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Analysis of the optimum tilt angle for a soiled PV panel

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ABSTRACT

A new model of the optimum tilt angle of a soiled photovoltaic (PV) panel is proposed in this paper. The tilt angle is a key factor that influences the output power of PV panel, while dust deposition is an inevitable external element to be considered. In this paper, the solar radiation model is studied by analysing the Hay, Davies, Klucher, Reindl (HDKR) model. The cell temperature of a PV panel is also investigated to evaluate the power output. A fitting formula is derived to express the relationship between the dust deposition density and the tilt angle, and it is integrated in the output model of a fixed-type PV panel. Besides, the effect of dust deposition on the transmittance is analysed. An inverse correlation between the dust deposition density and tilt angle can be obtained, and the optimum tilt angle is calculated to maximize the power output of a soiled PV panel. Simulation is conducted by Matlab to demonstrate the validity of the proposed model of the optimum tilt angle with the shielding effect by dust. Furthermore, the relationship between dust deposition and the working temperature of PV panel is investigated by indoor experiments.

1. Introduction

Due to the shortage of fossil fuels and the corresponding degradation of the atmosphere, development of renewable energy resources has attracted extensive attention around the world. As one of the most important renewable energy resources, solar energy has an enormous potential and wide applications since it is clean, free and abundant [1–3]. Solar energy can be directly converted into electric power through PV panels, and the tilt angel of PV panel significantly affects the power output. Therefore, many researches in the past decades focused on the algorithm optimization of tilt angle to maximize PV generation. Generally, the optimal tilt angle varies with several conditions such as the utilization period, geographic latitude, climate, surroundings and other atmospheric factors, i.e. dust and pollution [4–6].

Empirical formulas were employed in early studies to estimate the optimum tilt angles at different sites, which are only related to the local latitudes. In [7] the conclusion was given that the tilt angle can be calculated as (latitude ± 15°). Later, the authors in [8] conducted a series of experiments and proposed a new formula which is (latitude ± 8°) to derive the value of the tilt angle. For specific locations, according to coastal radiation data, PV panels should be installed with the tilt angle of 2.8° greater than the latitude [9]. However, the accuracy of these statistics is not guaranteed due to limitations of geographical conditions.

Many recent researches attempted to propose more accurate mathematical models of the optimum tilt angle, mainly considering the calculation of the maximum solar radiation incident on inclined panels. In [10], seven irradiance decomposition models for estimating Global Plane Irradiance (GPI) from Global Horizontal Irradiance (GHI) were evaluated for a region in South Africa, along with comparisons among six transposition models. Three meteorological datasets were combined with Perez and Hay-Davies models to compute the irradiance on tilted surfaces in [11], and the cooling effect of wind speed was considered to increase the accuracy of estimating the PV energy output. In [12] the best transposition model was to be found for Singapore's climatic conditions, and the maximum annual in-plane irradiation was obtained when surfaces were tilted eastward by employing the Perez et al. model.

Although solar radiation is the dominant factor for the output power of PV array, the effects caused by other factors also contribute to the variation in the PV power output [13–18]. Among these factors, dust deposition is a non-ignorable one that shields the panel surface and influences the solar radiation absorption.

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Table 1
Reduction ratio of transmittance versus several factors.

Influence factor	Reduction ratio of transmittance
Particle diameter ↑	Lower
PV tilt angle ↑	Lower
Dust deposition density ↑	Higher
Wind speed ↑	Higher
Humidity ↑	Higher

The shielding effect caused by dust can be considered as transmittance decrease of PV surface glass, and the reduction ratio of transmittance varies with several factors, which are described in Table 1. Since PV arrays are placed in outdoor environments for a long period, the particles such as the raised soiling, atmospheric pollutant and bird dropping that accumulate on the panel surface are inevitable. For the areas that receive intense solar radiation as well as serious dust fall, abundant solar energy resources are wasted. To maximize the efficiency of absorbing solar power for PV arrays, the performance of an electrodynamic screen that removes dust and particles was investigated [19–21]. In addition, researches in adhesion of dust to PV module surfaces were carried out, which offered possible pathways to more effective cleaning methodologies or the development of preventative dust mitigation coatings [22]. However, dust adhered to PV panels cannot be totally removed, and it takes decades for relevant mature technologies to be popularized worldwide. Therefore, currently the influence of dust deposition has to be considered, and the tilt angle should be adjusted in order to increase the power output of PV arrays.

Dust concentration and spectral transmittance were investigated in [23], and different tilt angles were applied to find the worst case for transmittance variation. In addition, the conclusion was derived in [24] that a horizontal position should be avoided since dust accumulation is the most serious under this situation. From the researches mentioned above, it can be seen that the tilt angle influences the volume of dust accumulation, and the dust affects the plate-transmittance and solar radiation absorption. However, there is no research that combined the optimum tilt angle model with the calculation of dust deposition density. Apart from the shielding effect, the temperature effect caused by dust deposition is to be investigated. For example, the area covered with dust has lower temperature due to less radiation. However, since the thermal resistance of dust is larger than that of glass, heat dissipation is weakened and the temperature of the shielded area increases. Therefore, it is hard to implement theoretical calculation to discuss the temperature effect.

In this paper, the Hay, Davies, Klucher, Reindl (HDKR) model is analysed for solar radiation, and the cell temperature of a PV panel is investigated under the standard test condition (STC). The mathematical model of the optimum tilt angle of PV panel is optimized by combining the correlation between the dust density and tilt angle, and a new model of the optimum tilt angle is proposed for fixed PV arrays. Additionally, a fitting formula is derived to represent the relationship, and the shielding effect of dust on the transmittance is analysed. Moreover, to investigate the relationship between the dust deposition density and the working temperature of a PV panel, experiments are carried out.

This paper is organized in the following structure: In Sections 2 and 3, models of the optimum tilt angle without and with the effect of dust deposition are respectively established. The relationship between the solar radiation and tilt angle is investigated in Section 4 by simulation and analysis. In Section 5, indoor experiments of temperature effect on PV panel are carried out by considering dust deposits. Finally, conclusions are obtained in Section 6.

2. The optimum tilt angle model without dust factor

2.1. Calculation of solar radiation on the plane of array

The solar radiation on an inclined surface is one of the most important parameters for tilted PV panels. Since a meteorological bureau only records the solar radiation on a horizontal surface, the collectible solar radiation on an inclined surface needs to be calculated.

Total solar radiation on a tilted surface H_T (W/m^2) consists of three components:

(1) "Direct radiation $H_{T,b}$", which is used to describe the solar beam travelling through the atmosphere and straight down to the surface.
(2) "Diffuse radiation $H_{T,d}$", which is used to describe the sunlight reaching the surface after being scattered by molecules and particles in the atmosphere.
(3) "Ground reflected radiation $H_{T,refl}$", namely the solar radiation is reflected by the ground and then it reaches the tilted surface.

As can be seen from Fig. 1, direct radiation can reach the panel from only one specific angle, while diffuse radiation can reach the surface from all the angles. Since the horizontal surface is not exposed to reflected radiation, the total radiation on the horizontal surface H recorded by the meteorological bureau is the sum of direct radiation H_b and diffuse radiation H_d, and the values of H_b and H_d can also be collected:

$$H = H_b + H_d \tag{1}$$

The total solar radiation on a panel with the tilt angle β can be expressed by using the HDKR model (Hay, Davies, Klucher, Reindl model) [26]:

$$H_T = H_{T,b} + H_{T,d} + H_{T,refl} \tag{2}$$

In particular, the direct radiation on a tilted surface $H_{T,b}$ can be calculated as follows:

$$H_{T,b} = H_b R_b \tag{3}$$

where R_b is the ratio of the direct radiation on an inclined surface to the direct radiation on a horizontal surface, which is defined in [27].

According to the modified Hay-and-Davies diffuse model [25], the diffuse radiation of a tilted surface can be expressed as:

$$H_{T,d} = H_d\left[(1-A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1+f\sin^3\left(\frac{\beta}{2}\right)\right]+A_iR_b\right] \tag{4}$$

where A_i is the isotropic index, f is the correction coefficient, and both of them can be calculated according to [25].

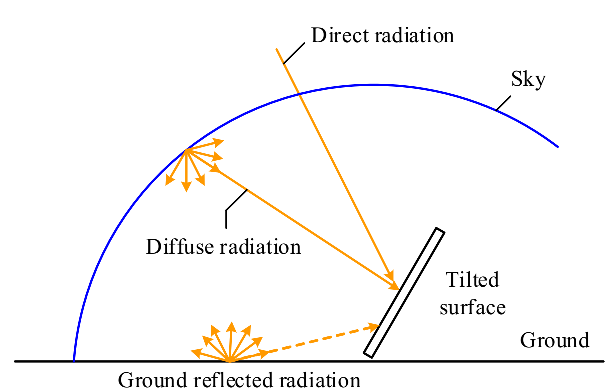

Fig. 1. Three solar radiation components [25].