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A Review of Research on the Influence of Photovoltaic Module Pollution on Power Generation Performance

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Abstract. With the depletion of energy, the increasingly prominent problem of environmental pollution and the proposal of carbon peaking and carbon neutrality goals, photovoltaic (hereinafter referred to as "PV") power generation technology has become a hot spot for many countries to develop, and PV power plants can make a significant contribution to the development of a sustainable energy system. However, PV modules pollution have become a serious problem for PV power plants, which have a great influence on power generation and operating costs. Air pollution, rainfall, module dust accumulation, and ground conditions are key factors that affect the performance and output power of PV modules. This article provides an overview of recent research on the impact of module contamination on PV systems. The study found that the PV power loss caused by component pollution in some power plants reached 5%-20%. This paper aims to analyze the source of module pollution and evaluate the research status of its influence on power generation, so as to provide guidance for the design, operation, and maintenance of PV power plants.

Keywords. PV module pollution, power generation, impact

1. Introduction

Solar photovoltaic power generation has the characteristics of inexhaustible and zero carbon emission and is considered one of the most promising energy sources. According to statistics, by the end of 2020, the cumulative installed PV capacity in the world was 760.4GW. China's PV power generation installed capacity is 253 million kW, of which 48.2 million kW will be newly installed nationwide in 2020 [1]. With the proposal of the carbon

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peaking and carbon neutrality goals, the installed capacity of PV power generation in our country will be higher and higher in the future. Therefore, higher requirements are placed on the power generation efficiency and stable operation of PV power plants.

Air pollution, rainfall, module dust accumulation, and ground condition are important factors that affect the performance and output power of PV modules. Among these factors, air pollution and module dust accumulation act as a barrier between PV module surface and solar radiation falling on it [2]. PV modules pollution have become a serious problem for PV power plants in many countries especially dusty ones. Some studies have found that compared with clean PV modules, the maximum power of dust-laden PV modules is reduced by 8.41-20.1%, which has caused huge economic losses to PV power stations [3].

The purpose of this paper is to review, categorize and discuss component contamination types and their impact on power generation and prediction methods. At present, the research on the influence of PV module pollution on power generation performance mainly focuses on the impact of dust on PV modules, and there is a lack of the research of the impact caused by air pollution and ground condition. The review will focus on the module pollution caused by air pollution, dust accumulation, ground condition and its impact on the efficiency of photovoltaic system.

This paper contains the following parts: (i) pollutiontypes of PV module and their influence on power generation, the pollution types include air pollution, dust accumulation and ground condition. (ii) Prediction of the impact of module pollution on power generation. (iii) Cleaning strategies in photovoltaic power plants. The first part focuses on the influence of each pollution type on power generation. The second part discusses the influence model about power generation caused by PV module pollution. Then, select the best module in terms of power generation for a comprehensive impact system related to air pollution, dust accumulation and ground condition. The third part discusses the cleaning methods of PV module and highlighting the advantages and disadvantages. Also, at the end of this paper is presented the main results and future work of proposed research. This review is expected to provide guidance for the design, site selection, operation, and maintenance of PV power plants in the future.

2. Pollution Types of PV Module and Their Influence on Power Generation

2.1. Air pollution

Air pollution has a significant impact on solar radiation, and it mainly affect the solar radiation received by module by changing atmospheric composition and turbidity [4]. According to the relevant national standards [5], the degree of air pollution is described by 6 indicators including $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3. Among them, $PM_{2.5}$ and PM_{10} are the primary pollutants in recent years [6]. $PM_{2.5}$ and PM_{10} indirectly affects the power generation of PV power plants through the following two aspects. On one hand, the suspended particles in the atmosphere combine with water vapor, and significantly affect the aerosol optical thickness (AOT) of the atmospheric radiation transfer process by scattering, absorbing, and reflecting sunlight, thereby weakening the surface irradiance and reducing the output power of PV power generation. On the other hand, due to the strong adsorption of $PM_{2.5}$ and PM_{10}, it can cover the surface of PV modules to generate dust and dirt, which blocks the radiation of sunlight to PV modules and further reduces the power generation [7].

In addition, studies have shown that air pollution has a certain impact on solar radiation and PV module power generation efficiency. Feng et al. [8] found that the output power of PV power generation is proportional to the irradiance as a whole. Elminir [9] believed that atmospheric pollution reduced the total ground radiation by 9.3%-22% under sunny days in Egypt. Wang et al. [10] found that on a sunny day, the average solar radiation attenuated by 10% and the direct radiation attenuated by 18% in Shenyang air quality level 3 compared with the second level. Sunny days are severely polluted, and air pollution can reduce direct radiation by 67% and total radiation by 34%. The shaving effect of $PM_{2.5}$ is more obvious, and the average direct solar radiation attenuation **o**n sunny days with $PM_{2.5}$ as the primary pollutant is significantly greater than that with SO_2 and PM_{10} as the primary pollutants. In addition, Mekhilef et al. [11] studied and analyzed the impact of environmental pollution on PV modules. The results showed that when the concentration of particulate matter in the air is higher, the surface of the module is more likely to accumulate dust, and a higher cleaning force is required to clean it. When the glass surface of the module interacts with the contaminants, the physical and chemical properties of contaminants significantly affect the optical properties of the glass. In addition, the irregular distribution of compounds such as sodium, potassium, magnesium, calcium, oxygen, silicon**,** and iron in the dust particles damages the surface softness and transmittance of the glass, which reduces the amount of radiation absorbed by the component and thereby reduces the output power. Therefore, it is necessary to study the influence of air pollution and composition on the output power of components.

2.2. Dust Accumulation

Dust is a generic term that applies to particulate matter with diameters varying between 0.10 μm and 1000 μm [12]. Dust accumulation is a natural phenomenon that adversely affects the energy of solar PV modules by absorbing or reflecting solar radiation. Wind speed, wind direction, humidity, rainfall, frequency of sandstorms, ambient temperature, surface finish, inclination angle, soil type, and surrounding vegetation, etc., all contribute to the adhesion of dust to the component surface [13]. The output power of PV modules has a linear relationship with the intensity of solar radiation. The dust on the surface of PV modules will reduce the light transmittance of the glass. The decrease in light transmittance will lead to a decrease in the output performance of the module pool [14]. In recent years, in the inland low wind speed areas, due to air pollution and abnormal weather and other reasons, the particle deposition problem increases the surface ash content of PV modules, increases the wear degree, and reduces the energy absorption rate. Therefore, it is necessary to study the impact of dust on PV modules on power generation [15].

Adinoyi et al. [16] found that the dust size, amount, chemical and physical characteristics have impact on PV modules performance. The results of Zhao et al. [17] show that the amount of dust accumulation has a greater impact on the PV transmittance. At 30% humidity, the dust accumulation was negatively correlated with particle size, when the particle size increased from 10mm to 30mm, the dust accumulation decreased from 9.76g/m^2 to 2.59g/m^2 at a wind speed of 1m/s, resulting in a reduction in PV efficiency from 14.64% to 3.89% and a reduction in transmittance from 25.32% to 8.38%. Essalaimeh et al. [18] studied the effect of dust accumulation on the performance of PV modules in Jordan, and the results showed that module dust accumulation reduced the PV power generation efficiency by 31-35%. Guo et al. [19] found that in Qatar, due to its high relative humidity, the daily power generation of PV modules was lost by 0.4~0.8% due to dust accumulation. Without monthly cleaning, PV power generation can be lost by 12% to 24%.

The results of Kymakis et al. [20] showed that in Crete, the deposition of dust on PV modules led to a decrease in power generation at a rate of 5.86% per year. Li et al. [21] investigated the effect of dust on PV modules absorption and emission of sunlight, and found that after the modules were exposed to dust for 11 days, the PV power generation efficiency decreased by 19.23%, and the average dust deposition was 7.07g/m^2/d. To sum up, dust mainly affects the power generation by affecting the solar irradiance received and the impact of dust's physical and chemical characteristics on module panel glass.

2.3. Ground Condition

Under different ground conditions, reflected radiation will have a certain impact on the total surface radiation of PV modules. The ground material with high reflectivity makes the component output power larger, and the ground material with low reflectivity makes the component output power smaller [22]. The research of Ma et al. [23] showed that the annual average power generation of double-sided PV modules with the same nominal power on the sandy ground is 18.21% higher than that of conventional single-sided PV modules; double-sided PV modules with the same nominal power on cement white paint ground. The annual average power generation of PV modules is 24.33% higher than that of conventional single-sided PV modules; the annual average power generation of double-sided PV modules with the same nominal power on the gravel ground is 18.72% higher than that of conventional single-sided PV modules. Ma et al. [24] compared and analyzed the characteristics of radiation balance and the diurnal variation of the surface energy budget of two different underlying surfaces in the Badain Jaran Desert in Inner Mongolia under typical sunny conditions. The results show that the total solar radiation on the desert point is 28.1MJ/m^2, and the lake area point is 27.2MJ/m^2. This is due to the different properties of the ground conditions and the different distribution of surface energy. Appelbaum [25] research found that the power gain of double-sided modules increases with the increase of the reflectivity of the ground, and decreases with the increase of irradiance. The power gains are 25.30% and 8.24%, respectively. Therefore, the influence of ground reflectivity on irradiance should be fully considered in the design stage of PV power plants to improve PV power generation efficiency.

3. Prediction of the Impact of Module Pollution on Power Generation and Cleaning Strategies

3.1. Prediction Model

In order to judge the influence of different types of component pollution on the power generation and ensure the stable operation of the power grid, it is necessary to predict the output power of the PV power generation system. At present, there have been studies to predict the impact of module pollution on output power from three aspects: air pollution, module surface pollution, and ground reflection. The impact of different pollution types on PV power generation is mainly predicted by the neural network, regression model, and optical model. However, all current studies considered the influence of a single type of pollution in the prediction of the output power of the module, and there was no prediction of the impact of the above three types of pollution on the output power of the module.

3.2. Cleaning strategies

3.2.1. Natural methods

The main strategies for cleaning PV modules by natural methods are rainfall, snowfall, wind, and gravity. Rainfall is the most effective method to clean the surface pollution of PV modules. The wind can achieve the effect of cleaning the modules by blowing the dust on the surface of the PV modules. Mekhilef et al. [26] found that the wind speed can not only blow away the dust on the component surface, but also increase the heat dissipation on the component surface and reduce the ambient humidity, thereby improving the power generation efficiency.

3.2.2. Mechanical methods

The strategies for mechanically cleaning PV modules mainly include mechanical wiping, purging, and cleaning robots. The mechanical wiping method mainly removes the dust on the component surface through vibration or ultrasonic action. Kang et al. [27] used the mechanical vibration method to clean the module fouling to restore the module power generation to 95% of the rated capacity. In addition, Lamont and Chaar [28] proposed a cleaning method (PIC) based on PLC and peripheral interface controller, which can effectively reduce dust and bird droppings on PV modules.

3.2.3. Electrostatic methods

Calle et al. [29] studied the electrostatic methods to mitigate the negative effects of dust on solar panels on the moon and applied it to NASA missions. The electrostatic precipitator method is to connect to the electrode through a single-phase or multi-phase AC power supply, generating an electromagnetic field on the surface of the component, and removing dust particles through electrostatic repulsion. In addition, Hudemani et al. [30] conducted a comparative study on various types of dust using different cleaning methods (manual cleaning, vacuum suction cleaning, automatic wiper cleaning, and electrostatic precipitator), and the results showed that the electrostatic precipitator using Arduino controller is effective. The ash on the surface of the module is removed from the module, which improves the power generation efficiency of the solar module.

3.2.4. Component Self-Cleaning Methods

The module self-cleaning method is to develop a self-cleaning PV module panel with optical properties through the technology of micro-nano surface processing [31]. This self-cleaning surface can improve the cleaning efficiency, reduce the cleaning frequency and improve the power generation efficiency. Verma et al. [32] developed a superhydrophilic nanostructured glass with a contact angle of less than 5°, which improved the net light transmission and surface self-cleaning properties of solar cells.

Table 1. Comparison of cleaning methods.

Number	Cleaning strategies	Major pollutants	Cleaning effect	Advantage	Disadvantage	References
1	Natural methods	dust naturally polluted	Dust causes a daily loss of PV performance over 20%	Neither cost nor resource	It relies on weather	Zorrilla-Casanova et al., 2011 [33]
2		dust	Dust particles greater than 1 mm are easily blown away by wind			S.Y. Jiang et al., 2018 [34]
3	Mechanical methods	dust naturally polluted	The cells cleaned daily can increase in the efficiency 29.76%.	Environment friendly, no electricity cost	High cost, human interventionand need water	Paudyal and Shakya, 2016 [35]
4		dust accumulation	The efficiency of the PV increase to 15%			Anderson et al., 2010 [36]
5		dust accumulation	The module power generation to 95% of the rated capacity			Kang et al.,2017 [27]
6		dust	The PV efficiency increase by 7%.			Lamont et al., 2011 [28]
7	Electrostatic methods	dust	The dust can be cleaned within 2 minutes	To remove dust without water	Additional electrical equipment is required and high-cost	Mazumder et al., 2011 [37]
8		dust	Increase the generation efficiency by 15%			Hudemani et al.,2017 [30]
9	Component self-cleaning methods	Naturally polluted	5% increase in the solar cell current	No additional parts are required.	Reduce photoelectric conversion efficiency	Verma et al., 2011 [32]
10		physical properties of accumulated dust	Increase the generation efficiency from 30 to 40%	It can effectively prevent pollution.		Fujiwara et al., 2011 [38]

4. Discussion and Conclusions

This review contains three parts: (i) pollution types of PV module and their impact on power generation, the pollution types include air pollution, dust accumulation and ground condition (ii) prediction of the impact of module pollution on power generation and (iii) the cleaning strategy. The research conducted air pollution, dust accumulation, ground condition and their impact on power generation impact on PV and prediction model, cleaning methods has been reviewed and discussed. The main conclusions summarized as follows:

(1) Air pollution mainly affects the solar radiation received by the module by changing the atmospheric composition and turbidity, thereby affecting the power generation efficiency of the module. Generally, the reduction of solar radiation caused by air pollution is about 10%-20%.

(2) The main pollution on the surface of the module is the accumulation of dust, which reduces the light transmittance of the panel glass of the module and reduces the amount of radiation absorbed by the panel, which in turn affects the output power. If it is not cleaned in time, the power loss caused by dust accumulation is generally about 5%-20%.

(3) The higher the ground reflectivity, the better the reflection of sunlight, the brighter the surrounding environment, the more reflected radiation received by the inclined surface of the PV module, and the higher the power generation.

(4) Air pollution, dust accumulation, and ground condition reflectivity all have a certain impact on the output power of PV power generation systems. Therefore, the effective way to improve PV power generation efficiency is not only to find more efficient modules technically but also to improve design, operation, and maintenance.

Considering the above pollution situation, removing the above pollution in time can improve the power generation efficiency of the module. In addition, finding an accurate method for predicting the power generation by the contamination of components is the key to future research. Although there are many effective cleaning methods for different types of pollution, the methods with low-cost, high efficiency and less human intervention are still the focus of experts and scholars. Future research should focus on the following aspects.

(1) In addition to understanding the meteorological and environment factors such as temperature, rainfall, wind speed and air pollution, etc. of the power plants, it is very important to understand the contaminants characteristics and properties to search for the suitable prediction models and cleaning strategies.

(2) The method of accurately predicting cleaning time and cleaning cost is very important. The authors suggest to devote more research in artificial intelligent cleaning method for the contaminants characteristics and properties. In addition, more research needs to be considered to develop economical and high efficiency cleaning methods.

By considering the influence of comprehensive factors on the power generation of modules, a mathematical model is established to determine the specific relationship and a reliable monitoring system to guide the operation and maintenance of the power plants so as to improve the power plants revenue and reduce the waste of solar energy resources.

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