JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. **11** No 5, 05008(7pp) (2019)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том **11** № 5, 05008(7cc) (2019)

Evaluation and Extraction of Electrical Parameters of Different Photovoltaic Models Using Iterative Methods

B. Benabdelkrim[1,2,*], A. Benatillah[2], T. Ghaitaoui[2,3]

[1] *Department of Material Sciences, Institute of Science and Technology, University of Ahmed Draia, Adrar, Algeria*
[2] *Laboratory of Energy, Environment and Systems of Information (LEESI), University Ahmed Draia Adrar, Algeria*
[3] *Unité de Recherche en Energies Renouvelables en Milieu Saharien, URERMS, Centre de Développement des Energies Renouvelables, CDER, 01000, Adrar, Algéria*

(Received 04 April 2019; revised manuscript received 20 October 2019; published online 25 October 2019)

The photovoltaic (PV) module is typically represented by an equivalent circuit whose parameters are calculated using the experimental current-voltage (*I-V*) characteristic. These parameters are crucial to predict accurate performance of a PV module. The precise determination of these parameters remains a challenge for researchers, which led to a diversification in models and numerical methods used for its computation. These parameters of the proposed solar PV moduls have been calculated using an efficient iterative technique. In this study, two mathematical models are used (single and double diode models) to extract the unknown parameters at standard test conditions (STC) of three different types of PV module technologies (multicrystalline, monocrystalline, and thin-film). A MATLAB simulation based comparative performance analysis of these models under different climatic conditions and the effect of variations in model parameters has been carried out. The results obtained showed a good agreement with the results obtained experimentally as well as these models are highly sensitive and respond to any variation of climatic conditions (temperature, irradiance).

Keywords: PV Modules, Single-diode model, Two-diode model, Performance *I-V* curves, Parameter extraction.

DOI: 10.21272/jnep.11(5).05008 PACS number: 88.40.hj

1. INTRODUCTION

The rapid growth of PV system utilizations is due to its availability everywhere, which avoids transmission costs and losses, free, abundant and pollution free. Silicon is the basic material required for the production of solar cells based crystalline or thin film technology.

The photovoltaic (PV) modules are generally rated under standard test conditions (STC) with the solar radiation of 1000 W/m^2, cell temperature of 25 °C, and solar spectrum of 1.5 by the manufacturers. The parameters required for the input of the PV modules are relying on the meteorological conditions of the area. The climatic conditions are unpredictable due to the random nature of their occurrence. These uncertainties lead to either over- or underestimation of energy yield from PV modules. An overestimation up to 40 % was reported as compared to the rated power output of PV modules [1]. The growing demand of PV technologies led to research in the various aspects of its components from cell technology to the modeling, size optimization, and system performance [2, 3].

There are various PV cell modules studied by researchers in the literature. One of the simplest is a single diode model. In broad sense, this model is derived by three parameters: short circuit current (I_{sc}), open circuit voltage (V_{oc}), and diode ideality factor (a). When the parameter series resistance (R_s) is added in this model, the accuracy of model gets improved. One drawback of this model is that it is not capable of temperature (T) variation handling. Parameter shunt resistance (R_{sh}) significantly improves the model efficiency [4]. This model has a drawback of reduced accuracy under low irradiance (G) level, especially at open circuit voltage (V_{oc}). Additional diode design is added to the model for the recombination loss in the depletion region of the cell of solar module [5]. This is a double-diode model. This model has more parameters to calculate. This model gives more accuracy because it is more practical especially under low voltages.

Extensive studies have been conducted to determine the series resistance (R_s) and parallel resistance (R_p). Some authors neglect R_p to simplify the model as the value of this resistance is generally high [6], and sometimes, R_s is neglected as its value is very low [5]. The neglect of R_s and R_p has significant impact on the model accuracy. Several algorithms have been proposed to determine both R_s and R_p through iterative techniques [7]. If the initialization of the variables and the convergence conditions are not proper, then these iterative techniques require many iterations and, sometimes, may not converge. Curve fitting method can be utilized in the current density-voltage curves to estimate both R_s and R_p [8]. In [9], R_s and R_p are evaluated by using additional parameters which can be extracted from the current-voltage (*I-V*) curve of a PV module. These methods are quite poor, inaccurate, and tedious mainly because R_s and R_p are adjusted separately, which is not a good practice, if an accurate model is required. Moreover, these methods are applicable only if the manufacturer-specified output characteristics are provided. Differential evolution (DE) can be used to extract the excess seven parameters of a double-diode PV module model utilizing only the information provided in the datasheets [10]. An explicit modeling method based on Lambert W-function for PV arrays that has been used in [11] to find the values of parameters is intricate and

---

[*] benaekbouchra@gmail.com

time consuming. Artificial intelligence (AI) such as fuzzy logic [12] and artificial neural network (ANN) [13] and genetic algorithms such as particle swarm optimization (PSO) have also been proposed to modeling the *I-V* curves [14]. However, they are not widely adopted due to high computation burden. In [15], a comprehensive parameter identification method is proposed to enhance model accuracy while keeping the parameterization procedure in a simple form.

In this paper, a comparative analysis details the behavioral *I-V* characteristics of a single-diode using analytical four and five parameter model and two-diode model. The accuracy of the simulation results is verified by comparing it with published data provided by manufacturers of three PV modules of different types (monocrystalline, multicrystalline and thin-film).

2. MATHEMATICAL MODELS OF PV MODULE

2.1 Single-diode Model

An electrical circuit with a single diode (single exponential) is considered as the equivalent PV cell in the present article. Two different models drawn from the equivalent electrical-circuit are studied, namely, four- and five-parameter models.

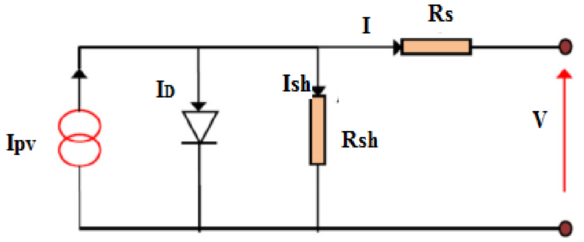


Fig. 1 – PV-cell equivalent-circuit models: single-diode model [16]

An output current equation of *I-V* characteristic using this model can be written as:

$$I = I_{pv} - I_0\left[\boldsymbol{exp}\left(\frac{V - I_0R_s}{V_T}\right) - 1\right] - \left[\frac{V + I_0R_s}{R_{sh}}\right], \quad (1)$$

where I_{pv} is the photocurrent, I_0 is the cell saturation current, R_{sh} is the shunt resistance, R_s is the series resistance, V_T is the thermal voltage ($V_T = a \cdot N_s \cdot k \cdot T/q$), N_s is the number of cells in series, a is the ideal factor of the PV diode, q is the electron charge ($1.60281 \cdot 10^{-19}$ C), k is the Boltzmann constant ($1.38066 \cdot 10^{-23}$ J/K), T is the cell operating temperature.

2.1.1 Four-parameter Model

The four-parameter model studied in this work has been used elsewhere [17]. Assuming R_{sh} as infinite and neglecting it in Eq. (1), the four-parameter model is obtained as follows:

$$I = I_{pv} - I_0\left[\boldsymbol{exp}\left(\frac{V - I_0R_s}{V_T}\right) - 1\right]. \quad (2)$$

The short circuit current can be found when $V = 0$

$$I_{pv} = \left[I_{pvn} + K_I \cdot (T - T_n)\right] \cdot G / G_n . \quad (3)$$

The following equations are used to calculate the other parameters at STC [6]:

$$I_0(T) = I_{0n}\left(\frac{T}{T_n}\right)^3 \boldsymbol{exp}\left[\left(\frac{qE_g}{aK}\right)\left(\frac{1}{T_n} - \frac{1}{T}\right)\right], \quad (4)$$

where

$$I_{0n} = \frac{I_{pvn}}{\boldsymbol{exp}\left(\frac{V_{ocn}}{VT_n}\right) - 1}. \quad (5)$$

From Eq. (2), either cell current or voltage could be calculated provided that the other is known. Alternatively, cell current and voltage could both be calculated at the maximum-power point.

2.1.2 Five Parameter Model

As given in Eq. (1), the five-parameter model is an implicit non-linear equation, which can be solved with a numerical iterative method such as Newton-Raphson method [18]. However, this requires a close approximation of initial parameter values to attain convergence. Alternatively, the parameters may be extracted by means of analytical methods. Some of the analytical methods are studied elsewhere [19].

The five parameters I_{pv}, I_0, R_s, R_{sh}, and m are calculated at a particular temperature and solar-irradiance level from the limiting conditions of V_{oc}, I_{sc}, V_{mp}, I_{mp}.

The following equations are used to calculate the five parameters required:

$$I_{pv} = I_{sc}\left(1 + \frac{R_s}{R_{sh}}\right) + I_0\left[\boldsymbol{exp}\left(\frac{I_{sc}R_s}{V_T}\right) - 1\right], \quad (6)$$

$$I_0 = \left[I_{sc} - \frac{V_{oc}}{V_{sh}}\right]\boldsymbol{exp}\left(-\frac{V_{oc}}{V_T}\right). \quad (7)$$

The value of the diode ideality factor (a) may be arbitrarily chosen. Many authors discuss ways to estimate the correct value of this constant. Usually, $1 \le a \le 2$, and the chosen value depends on other parameters of the *I-V* model. As it is given in [7], there are different opinions about the best way to choose a. Because a expresses the degree of ideality of the diode and it is totally empirical, any initial value of a can be chosen in order to adjust the model.

The resistances R_s and R_{sh} are calculated by iterative methods. The relation between R_s and R_{sh} may be found by making the maximum power calculated by the *I-V* model, equal to the maximum experimental power from the datasheet ($P_{max,m} = P_{max,e}$) at the (V_m; I_m) point. In the iterative process, R_s must be slowly incremented starting from $R_s = 0$, and for every iteration, the value of R_{sh} is calculated simultaneously:

$$P_{\boldsymbol{max,m}} = P_{\boldsymbol{max,e}} = V_{mp} \times$$

$$\left\{I_{pV} - I_0\left[\boldsymbol{exp}\left(\frac{V_{mp} + \boldsymbol{I}_{\boldsymbol{m}p}R_s}{V_T}\right) - 1\right]\right\} - \left(\frac{V_{mp} + \boldsymbol{I}_{\boldsymbol{m}p}R_s}{R_{sh}}\right). \quad (8)$$

In the proposed iterative method, the series resistance must be slowly incremented starting from a null value. Adjusting the *I-V* curve to match the cell reference condition requires finding the curve for several values of series and equivalent shunt resistances. The Newton-Raphson method was used in the proposed iterative method due to the ability to overcome undesired behaviors [20].

2.2 Two-diode Model

The two-diode model equation of the *I-V* curve is expressed as [8]:

$$I = I_{pv} - I_{01}\left[\boldsymbol{exp}\left(\frac{V + I_0R_s}{V_{T1}}\right) - 1\right] - \\ -I_{02}\left[\boldsymbol{exp}\left(\frac{V + I_0R_s}{V_{T2}}\right) - 1\right] - \left[\frac{V + I_0R_s}{R_{sh}}\right]. \qquad (9)$$

where the diode factors $a_1 = 1$ and a_2 can be derived from $\frac{a_1 + a_2}{p} \geq 1$, where p can be chosen greater than 2.2.

The rest of parameters can be deduced from the following equations [7]:

$$I_{01} = I_{02} = I_0 = \frac{I_{sc} + K_I\Delta T}{\boldsymbol{exp}\left(\frac{q\left(V_{oc} + K_V\Delta T\right)}{kT\left(a_1 + a_2\right)/p}\right) - 1}. \qquad (10)$$

R_s and R_{sh} are calculated by iterative method similar to the procedure proposed in [12], where the relation between R_s and R_{sh} is chosen to verify that the calculated maximum power is equal to the experimental one ($P_{max,m} = P_{max,e}$) at (V_m, I_m) point.

3. RESULTS AND DISCUSSION

3.1 Extraction of Electrical Parameters

The modeling methods described in this paper are validated by measured parameters of selected PV modules. The experimental (*V*, *I*) data are extracted from the manufacturer's datasheet. Three different modules of different brands/models are utilized for verification; these include the multicrystalline (KC200GT) and monocrystalline (SP70) as well as thin-film (ST40) types. The specifications of these modules are summarized in Table 1.

Table 1 – Specification of the PV modules

Modules	I_{sc}, A	V_{oc}, V	I_{mp}, A	V_{mp}, V	$K_i(I_{sc})$, mA/°C	$K_v(V_{oc})$, mV/°C	N_s
Multicrystalline Kyocera KC200GT	8.21	32.9	7.61	26.3	3.18	– 123	54
Monocrystalline Shell SP70	4.7	21.4	4.25	16.5	2	– 76	36
Thin-Film Shell ST40	2.68	23.3	2.41	16.6	0.35	– 100	36

The equations of the previous section were implemented in MATLAB environment to simulate and evaluate the three models by means of the two estimation methods:

– Single-diode methods based on two different models drawn from the equivalent electrical-circuit are studied, namely four-parameter models which extracted the parameters, I_0, I_{PV}, a and R_s and five-parameter model, the additional calculated parameter is R_{sh}.

– Two-diode model has more variables, the actual number of parameters computed is four because $I_{01} = I_{02} = I_0$.

After calculation, the extracted parameters of KC200GT module are as follows: $n = 1.0758$; $R_s = 0.3541\ \Omega$; $I_0 = 2.1954\text{e-}9$ A, and $I_{PV} = 8.21$ A for 4-P model and for 5-P model the extracted parameters are as follows: $n = 1.3$; $R_s = 0.23\ \Omega$; $R_{sh} = 601.3368\ \Omega$; $I_0 = 9.8252\text{e-}8$ A, and $I_{PV} = 8.2146$ A and for two-diode model the extracted parameters are as follows: $n_1 = 1$; $n_2 = 1.2$; $R_s = 0.33\ \Omega$; $R_{sh} = 174.1551\ \Omega$; $I_{01} = I_{02} = 4.1280\text{e-}10$ A, and $I_{PV} = 8.21$A.

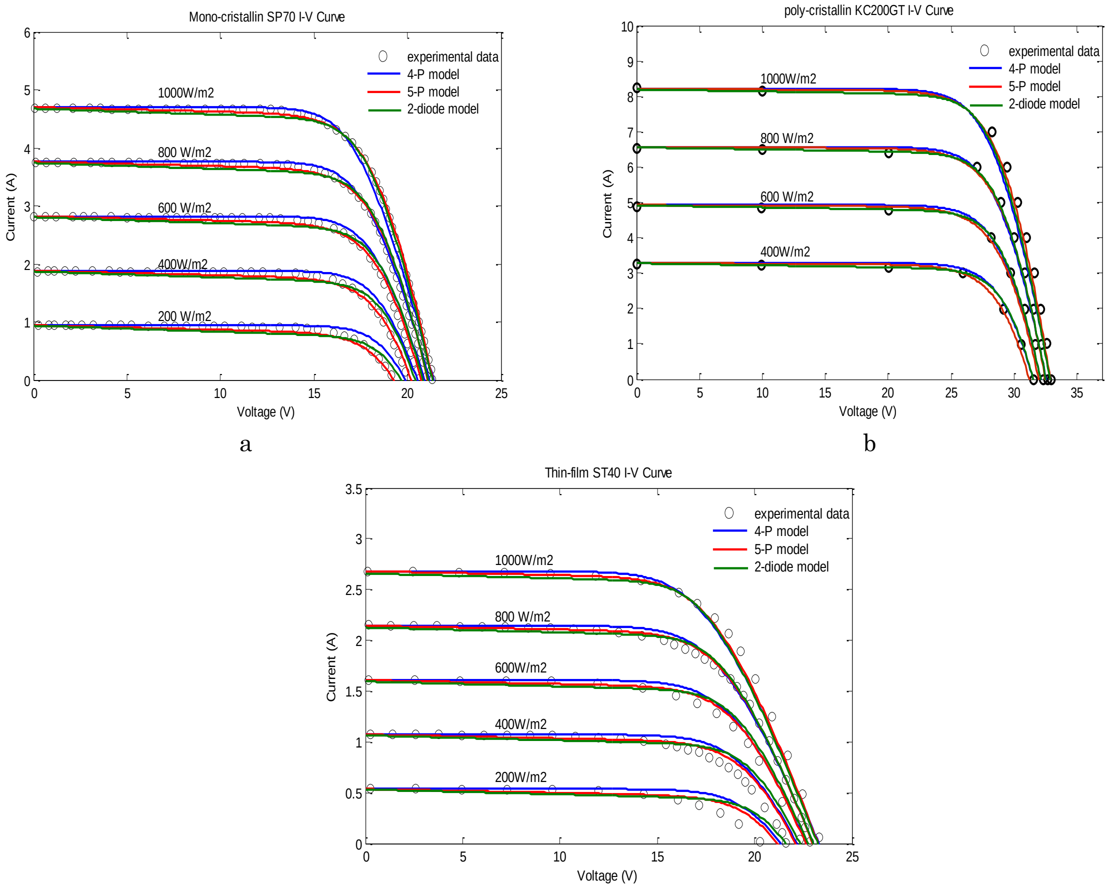
The extracted parameters of SP70 module are as follows: $n = 1.0222$; $R_s = 0.6310\ \Omega$; $I_0 = 6.9528\text{e-}10$ A, and $I_{PV} = 4.7$ A for 4-P model and for 5-P model the extracted parameters are as follows: $n = 1.3$; $R_s = 0.4\ \Omega$; $R_{sh} = 133.1309\ \Omega$; $I_0 = 8.7645\text{e-}8$ A, $I_{PV} = 4.715$ A and for two-diode model the extracted parameters are as follows: $n_1 = 1$; $n_2 = 1.2$; $R_s = 0.51\ \Omega$; $R_{sh} = 94.9643\ \Omega$; $I_{01} = I_{02} = 4.2065\text{e-}10$ A, and $I_{PV} = 4.7$ A.

The extracted parameters of ST40 module are as follows: $n = 1.3219$; $R_s = 1.6156\ \Omega$; $I_0 = 1.4202\text{e-}8$ A, and $I_{PV} = 2.68$ A for 4-P model and for 5-P model the extracted parameters are as follows: $n = 1.3$; $R_s = 1.51\ \Omega$; $R_{sh} = 266.5478\ \Omega$; $I_0 = 1.0292\text{e-}8$ A, $I_{PV} = 2.6961$ A and for two-diode model the extracted parameters are as follows: $n_1 = 1$; $n_2 = 1.2$; $R_s = 1.71\ \Omega$; $R_{sh} = 204.8492\ \Omega$; $I_{01} = I_{02} = 3.0748\text{e-}11$ A, and $I_{PV} = 2.68$ A.

The different calculation methods gave good correspondence with manufacturers' data for all the technologies evaluated especially in STC. It is generally observed that a generic statement in respect of the accuracy cannot be made as the best performance (of models when compared to the experimental value) varies from one parameter to the other.

3.2 Effect of Irradiance

The outputs of single and double diode models are compared with measured data extracted from PV modules datasheet to identify the effect of variation in incident insolation. The characteristic *I-V* curves for single-diode and two-diode models are obtained by varying the incident insolation and are shown in Fig. 2a, b, c for SP70, KC200GT and ST40 respectively. In order to find out the effect of irradiance on the output of the module,



a

b

c

Fig. 2 – The *I-V* characteristics of SP70 (a), KC200GT (b) and ST40 (c) modules at varying irradiance

the different values of irradiance are varying between 200 W/m^2 to 1000 W/m^2.

It is observed that the current I_{sc} is more affected by irradiance variation compared to its effect on voltage V_{oc}. An increase in insolation levels leads to an increase in current I_{sc}, and the corresponding value of P_m also increases.

It can be seen that for varying irradiance, despite the modeling curves do not match experimental data in all points, the tow diode model strongly agrees with experimental data than the four-parameter and five-parameter models for all types of modules, except for the thin-film (ST40) module at low irradiance of about 200 W/m², where the five-parameter modeled curve is closer to the experimental data than the four-parameter and tow diode models.

3.3 Effect of Temperature

Temperature is a very important parameter in the behavior of PV modules since they are exposed to solar radiation. We performed a simulation where we maintained a constant irradiance (1000 W/m^2) for different temperature levels.

After the comparison of single and two diode *I-V* performance curve, we can observe that the current have a minor variation when the temperature varies from 20 °C to 60 °C and the voltage is increasing when the atmospheric temperature reduces as illustrated in Fig. 3 a, b, c, thus solar cell shows inverse relationship with temperature.

It can be noted that all three methods show good general agreement with the experimental data. However, a close inspection reveals that the tow-diode model yields the most accurate results at all temperatures.

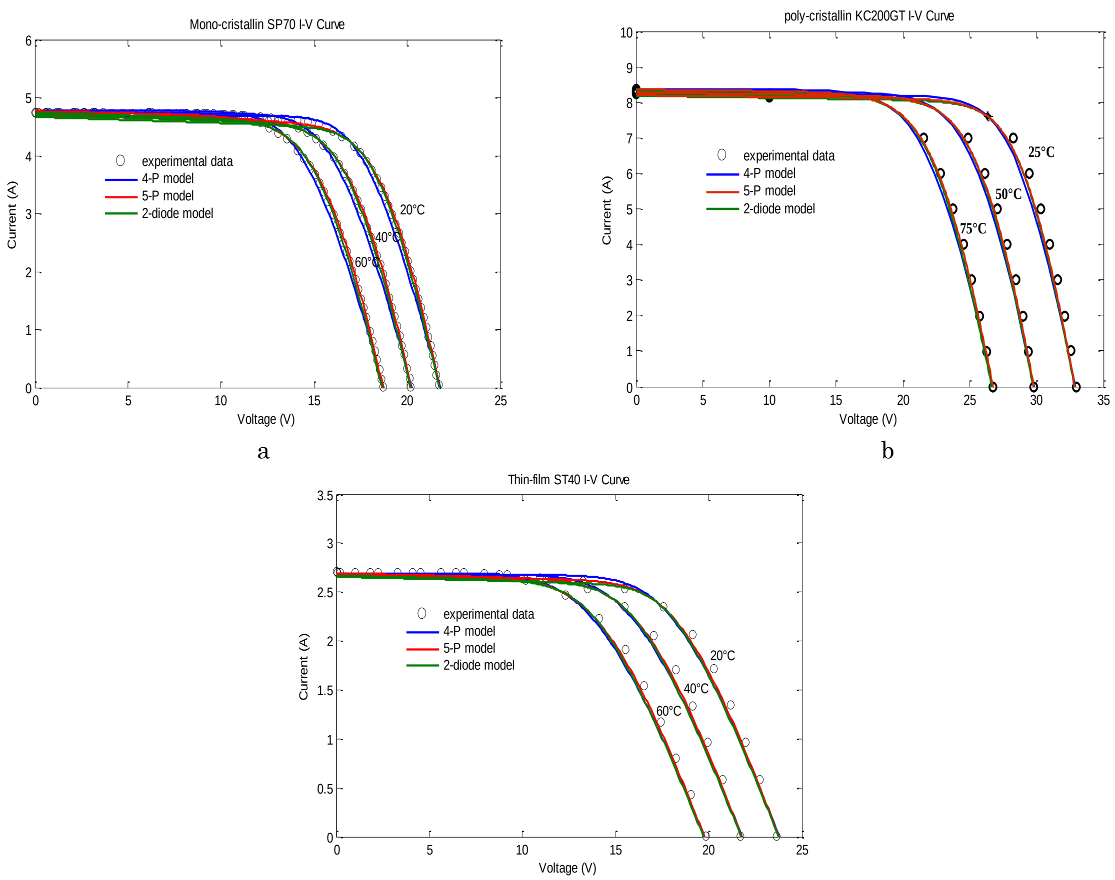
3.4 Accuracy of Different Models

Table 3 and Table 4 show the relative errors for P_{max}, V_{oc} and I_{sc} at varying irradiance and temperature of SP70 and ST40 modules.

The relative error is defined as

$$E_{reactive}(X)=\left(\frac{abs(X_{data}-X_{calcul})}{X_{data}}\right)\cdot 100. \qquad (11)$$

The irradiance is maintained constant at STC. From the data, it can be concluded that more accurate results are obtained from the two-diode model for the crystalline silicon technologies.



a b

c

Fig. 3 – The *I-V* characteristics of SP70 (a), KC200GT (b) and ST40 (c) modules at varying temperature

Table 3 – Relative errors of three models at different irradiances (T = 25 °C) for SP70 and ST40 modules

	Irradiance, W/m²	Parameters	Measured data	4-P model	Error %	5-P model	Error %	2D model	Error %
SP70 module	1000	P_{max} V_{oc} I_{sc}	70.07 21.33 4.682	70.5 21.39 4.7	0.61 0.28 0.38	70.11 21.35 4.7	0.057 0.094 0.38	70.22 21.34 4.675	0.21 0.047 0.15
	800	P_{max} V_{oc} I_{sc}	56.13 21.03 3.752	57.61 21.18 3.76	2.64 0.71 0.21	55.95 21.07 3.76	0.32 0.19 0.21	56.38 21.13 3.74	0.45 0.48 0.32
	600	P_{max} V_{oc} I_{sc}	41.89 20.5 2.815	43.96 20.91 2.82	4.94 2.00 0.18	41.46 20.72 2.82	1.026 1.073 0.18	41.99 20.84 2.805	0.24 1.66 0.36
	400	P_{max} V_{oc} I_{sc}	27.53 19.92 1.882	29.62 20.53 1.88	7.59 3.06 0.11	26.76 20.19 1.88	2.79 4.92 0.11	27.12 20.43 1.87	1.49 2.56 0.64
	200	P_{max} V_{oc} I_{sc}	13.17 19.12 0.9472	14.72 19.81 0.94	11.76 3.61 0.76	12.08 19.25 0.94	8.28 0.68 0.76	11.99 19.65 0.935	8.96 2.77 1.29
	Irradiance, W/m²	Parameters	Measured data	4-P model	Error %	5-P model	Error %	2D model	Error %
ST40 module	1000	P_{max} V_{oc} I_{sc}	40.21 23.29 2.677	40.03 23.30 2.68	0.45 0.04 0.11	39.99 23.27 2.68	0.55 0.086 0.11	40.04 23.26 2.658	0.42 0.13 0.71
	800	P_{max} V_{oc} I_{sc}	31.71 22.85 2.149	33.04 23.02 2.144	4.19 0.74 0.23	32.68 22.99 2.144	3.06 0.61 0.23	32.97 23.04 2.126	3.97 0.83 1.07

	600	P_{max} V_{oc} I_{sc}	23.52 22.33 1.607	25.44 22.67 1.608	8.16 1.52 0.062	24.80 22.62 1.608	5.44 1.30 0.062	25.17 22.76 1.595	7.02 1.92 0.75
	400	P_{max} V_{oc} I_{sc}	15.34 21.63 1.074	17.26 22.17 1.072	12.52 2.49 0.19	16.4 22.11 1.072	6.91 2.22 0.19	16.7 22.35 1.063	8.86 3.33 1.02
	200	P_{max} V_{oc} I_{sc}	6.967 20.28 0.537	8.611 21.33 0.536	23.59 5.18 0.19	7.615 21.17 0.536	9.30 4.39 0.19	7.655 21.61 0.5316	9.87 6.56 1.01

Table 4 – Relative errors of three models at different temperatures (E = 1000 W/m^2) for SP70 and ST40 modules

	T, °C	Parameters	Measured data	4-P model	Error %	5-P model	Error %	2D model	Error %
SP70 module	20	P_{max} V_{oc} I_{sc}	71.54 21.71 4.743	72.23 21.77 4.69	0.96 0.28 1.12	71.76 21.70 4.69	0.31 0.046 1.12	71.82 21.70 4.665	0.39 0.046 1.64
	40	P_{max} V_{oc} I_{sc}	64.77 20.18 4.736	65.29 20.26 4.73	0.80 0.39 0.13	65.15 20.25 4.73	0.59 0.35 0.13	65.38 20.24 4.705	0.94 0.29 0.65
	60	P_{max} V_{oc} I_{sc}	57.94 18.71 4.743	58.34 18.69 4.77	0.69 0.11 0.57	58.54 18.68 4.77	1.036 0.16 0.57	58.86 18.67 4.745	1.59 0.21 0.042

	T, °C	Parameters	Measured data	4-P model	Error %	5-P model	Error %	2D model	Error %
ST40 module	20	P_{max} V_{oc} I_{sc}	41.29 23.65 2.702	41.36 23.80 2.678	0.33 0.63 0.89	41.27 23.76 2.678	0.048 0.46 0.89	41.3 23.75 2.656	0.024 0.42 1.70
	40	P_{max} V_{oc} I_{sc}	36.36 21.7 2.702	36.09 21.79 2.685	0.74 0.41 0.63	36.19 21.77 2.685	0.47 0.32 0.63	36.29 21.75 2.663	0.19 0.23 1.44
	60	P_{max} V_{oc} I_{sc}	31.49 19.87 2.706	30.93 19.77 2.692	1.78 0.50 0.52	31.21 19.76 2.692	0.89 0.55 0.52	31.34 19.75 2.67	0.48 0.60 1.33

In Table 3, the analysis of relative error for I_{sc}, V_{oc} and the P_{max} of SP70 module at different irradiance levels is presented. In STC (1000 W/m^2, 25 °C), the voltage relative errors calculated by the 4-P, 5-P models and the two-diode model are 0.28 %, 0.094 % and 0.047 %, respectively, and the power relative errors calculated by the 4-P, 5-P models and the two-diode model are 1.61 %, 0.057 % and 0.21 %, respectively. However, as the irradiance is reduced, there is a significant deviation of V_{oc} calculated using the 4-P, 5-P and two-diode models. Similar results can be observed for P_{max}, but especially in the 4-P model, for irradiance lower than 400 W/m^2 the average error of the power exceeds 10 % and the voltage exceeds 3 % which explains the influence of the shunt resistance on the value of V_{oc} because of the term V_{oc}/R_{sh}.

Table 4 gives the performance of the three models at different temperatures with constant irradiance of 1000 W/m^2 for SP70 module, at T = 60 °C the voltage relative errors calculated by the 4-P, 5-P and two-diode models are 0.11 %, 0.16 % and 0.21 %, respectively, and the power relative errors calculated by the 4-P, 5-P and two-diode models are 0.69 %, 1.036 % and 1.59 %, respectively.

We note that the two-diode model and the five-parameter model are the least accurate at the three remarkable points at 60 °C compared to the four-parameter models. This is logical because the value of the ideality factor is assumed to be fixed in the five-parameter model and the two-diode model and, on the other hand, the values of the recombination and diffusion saturation currents are assumed to be equal in the two-diode model.

According to Table 4, the performance of the three models at different temperatures for ST40 module is presented. There is no significant difference between three models for V_{oc} at 60 °C.

Table 3 presents the analysis of the relative errors of I_{sc}, V_{oc} and P_{max} for ST40 module at different irradiance levels. However, the four-parameter model exhibits poor performance for P_{max} calculations, this difference can reach up to 12 % at 400 W/m^2. On the other hand, the 5-P model has good accuracy as manifested by the errors which are kept below 0.2 % for current, 2 % for voltage and 6 % for power A at low irradiation (400 W/m^2).

4. CONCLUSIONS

The present paper has proposed the comparison between the single-diode method (four- and five-parameter model) and tow-diode method. These models are used to predict the electrical response of three PV modules for various operating conditions. The accuracy of the three models is evaluated using experimental data given by the constructors for different types of technologies.

It can be concluded that the variation of ideality factor, shunt and series resistances have a large impact on the output power (P_{max}) of the ST40 module at different operating conditions. The results also indicate that the five-parameter model combined with the other models is the most adaptable for the thin-film modules (relative error = 6.91 %) at the low irradiance (400 W/m^2).

As a result of the study, it is observed that the two-diode circuit model has been shown to be more accurate representation of monocrystalline PV module SP70 (relative error = 1.49 %) at the low irradiance (400W/m^2).

In terms of accuracy, a generic statement cannot be easily made as to which of the method has the best performance. That is, there is no one model that performs best in all the parameter prediction.

In particular, excellent accuracy is exhibited at high irradiance and low temperature conditions for all models.

REFERENCES

1. Q. Jakhrani, A.K. Othman, A.R.H. Rigit, S.R. Samo, S.R. Kamboh, *Energy* **46** No 1, 675 (2012).
2. M.A. Green, *Prog. Photovolt.: Res. Appl.* **13**, 85 (2005).
3. T. Ghaitaoui, A. Benatiallah, Y. Sahli, H. Khachab, *J. Nano-Electron. Phys.* **10** No 1, 01008 (2018).
4. A. Kajihara, A.T. Harakawa, *IEEE International Conference on Industrial Technology* (ICIT), 866 (2005).
5. Y.T. Tan, D.S. Kirschen, N. Jenkins, *IEEE Trans. Energy Converts.* **19** No 4, 748 (2004).
6. A.N. Celik, N. Acikgoz, *Appl. Energy* **84** No 1, 1 (2007).
7. M.G. Villalva, J.R. Gazoli, E.R. Filho, *IEEE Trans. Power Electron.* **24** No 5, 1198 (2009).
8. K. Ishaque, Z. Salam, H. Taheri, *Sol. Energy Mater. Sol. Cells* **95** No2, 586 (2011).
9. T. Aernouts, W. Geens, J. Poortmans, P. Heremans, S. Borghs, R. Mertens, *Thin Solid Films* **403-404**, 297 (2002).
10. V.J. Chin, Z. Salam, K. Ishaque, *Energ. Convers. Manage.* **124**, 4250 (2016).
11. D.H. Muhsen, A.B. Ghazali, T. Khatib, I.A. Abed, *Energ. Convers. Manage.* **105**, 552 (2015).
12. S.-x. Lun, S. Wang, G.-h. Yang, T.-t. Guo, *Sol. Energy* **116**, 69 (2015).
13. F. Almonacid, C. Rus, L. Hontoria, F. J. Munoz, *Renewable Energy* **35**, 973 (2010).
14. T. Ghaitaoui, A. Benatiallah, H. Khachab, K. Koussa, *J. Ovonic Res.* **14** No 2, 79 (2018).
15. S. Jing Jun, L. Kay-Soon, *IEEE Trans. Power Electron.* **27** No 9, 3975 (2012).
16. P.H. Huang, W. Xiao, J.C.H. Peng, J.L. Kirtley, *IEEE Trans. Industrial Electron.* **63**, 1549 (2016).
17. A. Chatterjee, A. Keyhani, D. Kapoor, *Energy Conversion, IEEE Trans.* **PP**, 1 (2011).
18. A.H. Arab, F. Chenlo, M. Benghanem, *Sol. Energy* **76**, 713 (2004).
19. M.A. Blas, J.L., E. Prieto, A. Garcia, *Renewable Energy* **25**, 371 (2002).
20. G.R Walker, *J.Electri. Electron. Eng.* **21** No 1, 49 (2001).

Оцінка та вилучення електричних параметрів різних фотоелектричних моделей за допомогою ітераційних методів

B. Benabdelkrim[1,2], A. Benatillah[2], T. Ghaitaoui[2,3]

[1] *Department of Material Sciences, Institute of Science and Technology, University of Ahmed Draia, Adrar, Algeria*
[2] *Laboratory of Energy, Environment and Systems of Information (LEESI), University Ahmed Draia Adrar, Algeria*
[3] *Unité de Recherche en Energies Renouvelables en Milieu Saharien, URERMS, Centre de Développement des Energies Renouvelables, CDER, 01000, ADRAR, Algéria*

Фотоелектричний (PV) модуль зазвичай представлений еквівалентною схемою, параметри якої обчислюються за допомогою експериментальної вольт-амперної характеристики (I-V). Ці параметри мають вирішальне значення для прогнозування точної роботи PV модуля. Точне визначення цих параметрів залишається проблемою для дослідників, що призвело до диверсифікації в моделях та чисельних методах, які використовуються для їх обчислення. Ці параметри запропонованих сонячних PV модулей були розраховані за допомогою ефективної ітераційної методики. У цьому дослідженні використовуються дві математичні (одно- та дводіодні) моделі для вилучення невідомих параметрів у стандартних умовах тестування трьох різних типів технологій PV модулів (багатокристалічної, монокристалічної та тонкоплівкової). Проведено порівняльний аналіз цих моделей на основі моделювання MATLAB в різних кліматичних умовах та під впливом варіацій параметрів моделі. Отримані результати показали добре узгодження з результатами, отриманими експериментально, оскільки ці моделі відрізняються високою чутливістю і реагують на будь-які зміни кліматичних умов (температура, опромінення).

Ключові слова: PV модулі, Однодіодна модель, Двodіодна модель, Криві продуктивності I-V, Вилучення параметрів.