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Extraction of photovoltaic generator parameters through combination of an analytical and iterative approach

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ABSTRACT

In the present work, we propose an improved method based on a combination of an analytical and iterative approach to extract the photovoltaic (PV) module parameters using the measured current-voltage characteristics and the simple diode model. First, we calculate the series resistance using a set of analytical formulas for the base values of the three current-voltage curves. Then, the three other parameters are analytically expressed as functions of serial resistance and ideality factor based on the linear least-squares method. Finally, the ideality factor is calculated applying an iterative algorithm to minimize the normalized root mean square error (NRMSE) value. The proposed method was validated with a real experimental set of two PV generators, which showed the best fit to the I-V curve. Moreover, the proposed method needs only the initial value of the ideality factor.

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1. INTRODUCTION

Photovoltaic systems are used widely in employment, either solely or in confluence with other electrical power sources. Applications powered by photovoltaic (PV) systems include communication equipment, somehow powered telecommunications installations, remote monitoring, lighting, water pumping, and battery charging. The modeling of PV arrays and modules plays an essential role in the performance and productivity of PV systems. The extraction of solar cell or PV module parameters is critical for determining the performance of various jobs and carrying out their design and quality control.

Several techniques and approaches have been offered to obtain the five physical parameters using the one diode model. These approaches are grouped into three classes: analytical, numerical, and evolutionary approaches [1]–[23]. Villalva *et al.* [5], which is among the most cited diving factories in this area, proposed a simple algorithm to extract the five parameters. This algorithm uses the series resistance as a duplication parameter to minimize the error between the calculated and measured peak power values. The disadvantage of this method is that it's accurate near the maximum power point but inaccurate in other regions and uses a fixed value of ideality factor equal to 1.3. Cubas *et al.* [11] has proposed a coherent approach using four analytical expressions with some approximation to extract the four parameter values and an ideality factor equal to 1.3. Ma *et al.* [17] have presented an extraction algorithm based on bio-inspired. Furthermore, a study of two technics using an iterative algorithm and the Lambert function has been suggested in work [18] to determine the five parameters of the PV modules under varying environmental conditions.

New, Achouby *et al.* [21] provided an exact numerical approach to find the five physical parameters. This method is based on varying the ideality parameter and resolving a nonlinear system of four equations. This method requires appropriate initial guess for four physical parameters. Zaimi *et al.* [22] presented a method based on a combination of well-founded and numerical approaches. This technique needs two coherent initial values of series resistance and ideality factor. Stornelli *et al.* [23] suggested a new, five-parameter method. This simplified method allows one to find the optimal value of the ideality parameter and the shunt resistance.

In this investigation, we present another technique based on a combination of iterative and analytical approaches to extract physical parameters of a single diode model of a PV generator. In the first step, we use a well-founded expression to calculate the series resistance R_s. In the spare step, we derive three analytic equations giving the parallel resistor R_{sh}, the saturation current Is, and the photo-current I_{ph} as functions of series resistance R_s and ideality factor n using the linear least squares method. In the final step, we use the ideality factor as a parameter iteration to minimize the normalized root mean square error (NRMSE). This procedure has the advantage of using only one foremost value of an ideality parameter and allows us to reduce the number of unknowns to one.

2. PROPOSED METHOD

2.1. PV module modelling

A PV module consists of several solar cells in series or parallel that transform solar irradiation into electrical current. To describe the PV module behavior, we use in our work the one diode model with five parameters; this model is the most used in the literature. The electrical equivalent circuit of the model is depicted in Figure 1.

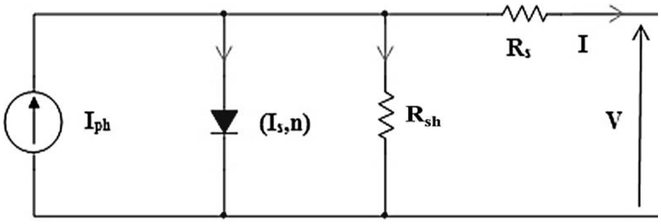


Figure 1. Equivalent circuit for one diode PV cell model

The mathematical behavior of the PV panel connecting the output current and voltage and the five parameters is given by (1).

$$I = I_{ph} - I_s\left(exp\left(\frac{V+R_S.I}{n.N_S.V_{th}}\right) - 1\right) - \frac{V+R_S.I}{R_{sh}} \tag{1}$$

Where I_{ph} is the photoelectric current, I_s is the current of saturation on the diode, R_{sh} is the parallel resistance, n is the ideality factor, R_s is the series resistance, N_s is the number of solar cell connected in series (N_s=1 for the solar cell), V_{th} is the thermal voltage given by: $V_{th} = \frac{k_B.T}{q}$. Where q is the electronic charge, k_B is the Boltzman's constant and T is the temperature in Kelvin. The equation (1) is implicit and requires numerical resolution. The explicit expression of this equation using the Lambert function is given by (2):

$$I = -\frac{I_S+I_{ph}}{1+R_S.G_{sh}} + \frac{G_{sh}}{1+R_S.G_{sh}}V + \frac{n.N_S.V_{th}}{R_S} LambertW\left(\frac{I_S.R_S}{n.N_S.V_{th}.(1+R_S.G_{sh})} exp\left(\frac{V+R_S.(I_S+I_{ph})}{n.N_S.V_{th}.(1+R_S.G_{sh})}\right)\right) \tag{2}$$

where G_{sh} is the parallel conductance given by $1/R_{sh}$.

2.2. Extraction method

2.2.1. Analytical expression of R_s

The evaluation of the (1) at the three remarkable points of I-V curve ($V=V_{oc}$, $I=0$), ($V=0$, $I=I_{sc}$) and ($V=V_{mp}$, $I=I_{mp}$) points, respectively, provide the equations:

$$0 = I_{ph} - I_s \left(exp\left(\frac{V_{oc}}{n.N_s.V_{th}}\right) - 1 \right) - \frac{V_{oc}}{R_{sh}} \tag{3}$$

$$I_{sc} = I_{ph} - I_s \left(exp\left(\frac{R_s I_{sc}}{n.N_s.V_{th}}\right) - 1 \right) - \frac{R_s I_{sc}}{R_{sh}} \tag{4}$$

$$I_{mp} = I_{ph} - I_s \left(exp\left(\frac{V_{mp}+R_s I_{mp}}{n.N_s.V_{th}}\right) - 1 \right) - \frac{V_{mp}+R_s I_{mp}}{R_{sh}} \tag{5}$$

According to [11] and using the three previous equations, R_s can be expressed analytically:

$$R_s = \frac{\alpha V_{mp} + \beta(V_{oc} - V_{mp})}{(\alpha+\beta) I_{mp}} \tag{6}$$

α and β are given by:

$$\alpha = \left(V_{mp} + \left(I_{mp} - I_{sc}\right) R_{sh0}\right) ln\left(\frac{V_{mp} + \left(I_{mp} - I_{sc}\right) R_{sh0}}{V_{oc} - I_{sc} R_{sh0}}\right); \beta = V_{mp} - R_{sh0} I_{mp} \tag{7}$$

R_{sh0} is the slope at the short circuit point:

$$R_{sh0} = -\left.\frac{dV}{dI}\right|_{I=I_{sc}} \tag{8}$$

2.2.2. Calculation of I_s, I_{ph} and G_{sh}

In order to calculate the three parameters I_{ph}, I_s and R_{sh} as function of R_s and n, we use a linear least square method to minimize the follow error expression:

$$F = \sum_{i=1}^{N} \left(I_{i,ca}\left(V_{i,ex}\right) - I_{i,ex}\right)^2 = \sum_{i=1}^{N} \left(I_{ph} - I_S \left(exp\left(\frac{V_{i,ex} + R_S.I_{i,ex}}{n.V_{th}}\right) - 1\right) - G_{sh}\left(V_{i,ex} + R_S.I_{i,ex}\right) - I_{i,ex}\right)^2 \tag{9}$$

$I_{i,ex}$ and $I_{i,ca}$ are the measured and the theoretical current. $V_{i,ex}$ is the experimental voltage of the PV module and N is the number of experimental points. The minimization of the F function requires the system resolution (10):

$$\begin{cases} \frac{\partial F}{\partial I_{ph}} = 2\sum_{i=1}^{N} \frac{\partial I_{i,ca}}{\partial I_{ph}} (I_{i,ca} - I_{i,ex}) = 0 \\ \frac{\partial F}{\partial I_s} = 2\sum_{i=1}^{N} \frac{\partial I_{i,ca}}{\partial I_s} (I_{i,ca} - I_{i,ex}) = 0 \\ \frac{\partial F}{\partial G_{sh}} = 2\sum_{i=1}^{N} \frac{\partial I_{i,ca}}{\partial G_{sh}} (I_{i,ca} - I_{i,ex}) = 0 \end{cases} \tag{10}$$

After some mathematical operations, the previous system of equations become [19]:

$$\begin{cases} I_{ph} N - I_s \sum_{i=1}^{N} EXP_i - G_{sh} \sum_{i=1}^{N} V_{sh,_i} = \sum_{i=1}^{N} I_{i,ex} \\ -I_{ph} \sum_{i=1}^{N} EXP_i + I_s \sum_{i=1}^{N} EXP_i^{\,2} + G_{sh} \sum_{i=1}^{N} V_{sh,_i} EXP_i = -\sum_{i=1}^{N} I_{i,ex} EXP_i \\ -I_{ph} \sum_{i=1}^{N} V_{sh,_i} + I_s \sum_{i=1}^{N} V_{sh,_i} EXP_i + G_{sh} \sum_{i=1}^{N} V_{sh,_i}^{\,2} = -\sum_{i=1}^{N} I_{i,ex} V_{sh,_i} \end{cases} \tag{11}$$

where EXP_i and $V_{sh,i}$ are given by (12):

$$EXP_i = exp\left(\frac{V_{i,ex} + R_S.I_{i,ex}}{n.N_S.V_{th}}\right) - 1; V_{sh,i} = V_{i,ex} + R_S.I_{i,ex} \tag{12}$$

2.2.3. Algorithm of ideality factor extraction

In this algorithm, we use ideality factor n as variation parameter which varies between 1 and 2 for silicon material and solve the linear system of (10) using MATLAB to find I_{ph}, I_s and R_{sh} values. Then, we select n that minimize the NRMSE value:

$$NRMSE = \frac{\left[\frac{1}{N}\sum_{i=1}^{N}\left(I_i - I_{i,m}\right)^2\right]^{\frac{1}{2}}}{\frac{1}{N}\sum_{i=1}^{N} I_{i,m}} \tag{13}$$

In Figure 2, we have detailed the extraction strategy of the five parameters using our proposed technique. The main steps are given by the following flowchart.

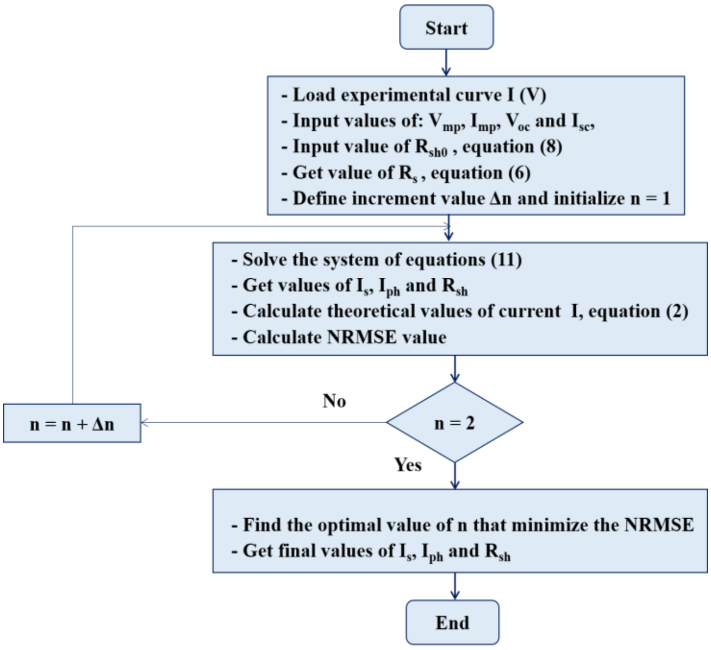


Figure 2. Proposed flowchart method

3. RESULTS AND DISCUSSION

We confirm the suggested approach through two experimental test cases: the RTC solar cell at 33 °C and 1000 W/m² [1] and the multicrystalline panel KC200GT operating at standard test conditions (STC) (T=25 °C and G=1000 W/m2), the experimental current-voltage curve are extracted from manufacturer's datasheet [24]. In order to evaluate the accuracy of our method, we use the NRMSE using (13) and the absolute error given by (14):

$$AE = \left|I_{i,exp} - I_{i,cal}\right| \tag{14}$$

In Table 1, we summarized the remarkable points values and R_{sh0} for the solar cell and the PV panel.

Table 1. Remarkable point's values and R_{sh0}

	RTC solar cell	KC200GT PV panel
I_{mp} (A)	0.67	7.61
V_{mp} (V)	0.46	26.3
I_{sc} (A)	0.76	8.21
V_{oc} (V)	0.57	32.9
R_{sh0} (Ω)	58.656	597

Tables 2 and 3 present the obtained values of the five parameters using the our technic for the solar cell and PV module respectively. For comprehensive comparison, the proposed algorithm is evaluated against previously techniques. According to this two tables, our method has the lowest NRMSE value. In Figures 3(a) and 3(b), we plot the NRMSE values versus ideality factor n, for the two experimental cases. According to these figures, the optimal value of n which minimizes the NRMSE is equal to 1.55 for solar cell and equal to 1.1 for PV module.

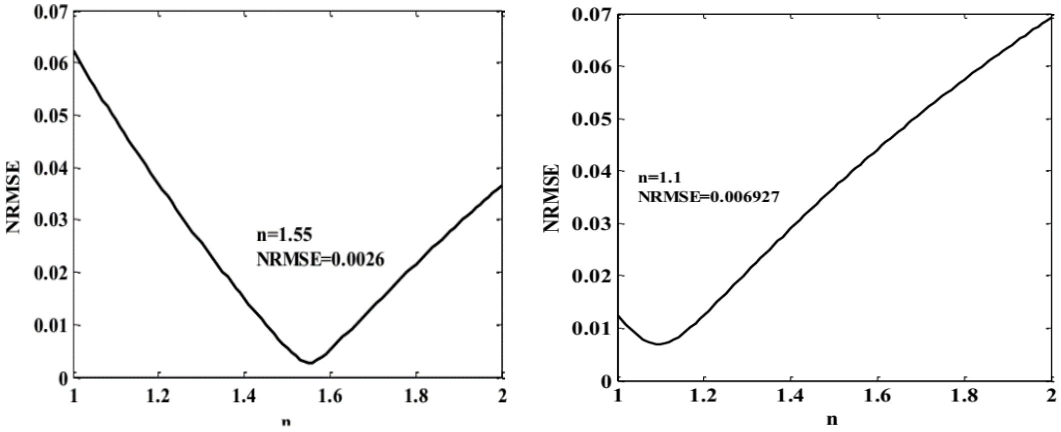
Figures 4(a) and 4(b) present the measured and the simulated current-voltage I (V) curves obtained by using the Lambert-function model, for the two cases studies, solar cell and KC200GT. As it can be seen for both cases, the simulated characteristics are in excellent accordance with the experimental data. The benefits of the proposed method are that need only one initial guess.

Table 2. Solar cell parameters at 33 °C and 1000 W/m²

Parameters	Method [3]	Method [6]	Method [25]	Proposed method
$R_s(\Omega)$	0.037	0.036	0.0355	0.033
n	1.45	1.48	1.4905	1.55
$I_{ph}(A)$	0.7611	0.7607	0.7611	0.7606
$I_s(A)$	$2.422.10^{-7}$	$3.267.10^{-7}$	$3.514.10^{-7}$	$6.271.10^{-7}$
$R_{sh}(\Omega)$	42	60.24	45.0472	66.36
NRMSE	0.078	0.068	0.0072	0.0026

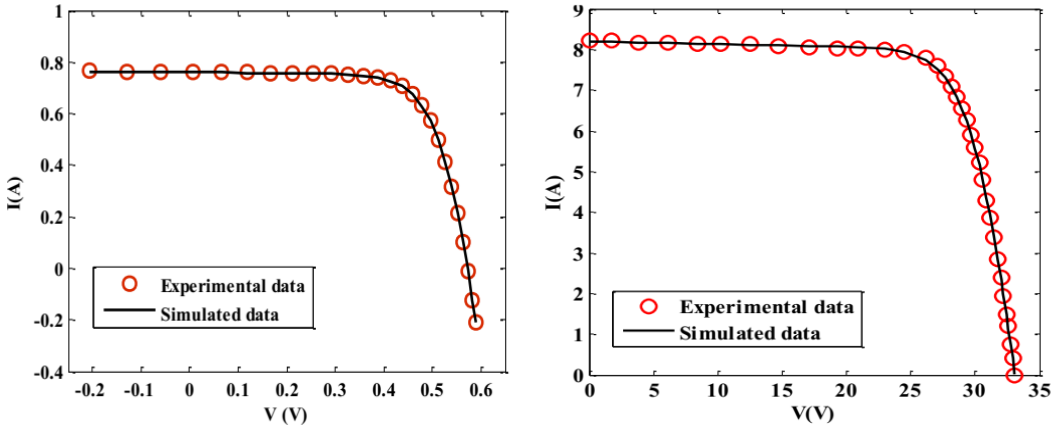
Table 3. PV module parameters at STC conditions

Parameters	Method [11]	Method [5]	Method [19]	Method [23]	Proposed method
$Rs(\Omega)$	0.23	0.221	0.233	0.2185	0.23
n	1.3	1.3	1.0758	1.1	1.1
$I_{ph}(A)$	8.213	8.214	8.211	8.196	8.211
$I_s(A)$	$9.76.10^{-8}$	$9.825.10^{-8}$	$2.12.10^{-9}$	$3.27.10^{-9}$	$3.143.10^{-9}$
$R_{sh}(\Omega)$	597.38	415.405	132.88	164.2	154.64
NRMSE	0.0571	0.0564	0.0086	0.0087	0.0069



(a) (b)

Figure 3. NRMSE vs. n for (a) solar cell and (b) KC200GT



(a) (b)

Figure 4. Measured and simulated characteristics I (V) for (a) solar cell and (b) KC200GT

In order to evaluate the impact of temperature cell T and irradiance level G on the five parameters and the I-V characteristic, we use the following expressions [19].

$$n(T,G) = n_{STC} \tag{15}$$

$$R_s(T,G) = R_{s,STC} \tag{16}$$

$$R_{sh}(T,G) = R_{sh,STC} \tag{17}$$

$$I_{ph}(T,G) = \frac{G}{G_{STC}}.(I_{ph,STC} + K_i.(T - T_{STC})) \tag{18}$$

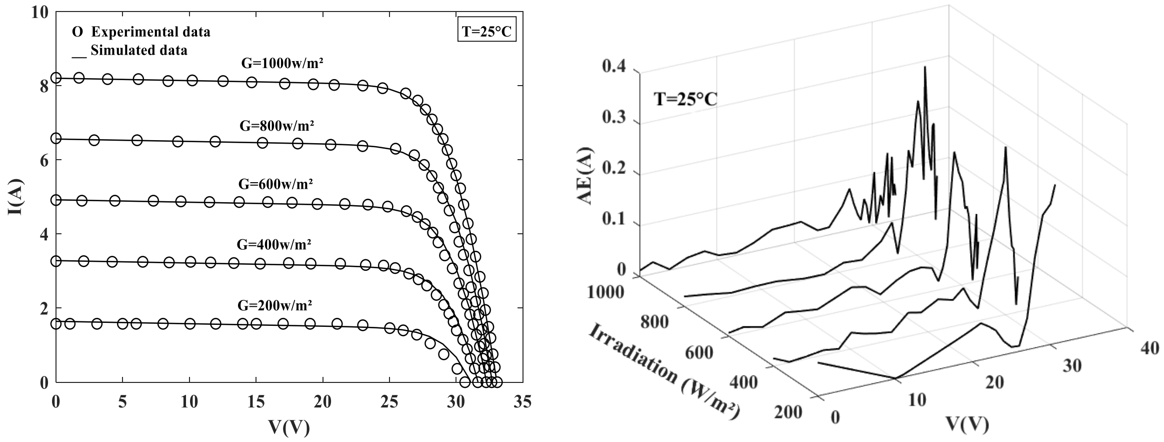
$$I_s(T,G) = \frac{I_{ph}(T,G) - G_{sh}.V_{oc}(T,G)}{exp\left(\frac{V_{oc}(T,G)}{N_S.n.V_{th}(T)}\right) - 1} \tag{19}$$

Where, G_{STC} and T_{STC} are the overall radiation ant temperature under STC conditions and V_{oc} is given by the following analytical model [21]:

$$V_{oc}(T,G) = V_{oc,STC} + K_V.(T - T_{STC}) + n.N_s.V_{th}(T).ln\left(\frac{G}{G_{STC}}\right) \tag{20}$$

Where, K_V is the temperature coefficient of V_{oc} and $V_{oc,\,STC}$ is the open-circuit voltage in STC conditions.

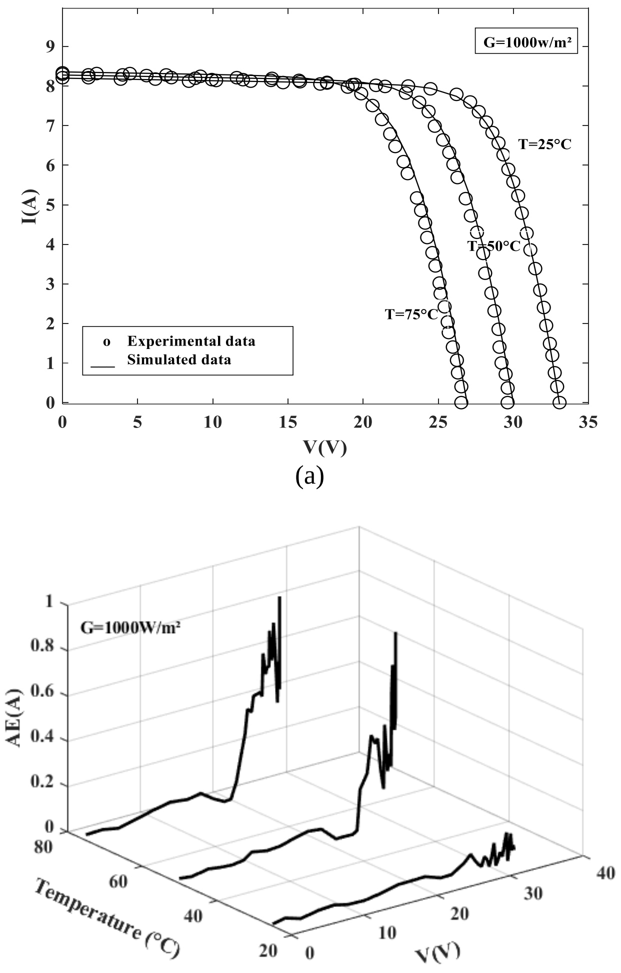
Figure 5(a) displays the measured and the simulated I-V characteristic for the KC200GT panel. As can be clearly seen, the simulated curve of the aforementioned PV module is in very close accord with the measured data at T=25 °C and at various irradiation levels. In Figure 5(b), we display variations of absolute error curve for a temparture 25 °C and different irradiation levels. In the voltage variation interval [0, V_{mp}], the theoretical and experimental I=f(V) curves are in good agreement and the absolute current error tends to cancel. When, at a voltage variation n the interval [V_{mp}, V_{oc}], the current decreases rapidly and the AE increases slightly but still remains below 0.15 for the irradiadiance 1000 W/m² and 0.3 for the iradainces 800 W/m², 600 W/m², 400 W/m² and 200 W/m². The current has an exponential characteristic in the zone [V_{mp},V_{oc}] at an almost constant voltage.



(a) (b)

Figure 5. Accuracy of the proposed method (a) measured and simulated I(V) characteristics and (b) absolute error AE(V), for KC200GT panel under varying irradiance

In Figure 6(a), we display the measured and the simulated I-V characteristic, for the KC200GT panel for fixed irradiation 1000 W/m² and at the temperature values 25 °C, 50 °C and 75 °C. We also display, in Figure 6(b), the curves AE=f(V). It is clearly that the simulated values of the model are in harmony with the measured data. In the voltage variation interval [0, Vmp], the theoretical and experimental I=f(V) curves are in good agreement and the absolute current error tends to cancel. When, at a voltage variation in the interval [V_{mp}, V_{oc}], the current decreases rapidly and the AE increases slightly but still remains below 0.2 for the temperature 25 °C and 0.8 for the temperatures 50 °C and 75 °C. In the [V_{mp},V_{oc}] area the voltage is almost constant while the current is exponential and is sensitive to a few simple variations.



(a)

(b)

Figure 6. Accuracy of the proposed method (a) measured and simulated I(V) characteristics and (b) absolute error AE(V), for KC200GT panel under varying temperature

4. CONCLUSION

This article proposed an efficient hybrid method to determine the five PV module parameters using the measured current-voltage characteristics and the simple diode model. This method is based on the analytical calculation of the series resistance using three specific points of the experimental current-voltage curves. The saturation current, the photo current and the parallel resistance are expressed depending on the ideality factor by solving of a system of three linear equations using the linear least squares approach. The ideality factor value is determined iteratively to minimize the NRMSE value. The results obtained for two experimental cases studies of solar cell and PV panel show a good agreement and low error between the measured and the simulated data.

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