Experimental Study on the Performance of PV Modules by Sand Density based on the Desert Environment

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Abstract. In this paper, the research on the performance of photovoltaic modules with different sediment density was carried out under the conditions of the laboratory, and the effects of different sediment density on the open circuit voltage, short circuit current, conversion efficiency, fill factor and power of the photovoltaic module were analyzed. The research results show that the power of the accumulated sand PV module is significantly lower than that of the clean module, but with the increase of the accumulated sand density (0 g/m²-68.3 g/m²), the short circuit current, output power, conversion efficiency and fill factor of the module show a downward trend. There is no significant impact on the open circuit voltage of the module compared with the clean module, and the output power of the module is reduced by 27.8%. The relative power generation rate shows a downward trend and the maximum value of the decline can reach 27.9%.

1. Introduction
The National Aeronautics and Space Administration of the United States conducted a study on the dust accumulation on the moon's surface in 1991. The results showed that when the dust on the moon's surface accumulated to 3 mg/cm², the transmittance of sunlight decreased by about 50% [1]. Based on this research result, scholars all over the world have paid attention to the relationship between dust accumulation and photovoltaic module power generation. Semaoui and others in the United States built a photovoltaic power generation platform. Research shows that when the surface area of the module is gray, the light transmittance of the glass plate on the surface of the photovoltaic module is significantly reduced [2]. Mexico’s Cabanillas found that after three months of ash accumulation, the output power of crystalline silicon photovoltaic modules decreased by 4% to 7%, and the output power of amorphous silicon photovoltaic modules decreased by 8% to 13% [3]. Xi’an Wang Feng conducted a comparative experiment on clean components and dust accumulation components at the photovoltaic power station. The experimental results show that: In the dust-inducing weather, the photovoltaic system power generation is greatly affected by the dust accumulation, and the maximum reduction in power generation is the original 15% [4]. Chen Fangju studied photovoltaic modules exposed to natural conditions for 1 to 3 months. The study found that ash accumulation reduced the module's transmittance by 1.3% to 4.0% [5]. Kaldellis in Greece conducted a study on four samples of ash deposits. The study found that the ash deposits on the surface of photovoltaic modules significantly reduced the performance of the modules. Different types of dust accumulation have different effects on the efficiency of components.[6]. MontoMani conducted a study on the performance of PV modules affected by dust accumulation, and
the results showed that, under different climatic characteristics and conditions of climatic zones, the period that the modules need to be cleaned was given [7]. It can be seen from the above research that the characteristics of the sand and dust in different regions are different, and the impact on the performance of the photovoltaic module is also different. For the sand-dust of different densities, the influence of the output characteristics of the photovoltaic module cannot be ignored.

2. Theoretical Analysis

2.1 Solar photovoltaic module model

Important indicators to measure the performance of PV modules are open circuit voltage, short circuit current, optimal output power, fill factor, and conversion efficiency.

(1) The photovoltaic panel selected for the experiment is a 10W polycrystalline silicon photovoltaic panel. Its equivalent circuit diagram is shown in Figure 1 below. $I_a$ is the photovoltaic generated current, $I_d$ is the diode junction current, $C$ is the junction capacitance, and $R_h$ and $R_s$ are the parallel resistance series resistance, $U_d$ is the voltage.

Figure 1. Photovoltaic module equivalent circuit diagram

Generally speaking, the series resistance is relatively small and can be ignored, then [8]:

$$I = I_{sh} - I_d = I_{sh} - I_0 \left[ \exp \left( \frac{qU_d}{nK_BT} \right) - 1 \right]$$  \hspace{1cm} (1)

In the above formula, $I$ is the output current, $I_0$ is the diode reverse saturation current, $q$ is the charge, $T$ is the temperature, $n$ is the ideal coefficient, and $K_B$ is the Boltzmann constant. Available from formula 1[9]:

$$I_{sc} = I_{sh}$$  \hspace{1cm} (2)

$$U_{oc} = NK_BT/q \ln \left( \frac{I_{sc}}{I_0} + 1 \right)$$  \hspace{1cm} (3)

(2) The best output power is also called peak power. The optimal output power refers to the maximum output power of the photovoltaic module under test or normal working conditions, that is, the product of the peak voltage ($U_{m}$) and the peak current ($I_{m}$):

$$P_m = U_m \times I_m$$  \hspace{1cm} (4)

(3) Fill factor (FF) is an important indicator to measure the working efficiency of PV modules:

$$FF = P_m/U_{oc}I_{sc}$$  \hspace{1cm} (5)

(4) Conversion efficiency ($\eta$) refers to the ratio of the optimal output power of the photovoltaic module to the solar power irradiated on the surface of the module. That is [10]:

$$\eta = \frac{P_m}{P_{in}} = \frac{P_m}{AG}$$  \hspace{1cm} (6)

In the above formula, $P_{in}$ is the incident optical power, $A$ is the surface area of the component, and $G$ is the irradiance on the surface of the component.

When the photovoltaic module is naturally placed in the desert, the sand accumulation on the surface of the module will affect the output index of the module, thus affecting the output performance of the module. The larger the amount of sand accumulation on the surface of the module, the more obvious it will affect the output performance of the module.

2.2 Experimental method

The experiment site was selected in the laboratory of Inner Mongolia University of Technology, Hohhot,
and eight 10w polycrystalline silicon photovoltaic modules were selected to keep one of the modules clean as a standard module for comparison. Taking sand in the Kubuqi Desert of Inner Mongolia, using JY202 electronic balance (accuracy is 0.01g) to weigh 1.00, 2.00, 3.00, 4.00, 5.00, 5.50, 6.00, 6.50g of sand-dust, covering the surface of the photovoltaic modules numbered 01 to 07 with the dust of different sediment density, and keeping the surface of the photovoltaic module No. 08 clean (The specific situation is shown in Figure 2).

![Figure 2. Testing platform](image)

Considering the adhesion of sand-dust and the best local installation inclination angle, the installation inclination angle is 30 °, facing south, and the wind speed, ambient temperature and irradiance on the day of the experiment are shown in Figure 3. The small wind speed prevents sand-dust from blowing up, and the temperature difference during the experiment is small, so it has little effect on the accuracy of the experiment.

![Figure 3. The change of irradiance, wind speed and temperature on the day of the experiment](image)

3. Analysis of experimental results

3.1 The impact of different sediment density on the output power, open circuit voltage and short circuit current of the module

Sand particles with different sand density are laid on the surface of the photovoltaic modules numbered 01 to 07. The sand density on the module surface is 0g / m², 10.5g / m², 21g / m², 31.5g / m², 42g / m², 52.5g / m², 57.8g / m², 63g / m², 68.3g / m². Figure 4 shows the variation of photovoltaic module power under different sand density. As can be seen from it, the output power of the module decreases with the increase of the sand density. This is because when the surface of the module is covered with sand and dust, part of the light is absorbed or reflected by the sand particles, which will cause the irradiance received by the module to decrease. The solar radiation energy obtained by the module is reduced, which leads to a decrease in the output work of the photovoltaic module. When the density of sand accumulation on the surface of the module increases to a certain amount, the power generated by the module will not decrease, and the power generation will tend to stabilize. This is because with the increase of the density of sand accumulation, the area of the module that is blocked increases. But the component area is fixed, so when the power is reduced to a certain value, there will be no large fluctuations. When the sediment density on the surface of the module increased from 0g / m² to 68.3g / m², the power generation decreased by 27.8%.
Figure 4. Power variation of photovoltaic modules covered by different sand density

Figures 5 and 6 show the changes of the open circuit voltage and short circuit current of photovoltaic modules under different density coverage, respectively. It can be seen from Fig. 5 that with the change of the sediment density, the open circuit voltage fluctuation of the components in the same time period is small. Over time, from 13:34 to 15:10, the open-circuit voltage of the module decreased by about 3.9%. Therefore, the surface area of the component has little effect on its open circuit voltage. It can be seen from Fig. 6 that with the change of the sediment density, the short-circuit current of the component decreases first and then tends to be stable. This is because the reason for affecting the short-circuit current is mainly the absorption rate of the photovoltaic module to absorb sunlight.

Figure 5. Changes in open circuit voltage of photovoltaic modules under different density coverage (Left one)

Figure 6. Short-circuit current changes of photovoltaic modules under different density coverage (Right one)

The smaller the absorption rate, the smaller the short-circuit current of the module. When there is sand on the surface of the module, some cells in the module cannot be received normally light, so that the absorption rate of the module to absorb sunlight decreases, resulting in a reduction in the loop current of the blocked cell. From Kirchhoff’s law, the current of the entire loop of the module will also decrease. As the density of accumulated sand increases, the blocked area increases but the component area is constant, so the loop current will tend to stabilize when it decreases to a certain value.

In order to better analyze the impact of different sediment density on module power generation, the relative power generation rate is defined. The relative power generation rate is the ratio of the power generated by the sand-sand module to the standard clean module at the same time. which is:

$$\omega = \frac{P}{P'} \times 100\%$$

Here Figure 7 is the variation of the relative power generation rate of modules with different sediment density.

It can be seen that as the density of the accumulated sand increases, the relative power generation rate of the module decreases, and the relative generation rate of the photovoltaic modules with the same sediment density fluctuates less. When the time is 13:34 and the sediment density is 68.3g / m², the relative power generation rate reaches the lowest, and the maximum value of its decline can reach 27.9%.
3.2 The effect of different densities on the conversion efficiency of photovoltaic modules

Figure 8 shows the effect of different sediment density on module conversion efficiency. It can be seen from formula (6) that the main factors affecting the conversion efficiency of the module are irradiance and optimal output power. As can be seen from it, when there is dust on the surface of the photovoltaic module, the irradiance received by the module will be reduced, resulting in a significant decrease in the conversion efficiency of the photovoltaic module. As the density of sand and dust continues to increase, the conversion efficiency of the module begins to decline again. This is because the greater the density of sand and dust, the smaller the gap between the particles of sand and dust, which increases the heat dissipation on the surface of the module and increases the temperature of the module.

The forbidden band width of the photovoltaic module becomes smaller, and the photovoltaic module's ability to absorb photons becomes greater, but the energy released when converted into carriers will increase, that is, the energy used to convert into electrical energy is reduced [11]. The excess energy is converted into heat energy, which causes the temperature of the components to start to rise again, which leads to a decrease in conversion efficiency. When the dust density increases to a certain amount, the conversion efficiency will gradually stabilize.

3.3 The effect of different densities on the fill factor of photovoltaic modules

Figure 9 is the effect of different sediment density on the fill factor of components. As can be seen from it, compared with the standard cleaning module, the maximum variation of the filling factor of the photovoltaic module is about 21%. With the increase of the sediment density, the change curve of the filling factor shows an upward trend, which shows that the dust with large sediment density is more conducive to the increase of the filling factor of the photovoltaic module than the sand with low sediment density. When the sediment density is 52.5g/m², the filling factor of the module decreases significantly. This is because the factor that affects the fill factor of the module is mainly the temperature of the module. For most photovoltaic modules, the fill factor decreases monotonically with increasing temperature [12]. When sunlight hits the surface of the photovoltaic module, part of the light and heat is absorbed by the sand and dust covering the surface of the module, and the thermal conductivity of the sand material itself is small and the thermal conductivity is weak. The part of the heat absorbed by the dust on the surface of the component is transferred slowly downwards, mostly staying inside the sand particles, causing the surface temperature of the sand particles to rise rapidly.
At the same time, as the density of accumulated sand increases, the shielding area of photovoltaic modules becomes larger, and the dust accumulation is no longer evenly distributed, but appears to be superimposed or clustered [13]. Therefore, the temperature of the component surface will increase, and its fill factor will also decrease accordingly.

### 4 Conclusion

1. The power of accumulated sand PV modules is less than that of clean modules, but as the density of accumulated sand increases, the output power of photovoltaic modules shows a downward trend. When the sediment density reaches 68.3g / m², the output power of the module is reduced by 27.8% compared with the clean module; the relative power generation rate shows a downward trend, and the maximum value of the decline can reach 27.9%.

2. As the surface area density of photovoltaic modules increases, the conversion efficiency of photovoltaic modules decreases, and its maximum value can reach 2.9%.

3. Compared with standard sand modules, the largest change in the fill factor of photovoltaic modules is about 21%. With the increase of the sediment density, the change curve of the fill factor shows an upward trend, which indicates that the dust density is larger than the sand dust density, which is more conducive to increasing the fill factor of the photovoltaic module.

In summary, when there is sand on the surface of the module, it will have a greater impact on the output power of the module. Therefore, the establishment of photovoltaic power plants in desert areas should pay attention to the impact of accumulated sand on the power generation capacity of the power station, and provide a basis for the rational arrangement of the time for cleaning up the components.

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