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An accurate modelling of the two-diode model of PV module using a hybrid solution based on differential evolution

Vun Jack Chin [a,b], Zainal Salam [a,b,*], Kashif Ishaque [c]

[a] Centre of Electrical Energy Systems, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia
[b] Institute of Future Energy, Universiti Teknologi Malaysia, Johor Bahru, Malaysia
[c] Department of Electrical Engineering, Mohammad Ali Jinnah University, Karachi, Pakistan

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ABSTRACT

This paper proposes an accurate computational technique for the two-diode model of PV module. Unlike previous methods, it does not rely on assumptions that cause the accuracy to be compromised. The key to this improvement is the implementation of a hybrid solution, i.e. by incorporating the analytical method with the differential evolution (DE) optimization technique. Three parameters, i.e. I_{PV}, I_{o1}, and R_p are computed analytically, while the remaining, a_1, a_2, I_{o2} and R_s are optimized using the DE. To validate its accuracy, the proposed method is tested on three PV modules of different technologies: mono-crystalline, poly-crystalline and thin film. Furthermore, its performance is evaluated against two popular computational methods for the two-diode model. The proposed method is found to exhibit superior accuracy for the variation in irradiance and temperature for all module types. In particular, the improvement in accuracy is evident at low irradiance conditions; the root-mean-square error is one order of magnitude lower than that of the other methods. In addition, the values of the model parameters are consistent with the physics of PV cell. It is envisaged that the method can be very useful for PV simulation, in which accuracy of the model is of prime concern.

1. Introduction

The two-diode (electrical circuit) model of the photovoltaic (PV) cell/module is fast becoming a viable alternative to the highly popular single-diode model for PV simulation. This can be attributed to its superiority in predicting the *I-V* characteristics over a wide range of irradiance (G) and temperature (T) variations [1–3]. The shape and amplitude of the *I-V* curve, in turn, depends on the values of the model parameters. These parameters can be calculated using several key information which are commonly available from the datasheet, namely the open circuit voltage (V_{OC}), the short circuit current (I_{SC}), the voltage and current at maximum power point (MPP) (V_{MPP}, I_{MPP}) and the temperature coefficients—which are published at the standard test condition (STC[1]). However, in real set-up, the PV systems do not operate at STC; for a considerable amount of time they are subjected to much lower irradiance and higher temperature [4–6]. Thus a precise and robust estimation of the parameters is required to ensure that the output of the PV system is correctly predicted under all possible environmental variations [7,8].

The parameters of the two-diode model can be calculated using two approaches, namely the analytical solution and soft computing algorithms [10]. The former is based on the algebraic manipulation; normally, it involves numerical iteration such as the Newton-Raphson. Computing-wise, the analytical method is fast. However, due to the complexity of the two-diode model (which requires the solving of seven parameters), only several papers are reported to go along this approach [1,9,11,12]. In most cases, some sort of approximations are needed to ensure the model is analytically manageable. As a result, the accuracy of the solution is compromised.

For example, authors in [1] assume the values of both saturation currents are equal ($I_{o1} = I_{o2}$), while the second diode ideality factor (a_2) is arbitrarily assigned to be larger than 1.2. These simplifications contradict the well-known fact that I_{o2} is at least two orders of magnitude greater than I_{o1} [13]. Thus, equating the two currents does not make any physical sense. Moreover, a wrong choice of a_2 may result in considerable error in the computation of other parameters. In another work [9], the effects of both series

* Corresponding author at: Centre of Electrical Energy Systems, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia. Tel.: +60 7 5536187; fax: +60 7 5566272.
E-mail addresses: chinvunjack89@hotmail.com (V.J. Chin), zainals@fke.utm.my (Z. Salam), kashif.ishaque@jinnah.edu (K. Ishaque).

[1] STC: solar irradiance is fixed at 1000 W/m^2 and temperature is at 25 °C.

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(R_s) and shunt (R_p) resistances are omitted, in order to simplify the model equation. The exclusion of R_s greatly affects the model accuracy, particularly for the data points which are in the vicinity of the V_{OC} region. In [11], the authors assume $a_1 + a_2 = 3$ for the polycrystalline and thin film, and $a_1 + a_2 = 4$ for amorphous cell. However, these relationships have no physical basis and are not always reliable [14]. Besides these works, other analytical methods for the two-diode model can be found in [12,15,16]. Nonetheless, these techniques introduce many new coefficients, which results in unnecessarily tedious computations. Furthermore, the algorithms are sensitive to the choice of the initial values. More often than not, the solutions converge to local optima and in some cases, inappropriate initial conditions lead to non-convergence [12,17].

Recently, the soft computing approach—in particular the evolutionary algorithm, has gained significant interest in PV modelling [17–25]. This is due to its versatile global search capability and its effectiveness in handling non-linear functions [26,27]. Furthermore, due to its non-derivative nature, a proper selection of the initial condition is not required. Despite these notable potential, there has been an absence of reliable work employing the evolutionary algorithm for the two-diode model. Although the artificial immune system technique is proposed in [28], the paper contains several issues that seem to be unresolved. First, the equation to calculate the I_{MPP} results in $I_{MPP} = 0$ at STC, which is clearly erroneous. Besides, the saturation current of the first diode (I_{o1}) is computed to be much greater than that of the second diode (I_{o2}). This is not possible, as in actual cell, it is known to be otherwise [13]. Furthermore, the computations of certain variables are not clearly explained; for example the procedures to determine the values of α and β (coefficients introduced for the computation of V_{OC} and V_{MPP}) are not clarified; hence the work in [28] cannot be repeated.

Recently, several authors have shown that another evolutionary technique, known as the differential evolution (DE) is effective in extracting the parameters of the PV module [14,17,29,30]. This can be attributed to its remarkable ability in locating global optimum and fast convergence with a low number of control parameters. However, the DE-based modelling method has only been proposed for the single-diode model [17]. The existing DE works on the two-diode model are mainly focused on the curve-fitting of *I-V* curves at a specific *G* and *T* [21,29,31]. They are not meant to be used as the computational engine for the PV simulator due to its slow execution and inability to predict the module performance at other environmental conditions.

In light of the preceding discussions, this paper proposes a computational method for the two-diode model using the combination (hybrid) of DE and analytical approach. As discussed earlier, the analytical methods rely on certain assumptions to simplify the computation. This is due to the insufficient number of equations that can be formulated from the physical characteristic of the cell. Although the simplifications allow for the parameters to be directly computed with respect to *G* and *T*, the accuracy is compromised. On the other hand, DE (by itself) is only capable of optimizing the parameters based on a certain fitness function. Without the analytical equations, it could not predict the output for varying *G* and *T*. Thus, the application of DE in conjunction with the analytical method allows the parameters to be computed based on the physical equations, while DE optimizes them to achieve the best possible values. Furthermore, the proposed algorithm only requires the standard datasheet information, i.e. V_{OC}, I_{SC}, V_{MPP}, I_{MPP} and temperature coefficients; consequently, it is more practical for PV simulation applications. At the same time, it avoids the costly assumptions that may affect the model accuracy.

To verify its performance, the method is applied to PV modules of three different technologies, i.e. poly-crystalline, mono-crystalline and thin-film. In addition, its accuracy is evaluated against the popular modelling methods for the two-diode model [1,9].

2. The two-diode PV model

The two-diode model of the PV module is depicted in Fig. 1. Note that a PV module is a collection of PV cells with identical characteristics, connected in series to achieve specific voltage and power levels [15]. Using Kirchhoff's current law, the output current of a PV module can be written as

$$I = I_{PV} - I_{o1}\left(e^{\frac{V+IR_s}{N_s a_1 V_t}} - 1\right) - I_{o2}\left(e^{\frac{V+IR_s}{N_s a_2 V_t}} - 1\right) - \frac{V + IR_s}{R_p} \quad (1)$$

where I_{PV} is the photocurrent, while I_{o1} and I_{o2} are the saturation current of the first and the second diode, respectively. Variable N_s represents the number of cells in series, V_t (=kT/q) is the thermal voltage for PV cell, k is the Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K), T is temperature in Kelvin (K), and q is the electron charge ($1.60217646 \times 10^{-19}$ C). The diode ideality factors of the first and the second diodes are denoted by a_1 and a_2, respectively. In all, there are seven parameters to be determined simultaneously: I_{PV}, I_{o1}, I_{o2}, a_1, a_2, R_s, and R_p. These parameters, when used along with the datasheet information, determine the characteristics of the *I-V* curve. Thus, the objective of modelling work is to ensure that the *I-V* curve obtained using the computed parameters fits well with the curve provided by the manufacturer of the module. Nonetheless, it is important to note that (1) is only applicable for cases where the number of series connected cells in inside the module, i.e. N_s is known. In the case where N_s is indeterminable or the cells interconnection are not in series (for example, custom-made modules that configures the cells in compound connections), the modelling should be done at cell level, i.e. to treat every PV cell as a basic unit.

3. Differential evolution (DE)

DE is among the most powerful stochastic, real-parameter optimization algorithm currently in use [32]. The algorithm is known for its three main advantages: (1) the ability to locate the global optimum regardless of the initial parameter values, (2) rapid convergence rate and (3) utilization of few control parameters [14]. The working principle of DE is similar to that of the genetic algorithm (GA). However, in contrast to GA—which relies mainly on crossover operation to diversify the population, DE utilizes mutation as the key mechanism to explore prospective regions in the search space. It refines the population of random candidate solutions through the generations of mutation, crossover and selection operations. Usually a satisfactory fitness value i.e. value-to-reach (*VTR*), or a maximum number of generations ($Gen_{\max}$) is used as the stopping condition for the algorithm.

3.1. Initialization

DE starts by defining a population size (*NP*) of *D*-dimensional real-valued vectors: $X_{i,Gen} = [X_{1,i,Gen}, X_{2,i,Gen}, \ldots, X_{j,i,Gen}, \ldots, X_{D,i,Gen}]$,

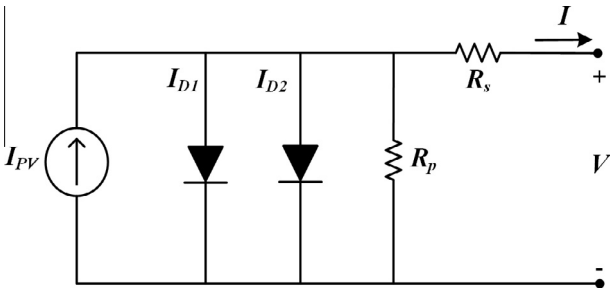

Fig. 1. The two-diode circuit model for PV module.