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Evaluation of photovoltaic panel temperature in realistic scenarios

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ABSTRACT

Photovoltaic (PV) panel temperature was evaluated by developing theoretical models that are feasible to be used in realistic scenarios. Effects of solar irradiance, wind speed and ambient temperature on the PV panel temperature were studied. The parametric study shows significant influence of solar irradiance and wind speed on the PV panel temperature. With an increase of ambient temperature, the temperature rise of solar cells is reduced. The characteristics of panel temperature in realistic scenarios were analyzed. In steady weather conditions, the thermal response time of a solar cell with a Si thickness of 100–500 μm is around 50–250 s. While in realistic scenarios, the panel temperature variation in a day is different from that in steady weather conditions due to the effect of thermal hysteresis. The heating effect on the photovoltaic efficiency was assessed based on real-time temperature measurement of solar cells in realistic weather conditions. For solar cells with a temperature coefficient in the range of −0.21%∼−0.50%, the current field tests indicated an approximate efficiency loss between 2.9% and 9.0%.

1. Introduction

The future viability of energy supply depends on a paradigm shift away from pollution-generating non-renewable fossil fuels to renewable sources. Solar energy is an attractive option and has attracted a great attention since the last few decades, especially the last few years due to the significant price drop in photovoltaic (PV) cells. The current non-concentrator PV technologies have been developed from the first generation (e.g. monocrystalline silicon, polycrystalline silicon, and GaAs) to the second (e.g. amorphous silicon thin film, CIS/CIGS thin film, and CdTe thin film) and third generations (e.g. organic, dye-sensitized and multi-junction) [1]. A significant challenge of the solar cell technologies lies in the efficiency enhancement for converting light into electricity. A significant effort has been made for improving PV panel performance in areas such as minimizing optical losses and maximizing absorption [2–4], reducing series and shunt resistive losses [5–7], reducing surface and bulk recombination losses [8–10].

For concentrated photovoltaic (CPV) systems, various techniques have been developed for addressing the efficiency issue [11] such as using Fresnel lenses [12], parabolic dish reflectors [13], parabolic trough reflectors [14], compound parabolic concentrators [15] and central receiver systems [16]. As a result, the efficiency of CPV systems is largely improved in comparison with the non-concentrator PV systems [17]. However, the use of solar concentrators causes an uneven temperature distribution, electrical resistance and heating effect on the PV panels [18], leading to efficiency loss and longevity reduction due to properties changes of silicon layer (e.g. the long-term degradation, [19]).

The temperature influence on the performance of different PV panels is a well-known fact [20,21] and has attracted attention since the last few decades [22–24]. It has been found that heating effect varies with the panel temperature, PV materials and design parameters. The temperature coefficients of different PV modules were summarized to show the variation of the heating effect in different conditions for space applications [25].

For quantifying the heating effect on PV panels, the evaluation of panel temperatures in various weather conditions is necessary to be conducted due to its importance in identifying temperature coefficients that differ from PV materials and design of the solar cells; furthermore, the value of assessed PV panel temperature in

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the worst operating conditions is crucial for dictating the array size in the design and sizing of PV systems [26]. Numerous studies have been carried out for determining the PV panel temperature [27–31]. For example, Skoplaki and Palyvos [28] investigated the operating temperature of PV modules by developing a linear correlation of solar irradiance and PV temperature. Correlations established by different researchers were summarized and compared. Faiman [29] studied the PV module temperature by a modified Hottel–Whillier–Bliss (HWB) equation. The results agreed well with the outdoor measurements. However, the module temperatures need to be measured together with the use of the established model for deriving precise values of coefficients in the equation. Mohamed and Khatib [30] established a new equation for estimating solar cell temperature, using the ambient temperature and nominal operating cell temperature. The formula was based on the measurements of climatic parameters in certain geographic areas. Jones and Underwood [31] used the energy balance of PV cells to calculate the module temperature, where cooling strategies of short-wave radiation, long-wave radiation and convection were all considered.

In spite of the effort reported so far, the method for predicting PV temperature in different weather conditions has not been reported with details. The aim of this study is to develop theoretical models for evaluating temperature of PV panels in realistic scenarios. The characteristics of temperature variations in different weather conditions will be analyzed. The heating effect on photoelectric efficiency of solar cells will be assessed based on real-time temperature measurements in the current field tests.

2. Theoretical models

2.1. Energy-balanced model

The energy flowing chart of a PV panel is shown in Fig. 1. Q_{in} is the power of solar illumination absorbed by the solar cell, while Q_{out} represents the heat dissipation; ΔE is the increase of internal thermal energy of the solar cell. For the PV panel, the energy conservation equation can be formulated in Eq. (1):

$$Q_{in} - Q_{out} = \Delta E. \tag{1}$$

In steady conditions, the energy balance can be achieved, so Eq. (1) can be written as:

$$Q_{out} = Q_{in}. \tag{2a}$$

The heat fluxes due to different approaches for heat dissipation are considered. Specifically, q_s is the heat flux from the solar radiation; q_c and q_r are the heat fluxes dissipated by heat convection and thermal radiation, respectively; q_e represents the power flux of electrical energy converted from solar radiation; q_n denotes the heat dissipation if thermal management is applied. Therefore, the above equation can be specified as:

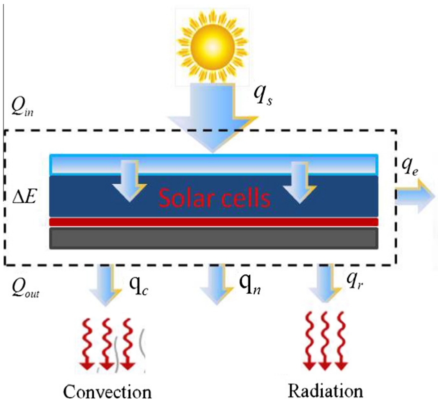

Fig. 1. Energy conservation for PV panel.

$$q_s = q_c + q_r + q_e + q_n. \tag{2b}$$

q_s and q_e can be calculated by

$$q_s = \varepsilon_0 Q_s, \tag{3}$$

and

$$q_e = \beta Q_s, \tag{4}$$

respectively. Here Q_s is the solar irradiance (W/m^2); ε_0 is the absorption rate for the solar energy; β is the photoelectric efficiency of the solar cell. The heat dissipation by convection and radiation can be expressed, respectively, by

$$q_c = 2h_c(T_s - T_a), \tag{5}$$

and

$$q_r = 2\varepsilon_1 \sigma_{sb}(T_s^4 - T_a^4), \tag{6}$$

where ε_1 is the emissivity of the solar cell for thermal radiation; T_a is the ambient temperature; T_s is the PV panel temperature; h_c is the convective heat transfer coefficient, which can be calculated as reported in [32]:

$$h_c = 2.8 + 3.8u_{wind}. \tag{7}$$

From Eqs. (2)–(6), the energy balance equation can be re-written as:

$$T_s = \frac{[(\varepsilon_0 - \beta)Q_s - 2\varepsilon_1\sigma_{sb}(T_s^4 - T_a^4) - q_n]}{2h_c} + T_a. \tag{8}$$

The convergent solution of solar panel temperature can be obtained numerically.

2.2. Unsteady-state model

The predicted panel temperature by the above model is based on the energy balance equation. The internal thermal energy of the Si layer at the bottom of the solar cells is not considered. In consideration of the effect of Si layer, the energy equation can be formulated as:

$$\rho Cp\delta \frac{dT_s}{dt} = q_s - q_e - q_c - q_r, \tag{9}$$

where ρ, Cp, δ are the density, heat capacity and thickness of the Si layer, respectively. For the first-order nonlinear non-homogeneous equation, it is difficult to obtain a solution by mathematical transformation. To simplify the analysis, heat flux ratio of thermal radiation to heat convection (α) is used for obtaining an analytical solution of the PV panel temperature. The heat flux ratio at different operating PV temperatures is evaluated, as shown in Fig. 2. It is seen that the value of the ratio in summer seasons varies from 0.578 to 0.670 as a function of the panel temperature. The average ratio is 0.62 with the maximum deviation of 8.1%. While in winter seasons, the ratio fluctuates in the range of 0.420–0.496, leading to an average ratio of 0.46 with the maximum deviation of 7.7%.

With introduction of α, Eq. (9) can be modified as:

$$\rho Cp\delta \frac{dT_s}{dt} = q_s - q_e - (1+\alpha)q_c, \tag{10}$$

where the heat flux ratio α is approximately equal to 0.62 and 0.46 in summer and winter, respectively. Therefore, the analytical solution of panel temperature can be obtained as,

$$T_s = \frac{(\varepsilon_0 - \beta)Q_s}{2(1+\alpha)h_c}\left[1 - \exp\left(-\frac{2(1+\alpha)h_c}{\rho Cp\delta}t\right)\right] + T_a. \tag{11}$$