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An iterative approach for modeling photovoltaic modules without implicit equations

Gang Wang [a], Ke Zhao [b], Jiangtao Shi [c], Wei Chen [a], Haiyang Zhang [a], Xinsheng Yang [a,*], Yong Zhao [a]

[a] Key Laboratory of Magnetic Levitation Technologies and Maglev Trains (Ministry of Education), School of Electrical Engineering, Superconductivity and New Energy R&D Center, Mail Stop 165#, Southwest Jiaotong University, Chengdu 610031, China

[b] School of Physical Science and Technology, Southwest Jiaotong University, Chengdu 610031, China

[c] Key Laboratory of Advanced Technology of Materials (Ministry of Education), Superconductivity and New Energy R&D Center, Southwest Jiaotong University, Chengdu 610031, China

HIGHLIGHTS

- A method for modeling PV modules without using implicit equation is proposed.
- The modeling time of our method is almost as fast as analytical methods.
- The result show our proposed method have high accurate.
- The proposed method is a simply way no need powerful mathematical tools.
- The proposed method use only data from the manufacturer datasheet.

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ABSTRACT

The most widely used five-parameter model for photovoltaic (PV) modules has good balance between the accuracy and computing efficiency. However, the existing modeling methods that have high accuracy require solving implicit equations of voltage and current, greatly increasing the complexity of the modeling. In this work, we propose a novel iterative method that has no implicit equation to deal with. This method can extract the parameters directly from manufacturer's datasheet, with only one point calculated for each step of iteration. By testing three different types of PV modules, the proposed method is proved to be both accurate and time-efficient, compared with some well-known modeling methods.

1. Instruction

Photovoltaic (PV) system is the primary method to convert solar energy to electrical power [1,2]. The constantly reducing cost of photovoltaic modules has greatly boosted worldwide PV industry [3]. The majority of the cost of such a power generation system, however, is still coming from the PV modules [4]. Therefore, designing PV modules that can run efficiently is crucial for reducing the cost of power generation. As a result, PV model that can accurately predict the output of each PV module would be very important for designing such efficient PV systems. For example, a good PV model can find the optimal array of PV modules [5], and it can help test the performances of the Maximum Power Point Tracking (MPPT) algorithms [6,7] and anti-islanding techniques [8] used for PV systems. PV models are also important in analyzing the effect of PV system for grid stability [9].

The three-parameter model [10] that has the diode ideality factor a, the light-generated current I_{pv}, and the reverse saturation current I_o as model parameters, and the four-parameter model [11,12] that has an additional parameter of the series resistance R_s were used in PV modeling. To improve the accuracy at high temperatures or low irradiations [4,13], a parallel resistance R_p has been added, making a five-parameter model [14]. All of these models don't have the recombination loss in the depletion region in consideration, so the two-diode configuration has been used by some researchers [4,15,16]. The additional diode, however, would introduce two more parameters and more difficulties in the calculation of the initial values [17], as well as a low computational efficiency [18]. A comprehensive review and comparative assessment of such methods can be found in Refs. [19–21]. Generally speaking,

* Corresponding author.
E-mail address: xsyang@swjtu.edu.cn (X. Yang).

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Nomenclature

STC	standard test conditions
K	Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K)
q	electron charge ($1.60217646 \times 10^{-19}$ C)
T	temperature of the cell (K)
T_n	temperature of the cell at STC: 298.15 K (K)
N	number of cells in series in one module
G	surface irradiance of the cell (W/m^2)
G_n	surface irradiance of the cell at STC:1000 W/m^2 (W/m^2)
K_i	short circuit current temperature coefficient (A/°C)
K_v	open circuit voltage temperature coefficient (V/°C)
a	diode ideality factor
a_n	diode ideality factor at STC
$V_t = kNT/q$	thermal voltage of the diode
$V_{t.n} = kN\,T_n/q$	thermal voltage of the diode at STC
I_o	reverse saturation current (A)
$I_{o.n}$	reverse saturation current at STC (A)
I_{pv}	light-generated current (A)
$I_{pv.n}$	light-generated current at STC (A)
I_D	Shockley diode equation (A)
R_s	series resistance (Ω)
$R_{s.n}$	series resistance at STC (Ω)
$R_{s.nr}$	upper limit of $R_{s.n}$ (Ω)
R_p	parallel resistance (Ω)
$R_{p.n}$	parallel resistance at STC (Ω)
V_{oc}	open circuit voltage (V)
$V_{oc.n}$	open circuit voltage at STC (V)
I_{sc}	short circuit current (A)
$I_{sc.n}$	short circuit current at STC (A)
V_m	maximum power voltage (V)
$V_{m.n}$	maximum power voltage at STC (V)
I_m	maximum power current (A)
$I_{m.n}$	maximum power current at STC (A)
P_m	maximum power (W)
$P_{m.n}$	maximum power at STC (W)
MPPT	Maximum Power Point Tracking
RMSE	root-mean-square error

the five-parameter model has a good balance between accuracy and efficiency [19,20,22,23].

The main challenge for the five-parameter model is how to extract the model parameters, as this model has an implicit equation [24,25]. In most cases, the model parameters of PV modules need to be acquired experimentally [26], or from the data sheet provided by manufacturers [27]. Parameters in *I-V* curve in terms of semiconducting material constants could be calculated by equations presented by Hyvarinen et al. and Chan et al. [26,28]. Various methods have been proposed to extract the parameters for the five-parameter model at the standard test conditions (STC). The main types of these methods include solving implicit equations, analytical methods, iterative methods and artificial intelligence algorithms.

Some methods extract the parameters through a system of implicit equations. De Soto et al. [29] and Boyd et al. [30] proposed methods that have additional equations from the expressions of open circuit voltage and the short circuit temperature coefficients, as well as several implicit equations to solve. Batzelis et al. [24] considered that the method provided by De Soto et al. [29] was a representative method. It was even considered a milestone in this area [16]. Chan et al. [28] proposed a method that had additional equations involving the derivative of the current with respect to the voltage at the short circuit current point and open circuit voltage point. Usually powerful mathematical tools were required to solve the implicit equations [2,31].

An analytical method proposed by Peng et al. [32] and Ghani et al. [33] used Lambert W function to extract the model parameters. The Lambert W function, however, did not have an explicit solution, and its solving was not straight forward as it required nontrivial calculations [34]. Other analytical methods were also proposed [2,35,36], but they still needed the data of *I-V* curves or the reciprocal of slopes at special points. Some analytical methods used approximate techniques to estimate the model in an explicit manner, however, the model accuracy was reduced [24,37].

An iterative method proposed by Brano et al. [31] had no complex implicit equations to solve. This method, however, still required the derivative of the current with respect to the voltage at the short circuit current point and open circuit voltage point which were not easily available from the manufacturer's data [2]. Another iterative method proposed by Villalva et al. [38,39] only needed to solve one implicit equation instead of a system of implicit equations. Also Villalva et al. [38,39] introduced an equation to modify the diode saturation current by using only the manufacturer's datasheet. This method was considered to have a good balance between the calculation time and the accuracy [27]. Due to the step of increasing R_s being fixed, the iterative algorithm proposed by Villalva et al. [38,39] may fail to converge when the tolerances band was not suitable.

Recently, artificial intelligence algorithms such as artificial neural network [40,41], genetic algorithm [42], artificial bee swarm [43], bacterial foraging algorithm [44] and artificial bee colony [45] have been reported to obtain model parameters accurately. The disadvantage was long calculation time [4].

Overall, solving the system of implicit equations needs powerful mathematical tools [2], and also brings calculation problems such as unpredictable errors, more computation tasks or difficulty in attaining convergence [2]. Analytical method can decrease computational time, however, the model accuracy was reduced [24,37] and requires non-easily available data [2]. Artificial intelligence algorithms have high accuracy, but require long calculation time. Iterative methods reduce the computing difficulty compared with implicit equation solver methods, and increase the accuracy compared with analytical methods. Generally speaking, iterative methods are most promising in engineering application. We should use the method proposed by Villalva et al. [38,39] as a reference to evaluate other methods, as it has been widely used. All the previously reported high-accuracy modeling methods for the five-parameter models have implicit equations to solve.

In this paper, we propose an iterative method to extract the model parameters of the five-parameter model. The proposed method not only simplifies the calculation procedures, but also improves the accuracy. The key feature of this method is that the equations used for extracting parameters are all explicit. Without implicit equations to deal with, the proposed method is simple with much less computation. The maximum value of the series resistance can be obtained directly without iteration. In addition, the amount of calculation can be further reduced by a straight-line approximation. By comparing the calculated results and the experimental data of a monocrystalline silicon PV module, two polycrystalline PV modules and a thin film PV module, the validity and efficiency of this new method will be proven.