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A fast modeling of the double-diode model for PV modules using combined analytical and numerical approach

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ABSTRACT

This paper proposes a fast and accurate method through utilizing combined analytical and numerical approach to determine the five parameters double diode model of photovoltaic (PV) modules. The proposed formulations are developed based on the main points given by the PV datasheets i.e., the open circuit voltage (V_{OC}), the short circuit current (I_{SC}), and the current and voltage at the maximum power point (I_M,V_M). In order to reduce computational time, some approximations and simplifications have been applied to make analytical equations and calculations simpler and manageable. In addition, a rapid and accurate iterative numerical method is proposed to determine the value of series resistance R_S. To validate its accuracy the obtained results from proposed method are compared with experimental data of PV module from different technologies: mono-crystalline, poly-crystalline and thin film. Furthermore, the effectiveness of the model is shown by comparing its accuracy and computational time, against two well-known modeling methods for double diode model. The results show that in the proposed method, in spite of computational time reduction, better precision is provided as well. It is envisaged that the proposed model can be useful for PV designers who require a fast, accurate and simple approach for modeling the PV modules.

1. Introduction

Nowadays, economic growth of countries is highly dependent on energy supplies. As a result, to reduce the usage of finite natural resources and fossil fuels which are harmful to the environment, some activities are raised worldwide in terms of technology to access clean and renewable energy sources instead. From among all renewable energy sources, solar energy is the most promising energy and photovoltaic (PV) systems provide the most direct way to convert solar energy into electrical energy by utilizing the inherent properties of semiconductors (Sheraz Khalid and Abido, 2014).

Due to high investment costs and ensuring optimized utilization of solar energy, accurate and reliable simulation for designed PV systems before installation is highly essential.

PV electrical characteristics can be modeled through representing it with equivalent electrical circuit. It is always desirable to provide a model that closely emulate the behavior of physical solar cells i.e., matches the measured *I-V* data under all operating conditions (Chin et al., 2015a). In order to describe the current-voltage relationship for PV cells/modules, two main equivalent electrical circuit models, namely the single-diode (Majdoul et al., 2015; Villalva et al., 2009; Ding et al., 2014; Cubas et al., 2014; Shongwe and Hanif, 2015; Silva et al., 2016; Park and Choi, 2015; Ayodele et al., 2016; Yildiran and Tacer, 2016; Deihimi et al., 2016) and double-diode (Ishaque et al., 2011; Gupta and et al., 2012; Hejri et al., 2014; Babu and Gurjar, 2014; Adel, 2014; Jacob et al., 2015; Muhsen and Ghazali, 2015; Chin et al., 2015b, 2016) models are widely used by various researchers, which have difference in precision and simplicity. Increasing the number of parameters in double diode model demands a significant challenge to maintain a reasonable computational time. However, due to providing more accuracy in predicting the *I-V* characteristic behavior especially under low irradiation levels conditions, it poses an attractive option in the literature (Chin et al., 2015a; Ishaque et al., 2011).

In general, there are two types of methods to extract the parameters of the solar cell/module models proposed in the literatures, namely: analytical and numerical approach (Chin et al., 2015a). Analytical solution is fast, but due to the nonlinearity and multi-variability in extracting the parameters of solar cells /modules, it is difficult to determine parameters accurately alone with analytical methods without any simplifications and assumptions in it (Majdoul et al., 2015). Therefore, recent numerical approaches use artificial intelligence techniques or the soft computing methods to determine the double diode model parameters, such as: Differential evolution (DE) Chin et al., 2015b, 2016, Artificial Immune System (AIS) Jacob et al., 2015 and

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Hybrid evolutionary algorithms (EA) Muhsen and Ghazali, 2015. However, many of these algorithms are inaccessible and difficult to use. Furthermore, these methods lead to longer computational time compared with common simple iterative numerical approaches. As mentioned above, another aspect that must be considered in double-diode model parameters extraction is about the complexity of the analytical equations. In this case, in order to make it simpler and manageable, some reasonable approximation is required. For example, in Ishaque et al. (2011) both diode saturation current values are considered equal, it contradicts the well-known fact that I_{S2} is at least two orders of magnitude greater than I_{S1} Chin et al. (2016). For double diode models, several authors have also calculated both I_{S1} and I_{S2} parameters with analytical and iterative numerical methods, which leads to complexity of equations (Hejri et al., 2014; Adel, 2014). In (Babu and Gurjar, 2014), in order to simplify the model equations, the effects of both shunt R_{SH} and series R_S resistances are neglected. Ignoring R_S greatly affects the model accuracy, particularly for the data points which are in the vicinity of the V_{OC} region Chin et al. (2016).

To simplify, several authors assumed diode ideality factors a_1 and a_2 equal to 1 and 2 respectively, based on the approximations of the Schokley–Read–Hall recombination in the depletion region in the photodiode. However, this assumption is not always true (Ishaque et al., 2011). The value of "a_1" and "a_2" is considered "1" and "larger than 1.2" respectively in Ishaque et al. (2011). It should be noted that the wrong choice of a_2 yeilds significant error in calculation of other parameters. In (Adel, 2014), the ideality factors are given as $a_1 + a_2 = 3$ for multi-crystalline and thin film solar cells and $a_1 + a_2 = 4$ for amorphous solar cell. However, these relationships do not always lead to reliable convergence and have no physical basis (Chin et al., 2016). Authors in Chin et al. (2015b, 2016) extract the double diode parameters by using Differential Evolution method (DE). It has been found that diode ideality factors a_1 and a_2 obtained from mentioned methods are reliable and give more accurate results in calculation of other parameters which lead to the model, fitting well with the *I-V* curve. Thus, the authors decided to use these values in their computational methods.

The iterative algorithm proposed by Ishaque et al. (2011) which extended the (Villalva et al., 2009) method for double diode model can efficiently extract the series and parallel resistances with a reasonable computational time, but this model is not very accurate in the proximities of the open circuit point region under standard test conditions (STC), due to ignoring the series and parallel resistances during the analytical calculation of the reverse saturation current (Wang et al., 2016). Authors in Babu and Gurjar (2014) have also used the same algorithm, but instead of determining the exclusion R_S and R_{SH}, the values of the diode ideality factors a_1 and a_2 are estimated with the similar conditions. Recently, a combined analytical and numerical method is proposed in Majdoul et al. (2015) to extract the single diode five parameters model. Its iterative numerical algorithm has excellent balance between the calculation time and the accuracy.

In this work, the authors have extended single diode method proposed in Majdoul et al. (2015) and applied it to the double-diode model. In fact, combined analytical and numerical methods have been proposed to extract the parameters of a five-parameter double-diode model of PV modules which only require coordinates of three key points of the *I-V* curves, i.e., the open circuit voltage (V_{OC}), the short circuit current (I_{SC}), and the current and voltage at the maximum power point (I_M, V_M). This method is commonly used due to the fast calculation and requires limited information of the *I-V* curve, which is usually available in datasheets (Hejri et al., 2014). Initially, all the parameters are determined analytically according to the value of the series resistance R_S. In the following, fast and simple iterative algorithm is designed to solve nonlinear equation order to extract the value of R_S. The algorithm reduces the computational time. To validate the model accuracy, the obtained results from proposed method are compared with experimental data of three different PV module technologies, i.e., mono-crystalline, poly-crystalline and thin film. Furthermore, computational

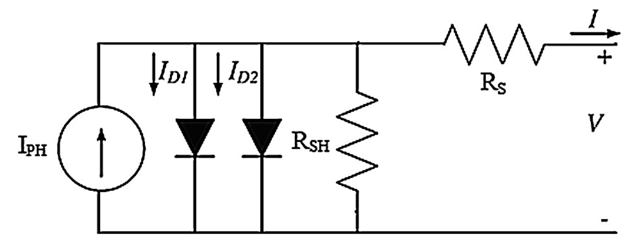

Fig. 1. Equivalent circuit for a double-diode PV model.

time and root mean square error (RMSE) are also calculated. To show the effectiveness of the proposed model, it is evaluated against the popular modeling methods for the double diode model (Ishaque et al., 2011; Babu and Gurjar, 2014).

2. Extraction of double-diode PV model parameters

2.1. Introducing the double diode PV model

Unlike the single diode model, in the double-diode model, the effect of recombination current losses within depletion region is considered which leads to further improvement in the accuracy (Chin et al., 2015a). The double diode equivalent circuit model is shown in Fig. 1. It is comprised of a current source connected in parallel with two diodes. Additionally, along with parallel and series resistances, two diodes were used in this model; one relates to the diffusion process and the other one associates with the carrier recombination in space-charge region of the junction. Series resistance R_S represents the internal resistive losses and shunt resistance R_{SH} corresponds to the leakage current in the p-n junction and its magnitude varies according to different fabrication methods (Chin et al., 2015a).

Using Kirchhoff's current law, the *I-V* equation or the output current of a PV module, shown in Fig. 1, can be written as:

$$I = I_{PH} - I_{S1}\left[\exp\left(\frac{V + R_S I}{a_1 N_S V_{T1}}\right) - 1\right] - I_{S2}\left[\exp\left(\frac{V + R_S I}{a_2 N_S V_{T2}}\right) - 1\right] - \left(\frac{V + R_S I}{R_{SH}}\right) \tag{1}$$

where I_{PH} is the current generated by the incidence of light, I_{S1} and I_{S2} are the reverse saturation currents of diode 1 and diode 2, respectively, $V_{T1,2}$ are the thermal voltage of the PV module and is given by (kT/q), N_s is the number of cells connected in series, q is the electron charge (1.602×10^{-19} C), k is the Boltzmann constant (1.38×10^{-23} J/K), T is the temperature of the p−n junction in Kelvin. Variables a_1 and a_2 represent the ideality factor of diode 1 and diode 2.

In order to utilize double-diode model, values of circuit's elements should be determined. As mentioned before, double-diode model requires calculating seven parameters, i.e. I_{PH}, I_{S1}, I_{S2}, R_{SH}, R_S, a_1 and a_2. In order to make the double-diode model analytically manageable, seven unknown parameters of this model are reduced to five parameters: I_{PH}, I_{S1}, I_{S2}, R_{SH} and R_S. Values of these five parameters can be calculated using analytical relationships and the proposed numerical algorithm. Diode ideality factors values a_1 and a_2 are assumed to be constant and the values stated in the literature (Chin et al., 2015b, 2016) are used.

Common approach to calculate parameters is to estimate their values using information available in manufacturer's datasheet. Equations are obtained from three operational point conditions of the $I-V$ curve, i.e., Short-circuit point where $V = 0, I = I_{SC}$, Open circuit point where $V = V_{OC}, I = 0$ and Maximum power point where $V = V_M, I = I_M$. This information is always availabled at standard test conditions (STC) of temperature and solar irradiation. STC means radiation level is 1000 W/m^2, with a module temperature of 25 °C (298 °K) and air mass of AM1.5 spectrum (Villalva et al., 2009).

Authors, in Majdoul et al. (2015), proposed combined analytical