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A simplified model for photovoltaic modules based on improved translation equations

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Abstract

In this paper, a simplified single-diode model for photovoltaic (PV) modules is presented. Improved current and voltage translation equations were also deduced. Combined with conventional and improved translation equations respectively, the accuracy of two models was analyzed. Experimental results showed that two models both reveal good conformance with outdoor measured current–voltage (*I–V*) curves. And improved translation equations can make the simplified model more accurate under low irradiance levels. Data sheet provided by manufactures and the outdoor measured reference data were respectively utilized to calculate model parameters for comparison. Comparison results showed that manufacture's data sheet would cause higher deviation for proposed models. Finally, the simplified model combined with improved translation equations is recommended. This model can be programmed conveniently in MATLAB. Corresponding PV module block was also designed in Simulink and detail building procedures of the block was introduced.

Keywords: Photovoltaic (PV) module; Simplified model; Translation equations; Experimental verification

1. Introduction

With the consumption of traditional fossil fuels, people have focused on renewable energy. In recent decades, photovoltaic (PV) energy is developing rapidly and has been mainly applied in Japan, Australia, Europe, and North America. Designers and users of PV systems also attempt to evaluate the performance of PV modules or predict the energy generated by designed PV systems. Hence, many accurate mathematical models of solar cells or PV modules have been presented.

Solar cells are the basic components to convert solar radiation into electrical power. And they are connected in series or in parallel to form a PV module. Similarly, PV modules are connected to form a PV array. Thus, based on the semiconductor diode theory, the single-diode model and double-diode model for solar cells or PV modules are mostly utilized to describe the characteristic, which is also refer to the current–voltage (*I–V*) relationship (Duffie and Beckman, 2006; Masters, 2005), of solar cells or PV modules. The single-diode model has been proposed because it is simpler and has fewer parameters to calculate than double-diode model. Some researchers have presented methods to extract these parameters from data mainly provided by manufacturers (De Soto et al., 2006; Carrero et al., 2011; Villalva et al., 2009; Sera et al., 2007). For instance, De Soto et al. (2006) and Tian et al. (2012) applied the five-parameter model to describe the characteristics of different cell types. In order to solve all the five reference parameters, the nonlinear

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equation system has to be solved by Engineering Equation Solver (EES). Then the five parameters on various conditions can be derived (De Soto et al., 2006). Due to the five parameters cannot be easily calculated simultaneously, some simplified models are also presented, such as the fast convergence method. Carrero et al. (2011) used this method to solve critical parameters of the model. In this model, only three basic parameters need to be solved by iterated calculation. Villalva et al. (2009) also implemented another convergence method in the simplified single-diode model. It presented corresponding algorithm to adjust the *I–V* model. In order to solve these parameters more quickly and achieve modest accuracy, Saloux et al. (2011) and Lun (2013) tried to evade solving complicated nonlinear equation systems, so the explicit models were carried out. Nevertheless, it must be pointed out that the accuracy of these single-diode models mentioned above may deteriorate at low irradiance (Salam et al., 2010). Therefore, Salam et al. (2010) and Ishaque et al. (2011) proposed double-diode models to simulate the behavior of solar cells. Due to the double-diode model has more parameters to determine, simplified double-diode models are also investigated.

Besides, based on IEC 60891 (2009) and *I–V* translation procedure (Herrmann and Wiesner, 1996), Ding et al. (2012) applied similar translation procedure to approximately describe the *I–V* relationship of PV modules. In this model, the parallel resistance is neglected to simplify calculation. Unfortunately, in order to limit uncertainties, Herrmann and Wiesner (1996) suggested the measured (referenced) solar irradiance should be take values above 600 W/m^2. Thus the translation procedure may deteriorate under low irradiance when the *I–V* curve is extrapolated.

In this paper, a novel simplifying method is investigated for proposed model to simulate the behavior of *I–V* characteristic of PV modules. In order to build the model more conveniently and solve model parameters more quickly, three parameters were applied and corresponding extraction procedures were discussed. Due to traditional single diode model may deteriorate under low irradiance levels, the conventional translation equations were modified for proposed model to achieve better accuracy and be suitable for modeling under low irradiance conditions. Then the simplified model was combined with conventional and improved translation equations respectively for comparison. Eventually, the results of comparisons between experimental data and models' output showed good performance of proposed models to describe *I–V* characteristics for silicon PV modules. We also implemented all the derived equations in MATLAB and formed a Simulink block to simulate a PV system conveniently.

2. Modeling a PV module

2.1. I–V relationship of a PV module

According to the semiconductor theory, a solar cell is commonly modeled by the single-diode model (Duffie and Beckman, 2006). As presented in Fig.1, the equivalent circuit of an ideal PV device consists of a current source and a diode in parallel. The diode is used to describe the behavior of P–N junction of a solar cell. Besides, an equivalent series resistor and a shunt resistor is connected due to parasitic resistance or the manufacturing defects of solar cells (d'Alessandro, 2011).

Therefore, the *I–V* relationship of a solar cell can be expressed by the following equation:

$$J_{cell} = J_{ph\_cell} - J_{o\_cell}\left\{e^{\frac{q(V_{cell}+R_{s\_cell}J_{cell})}{n_{cell}KT}} - 1\right\} - \frac{V_{cell}+R_{s\_cell}J_{cell}}{R_{sh\_cell}} \tag{1}$$

V_{cell} and J_{cell} are the output voltage and current density of a solar cell under a fixed ambient condition. J_{ph_cell} is the photocurrent density, which is mainly influenced by absorbed radiation. J_{o_cell} is the reverse saturation current density of solar cell. q is the electronic charge (1.602×10^{-19} C), n_{cell} is the ideal factor of the diode, K is the Boltzman constant ($1.3806503 \times 10^{-23}$ J/K), T is cell temperature. R_s and R_{sh} are the series and shunt resistance respectively (Duffie and Beckman, 2006; Masters, 2005).

Due to a PV module is formed by connecting solar cells in series or sometimes in parallel, so the *I–V* equation can be described as (Tian et al., 2012):

$$J = N_pJ_{ph\_cell} - N_pJ_{o\_cell}\left\{e^{\frac{q\left(V+\frac{N_s}{N_p}R_{s\_cell}J\right)}{N_sn_{cell}KT}} - 1\right\} - \frac{V+\frac{N_s}{N_p}R_{s\_cell}J}{\frac{N_s}{N_p}R_{sh\_cell}} \tag{2}$$

V and J represent the output voltage and current density of a PV module. N_p and N_s are the number of solar cells in series and in parallel in a module (Tian et al., 2012). In order to express more briefly, some terms in Eq. (2) can be substituted as following equation shows:

$$J = J_{ph} - J_o\left\{e^{\frac{q(V+R_sJ)}{nKT}} - 1\right\} - \frac{V+R_sJ}{R_{sh}} \tag{3}$$

where J_{ph}, J_o, n, R_s and R_{sh} are photocurrent density, reverse saturation current density, ideal factor, series and shunt resistance for a PV module, respectively.

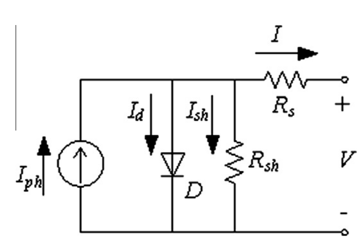

Fig. 1. Equivalent circuit of a solar cell.