People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific research
M'hamed Bougara University, Boumerdes
Institute of Electrical and Electronic Engineering,
Laboratory of Signals and Systems (LSS)

ALGERIAN JOURNAL OF SIGNALS AND SYSTEMS

ISSN : 2543-3792

Title: **Mathematical Method for Parameters Calculation of electric Characteristic of Photovoltaic Module**

Authors: **B. Benabdelkrim [(1)] and A. Benatillah[(2)]**

Affiliations:

[(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,

Page range: **190- 200**

Volume : 3 Issue : 4 (December 2018)

Laboratory of Signals and Systems
Address : IGEE (Ex-INELEC), Boumerdes University, Avenue de l'indépendance, 35000, Boumerdes, Algeria
Phone/Fax : 024 79 57 66
Email : lss@univ-boumerdes.dz ; ajsyssig@gmail.com

ALGERIAN JOURNAL OF SIGNALS AND SYSTEMS (AJSS)

Mathematical Method for Parameters Calculation of electric Characteristic of Photovoltaic Module

B. Benabdelkrim [(1)*] A. Benatillah[(2)]
[(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,
*benaekbouchra@gmail.com

Abstract— The study of photovoltaic systems (PV) in an efficient manner requires a precise knowledge of the I-V characteristic curves of PV modules. An accurate current-voltage (I-V) model of PV modules is inherently implicit and non-linear and calls for iterative computations to obtain an analytical expression of current as a function of voltage. In this paper, numerical approaches are proposed to forecast the PV modules performance for engineering applications. The proposed approaches were implemented in a Matlab script and the results have been compared with the datasheet values provided by manufacturers in standard test conditions (STC). These approaches permit to extract the unknown parameters and also allow quantifying the effects of module temperature and irradiance on key cells parameters. In this work, a comparative study of the performance characteristics for different modules thin films and solid is analyzed by a single-diode equivalent circuit using four- and five-parameter models and two diode model.

Keywords- PV modules; Parameter extraction; Four parameter model; Five parameter model; Two diode model; Environmental conditions.

1. INTRODUCTION

The photovoltaic (PV) modules are generally rated under standard test conditions (STC) with the solar radiation of 1000 W/m2, 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, 2]. The growing demand of photovoltaic technologies led to research in the various aspects of its components from cell technology to the modeling, size optimization, and system performance [3–5]. Modeling of PV modules is one of the major components responsible for proper functioning of PV systems. Modeling provides the ways to understand the current, voltage, and power relationships of PV modules [6–8]. However, the estimation of models is affected by various intrinsic and extrinsic factors, which ultimately influence the behavior of current and voltage. Therefore, perfect modeling is essential to estimate the performance of PV modules in different environmental conditions. Hernanz et al. [9] compared the performance of solar cells with different models and pointed out that the manufacturers did not provide the values of the resistance in series and parallel of the manufactured cell.

Photovoltaic energy systems have become a key area of research in the recent times. The output of PV module mainly depends on solar irradiance and module temperature. There are many mathematical models in the literature for obtaining the characteristics of photovoltaic module. The mathematical model is expressed in terms of equivalent circuit. The parameters of the equivalent circuits are light generated current (Ipv), diode reverse saturation current (Io), series resistance (Rs), shunt resistance (Rsh) and diode ideality factor (a). All these parameters are calculated using the values available in PV datasheet [10].
This paper presents the modeling of electrical response of illuminated PV modules using analytical four-parameter model, an algebraic and analytical 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 (mono-crystalline, multi-crystalline, and thin-film).

2. PV MODULE MODELS

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

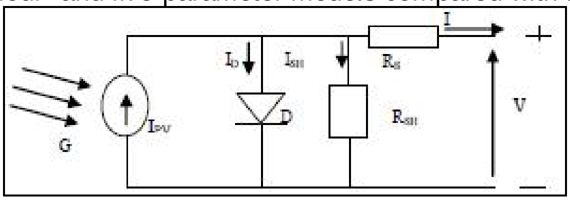


Figure.1. PV-cell equivalent-circuit models: single-diode model [11].

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

$$I = I_{pv} - I_0 \cdot \left(\exp\left(\frac{V + R_s . I}{V_T} \right) - 1 \right) - \left(\frac{V + R_s . I}{R_{sh}} \right) \quad (1)$$

Where

I_{pv}	Photocurrent
I_0	Cell saturation current
R_{sh}	Shunt resistance
R_s	Series resistance
V_T	the thermal voltage (V_T=a.Ns.k.T/q)
N_s	Number of cells in series
a	Ideal factor of the PV diode
q	Electron charge (1.60281×10^{-19} C)
k	Boltzmann's constant=1.38066×10^{-23} J/K
T	Cell operating temperature

2.1. Four-parameter model

The four-parameter model studied in this work has been used elsewhere [12, 13]. Assuming R_{sh} as infinite and neglecting it in Equation (1), the four-parameter model is obtained as follows:

$$I = I_{pv} - I_0 \cdot \left(\exp\left(\frac{V + R_s . I}{V_T} \right) - 1 \right) \quad (2)$$

The unknown parameters are denoted at STC as I_{pvn}, I_{0n}, a_n and R_{sn} ; where the "n" subscript refers to the reference operating conditions. The short circuit current can be found when V=0

$$I_{scn} = I_{pvn} \quad (3)$$

The following equations are used to calculate the other parameters at STC [12].

$$a_n = \frac{K_v - \frac{V_{ocn}}{T_n}}{V_{Tn} . \left(\frac{K_i}{I_{pvn}} - \frac{3}{T_n} - \frac{E_g}{k T_n^2} \right)} \quad (4)$$

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

$$R_{sn} = \frac{V_{Tn} . \ln\left(1 - \frac{I_{mpn}}{I_{pvn}}\right) + V_{ocn} - V_{mpn}}{I_{mpn}} \quad (6)$$

Where Eg is the band gap of the material The parameters can be found at any other operating conditions by using following equations:

$$I_{pv} = \frac{G}{G_n}\left[I_{pvn} + K_i(T - T_n)\right] \quad (7)$$

$$I_0 = I_{0n}\left(\frac{T}{T_n}\right)^3 \exp\left[\left(\frac{q.E_g}{a.k}\right)\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \quad (8)$$

$$R_s = R_{sn} \quad (9)$$

$$a = a_n.\frac{T}{T_n} \quad (10)$$

This model is implemented as follows: Eqs. (3)–(6) are used to find values of the four parameters under reference conditions. These four parameters are corrected for environmental conditions using Eqs. (7)–(10) and used in Eq. (2), which relates cell current to cell voltage. 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.

Accuracy test:
For example the above model equations are used to simulate Shell SP70 module in order to test its performance in fitting the I–V curve at standard test conditions (E =1000 W/m^2; T =25 °C), The specifications of this module is given in Table 1.

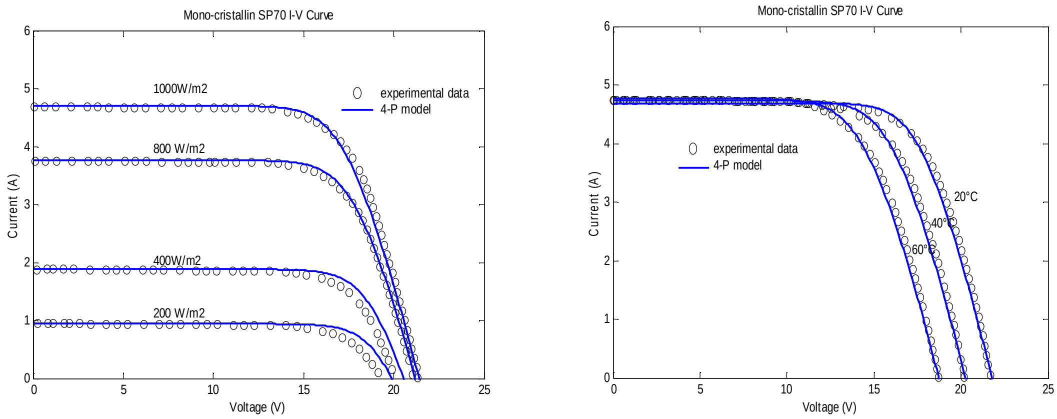


Figure.2. I(V) characteristic for Shell SP70 module using the 4-P model and for various irradiances and temperatures.

We can see in Figure. 2 that the model fits the I–V curve at the standard test conditions is accurate compared with the curve given by the manufacturer. However, the differences become apparent when conditions are farther away from the reference conditions.

2.2. 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 [14]. 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 [14-17].
The five parameters I_{pv}, I_o, 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} and using the following definitions of R_{so} and R_{sho}:

$$R_{s0} = -\left.\frac{dV}{dI}\right|_{V=V_{oc}} \quad (11)$$

$$R_{sh0} = -\left.\frac{dV}{dI}\right|_{I=I_{sc}} \tag{12}$$

Where R_{s0} and R_{sh0} are the reciprocals of the slopes at the open-circuit point and short-circuit point, respectively. The values of these resistances are not usually provided by module manufacturers. The other parameters are calculated as follows. The following equations are used to calculate the five parameters required.

$$I_{pv} = I_{sc}\left(1+\frac{R_s}{R_{sh}}\right) + I_0 \cdot \left(\exp\left(\frac{I_{sc}.R_s}{V_T}\right) - 1\right) \tag{13}$$

$$I_0 = \left(I_{sc} - \frac{V_{oc}}{R_{sh}}\right).\exp\left(-\frac{V_{oc}}{V_T}\right) \tag{14}$$

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 ≤ a≤ 2 and the chosen value depend on other parameters of the I–V model. As it's given in [18], 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 value of a can be later modified by using the proposed iterative method, in order to improve the model fitting [19].

$$a = \frac{V_{mp} + R_{s0} \cdot I_{mp} - V_{oc}}{V_T\left[\ln\left(I_{sc} - \frac{V_{mp}}{R_{sh}} - I_{mp}\right) - \ln\left(I_{sc} - \frac{V_{oc}}{R_{sh}}\right) + \frac{I_{mp}}{I_{sc} - \frac{V_{oc}}{R_{sh}}}\right]} \tag{15}$$

Where : $R_{sh} = R_{sh0}$ (16)

The R_s and R_{sh} resistances 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:

$$P_{max,m} = V_{mp} \times \left\{I_{pv} - I_0 \cdot \left(\exp\left(\frac{V_{mp} + R_s . I_{mp}}{V_T}\right) - 1\right) - \left(\frac{V_{mp} + R_s . I_{mp}}{R_{sh}}\right)\right\} = P_{max,e} \tag{17}$$

$$R_s = R_{s0} - \frac{V_T}{I_0}\exp\left(-\frac{V_{oc}}{V_T}\right) \tag{18}$$

$$R_{sh} = \frac{V_{mp} + R_s . I_{mp}}{I_{pv} - I_0 \cdot \left(\exp\left(\frac{V_{mp} + R_s . I_{mp}}{V_T}\right) - 1\right) - \frac{P_{max,e}}{V_{mp}}} \tag{19}$$

The initial condition for the shunt resistance R_{sh} can be found when considering the initial value of R_s=0 [20, 21]

$$R_{sh,min} = \frac{V_{mp}}{I_{sc} - I_{mp}} - \frac{V_{oc} - V_{mp}}{I_{mp}} \tag{20}$$

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 [22]. The flowchart of the proposed iterative method to adjust the I-V output characteristics of the solar cell is shown in Figure 3.

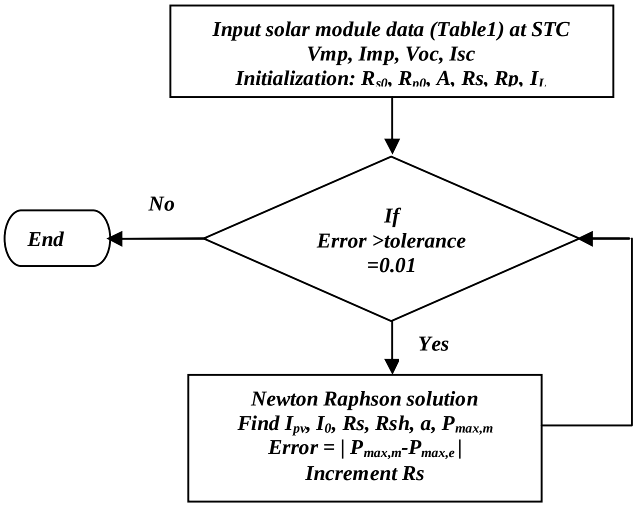


Figure3. Flowchart of the proposed iterative method to adjust the I-V output characteristics of the solar cell.

Accuracy test:

The accuracy is validated by comparing the results to the experimental I-V data extracted from the manufacturer datasheets (figs4).

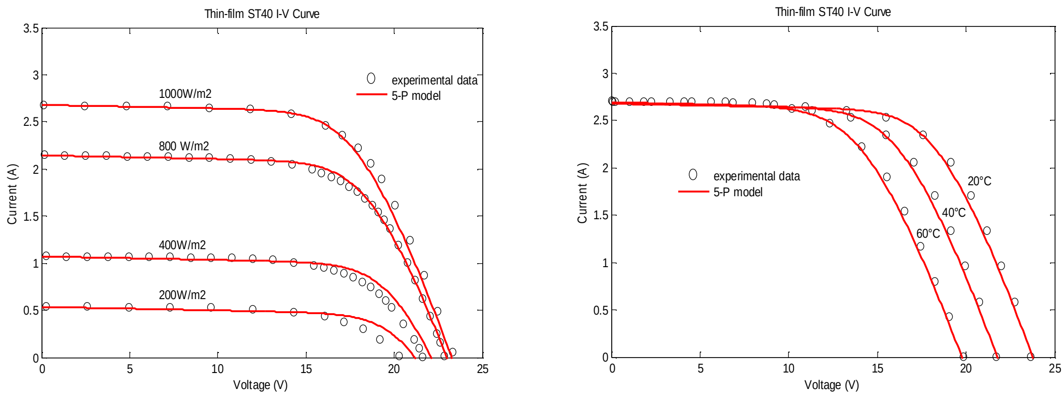


Figure.4. I(V) characteristic for Shell ST40 module using the 5-P model and for various irradiances and temperatures.

As an illustration, the IV characteristics of one of the PV modules, Shell ST40 (thin-film) is compared with the experimental result in Figure.4. A good agreement was observed between the simulated and the experimental data at higher irradiance and deviate from the actual at low irradiance.

2.3. Two- diode model

The two diode model (Fig.5) equation of the I–V curve is expressed as [23]:

$$I = I_{pv} - I_{01} \cdot \left(\exp\left(\frac{V + R_S . I}{V_{T1}} \right) - 1 \right) - I_{02} \cdot \left(\exp\left(\frac{V + R_S . I}{V_{T2}} \right) - 1 \right) - \left(\frac{V + R_S . I}{R_{sh}} \right) \quad (21)$$

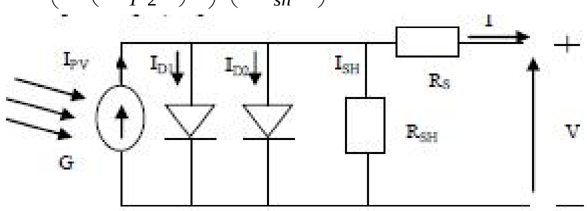


Figure.5. PV-cell equivalent-circuit models: two-diode model

Where the diode factors a_1=1 and a_2 can be derived from:

$$\frac{a_1 + a_2}{p} \geq 1 \qquad (22)$$

Where, p can be chosen greater than 2.2.
The rest of parameters can be deduced from the following equations [23]:

$$I_{pv} = I_{sc} \qquad (23)$$

$$I_{01} = I_{02} = \frac{I_{sc} + K_i.\Delta T}{\exp\left(\frac{q.(V_{oc} + K_v.\Delta T)}{kT.(a_1 + a_2)/p}\right) - 1} \qquad (24)$$

Rs and Rsh are calculated by iterative method, similar to the procedure proposed by [24], where the relation between Rs and Rsh is chosen to verify that the calculated maximum power is equal to the experimental one ($P_{max,m} = P_{max,e}$) at (V m, Im) point.
The Rs value is found by a slow incrementation by the same manner as the above subsection.
The expression of Rsh can be written as:

$$R_{sh} = \frac{V_{mp} + R_s.I_{mp}}{I_{pv} - I_{01}\left(\exp\left(q\frac{V_{mp} + R_s.I_{mp}}{k.T}\right) + \exp\left(q\frac{V_{mp} + R_s.I_{mp}}{(p-1)k.T}\right) + 2\right) - \frac{P_{max,e}}{V_{mp}}} \qquad (25)$$

Accuracy test:

Fig. 6 compares some of the results obtained at different operating conditions using the two diode model.

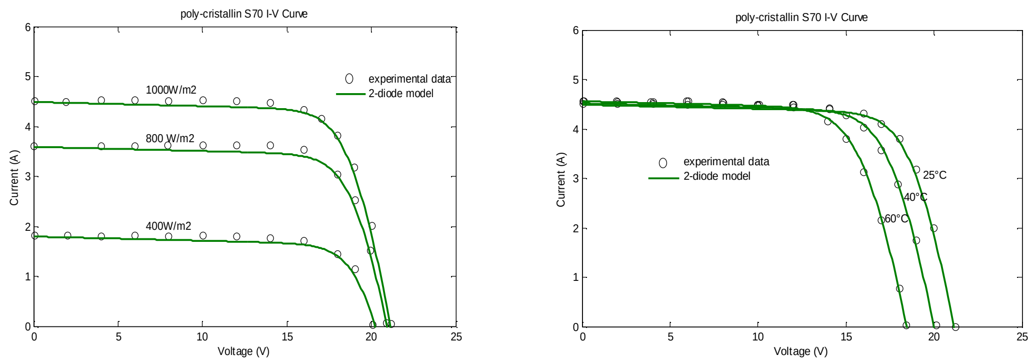


Figure.6. I(V) characteristic for Shell S70 module using the 2-D model and for various irradiances and temperatures.

It can be seen that the two-diode model is strongly agrees to experimental data for the poly-crystalline module.

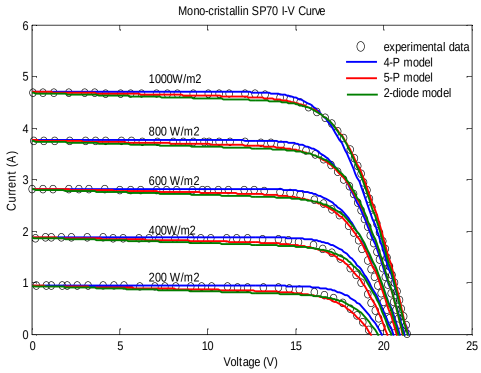
3. COMPARISON RESULTS AND DISCUSSION

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 multi- and mono-crystalline as well as thin-film types. The specifications of these modules are summarized in Table.1

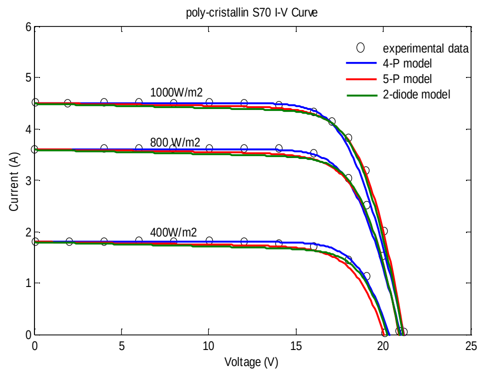
TABLE.1 STC specifications for the three modules.

Parameters	**Symbol**	**Mono-crystalline**	**Poly-crystalline**	**Thin-film**
		Shell SP70	**Shell S70**	**Shell ST40**
Rated power	P_{mp} (W)	70	70	40
Open circuit voltage	V_{oc} (V)	21.4	21.2	23.3
Short circuit current	I_{sc} (A)	4.7	4.5	2.68
Voltage at maximum power	V_{mp} (V)	16.5	17.0	16.6
Current at maximum power	I_{mp} (A)	4.25	4.12	2.41
Temperature coefficient of open-circuit voltage	K_v (mV/°C)	-76	-76	-100
Temperature coefficient of short-circuit current	K_i (mA/°C)	2	2	0.35
Number of cells	N_s	36	36	36

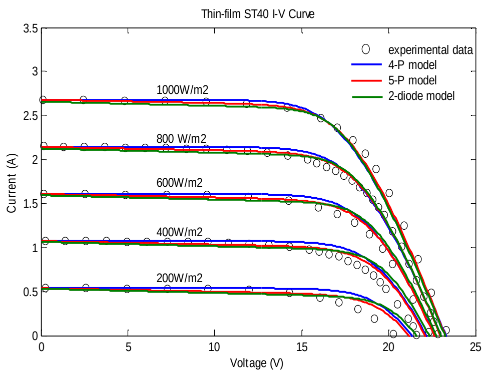
Figs. 7, 8 compare some of the results obtained at different operating conditions using the four parameter, five parameter and two diode models.
Fig (7) shows the I-V curves for modules for different levels of irradiance. It can be seen that, despite the modeling curves do not match experimental data in all points, the tow diode model strongly agrees to 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 four-parameter and tow diode models.
The performances with varying T are shown in Fig (8). In this case, G is kept constant at 1000 W/m^2. 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 method yields the most accurate results at all T.



(a)

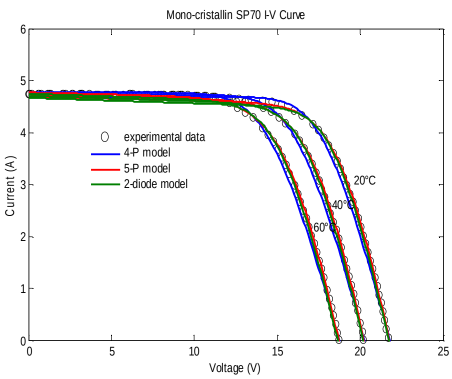


(b)

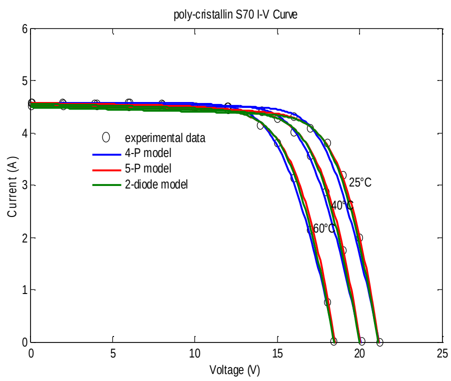


(c)

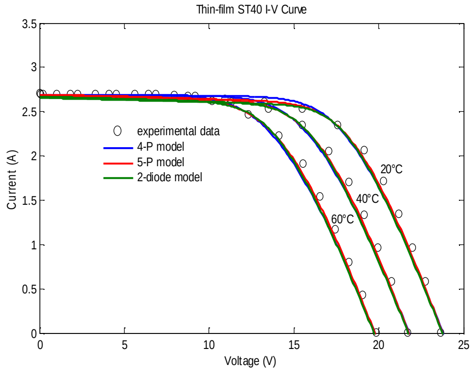
Figure.7. The I-V characteristics at varying irradiance (a) SP70, (b) S70, (c) ST40.



(a)



(b)



(c)

Figure.8. The I-V characteristics at varying temperature (a) SP70, (b) S70, (c) ST40.

Table.2 shows the parameters used for the four-parameter model. Four parameters are calculated namely, I_0, I_{PV}, ideality factor (a) and Rs. In the five parameter model, the additional calculated parameter is the shunt resistance; Rsh. and the two-diode model has more variables, the actual number of parameters computed is four because $I_{01}=I_{02}=I_0$ while a1=1 and p can be chosen arbitrarily, i.e. $p \geq 2.2$.

The two-diode model and the five parameter model exhibit similar results at STC. This is to be expected because both models use the similar max power matching algorithm to evaluate the model parameters at STC. However, at low irradiance, more accurate results are obtained from the two-diode model.

The value of Rsh accounts for the effects of leakage current in the p-n junction; its value is known to be relatively large, i.e. in the kΩ ranges [25]. Considering *Rsh* greatly affects the shape of the curve in the region between the short circuit point and MPP [26], this explains why the tow diode model tends to underestimate *I* at lower voltages, as observed in Fig. 7 and 8. This idea is reflected well by the five parameter method, where the computed value of Rsh is substantially larger than that of two-diode model for all modules.

TABLE.2 computed model parameters at STC

Parameters	Mono-crystalline Shell SP70	Poly-crystalline Shell S70	Thin-film Shell ST40
Four parameter model			
I_{pv} (A)	4.7	4.5	2.68
I_0 (A)	6.95284×10^{-10}	7.44601×10^{-10}	1.4202×10^{-8}
a	1.022	1.018	1.322
R_s (Ω)	0.631	0.455	1.616
Five parameter model			
I_{pv} (A)	4.715	4.505	2.696
I_0 (A)	8.7645×10^{-8}	9.910×10^{-8}	1.0292×10^{-8}
a	1.3	1.3	1.3
R_s (Ω)	0.4	0.22	1.51
R_{sh} (Ω)	133.131	189.026	266.548
Two diode model			
I_{pv} (A)	4.7	4.5	2.68
$I_{01}=I_{02}$ (A)	4.206×10^{-10}	4.999658×10^{-10}	3.074866×10^{-11}
R_s (Ω)	0.51	0.34	1.71
R_{sh} (Ω)	94.964	119.588	204.849192

Tables 3-6 present values of performance parameters under variation of irradiations and temperature levels for SP70 and ST40 modules.

TABLE.3. Relative errors of three models at different irradiances (T =25°C) for SP70 module.

Irradiance (W/m^2)	Parameters	Measured data	4-P model	5-P model	2D model
	Pmax	70.07	70.5	70.11	70.22
1000	Voc	21.33	21.39	21.35	21.34
	Isc	4.682	4.7	4.7	4.675
	Pmax	56.13	57.61	55.95	56.38
800	Voc	21.03	21.18	21.07	21.13
	Isc	3.752	3.76	3.76	3.74
	Pmax	27.53	29.62	26.76	27.12
400	Voc	19.92	20.53	20.19	20.43
	Isc	1.882	1.88	1.88	1.87
	Pmax	13.17	14.72	12.08	11.99
200	Voc	19.12	19.81	19.25	19.65
	Isc	0.9472	0.94	0.94	0.935

TABLE.4: Relative errors of three models at different temperatures (E =1000 W/m^2) for SP70 module.

Temperature (°C)	Parameters	Measured data	4-P model	5-P model	2D model
	Pmax	71.54	72.23	71.76	71.82
20	Voc	21.71	21.77	21.70	21.70
	Isc	4.743	4.69	4.69	4.665
	Pmax	64.77	65.29	65.15	65.38
40	Voc	20.18	20.26	20.25	20.24
	Isc	4.736	4.73	4.73	4.705
	Pmax	57.94	58.34	58.54	58.86
60	Voc	18.71	18.69	18.68	18.67
	Isc	4.743	4.77	4.77	4.745

TABLE.5. Relative errors of three models at different irradiances (T =25°C) for ST40 module.

Irradiance (W/m^2)	Parameters	Measured data	4-P model	5-P model	2D model
	Pmax	40.21	40.03	39.99	40.04
1000	Voc	23.29	23.30	23.27	23.26
	Isc	2.677	2.68	2.68	2.658
	Pmax	31.71	33.04	32.68	32.97
800	Voc	22.85	23.02	22.99	23.04
	Isc	2.149	2.144	2.144	2.126
	Pmax	15.34	17.26	16.4	16.7
400	Voc	21.63	22.17	22.11	22.35
	Isc	1.074	1.072	1.072	1.063
	Pmax	6.967	8.611	7.615	7.655
200	Voc	20.28	21.33	21.17	21.61
	Isc	0.537	0.536	0.536	0.5316

TABLE.6: Relative errors of three models at different temperatures (E =1000 W/m^2) for ST40 module.

Tempetaure (°C)	Parameters	Measured data	4-P model	5-P model	2D model
20	Pmax	41.29	41.36	41.27	41.3
	Voc	23.65	23.80	23.76	23.75
	Isc	2.702	2.678	2.678	2.656
40	Pmax	36.36	36.09	36.19	36.29
	Voc	21.7	21.79	21.77	21.75
	Isc	2.702	2.685	2.685	2.663
60	Pmax	31.49	30.93	31.21	31.34
	Voc	19.87	19.77	19.76	19.75
	Isc	2.706	2.692	2.692	2.67

4. CONCLUSION

The present paper has proposed the investigation of the performance of four-parameter, five-parameter and tow-diode models. These models used to predict the electrical response of illuminated mono-crystalline Shell SP70, poly-crystalline S70 and thin-film ST40 PV modules for various operating conditions. The accuracy of the proposed models is evaluated using practical data from manufacturers of three different types of PV modules. Its performances are compared with the experimental values given by the constructors of the different modules. It has been found that, the tow-diode model is better when subjected to variations in irradiance and temperature. And gives better accuracy for reconstructing the electrical characteristics of mono-crystalline and poly-crystalline PV modules, but for thin-film PV module the five parameter model is closer to the experimental data at the low irradiance.

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.

Accordingly, the proposed study may help in the development of new photovoltaic systems by reducing costs and time as well as a better understanding of their performance

References

[1] W. Durisch, D. Tille, A. Worz, and W. Plapp, "Characterisation ¨ of photovoltaic generators," *Applied Energy*, vol. 65, no. 1–4, pp. 273–284, 2000.

[2] A. Q. Jakhrani, A. K. Othman, A. R. H. Rigit, S. R. Samo, and S. R. Kamboh, "A novel analytical model for optimal sizing of standalone photovoltaic systems," *Energy*, vol. 46, no. 1, pp. 675– 682, 2012.

[3] N. Celik, "A simplifed model based on clearness index for estimating yearly performance of hybrid pv energy systems," *Progress in Photovoltaics: Research and Applications*, vol. 10, no. 8, pp. 545–554, 2002.

[4] H. Fanney and B. P. Dougherty, "Building integrated photovoltaic test facility," *Journal of Solar Energy Engineering*, vol. 123, no. 3, pp. 194–199, 2001.

[5] M. A. Green, "Short communication: price/efciency correlations for 2004 photovoltaic modules," *Progress in Photovoltaics: Research and Applications*, vol. 13, pp. 85–87, 2005.

[6] A. Q. Jakhrani, A. K. Othman, A. R. H. Rigit, and S. R. Samo, "Model for estimation of global solar radiation in Sarawak, Malaysia," *World Applied Sciences Journal*, vol. 14, pp. 83–90, 2011.

[7] Q. Jakhrani, A. K. Othman, A. R. H. Rigit, and S. R. Samo, "Assessment of solar and wind energy resources at fve typical locations in Sarawak," *Journal of Energy & Environment*, vol. 3, pp. 8–13, 2012.

[8] R. Ramaprabha and B. L. Mathur, "Development of an improved model of SPV cell for partially shaded solar photovoltaic arrays," *European Journal of Scientifc Research*, vol. 47, no. 1, pp. 122–134, 2010.

[9] J. A. R. Hernanz, J. J. C. ampayo Martin, I. Z. Belver, J. L. Lesaka, E. Z. Guerrero, and E. P. Perez, "Modelling of photovoltaic module," in *Proceedings of the International Conference on Renewable Energies and Power Quality (ICREPQ '10)*, Granada, Spain, March 2010.

[10] Villalva, M. G., and Gazoli, J. R., "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Transactions on Power Electronics*, vol. 24, no. 5, pp. 1198-1208, 2009.

[11] A. Chatterjee, A. Keyhani, and D. Kapoor, "Identification of Photovoltaic Source Models," *Energy Conversion, IEEE Transactions on,* vol. PP, pp. 1-7, 2011.

[12] Celik, A. N. and Acikgoz, N. "Modelling and experimental verification of the operating current of mono-crystalline photovoltaic modules using four- and five-parameter models", Applied Energy 84 (2007): 1–15.

[13] Arab, A. H., Chenlo, F., Benghanem, M.,. "Loss- of-load probability of photovoltaic water pumping systems", Solar Energy 76 (2004): 713–723.

[14] Phang JCH, Chan DSH, Philips JR. Accurate analytical method for the extraction of solar-cell model parameters. Electron Letters, 20 (1984) 406–408.

[15] Blas MA, Torres JL, Prieto E, Garcia A. Selecting a suitable model for characterizing photovoltaic devices. Renewable Energy, 25 (2002) 371–380.

[16] Kou Q, Klein A, Beckman WA. A method for estimating the long-term performance of direct-coupled PV pumping systems. Solar Energy, 64 (1998) 33–40.

[17] Chenlo F, Fabero F, Alonso MC. Testing, norms, reliability and harmonization: a comparative study between indoor and outdoor measurement. Agencia EUREC, Joule. JOUII-CT92-0178, Brussels: European Commission, (1996).

[18] Marcelo G. Villalva, Jonas R. Gazoli, and Ernesto R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays ", IEEE Transactions on Power Electronics, 24 (2009) 1198 - 1208.

[19] A. Gastli and H. Bourdoucen, "Study and Modeling of PV Arrays Built with Non-Equivalent Units", International Conference on Communication, Computer & Power (ICCCP'07), (2007) 186- 191.

[20] Villalva, M.G., Gazoli, J.R., Filho, E.R. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Trans. Power Electron. 24 (2009) 1198–1208

[21] Ishaque, K., Salam, Z., Taheri, H., Shamsudin, A. A critical evaluation of EA computational methods for photovoltaic cell parameter extraction based on two diode model. Sol. Energy 85 (2011) 1768–1779**.**

[22] Walker, G.R.: Evaluating MPPT topologies using a Matlab PV model. Journal of Electrical & Electronics Engineering 21 (2001) 49-56.

[23] Ishaque, K., Salam, Z., Taheri, H., 2011a. Simple, fast and accurate twodiode model for photovoltaic modules. Sol. Energy Mater. Sol. Cells 95 (2), 586–594.

[24] Villalva, M.G., Gazoli, J.R., Filho, E.R., 2009. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Trans. Power Electron. 24, 1198–1208.

[25] V. J. Chin, Z. Salam, and K. Ishaque, "Cell modelling and model parameters estimation techniques for photovoltaic simulator application: A review," *Applied Energy,* vol. 154, no. 0, pp. 500-519, 9/15/, 2015.

[26] J. A. Gow, and C. D. Manning, "Development of a photovoltaic array model for use in power-electronics simulation studies," *Electric Power Applications, IEE Proceedings -,* vol. 146, no. 2, pp. 193-200, 1999.