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Degradation of PV Module Performance Due to Dust Accumulation on the High-rise Buildings

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Abstract— **Dust accumulation on photovoltaic (PV) modules causes a significant reduction in the electrical energy output by partially blocking the solar irradiance incident on the PV modules. The effect is more pronounced during the dry season when the environment is dustier. In this work, an investigation is conducted to understand how dust particles can affect the performance of the PV panels installed on the rooftop of a high-rise building during the dry season. Two monocrystalline 20W PV panels, deployed on the rooftop of a seven-story building in Gabtoli, Dhaka, Bangladesh, have been used for this purpose. Measurements are carried out over four months, starting from 1st November 2019 to 29th February 2020, during which the weather remains mostly cold, dry, and dusty. It has been observed that dust accumulation monthly decreases the short-circuit current from a minimum of 5.52% to a maximum of 22.31% during this period. The maximum reduction in the daily output energy during this period is observed to be about 35%. The effect of dust has been observed to be most pronounced during December 2019, which shows a decrease of over 22% in total monthly energy output in the dusty panel compared to that of the clean panel.**

Keywords—Short circuit current, Solar PV panel, Open-circuit voltage, Maximum power, Dust accumulation.

I. INTRODUCTION

The energy demand is escalating significantly all over the world due to the global race for economic supremacy. Fossil energy is incapable of meeting the total energy demand. Besides, the world is currently experiencing an adverse effect of greenhouse gases leading to global warming. As a result, a variety of sustainable development projects have been declared and carried out worldwide. Solar energy is the most readily extractable and usable form of renewable energy to meet the required demands in a low and cost-effective manner. In contrast, PV generation is affected by the weather parameters such as solar irradiance, temperature, humidity, etc., and weather conditions like rain, cloud, dust, etc. However, the dust effect on the PV panel's performance is also significantly notable because dust accumulation on the PV panel obstructs solar irradiance consumption, consequently hampering the PV generation. Hence, the study of dust effect on the PV panel becomes essential to perceive the total loss to take further action in the future.

Numerous works of literature highlight the dust effect on the performance of the solar PV panel output. In several studies, the impact of external factors such as solar irradiance, ambient temperature, dust, and humidity on PV technology is presented [1], [2]. Moreover, one research shows dust particles, including carbon, iron oxide, manganese dioxide, calcium oxide, and natural dust, significantly impact PV panel performance [3]. Few other research works show that PV panels' electrical characteristics are greatly affected by the dust accumulation conducted in the desert climate [4], [5]. The shading effect of PV modules caused by dust deposition, trees, buildings, etc., is exceptionally adverse for a PV panel power generation system [6]. Similarly, the factors such as dust properties, wind characteristics, tilt angle, and panel characteristics that affect the power loss by accumulating dust particles are presented in [7].

Many studies have been done on the dust effect. However, this study's primary purpose is to investigate the dust effect on the PV panel's performance by comparing two panels output over four months experimented dataset under outdoor conditions. Hence, the dust impact on the solar PV panel parameters such as short circuit current, open-circuit voltage, output power, and output energy are analyzed in this study.

II. THEORETICAL BACKGROUND

A. Single Diode Model

Solar cells are semiconductor material made of silicon; therefore, it works as p-n junctions. Numerous cells are connected in series-parallel to boost the current and voltage from the solar panel. The equivalent circuit of the single diode model is shown in Fig.1.

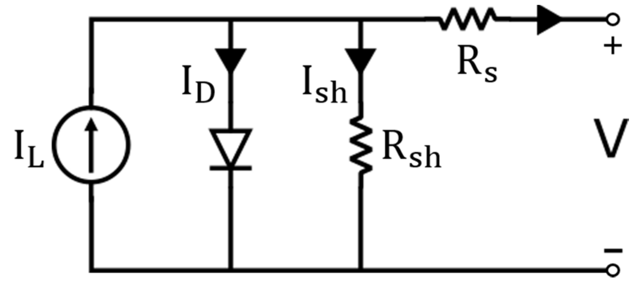

Fig.1. Equivalent circuit diagram of a solar cell using single diode model.

Where, I_L representing the light-induced current generated in the cell is parallel with the P-N junction diode. R_s and R_{sh} represents series resistance, and shunt resistances of the cell. I_D and I_{sh} are respectively current across the diode and shunt resistance. The total current (I) can be expressed as [8].

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$$I = I_L - I_D - I_{sh}$$

$$= I_L - I_0\left(e^{\frac{q\left(\frac{V}{N_s}+IR_s\right)}{nkT}} - 1\right) - \frac{\frac{V}{N_s} + IR_s}{R_{sh}} \quad (1)$$

Here, q is the charge of an electron, k is the Boltzmann's constant, N_s is the number of cells connected in series in the solar panel, n is the ideality factor, I_0 is the reverse saturation current, V is the output voltage, T is the absolute temperature.

B. Determining PV Panel Output Power

In Fig. 1, under open-circuit condition, voltage $V=V_{oc}$ and current I=0. Equation (1) can be expressed as below,

$$I_{sc} = I_0\left(e^{\frac{qV_{oc}}{nN_skT}} - 1\right) \quad (2)$$

using (2) the equation can be written as below,

$$I_0 = \frac{I_{sc}}{e^{\left(\frac{V_{oc}*q}{n*k*T*N_s}\right)}} \quad (3)$$

At new temperature T_{new} the reverse saturation current can be calculated from the following equation [9],

$$I_{01} = B*(T)^3 * e^{\left(-\frac{E_g}{k}\right)} \quad (4)$$

$$I_{0(new)} = B*(T_{new})^3 * e^{\left(-\frac{E_g}{k}\right)} \quad (5)$$

where, E_g is the energy bandgap of silicon. Furthermore, $I_{0(new)}$ can be calculated using (4) and (5) which is given below,

$$I_{0(new)} = I_{01} * \left(\frac{T_{new}}{T}\right)^3 * e^{\left(\left(\frac{E_g}{k}\right)*\left(\frac{1}{T} - \frac{1}{T_{new}}\right)\right)} \quad (6)$$

Another, solar cell parameter is the open-circuit voltage (V_{oc}). The equation of V_{oc} can be expressed as [9].

$$V_{oc} = \frac{n*k*T*N_s}{q}\ln\left(\frac{I_{sc}}{I_0}\right) \quad (7)$$

If the I-V measurement of the PV panel is taken at two different illumination conditions while the surface's temperature is same, then (3) can be written as,

$$I_{sc1} = I_0\left(e^{\frac{qV_{oc1}}{nN_skT}}\right) \quad (8)$$

$$I_{sc2} = I_0\left(e^{\frac{qV_{oc2}}{nN_skT}}\right) \quad (9)$$

here, I_{sc1} , V_{oc1} and I_{sc2} , V_{oc2} indicates two different illumination levels. Using (8) and (9) it can be written as,

$$n = \frac{(V_{oc1} - V_{oc2}) * q}{k*T*N_s*\ln\left(\frac{I_{sc1}}{I_{sc2}}\right)} \quad (10)$$

Moreover, fill factor can be calculated using the I-V characteristic curve, and the equation is given below [9],

$$FF = \frac{P_{mp}}{V_{oc} * I_{sc}} \quad (11)$$

where, $P_{mp}$is the maximum power and can be written as [9],

$$P_{mp} = V_{mp} * I_{mp} \quad (12)$$

Maximum power can be expressed using (11) which is,

$$P_{mp} = V_{oc} * I_{sc} * FF \quad (13)$$

Lastly, energy can be calculated by integrating the maximum power of the solar panel using the trapezoidal method of integration concerning time; this will give the panel cumulative electrical output energy (Wh).

C. Solar Irradiance

Solar irradiance (W/m^2) is the measurement of the sunlight energy on the earth's surface and can be calculated using the following empirical formula [10] which is given below,

$$G = G_0 * (0.7)^{AM^{0.078}} \quad (14)$$

here, G_0 is the solar irradiance in space outside the atmosphere, which is 1376 W/m^2 and AM is the air mass. The equation of the air mass can be expressed as [10],

$$AM = \frac{1}{\cos\theta_z} = \csc\alpha = \sec\theta z \quad (15)$$

where, θz is the zenith angle [10] and can be expressed as,

$$\theta z = 90° - \alpha \quad (16)$$

here, α is the solar altitude angle [10] and can be written as,

$$\alpha = \sin - 1(\sin\delta * \sin\varphi + \cos\delta * \cos\varphi * \cos\omega) \quad (17)$$

where, φ and δ respectively are the latitude angle [10] and the solar irradiance declination angle, where ω is the hour angle [10]. The equations are given below,

$$\delta = 23.45° \sin\left[\frac{360(n-80)}{365}\right] \quad (18)$$

$$\omega = \omega_s - 15(t - t_{sr}) \quad (19)$$

in the above equations, n is the particular day of the year, t is the apparent local time and t_{sr} is the sunrise time. ω_s is the sunrise angle [10], and the equation is stated as,

$$\omega_s = \cos^{-1}(-\tan\varphi * \tan\delta) \quad (20)$$

For measurement of the fixed axis solar panel irradiance below equation has been used,

$$G_f = G * \cos\delta * \cos\theta z \quad (21)$$

III. Experimental Setup And Methodology

A. Hardware Setup

For this study, two monocrystalline PV panels of 20W output power are set up on a rooftop of a seven-story building in Gabtoli, Dhaka, to collect the short circuit currents and surface temperatures of both panels. A block diagram of the experimental set-up of the PV modules is shown in Fig. 2. In the set-up, two current sensors (INA219), two temperature sensors (DS18B20), two Raspberry Pi 3 B+, and two Arduino Uno are used to collect panels I_{sc} and T. Collected data is directly saved in Raspberry Pi, while using Putty and TightVNC data are collected remotely to a Windows operated computer. Data collection continued from 1st November to 29th February to cover the whole winter season. In the meantime, a few days of data collection is missed due to technical maintenance.

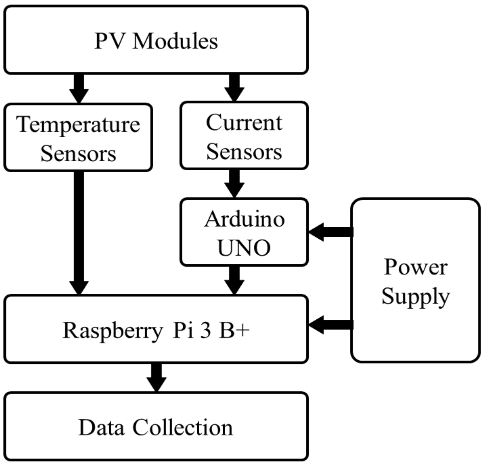

Fig. 2. Block diagram of the experimental setup for data collection.

TABLE. I. Specifications Of The Solar Module

Parameter	Value
Type	Monocrystalline
Maximum Power (P_{mp})	20WP
Open Circuit Voltage (V_{oc})	22V
Short Circuit Current (I_{sc})	1.46A
Voltage at Maximum Power (V_{mp})	18V
Current at Maximum Power (I_{mp})	1.11A
Module Dimension	460*350*25mm

B. *I-V Characteristic Measurement*

A small experiment has been conducted to measure the I-V characteristic curve. The I-V Characteristics plotting of 1st March 2020 is shown in Fig. 3.

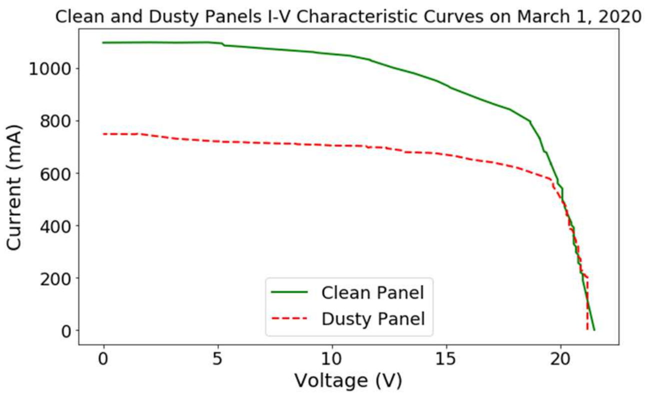

Fig. 3. I-V characteristics curve of clean and dusty Panels.

Using Fig. 3, maximum power has been calculated. And the fill factor is computed using (11), which is 0.65 for this PV panel. Using this same set-up but in two different illumination levels with the same temperature, the ideality factor has been calculated using (10), which is 1.35 for this PV panel.

IV. Results And Discussions

From the experimental set-up, the PV panel short circuit current has been collected, and the other PV parameters have been computed by some additional experimental and theoretical calculations using the short circuit current. The plots of the short circuit currents for four sunny days are shown for each month in Fig. 4.

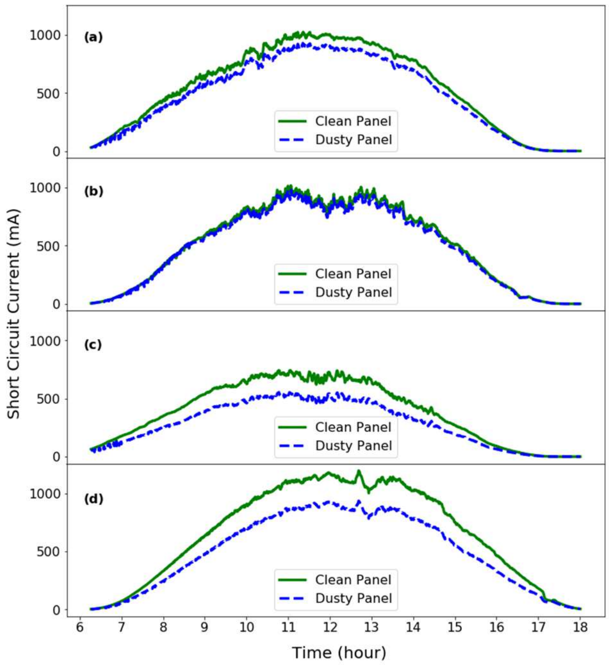

Fig. 4. PV Panel Short Circuit Current recorded on (a) 28th November 2019 (b) 31st December 2019 (c) 28th January 2020 (d) 29th February 2020.

Fig. 4 shows that the short circuit current curves of both clean and dusty panels have a lacuna in between them due to the dust accumulation on the dusty panel's surface. The percentage differences between the two panels are 10.96%, 4.45%, 26.79%, and 23.62%, respectively, which indicates the performance degradation of the dusty panel.

The plots of various PV panels' parameters on 29th February 2020, are shown in Fig. 5.

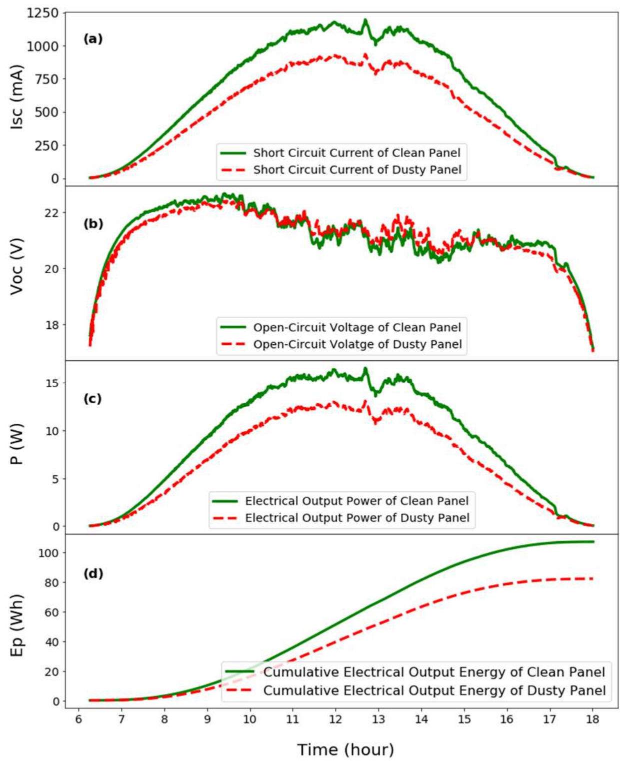

Fig. 5. Plots of experimental values of (a) short circuit current, recorded on 29th February 2020, and theoretically calculated values of (b) open-circuit voltage (c) output power (d) cumulative output energy, for the clean and dusty panels.

The short circuit current plots in Fig. 5 (a) show that the clean panel's short circuit current curve is higher than the dusty panel. The percentage difference between the clean and the dusty panel short circuit current is 23.62% after the installation period of four months due to dust accumulation. There is a clear energy difference between the clean and dusty panels, which shows the panels' electrical output energies are 107.16Wh and 82.19Wh. Besides, the clean and dusty panels' efficiency is 14.55% and 11.16%, which also indicates that the dusty panel efficiency decreases due to the dust effect.

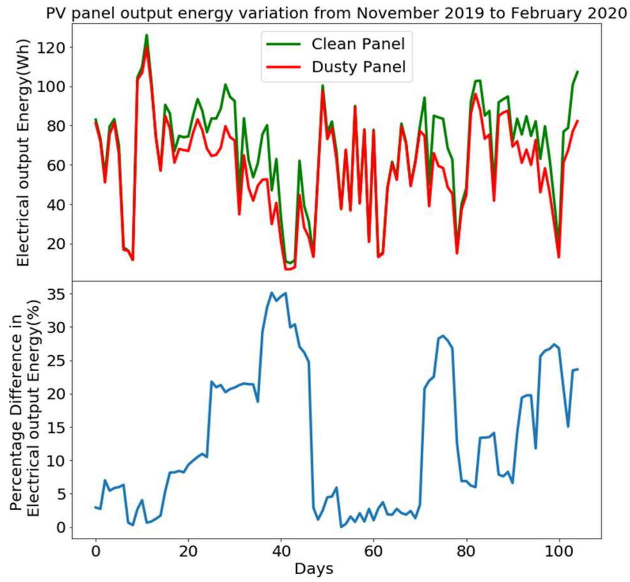

Fig. 6. Plots of variation in the (a) electrical output Energy of the clean and dusty panels and (b) percentage difference in output energy between the two panels, during the measurement period.

The dust effect on the PV panel output energy for both panels can be seen from Fig. 6 for the whole winter season. Here, with the increase of the dust accumulation on the dusty panel's surface, the performance gradually decreases. However, it is observed that the dusty panel's performance improves significantly after a wash by rainfall.

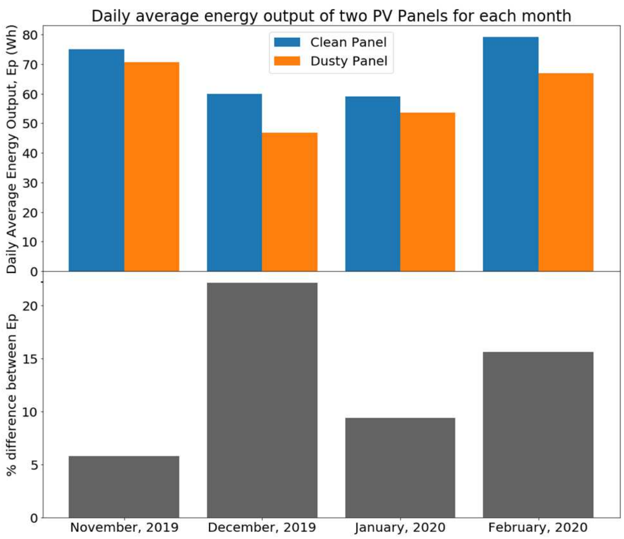

Fig. 7. Plots of (a) daily average energy output of the clean and dusty panels and (b) percentage difference between them, as determined for the four months of the measurement period.

Here, the percentage difference between energy outputs is 5.78%, 22.10%, 9.35% and 15.59% respectively for each month over the whole winter season.

V. Conclusion

In this work, an investigation has been carried out to study dust particles' effect on PV module performance, deployed on a high-rise building rooftop. The investigation is conducted over a period of four months, from November 2019 to February 2020, during which the weather remains mostly dry and dusty. Dust accumulation has been observed to reduce the short-circuit current from a minimum of 5.52% to a maximum of 22.31% throughout the winter season. During this time span, the maximum reduction in daily output energy is reported to be around 35%. During the month of December, the impact of dust is found to be most pronounced, which showed a decrease of over 22% in the overall monthly energy output due to dust.

In summary, it can be concluded that the effect of dust accumulation on the PV panel performance on the high-rise buildings is significant during the dry season, though one would expect a milder effect due to elevation and stronger winds on high-rise buildings' rooftop. It results in a substantial decrease in the short circuit current and the total energy output and therefore demands regular cleaning of the modules to maintain the module performance level. The development of effective and affordable PV panel cleaning technology can help to solve this problem.

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