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Adaptive position control of DC motor for brush-based photovoltaic cleaning system automation

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ABSTRACT

In this paper, we have developed an automatic brush-based PV cleaning system to control and synchronize the 3 motors together with a smooth periodic of cleaning while moving it horizontally over the PV surface. The mechanical design involved installing linear guides at the top and bottom of the rail to support the aluminium plate that holds the carrier motors and rotating brush. Two different movements of translational and rotational motion of the motors are managed by an algorithm programmed in Arduino Mega. In investigating the performance of motor parameters and dust removal rate, we conducted an experiment by spreading dry sand over the PV surface. Results showed that the torque of the cleaning brush motor increases with the increase in load. The obtained torque of the carrier motor was found to be 9.167 Nm (> stall torque, 9.8 Nm) with a full load of 18 brushes. The torque is inversely proportional to the speed but directly proportional to power. The required power to move the 2.93 kg of cleaning system was 19.20 W with 3.015 Nm of torque. The system achieved 86.8% of the dust removal rate from the four cycles of cleaning operations.

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1. INTRODUCTION

Since energy from fossil fuels is expensive, limited, difficult to store, and contributes to global warming, the availability of fuels have become increasingly crucial for the development of a nation [1]–[5]. Sustainable energy has attracted much attention in achieving greener energy solutions which shows an increased usage of photovoltaic (PV) not just in Malaysia but all over the world [6]–[10]. However, dust fall on the PV panel is the most significant factor that can reduce its efficiency up to 50% depending on the environment [11]–[14]. We observe a 40% deterioration in 6 months in Saudi Arabia [15], an 11% drop in efficiency in Thailand's tropical environment [16], a 29.6% decline in efficiency in Kathmandu, Nepal, and a 33.5% to 65.8% reduction in efficiency from an Egyptian research [17]. A PV cleaning system can clean dust, bird droppings, and other foreign particles from the PV surface automatically and is expected to boost energy production by 10%, on average [18]. Cleaning of the PV surface on rooftops or in large solar farms is a hard task (e.g., staff accidents, panel damage, movement difficulties, and poor maintenance) for human beings using a ladder and also proved to be pricey for large-scale PV generation [19], [20].

With evolving technology, many studies have been conducted by developing a mechanism using an automatic cleaning system [21]. A robot was developed using a rotary brush with water spray, which was powered by two motor drivers and a DC motor coalesce with light dependent resistor (LDR) sensors. It boosted the panel efficiency upto 90% [1]. Manju *et al.* [22], the cleaning system was embedded in an aluminium frame with a rack, gear wheels, and rubber wheels, DC gear motors, rolling brush, arduino, and driver boards. The cleaning actions took around 300 s to mop PV for both directions. The electrical sensors with microcontroller and windscreen wiper system were using a 12 V DC motor. It drove the wiper along the panel with two nozzles spraying water over the surface [23]. The wiper was energized when the output power approached to 50% of its value. Wang *et al.* [24] proposed a dynamic schedule-enabled cleaning system to minimize economic loss. Aidara *et al.* [25] compared degradation rate between dirty and clean modules by developing a cleaning system using microcontroller controlled DC motors with an L298 driver. A degradation rate of 17.13% of the dirty module was found compared to that of the clean module.

Referring to the previous studies, there is limited study on the motor performance by determining the optimum and suitable specification of it in controlling the cleaning brush. According to a study mentioned there are certain speed that does not exert sufficient force in cleaning the brush. This is a concern whereby the specification of the motors is essential for this implementation.

Therefore, this research has implemented an automatic PV cleaning system using two carrier and one brush rotating motors and analysed the performance of its parameters. We have considered the motors are capable of withstanding the weight and movement of the cleaning system when it performs the cleaning operation. The motor parameters, such as motor rating, speed, and torque are analysed to determine the suitability of the motor for this system. The aim of this project is to determine the suitable specification of DC motors involved in the time-based PV cleaning brush controller. The brush controller operates at a suitable speed and ensures sufficient force exertion on the PV surface to perform the automatic cleaning service. The novelty of this study is that we have developed an algorithm for the PV cleaning system that uses the DC motor-driven brush controller operated in a periodic manner, while investigating the performance of motor parameters and dust removal rate under Malaysia climate conditions. The findings from this research will provide useful information in choosing the effective brush controller and adequate references in motor selection for the maintenance and operation experts, industrial players, or other researchers who are considering the automated PV cleaning system.

The rest of the paper is organized as follows: section 2 explains the design and method of the cleaning system. In section 3, we have discussed the results of carrier and cleaning brush motors and analysed the dust removal rate. Finally, section 4 concludes the paper.

2. METHOD

The design of the PV cleaning system is based on the size of PV which can be referred to Figure 1(a). The specification of the PV is: peak power 100 W, maximum power current 5.56 A, maximum power voltage 18.00 V, and dimensions 1005×665×30 (mm). Motor sizes are according to the weight of the cleaning brush rod and brushes. Each slot of brush weighed around 150 g, while 18 slots of brush inserted in a rod weighed about 2.925 kg. We used a power window motor as a carrier motor, and a DC geared motor as a cleaning brush motor. All the components, such as MDD10A, L298N, DC geared motor, power window motor, and others are purchased through local supplier. The prototype of the cleaning brush with 18 brushes is shown in Figure 1(b).

For hardware implementation, the carrier motors are connected to the output port of MDD10A (i.e. M1A and M1B, M2A and M2B). DIR1, PWM1, DIR2, and PWM2 are connected to Arduino Mega digital pins which are 3, 4, 9, and 10, respectively. The cleaning brush motor is connected to the output port of L298N (i.e. OUT1 and OUT2). IN1 and IN2 of L298N are connected to Arduino Uno digital pins 5 and 6, respectively. Arduino IDE software was used to program the Arduino Mega embedded board. The algorithm of the project is written to control the three motors connected to the PV cleaning system. For the carrier motor, the speed is reduced to 50% using PWM bit. This system used real-time clock (RTC) to enable and activate time-based cleaning operations. The motor control system can be referred to Figures 1(c) and (d).

The system is operated according to the developed algorithm which is programmed into the Arduino

Mega embedded board. The cleaning brush is installed on the left side of the PV surface shown in Figure 1(e), in the premises of the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia. The RTC evaluates the current-time and compares it to the set-time to decide whether to activate the system. If it is decided to activate, the microcontroller sends signals to both motor drivers to move the carrier motors and brush forward. In this forward movement, all the motors rotate in the same rotation which is clockwise (CW). When the cleaning system reaches the other end of the PV (on the right), the system stops for 3 s and moves backward to its initial position. In backward movement, the motor rotates counter-clockwise (CCW). The RTC then compares the current-time to the set time, where if the current-time is not the same as the set-time, the cleaning system stops. Else, the cleaning system repeats its cleaning cycle until the set time ends.

We tested the system by analysing the motor parameters as well as dust removal rate for different numbers of brushes. The formula for calculating dust removal rate is shown in (1). To measure the DC current and speed of the rotating motor, we used clamp and tachometer meter respectively. Figure 1(f) shows data collection procedure during the testing period.

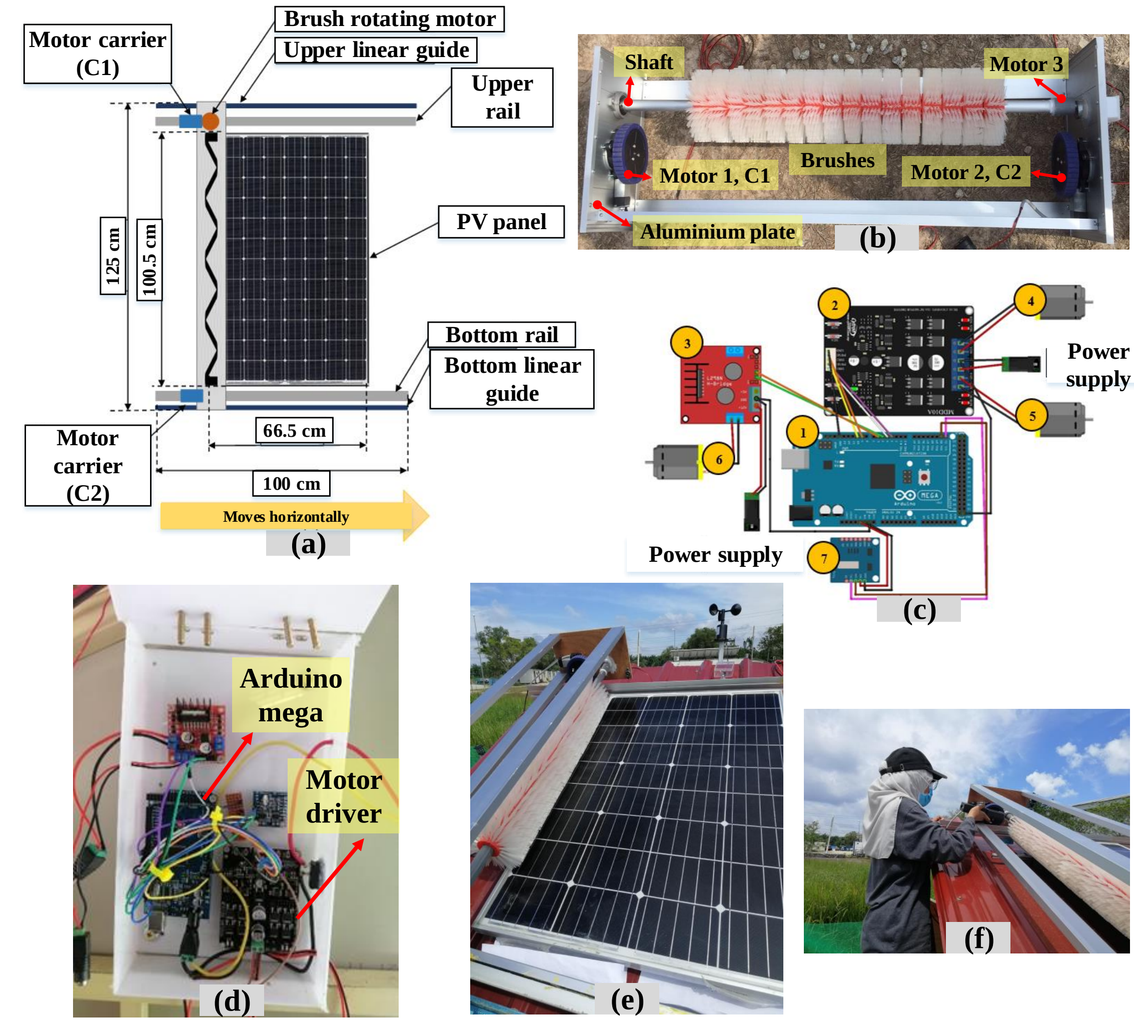


Figure 1. The PV cleaning system (a) design specification, (b) cleaning bruth prototype, (c) design circuit of motor controller: i) arduino mega microcontroller, ii) MDD10A dual-channel motor driver module to control speed and direction of both carrier motors, iii) L298N motor driver module to control the direction of cleaning brush motor, iv) and v) carrier motor 1 and 2 respectively, vi) cleaning brush motor that attaches to the cleaning brush rod and rotate over the PV surface, vii) RTC, (d) motor control board at PV installation site, (e) cleaning system prototype installed at FKEE, UTHM, and (f) data collection using DC clamp and tachometer by the researchers

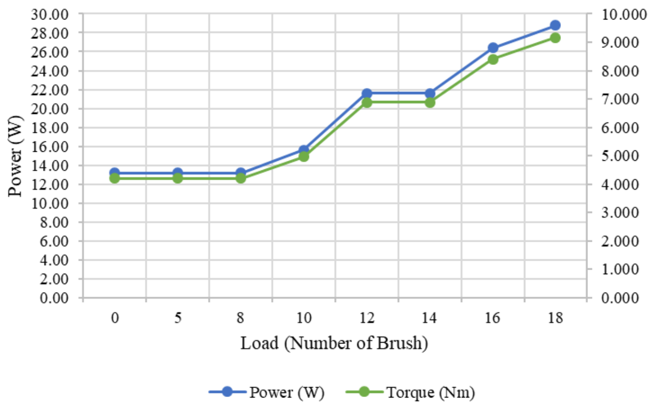
Before the cleaning cycle started, we sprinkled 5 g of sand and foreign particles over the PV surface. After each cycle of cleaning, we collected the residue and weighed the remaining particles. The data were recorded and calculated to obtain the findings. The number of brush slots is then reduced and repeated in the same process.

$$D_r = \frac{W_i - W_r}{W_i} \times 100 \tag{1}$$

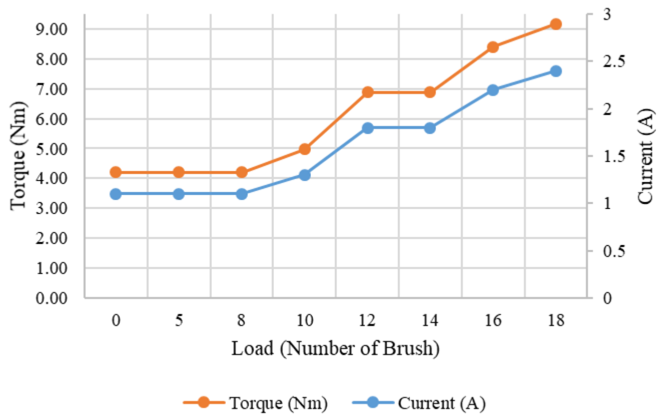
W_i is the initial of the sand and foreign particles. W_r is the residual weight of sand and foreign particles after the four cycles of PV cleaning. D_r is dust removal rate (%). Both W_i and W_r were measured in gram (g).

3. RESULT AND DISCUSSION
3.1. Parameters of carrier motors

The analysis of motor parameters, such as relation between power and torque against a number of brushes is shown in Figure 2(a). We observe that both parameters are constant up to 8 brushes installed at the cleaning rod. The stall torque of the carrier motor is 9.8 Nm, that is the motor is capable of withstanding the weight of the cleaning brushes and moves horizontally. This supports the analysis, where the obtained torque is found to be 9.167 Nm when all the 18 brushes are installed. Figure 2(b) shows the result of torque and current of the carrier motor. As the torque increases, the current of the motor also increases to energize the carrier motor in completing the cleaning cycles. With a full load of 18 brush slots and 9.167 Nm of torque, the current flow is found to be 2.4 A.



(a)



(b)

Figure 2. Analysis of carrier motor (a) power and torque against number of brush and (b) torque and current against number of brush

Based on Figure 3, the speed of the carrier motor remains constant as it is programmed to 30 rpm

(3.142 rad/s). Though the speed is constant, the increase of torque shows that there are changes in load's weight, and the carrier motor moves to its full capability for this cleaning service. With 18 brushes slot and speed of 30 rpm, the produced torque is 9.167 Nm. The intersection point between the 30 rpm motor speed and torque is at 8.403 Nm with 15.5 of brush slots. This finding suggests to use at least 15 brushes for this cleaning.

3.2. Cleaning brush motor

Referring to Figure 4, the range of power and torque are 4 W and 0.25 Nm respectively, upto 12 brush slots. However, we observe a sudden increase in these parameters when brush slots have exceeded 14 slots. The recorded power and torque for this load are 16.80 W and 1.925 Nm, respectively. This increase might be the cause of the sudden change in the weight of the cleaning system. When the system is fully equipped with 18 brush slots, the motor can produce a power of 19.20 W. With the increase of the load, the torque of the cleaning brush motor also increases. Thus to rotate a full load of cleaning brush, the required torque is 3.015 Nm with the power of 19.20 W.

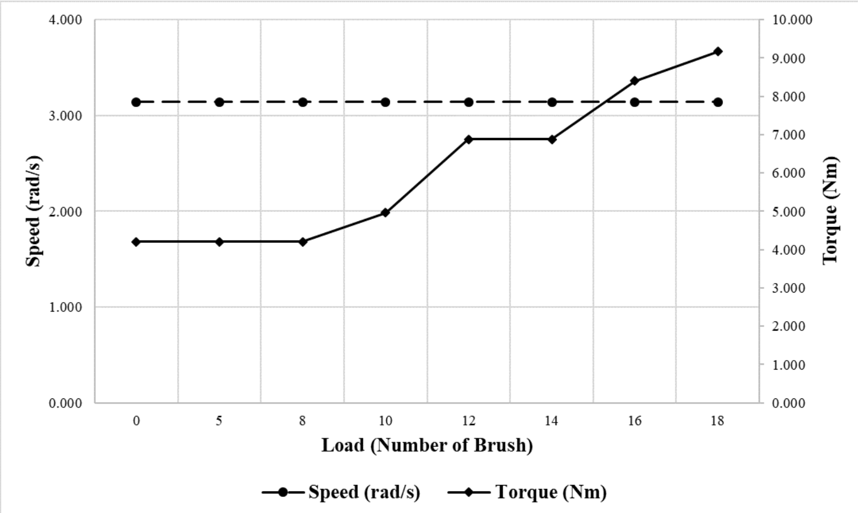


Figure 3. Speed and torque of carrier motor against number of brush during cleaning cycles

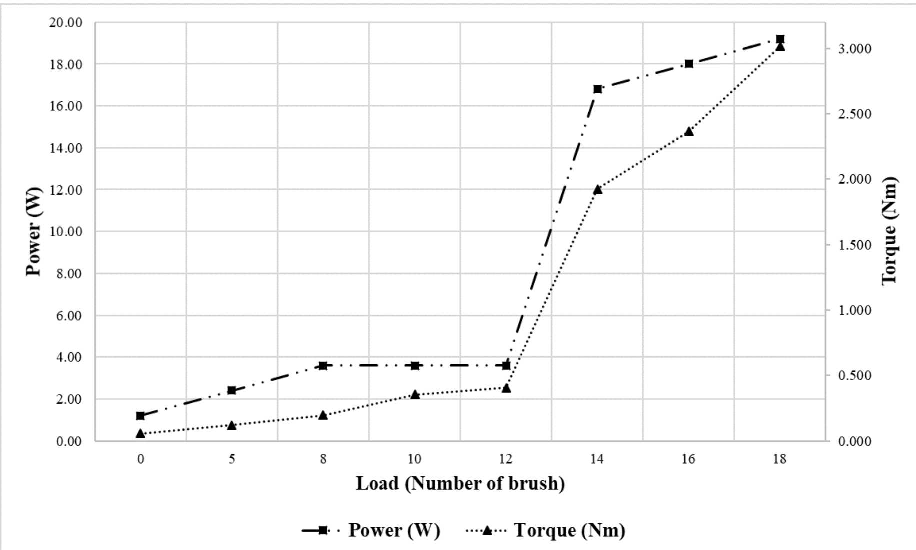


Figure 4. Power and torque of cleaning brush motor against number of brush during cleaning

According to Figure 5, the torque and current produce almost similar results of previous analysis. As the torque increases, the current of the motor also increases to energize the cleaning brush motor in completing the cleaning cycles. Similar to power and torque analysis, the sudden increase in current (from 0.3 to 1.4 A) occurs when brush slots are increased from 12 to 14. With a full load of 18 brush slots and 3.015 Nm torque, the current flow is found to be 1.6 A.

Based on Figure 6, the speed of the motor decreases as the load increases. During no load, the motor rotates at full speed of 20.944 rad/s (200 rpm). We notice the motor speed decreases significantly, from 18.221 to 10.137 rad/s when the brush slots are increased from 8 to 10. At full torque and brush weight, the motor speed is found to be 6.368 rad/s (61 rpm). This can be concluded that the torque is inversely proportional to the speed but directly proportional to power. Analysis shows that the required power to move 2.93 kg of cleaning brush is 19.20 W with 3.015 Nm of torque, and a speed of 61 rpm.

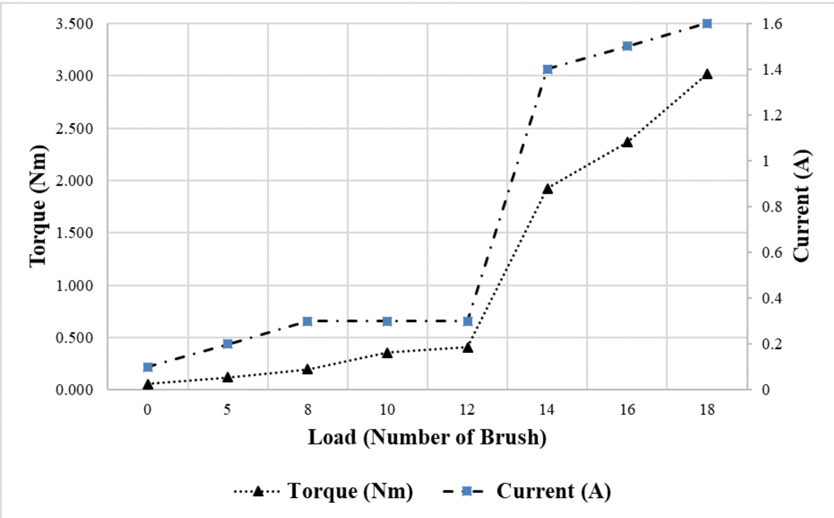


Figure 5. Torque and current against number of brush during cleaning

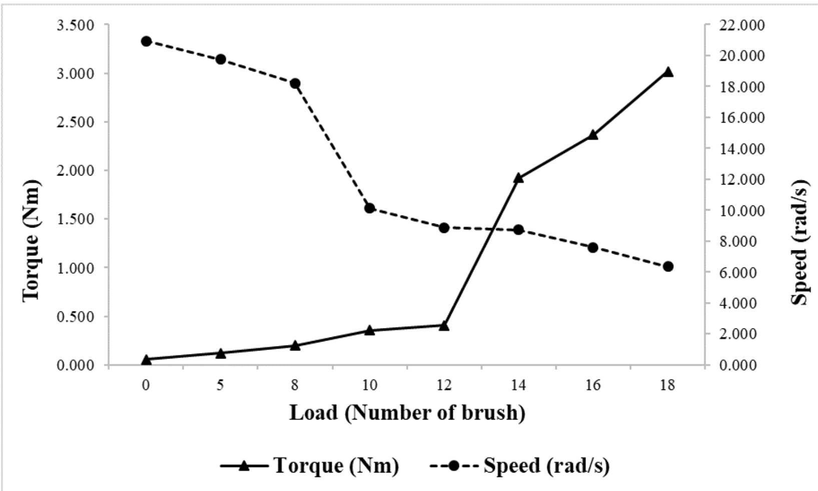


Figure 6. Speed and torque of cleaning brush motor against number of brush during cleaning

3.3. Analysis on dust removal rate

We have analysed the dust removal rate against different numbers of brushes at a constant cleaning cycles. As shown in Figure 7, the dust removal rate is found to be the highest, which is 86.80% as the cleaning brush manages to cover almost 90% of the PV surface area with the 18 brush slots. However, the motor speed is found to be slower, 61 rpm under this full load. When only 5 brush slots are used, it covers around 28% of PV surface area and 49.4% of dust removal rate is achieved. Due to less weight, the motor speed is also found to be 189 rpm. This outcome is based on a constant number of cleaning cycles of 4. Higher dust removal rate can be achieved if the cleaning cycle is increased to 8.

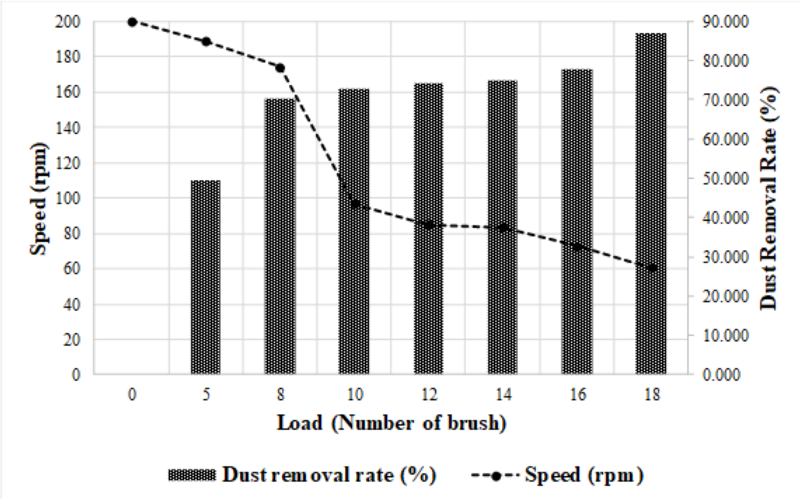


Figure 7. Motor speed and dust removal rate against different number of cleaning brush slots

4. CONCLUSION

The implementation of the PV cleaning system is believed to offer positive impacts on the energy yields of PV for rooftop or large solar farm applications. The prototype was built by using an Arduino Mega as a microcontroller in correlation to C++ program suited for the Arduino embedded board. The motor drivers in the circuit were used to control the direction and speed of both carrier and cleaning brush motors. The structure of the PV cleaning system was built according to the design plan so that it can support the weight of the carrier motor and the cleaning brush. The force exerted by the carrier motor with 12.7 cm radius wheels was 22.83 N, less than the sliding threshold of 43.57 N. The torque provided by the motors was safe to operate without any sliding and is enough to surpass all bumps of rail during operations. The motor torque (2.64 Nm) was always higher than calculated torque with load (0.22 Nm), which means the motor was capable of providing enough force to make the cleaning brush rotate during the cleaning operations.

During the cleaning operations, the DC motor parameters were also analyzed from experimental data which includes torque, current, and speed of the motors. The speed of the cleaning brush motor was obtained at 61 rpm with 3.015 Nm of torque during the operation of the system. The carrier motor drove along with the PV panel horizontally with a torque of 9.167 Nm at constant speed. The dust removal rate determines the efficiency of the cleaning brush, which achieved the highest percentage with only four cycles of cleaning of 86.80%. The system was able to withstand the weight and exert sufficient force during the cleaning of the PV. From the observation, the delay function used in the program can run the system smoothly, however, it is required to change if the size of PV panel changes. The presented analysis can be helpful in determining exact specifications and size of PV cleaning system.

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