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The error analysis of the reverse saturation current of the diode in the modeling of photovoltaic modules

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ABSTRACT

In the modeling and simulation of photovoltaic modules, especially in calculating the reverse saturation current of the diode, the series and parallel resistances are often neglected, causing certain errors. We analyzed the errors at the open circuit point, and proposed an iterative algorithm to calculate the modified values of the reverse saturation current, series resistance and parallel resistance of the diode, in order to reduce the errors. Assuming independent irradiation and temperature effects, the irradiation-dependence and the temperature-dependence of the open circuit voltage were introduced to obtain the modified formula of the open circuit voltage under any condition. Experimental results show that this modified formula has high accuracy, even at irradiance as low as 40 W/m^2. The errors of open circuit voltage were significantly reduced, indicating that this modified model is suitable for simulations of photovoltaic modules.

1. Instruction

Solar energy is a clean and renewable energy, which is considered one of the most important energy resources in the future. Photovoltaic (PV) systems convert solar energy to electrical power directly [1,2]. The worldwide PV industry has been growing very fast in the recent decade. With the constantly reducing cost of photovoltaic modules, a number of distributed and centralized photovoltaic power generation systems have been built all over the world. However, the majority of the cost of such a power generation system is still coming from the PV modules [3]. Therefore, developing an accurate PV model would be very important to help designing PV systems that can exploit solar energy more efficiently, and thus can reduce the cost of power generation.

The single-diode model and the two-diode model are often used to characterize the electrical properties of PV modules [1,3,4]. The simplest case is a current source in parallel with a diode [4], which has parameters including the diode ideality factor a, the light-generated current $I_{PV,}$ and the reverse saturation current I_o. It is often called the three-parameter model, or the ideal model. However, it is seldom used in real modeling, as it cannot simulate the behaviors of PV modules [5,6]. Taking into account the bulk resistance of the semiconductor and other series resistance, one may add a series resistance R_S into the three-factor model [4,7,8], called the four-parameter model. However, it often has serious deviation from the experimental data at high temperature and low irradiation [3,9], because it does not include the PN junction leakage current [10]. To increase the accuracy, researchers add another factor - a parallel resistance R_P – to the four-factor model [2,9,11–18], called five-factor model. All of these models don't have the recombination loss in the depletion region in consideration, so some researchers use the two-diode configuration [3,19–22], but the additional diode would introduce two more parameters and more difficulties in the calculation of the initial values, as well as a low computational efficiency [19]. Generally speaking, the five-parameter model has a good balance between accuracy and simplicity [5,6].

Various methods of extracting the parameters for the five-parameter model have been proposed by researchers. Hyvarinen et al. and Chan et al. used the device physics to develop expressions for the *I-V* curve parameters [23,24]. These parameters would be in terms of semiconductor material constants that were not provided in manufacturer's data sheet [23–25]. Methods proposed by De

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Soto et al. and Boyd et al. involved additional equations from the expressions of open circuit voltage and the short circuit temperature coefficients, along with several implicit equations to solve [15,26]. Some analytical methods for modeling have been proposed [2,27,28]. However, the data of $I-V$ curve or the reciprocal of slopes at the open circuit and short circuit points were needed, which was not easily available. An error minimization optimization analytical technique for modeling has been proposed by Silva et al. [29]. This approach needed an experimentally measured curve. Artificial intelligence algorithms for modeling have also been proposed [30–35]; nevertheless, they usually required long calculation time [3]. Practicably, the most common approach is to parameterize the PV model using information provided in manufactory datasheets [15–17,26]. The method proposed by Villalva et al. [16,17] has a good balance between the calculation time and the accuracy. It is considered very promising and highly regarded.

The iterative algorithm proposed by Villalva et al. [16,17]can efficiently extract the series and parallel resistances, but still with an error of simulation results at the open circuit point, under standard test conditions (STC), due to the series and parallel resistances being neglected during the calculation of the reverse saturation current. The errors of the calculated I_o values were not discussed [16]. To study this, we have analyzed the differences between calculated and experimental open circuit voltage values with groups of different series and parallel resistance. Then we propose an iteration algorithm to reduce the error. The open circuit voltage linearly depends on the temperature [10,36], an equation of the reverse saturation current of the diode I_o could be established. However, to obtain the open circuit voltage under any condition one still needs to solve the current-voltage characteristic equation. Assuming the effects from the irradiation and the temperature are independent to each other, we introduce both the irradiation-dependence and the temperature-dependence of the open circuit voltage to the ideal model, and thus find out the modified formula of the open circuit voltage under any condition. Using this formula, I_o under any condition can be calculated. To prove the efficiency of this algorithm, we have analyzed the experimental data of four solar cells in different environments.

2. The modeling of photovoltaic modules

2.1. The five-parameter model

This well known model consists of a voltage-dependent current source, a diode, a series resistor, and a shunt resistor. Fig. 1 shows the equivalent circuit of a PV module. The current-voltage relation is expressed in Eqn. (1)[2,9,11–18].where: I_{PV} is the light-generated current, I_D is the Shockley diode equation, I_o is the reverse saturation current of the diode, a is the diode ideality factor, k is the Boltzmann constant, q is the electron charge, T is the temperature of the p-n junction, $V_t = kNT/q$ is the thermal voltage of the diode, T is the temperature of the cell, N is number of cells in series in one module, R_s is the series resistance, and R_p is the parallel resistance.

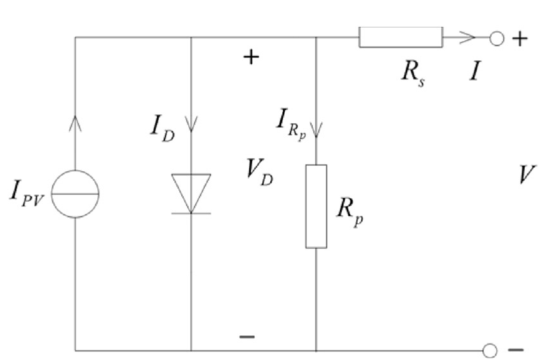

Fig. 1. Equivalent circuit of the five-parameter model.

$$I = I_{PV} - I_D - I_{R_p} = I_{PV} - I_o\left[\exp\left(\frac{V_D}{aNkT/q}\right) - 1\right] - \frac{V + IR_s}{R_p} \quad (1)$$

The equivalent series resistance includes the bulk resistance of the semiconducting material, and the contact resistances between the electrodes, the wiring, and semiconducting materials. The parallel resistance is caused by the leakage current of the p-n junction. This leakage may be from the surface current going around the solar cell, or the faults and impurities inside the materials [10].

The I-V characteristic curve of Eqn. (1) is shown in Fig. 2. There are three special points - the short circuit point $(0, I_{sc})$, the maximum power point (V_m, I_m) and the open circuit point $(V_{oc}, 0)$.

2.2. The fundamental equations of photovoltaic modules

The data provided by manufactures usually include the open circuit voltage ($V_{oc.n}$), the short circuit current ($I_{sc.n}$), the voltage ($V_{m.n}$) and the current ($I_{m.n}$) at the maximum power point, the power ($P_{m.n}$) at the maximum power point, the open circuit temperature coefficient (K_i) and the short circuit temperature coefficient (K_v). These data are always provided with reference to standard test conditions (STC). Some manufactures might also provide I-V characteristic curves at different temperatures and irradiation.

To determine the values of these parameters, the three known $I-V$ pairs at STC are substituted into Eqn. (1), resulting in Eqns. (2)–(5).

At the short circuit point: $I = I_{sc.n}$, $V = 0$

$$I_{sc.n} = I_{pv.n} - I_{o.n}\left(e^{\frac{I_{sc.n}R_{s.n}}{a_n V_t}} - 1\right) - \frac{I_{sc.n}R_{s.n}}{R_{p.n}}, \quad (2)$$

where: $I_{pv.n}$ is the light-generated current at Standard Test Conditions (STC), $I_o$is the reverse saturation current of the diode at STC,

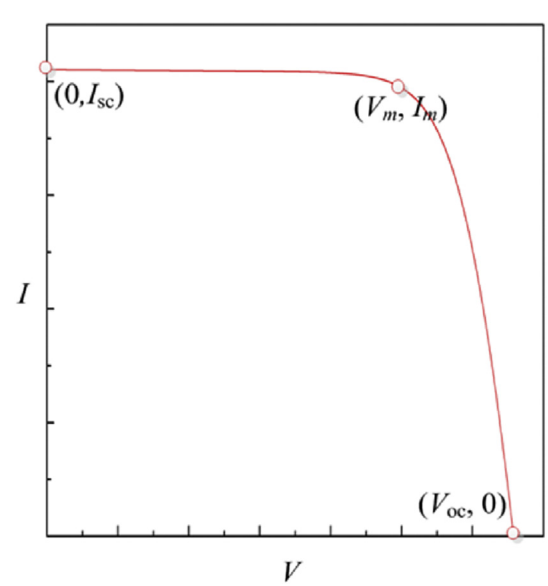

Fig. 2. Characteristic $I-V$ curve of PV modules and the three special points.