 3.1.1.1 with the blue coloured region, while the grey coloured region shows the area not cleaned by the wiper system. The wipers are pivoted at the points shown in the diagonal end positions of the panel.

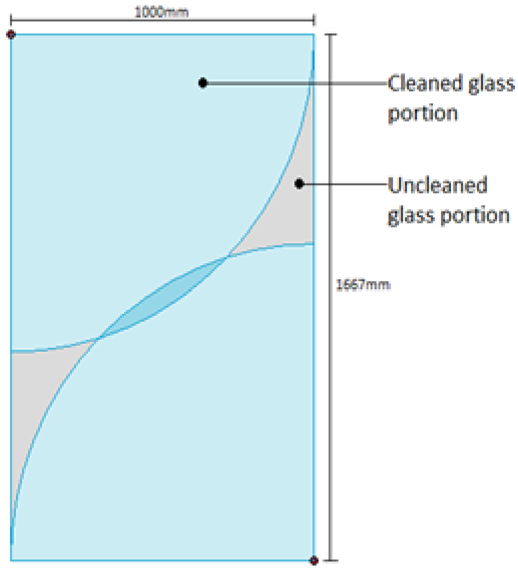

Figure 3.1.1.1: The area swept by the wipers in the system

3.1.2 Modified Geneva mechanism

In the two wiper system, if both the wipers are driven at the same time they may strike with each other in the over lapping zone as shown in the Figure 3.1.1.1 in the dark blue colour. So, the wipers are required to be operated one after the other to avoid collision, and for that purpose a modified form of Geneva mechanism was developed. This mechanism would drive the wipers in sequence, so at a time only one wiper would be driven and the other would be stationary. If two separate motors are used for driving two wipers, the cost of the system would rise, and also if one of the motor stops working in the middle of the cleaning operation, wiper collision may occur which could damage the system.

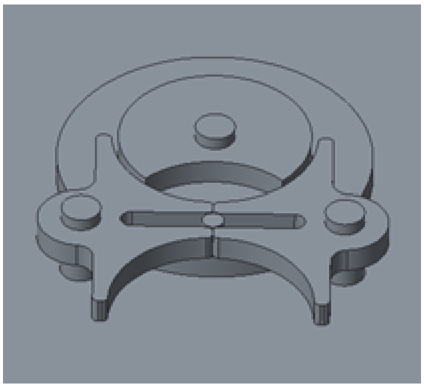

Figure 3.1.2.1: CREO model of modified Geneva mechanism

Geneva drive is a gear mechanism that translates a continuous rotation into an intermittent rotary motion. In the modified Geneva mechanism, there are two segments of the driven wheel used to power two wipers individually, and they are driven by the single driving wheel of the Geneva mechanism.

The driving wheel will have oscillatory motion with the 90^o angular amplitude on the either side of the current mean position as shown in Figure 3.1.2.1 and Figure 3.1.2.2**.** This motion of the driving wheel will turn the driven wheel segments by 90^o one by one. Each wheel segment is connected to the each of the wiper individually. This mechanism is enclosed in a casing and the shafts carrying the wheels and wheel segments are mounted on the bearings.

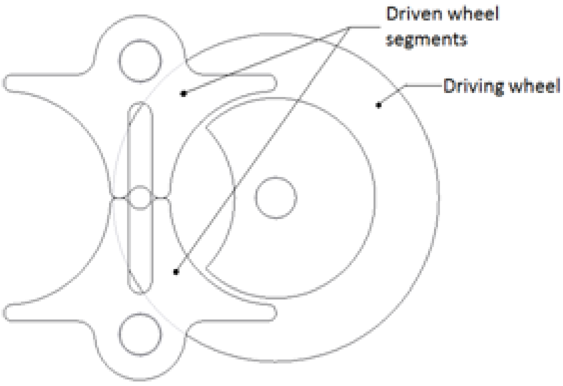

Figure 3.1.2.2: Modified Geneva mechanism

3.1.3 Linkages (levers and rods)

For transmitting power from the wheel segments to the wipers, levers and rods are used. The wipers are mounted on the bearing through shaft and bearings are in turn fixed in a frame or the base on which the solar panels are mounted. Two levers are connected to the two wipers at the end of their shafts and the other two are connected at the end of the shafts carrying driven wheel segments. Each pair of these levers is connected by two metal rods, strips or cables as shown in Figure 3.1.3.1. As in the case of huge solar panels the levers would be located at large distances, metal strips or cables are used which transmit the power through the tension force instead of the compressive forces, as in case of the rods, which may undergo buckling at greater lengths. If connecting element is to bear the tensile load, the use of thick rods generally used for transmitting push force will only increase the overall weight of the system, as they are very bulky as compared to metal strips or cables.

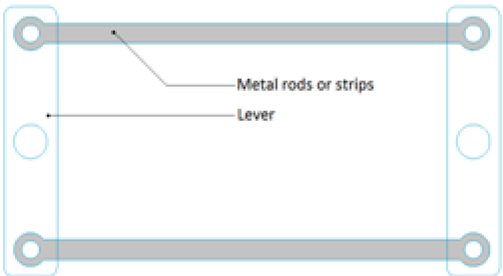

Figure 3.1.3.1: Levers connected with metal rods or strips

3.1.4 DC motor

The cleaning system is required to be powered by the external power source, and as the output of the solar PV system is in the form of DC current, DC motors were the best possible choice for driving the system. As the torque required would be high, the DC motor is required to be used in conjunction with a gear box. Also, the DC motor needs to provide oscillatory motion to the driving wheel in the mechanism, so the motion of the motor would be required to be controlled by limit switches or controllers. The arrangement can also be made to power DC motor by the ON grid power supply; other than the output of the solar PV system itself.

3.1.5 Water sprinklers

Finally, the water sprinkling arrangement would be required for the cleaning of glass on the regular basis. The water supply would not require a pump if there is an overhead tank with its bottom at some height above the panel setup. There is no requirement of the high pressure water jet, as the cleaning would be done by the wiper and the water is required just for reducing the friction and to carry the dust out of the panel along with the flow. So, even if required the power input of the pump used would be very low. The wiper system is not suggested to be used without the water, but if the water is not available for long time and if the power output of the panel has been drastically reduced, it can be used to clean surface temporarily to raise the power output. Frequent use of the wiper system without the water will produce scratches on the glass, and its impact on the power output of the panel depends on the nature of the glass cover and solar PV panel.

3.2 Design calculations

This solar panel cleaning system is designed considering compatibility with as many different types of solar panels as possible, but for the panels with the length to width ratio higher than 1.667 the cleaning efficiency falls below 93%.But, most of the panels used today are compatible with this cleaning system. The designing calculations for the cleaning system are carried out for the 250W solar panel with the dimensions 1667 × 1000mm and the length to width ratio 1.667. As this panel has large dimensions, the system designed for this panel will require maximum driving power and durability, and can be used on the other panels with smaller dimensions by just modifying the length of wiper blades and connecting linkages.

3.2.1 Wipers

The wipers used in the automobiles with the curved windscreen have the claw type construction. This design helps in distributing the load evenly along the entire blade and also keeps the blade in contact with the windscreen along the entire length. As the solar panels will have flat glass, the requirement of the claw design is not so crucial, which will eliminate the use of bulky wiper blades by using simple straight wiper blades. These wipers are also cheaper to manufacture due to their simple design. Typical automobile wipers have 100000 cycle of life, which shows their durability for the purpose.

The wiper blades have complex relations between the coefficient of friction, normal load and sliding velocities because of the intricate nature of rubber blade and glass contact for different value of parameters. As the interference of the wiper blade increases the coefficient of friction reduces. The coefficient of friction varies from 0.7 to 2.3 for the variation of the interference between 0.6 to 2.4 mm in a 4mm specimen of the wiper blade in the dry condition as per the test carried out by Gábor Bódai **[13]**.The test results also proves that the coefficient of friction decreases with the increase in the velocity in the wet conditions.

The variation of the normal force with the friction force is linear for low value of normal force, but for the higher values the curve changes significantly and the increment in the friction force with respect to the increment in the normal force reduces **[13]**. The coefficient of friction reduces with the increment in the normal force as a result of rise in the interference.

So, the value of coefficient of friction is taken as 2 for the calculations considering that the wiper may be required to be operated in the dry condition.

The standard value of normal force applied on the wiper blades for the flat wipers in the automobiles as per the wiper selection catalogue is between 10 to 15 Newtons per meter of the blade length. So, considering 10N/m normal force for the blades, as there are no shocks or vibrations while operating the wiper on the solar panel, as that are faced by the automobile wiper system, which demands higher amount of force to cling to the glass surface.

$\mu = 2$

$fi_N = 10$ N/m

$L = 1$ m

So, total normal force acting on the wiper blade is

$$F_N = f_N \times L \quad (1)$$
$$= 10 \times 1$$
$$= 10 \text{ N}$$

Hence, the torque required to drive one wiper is

$$T = \mu \times F_N \times (L/2) \quad (2)$$
$$= 2 \times 10 \times 0.5$$
$$T = 10 \text{ Nm}$$

Here, μ is coefficient of friction, f_N is normal force per unit length of the wiper blade, F_N is the total normal force on the wiper blade, T is the torque required to drive a wiper.

3.2.2 Torque required for driving the modified Geneva mechanism

A portion of Geneva mechanism with a four slot driven wheel is shown in Figure 3.2.2.1. Here, the centre of the driving wheel is B and the centre of the driven wheel segment is A. The point C represents the centre of the pin on the driving wheel.

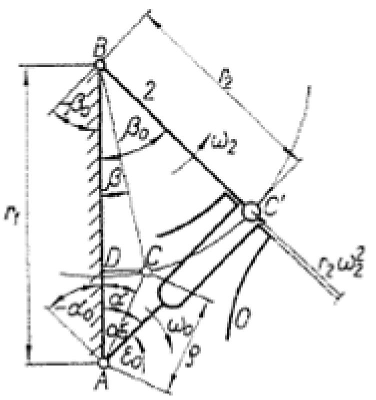

Figure 3.2.2.1: Geneva mechanism

$$M_2\, \omega_2 = M_0\, \omega_0 \quad (3)$$
$$M_0 = T + \Theta_0\, \varepsilon_0 \quad (4)$$

Where,

M_2 is torque acting on the driving shaft of the Geneva mechanism

T is the torque required to turn the wiper

ω_2 is angular velocity of the driving member

ω_0 is angular velocity of the driven wheel segment

Θ_0 is the moment of inertia of the members connected to the driven wheel axle

ε_0 angular acceleration of the driven wheel segment

So, the torque required by the driving wheel is

$$M_2 = \frac{\omega_0}{\omega_2}\,\frac{1}{\eta}\,[T + \Theta_0 \varepsilon_0] \quad (5)$$

Here, η is the efficiency of the Geneva mechanism.

For this cleaning system there is no requirement of high speed operation of the wiper blades, and if they are operated at high speed, very high value of inertia would increase the driving torque and also reduce the life of the system. So, the value of driving shaft speed is kept 5 rotations per minute and correspondingly the value of the angular velocity ω_2 would be 0.5235 rad/s.

As per the dynamic analysis carried out by E. Filemon **[14]** for the Geneva mechanism with the four slots driven wheel, the peak value of the ratio of ω_0 by ω_2 is

$$\frac{\omega_0}{\omega_2} = 2.41 \quad (6)$$

Also, the value of ε_0 for the value of ω_2= 0.5235 rad/s is

$\varepsilon_0 = 1.482\, rad/s^2$

So, the value of the ε_0 is very low and the inertia torque calculated for this value of angular acceleration is even lower than 0.3 Nm, which is lower than 3% of the calculated torque required for turning the wiper, so it is neglected. As the driving and driven wheels are mounted on the shafts supported by the bearings, the friction losses are very less and so the efficiency of the mechanism can be assumed to be 95%.

Now placing all the values in the equation (5),

$$M_2 = 2.41 \times \frac{1}{0.95}\,[10 + 0]$$
$$M_2 = 25.36\, Nm$$

Considering this value of torque for driving the modified Geneva mechanism, the design of the mechanism was checked for safety under various stress conditions and was in the safe limits. The factor of safety for the design was taken as 2, and mild steel was selected for making the components of the mechanism because of its strength, machinability and wear resistant characteristics.

4. Model Testing and Analysis

The model of the solar panel cleaning system was made on a small scale to operate on a glass sheet with dimensions 600 × 400mm. The driving wheel and the driven wheel segments of the modified Geneva mechanism were cut from the acrylic sheets by the laser cutting machine as shown in Figure 4.1. The design of the mechanism was prepared in CREO, which was used to feed as an input to the machine for cutting parts. The mechanism in the actual cleaning system would be built from mild steel, but as the model is smaller in size and as the inertia forces are neglected, the effect of material in the operational characteristics would be very low. The shafts were made of mild steel and were turned on the lathe machine. The entire mechanism was enclosed in a wooden box and the shafts were supported by the ball bearings as shown in Figure 4.2 and Figure 4.3.

Figure 4.1: Driving wheel and driven wheel segments

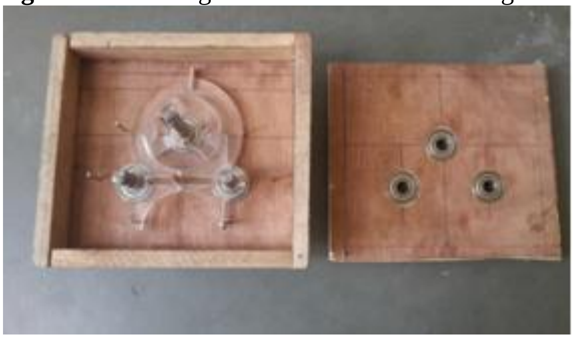

Figure 4.2: Modified Geneva mechanism in wooden box

Figure 4.3: Wooden box with input or driving shaft on the top and two driven shafts at the bottom

The rubber strips of the automobile wipers with the claws were installed in the straight aluminium sections for making straight wipers as shown in Figure 4.4, as the straight wipers have less weight and they operate properly on the flat glass. These wipers are mounted on the shafts, through a pin joint to assist them to adjust for sticking to the surface of the glass. Generally, the normal force on the wiper is applied by using a spring but, for the model additional weights were attached to the wipers to simulate the effect of the spring force. The shafts carrying the wipers were supported on the bearings fitted on the wooden pieces as shown in Figure 4.5.

Figure 4.4: Straight or flat wiper blades

Figure 4.5: Supporting plates for wiper shafts

The wooden box with the mechanism and the two wooden pieces supporting the wipers were then fixed rigidly on a drawing board and a wood board was placed on it to act as a panel. A glass sheet was placed above the wood board on which the test was to be conducted. The Levers as shown in Figure 4.6 and Figure 4.7 were wielded to the end of the wiper shafts and the two shafts(output shafts) on which the driven wheel segments are mounted. The levers were then connected by the stainless steel strips with 2×1mm rectangular cross-section, which will transmit motion from the driven wheel segments to the wiper.

Figure 4.6: Lever

Figure 4.7: Levers connected on the output shafts of the mechanism enclosed in the box.

The mechanism is required to be run at low RPM, in the range 5-10, and the torque required to drive the model of the system would be 4.058 Nm i.e. torque required for 40% of the blade length of wiper compared to designed system. So, for the power supply, custom built motor would be required as the commercially available wiper motors with worm gearbox for high output torque, are having high value of RPM ranging from 35-60 and driving the system at high rpm would not give the expected results. So, the system was operated manually at low speeds to test the cleaning of glass and then separately using the high speed motor for testing the torque requirement of the model. The setup for the test on the glass is as shown in the Figure 4.8.

Figure 4.8: Model test setup of solar panel cleaning system

Firstly, the glass sheet was cleaned thoroughly with wet cloth and tested for its transmittance in the sunlight using light meter. The ratio of the illuminance of sunlight through the glass to that of illuminance from direct sunlight was taken to obtain transmittance. A layer of dust was then spread on the glass surface and then the transmittance of glass was measured. Then this glass was placed on the wood board and cleaned using the cleaning system by operating it manually in the dry condition and then the swept or the cleaned portion of the glass was measured for its transmittance. The entire test was carried again and this time wiping was done along with sprinkled water. The values of transmittance of glass measured at different stages in both the cases are given in the table 4.1.

Table 4.1

Transmittance (in %)	Cleaned glass	Dust laden glass	Wiped glass
Wiping without water	87.8	72.3	84.7
Wiping with water	87.84	73.6	87.2

The system was then coupled with a 10Nm DC motor as for the system, the motor used will always be of higher capacity than the driving torque required for avoiding the stalling of the system. The wiper system worked as required without any stall. In the designed cleaning system the motion to be given at the input shaft of the mechanism would be of oscillatory type with the angular amplitude of 90^0, so the motion of the driving motor is required to be controlled using controllers or limit switches.

The 250W solar panel with 1667×1000mm dimensions, for which the system was designed previously, has the cost of around 12,000 Rs, and the other 230 or 240W solar panels have the cost nearly around 11,000 Rs in the market. The estimated cost of the wiper based cleaning system for a single panel of 250W would be around 3000 Rs and could be reduced in future with further improvements in the design. For 1KW solar PV system in India, the estimated energy generation over a year is 1125 KWh (it is the average value, actual value varies by location, panels and other environmental factors. The value without considering loss is 1500KWh). Here the total energy generated is assumed to undergo 25% loss due to the dust collection on the panel (the amount of loss is considered still assuming the cleaning of PV system is done 3 to 4times in a year, if not, the value may raise even higher). As per this consideration, if per KWh cost of electricity is taken as 7 Rs then the amount saved by cleaning the panels using this system would be 2625 Rs yearly. For 1 KW PV system, the wiper cleaning system would cost around 3000×4=12000 Rs. So, the payback period of the cleaning system is 12000/2625= 4.57 years only. While, the payback period of the solar PV system solely would be 48000/7875= 6.09 years. So, the places where the soiling losses are significant, the use of solar panel cleaning system with the PV panels would reduce the overall payback period of the system.

5. Conclusion

Many factors determine the ideal output or the optimum yield in the PV module. Among these factors the most crucial one for the areas in the tropical zone is the dust, which has its deteriorating effects on the output of the PV module. Great efforts are being made to raise the efficiency of the solar cell but, it won't help to give high output if the dust laden solar panels are not cleaned timely. Solar panels are generally fitted at places which are at greater heights and are not easily accessible so, it becomes difficult to clean them. Also, in a dusty environment, the cleaning required could be as frequent as daily or weekly, which is not practically possible for small scale units used for supplying power to house or public places. The cost of solar panel cleaning system is comparatively low, and could be easily recovered back within the time equivalent to the time taken by the solar PV system itself to reimburse. So, the areas where dust deposition on the solar panel causes considerable power loss, the use of wiper based solar panel cleaning system would be beneficial.

6. Future Scope

The solar panel cleaning system design proposed in here is for the 250W solar panel with the dimension 1667×1000mm. Use of this design would be favourable with the other panels for small variations in the dimensions but, for very small panels like 40W or 50W, the system will require modifications to make its use economically viable. For small panels, the use of a single driving mechanism and DC motor will be done for a group of 4 to 5 panels. The wipers of these panels would be linked together by the linkages in series, and would be driven by a single modified Geneva mechanism and a DC motor to reduce the cost of the system.

The cleaning system could be driven automatically at fixed time intervals or on the basis of drop of the output of the PV system to a preset value. Thus, in this way the operation of the cleaning system could be optimised.

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