Numerical approach for extraction of photovoltaic generator single-diode model parameters

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Abstract

In this work, a numerical approach has been proposed to estimate the five single-diode circuit model physical parameters of photovoltaic generators from their experimental current-voltage characteristics. Linear least square method has been used to solve the system of three linear equations to express the shunt resistance, the saturation current and the photocurrent as a function of the series resistance and the ideality factor. Two key points have been used to solve the system of two nonlinear equations to extract values of series resistance and ideality factor. The advantage of the proposed method with respect of existing numerical techniques is that use only two key points of the experimental characteristic and need only two initial guesses and does not use any approximation. To evaluate the proposed method, three PV generators data have been used to compare the experimental and the theoretical curves. The application of the proposed method provides a good agreement with the experimental.

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1. INTRODUCTION

The photovoltaic (PV) generator is the basic element of the photovoltaic system. This element is made of semiconductor material with a p-n junction which has the property of, when exposed to sunlight, producing direct current electricity proportional to the solar irradiation. The behavior of PV generator has a non-linear current-voltage (I-V) characteristic. Various representations have been employed to describe the current-voltage (I-V) relationship in solar cells. In practice, the single diode model is the commonly equivalent circuit used to describe the I-V relationship. However, regardless of this model, there are important PV parameters that must be accurate and extracted for the simulation, design, performance, evaluation and control of PV systems. The five main parameters that describe the behavior of PV generator models are the generated photocurrent (I_ph), the saturation current (I_0), the series resistance (R_s), shunt resistance or parallel resistance (R_p) and the diode ideality factor (n). The electric current produced by a solar cell depends on the intensity of the incident light and its properties.

Several methods have been suggested in the literature to extract the five parameters. We can divide these methods into three categories: analytical, numerical and evolutionary methods [1]-[22]. Maouhoub has proposed an analytical method to determine the five physical parameters [15]. The key points have been used
to calculate the series resistance and the ideality factor. The linear least square technique has been used to
determine to parallel resistance, the photo current and the saturation current. Ghani et al. [16] provided a
numerical method to extract the values of the series and shunt resistors using the Newton-Raphson algorithm
and the Lambert W-function. A singularity problem, which is divided by zero, can occur if the initial conditions
of the parameters are incorrectly chosen. Moreover, these methods require many assumptions to simplify the
problem of extracting the five parameters. Zhang et al. [17] proposes a simple and efficient numerical method
for extracting all the parameters of a solar cell from a single current-voltage (I-V) curve under constant
illumination by reducing the parameters to three. The disadvantage of this approach is that it allows several
simplifications by eliminating terms of the analytical equation of current (I-V). Hejri et al. [18] proposed a
numerical procedure using three key points from manufacturer’s data sheets and by solving a system of four
nonlinear equations; this method needs four suitable initial guesses. Recently, Stornelli et al. [19] proposed a
new simplified method for the iterative estimation of the five PV module parameters. This method uses some
approximations to determine the values of $R_s$ and $n$. Yadir et al. [20] proposed another numerical method based
on key points and solving a system of four nonlinear equations. El Achouby et al [21] proposed numerical
method to extract the five physical parameters, operating at standard test conditions (STC). This method is
based on the variation of the ideality factor and solving a system of four nonlinear equations. The problem of
this iterative method is that needs suitable initial values of four physical parameters.

In the present work, we propose a numerical approach to extract the five physical parameters based
on the single diode model. In a first step, we formulate three analytical expressions of the parallel resistance
$R_p$, the photocurrent $I_p$ and the saturation current $I_0$ using the linear least square method. These three
expressions depend on the diode ideality factor $n$ and the series resistance $R_s$. Then, we extract these two
parameters numerically by solving a nonlinear system of two transcendental equations at two key points, namely,
short circuit point and maximum power point. The proposed method has the advantage of other methods
of employing only two key points of the experimental I-V curve and only two initial guesses and does not use
any approximation and any computing of the slope at open-circuit voltage or at short-circuit current. To check
the precision of our method, we extract the five physical parameters of the commercial RTC PV cell, the
PWP201 PV module and the KC200GT PV module and we compare the theoretical current-voltage curve with
the experimental one. We organize our paper into four sections. After an introduction, we present in the second
section the one-diode equivalent circuit model and the proposed five-parameter extraction methods. In the third
section, we use three photovoltaic generators experimental data to validate our proposed method and to
compare with other methods; we evaluate the accuracy of the presented method by calculating the absolute
error and the root mean square error. Finally, we close our paper with a conclusion.

2. PROPOSED METHOD
2.1. Single diode model

In our study, we use the equivalent single diode circuit model to describe the behavior of the
photovoltaic generator. This circuit is illustrated in the Figure 1.

![Figure 1. Electrical circuit for single diode PV model](image)

The output current of the PV generator, with five parameters, is a function of the output voltage:

$$I = I_{ph} - I_0 \left( \exp \left( \frac{V + R_s I}{nV_t} \right) - 1 \right) - \frac{V + R_s I}{R_p}$$

(1)
The five parameters of this model are: the shunt resistance $R_p$, the saturation current $I_0$, the photo-current $I_{ph}$, the ideality factor $n$ and the series resistance $R_s$. 

- $N_s$ is the number of cells in series in the PV module ($N_s = 1$ for one solar cell),
- $V_{th} = kT/q$ is the thermal voltage,
- $q$ is the electronic charge,
- $k_B$ is the Boltzman's constant
- $T$ is the temperature in Kelvin.

This (1) is a nonlinear transcendent equation. We can write the current $I = f (V)$ by introducing the Lambert (2).

$$I = \frac{I_0 + I_{ph}}{1 + R_p G_p} - \frac{G_p}{1 + R_s G_p} V - \frac{nV_{th}}{R_s} LambertW \left( \frac{l_0 R_p}{n V_{th} (1 + R_s G_p)} \right) \exp \left( \frac{V + R_s (l_0 + I_{ph})}{n V_{th} (1 + R_s G_p)} \right)$$

(2)

### 2.2. Proposed five parameters estimation method

#### 2.2.1. Analytical expressions of $I_0$, $I_{ph}$ and $R_p$

According to our previous works [11, 15], we rewrite the (1) as (3).

$$I_i = I_{ph} - I_0 A_i - G_p B_i$$

(3)

where

$$A_i = \exp \left( \frac{V_{l,m} + R_p l_{1,m}}{n N \ V_{th}} \right) - 1$$

$$B_i = V_{l,m} + R_p l_{1,m}$$

(4)

$V_{l,m}$ is the measured voltage of the PV generator and $N$ is the number of measured points. In order to formulate the analytical expression of $I_{ph}$, $I_0$ and $R_p$, we use the linear least squares method based on minimizing the following objective (5).

$$S = \sum_{i=1}^{N} (I_i - I_{l,m})^2$$

(5)

$I_{l,m}$ is the measured current of the PV generator and $I_{l}$ is the theoretical current given in the (1). After application of this method, we formulate the following linear system of three equations [15]:

$$\begin{align*}
I_p N - I_0 & = \sum_{i=1}^{N} A_i - G_p \sum_{i=1}^{N} B_i = \sum_{i=1}^{N} I_{l,exp} \\
- I_p & = \sum_{i=1}^{N} A_i + I_0 \sum_{i=1}^{N} A_i^2 + G_p \sum_{i=1}^{N} B_i A_i = - \sum_{i=1}^{N} I_{l,exp} A_i \\
- I_p & = \sum_{i=1}^{N} B_i + I_0 \sum_{i=1}^{N} B_i A_i + G_p \sum_{i=1}^{N} B_i^2 = - \sum_{i=1}^{N} I_{l,exp} B_i
\end{align*}$$

(6)

Where $G_p = 1 / R_p$

The solution of the previous system, provides three analytical expressions of $I_{ph}$ ($n$, $R_s$), $I_0$ ($n$, $R_s$) and $R_p$ ($n$, $R_s$) as a function of ideality factor $n$ and series resistance $R_s$.

#### 2.2.2. Numerical extraction of $n$ and $R_s$

In order to extract the series resistance $R_s$ and the ideality factor $n$, we use two transcendent equations. By setting $(V, I) = (V_{mpp}, I_{mpp})$ using (1), we establish a first transcendent equation linking maximum power point to two physical model parameters.

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\[ RMSE = \left( \frac{1}{N} \sum_{i=1}^{N} (I_i - I_{i,m})^2 \right)^{1/2} \]  
(9)

\[ AE = |I_i - I_{i,m}| \]  
(10)

The Table 1 shows the physical characteristics extracted from the experimental I-V curve of the three photovoltaic generators RTC France at 33 °C, PWP201 at 45 °C and KC200GT at STC. The experimental I-V curves of these two cases are extracted from [1]. For the KC200GT panel, the experimental I-V data are extracted from the datasheet [23] under standard STC test conditions (irradiation level 1000 W /m², AM spectrum 1.5 and cell temperature 25 °C).

| Parameter                  | RTC (33 °C) | PWP201 (45 °C) | KC200GT (STC) |
|----------------------------|-------------|----------------|---------------|
| Vmpp (V)                   | 0.4590      | 12.6490        | 27.11         |
| Impp (A)                   | 0.6755      | 0.9120         | 7.59          |
| Voc (V)                    | 0.5727      | 16.7785        | 33.07         |
| Isc (A)                    | 0.7605      | 1.0317         | 8.21          |
| Ns                         | 1           | 36             | 54            |
| K_i (mA/°C)                | -           | -              | 3.18          |
| K_v (mV/°C)                | -           | -              | -123          |

3.1. Case study 1: RTC solar cell

Referring to the numerical method proposed previously, using the data listed in Table 1, we extract the values of the five parameters for the RTC France solar cell. The values, thus obtained in comparison with other proposed numerical approaches [8], [17], [20] are summarized in Table 2. As can be seen, the approach proposed provides a minimum value of (RMSE). The presented method has the advantage of using only two initial guesses, reducing the research space to the two unknown parameters and does not use any approximation and any computing of the slope at open-circuit voltage or at short-circuit current compared to other methods that use four or five initial guesses. Several of these methods determine the values of the slope at open-circuit voltage or at short-circuit current with many approximations.

| Method       | n [µA] | Iph (A) | Rs (Ω) | Rp (Ω) | RMSE         |
|--------------|--------|---------|--------|--------|--------------|
| Proposed     | 1.4877 | 0.3477  | 0.7611 | 0.0349 | 42.9764      | 1.4938E-3  |
| Yadir        | 1.4905 | 0.3514  | 0.7611 | 0.0355 | 45.0472      | 1.5555E-3  |
| Zhang        | 1.48   | 0.3267  | 0.7607 | 0.036  | 60.24        | 2.0135E-3  |
| Cannizzaro   | 1.4899 | 0.3604  | 0.7611 | 0.0355 | 44.8997      | 6.3813E-3  |

Figure 3 shows the experimental characteristic I-V and the theoretical curve using the five estimated parameters, for RTC France solar cell. Theoretical curves are determined using the (2) and using the five extracted parameters. As it can be ascertained, the theoretical curves are in very agreement with the experimental measurement. Figure 4 shows the plot of the absolute error for RTC France solar cell compared with different methods. It is distinctly indicated that the proposed method in this work has a small error. The absolute error does not exceed 0.003 A.
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3.3. Case study 3: KC200GT PV module

The values achieved by this method for KC200GT module are summarized in Table 4. The extracted values are compared with those of other research authors [15], [18], [19]. In Figure 7, we display the absolute error curve for the KC200GT module in relation to the several comparison methods. The proposed method has a very low error value and the absolute error does not exceed 0.1 A.

Table 4. Comparison of the different methods for the KC200GT module in STC

| Method   | n (µA) | Iph (A) | Rs (Ω) | Rp (Ω) | RMSE |
|----------|--------|---------|--------|--------|------|
| Proposed | 1.089  | 2.56    | 8.225  | 0.229  | 128.96 |
| Maouhoub | 1.0758 | 2.12    | 8.196  | 0.233  | 132.88 |
| Stornelli | 1.1    | 3.27    | 8.196  | 0.2185 | 164.2 |
| Hejri    | 1.34   | 171     | 8.21   | 0.220  | 951.93 |

To study the effect of temperature T and irradiance level G on the I-V characteristic, we suppose that the influence of the temperature and irradiation on n, Rs and Rp are negligible [15]. The other two parameters Iph and I0 are given by (11) and (12).

\[
I_{ph}(T,G) = \frac{G}{G_{STC}} \left( I_{ph,STC} + K_i (T - T_{STC}) \right) \tag{11}
\]

\[
I_0(T,G) = \frac{I_{ph}(T,G) - G_p V_{oc}(T,G)}{\exp \left( \frac{V_{oc}(T,G)}{N_v n V_{th}(T)} \right) - 1} \tag{12}
\]

![Figure 7. Plot of absolute error vs. voltage for KC200GT at STC](image)

Where \( I_{ph,STC} \) is the photo-current in STC conditions, \( G_{STC} \) is the global irradiation under STC conditions (\( G_{STC} = 1000 \text{ W/m}^2 \)), \( T_{STC} \) is the temperature under STC conditions (\( T_{STC} = 25 \text{ °C} \)) and \( K_i \) is the temperature coefficient of \( I_{ph} \). The temperature and irradiation dependence of \( V_{oc} \) is given by (13).

\[
V_{oc}(T,G) = V_{oc,STC} + K_o (T - T_{STC}) + n N_v V_{th} \ln \left( \frac{G}{G_{STC}} \right) \tag{13}
\]

\( K_i \) is the temperature coefficient of \( V_{oc} \) and \( V_{oc,STC} \) is open-circuit voltage in STC conditions. Figure 8 presents the experimental I-V characteristic and the theoretical curve using the five estimated parameters, for the KC200GT PV modules. As can be viewed, the theoretical curve of the above-mentioned PV module is in very good agreement with the experimental measurement extracted from the data sheet under the conditions of constant temperature \( T=25 \text{ °C} \) and at different irradiation levels. In Figure 9, we plot the experimental I-V
characteristic and the theoretical curve, for the KC200GT PV module for fixed irradiation 1000W/m² and at different temperatures. It is clear that the theoretical values of the model are in accord with the experimental measurements.

Figure 8. Experimental and theoretical I–V characteristic for KC200GT module under varying irradiance

Figure 9. Experimental and theoretical I–V characteristic for KC200GT module under varying temperature

4. CONCLUSION

This paper proposed a numerical method to extract and evaluate the physical parameters of photovoltaic generators. The equivalent single-diode circuit with five parameters is applied for modeling the electrical behavior of the PV generators. This technique is based on the analytical extraction of the saturation current, the parallel resistance and the photocurrent as a function of the ideality factor and series resistance using the linear least squares method. Then, the estimation of the series resistance and the ideality factor has been found by solving numerically a system of two nonlinear equations. The suggested numerical method reduces the number of the initial values to two and extract the five parameters without approximation. The application of this method for the RTC France solar cell, PWP201 and the KC200GT panels indicated a low error and a good agreement with the experimental data.
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