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Modeling improvement of the four parameter model for photovoltaic modules

R. Khezzar [a,*], M. Zereg [a], A. Khezzar [b]

[a] Laboratoire de Physique Energétique Appliquée (LPEA), Université Hadj Lakhdar, 05000 Batna, Algeria
[b] Laboratoire d'électrotechnique de Constantine, Université Constantine 1, Algeria

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Abstract

The aim of the present work is to introduce some improvements on the four parameter model of the photovoltaic cells in order to fit the variation of the current voltage characteristic *I–V* under various operating conditions. That is achieved by modifying both the open voltage equation and the voltage at the maximum power point, in order to take into consideration the effects of the variation of the equivalent circuit parameters with irradiation and temperature. The accuracy of this model is verified by using seven PV modules of different types (mono-crystalline, multi-crystalline, and thin-film) from various manufacturers and compared with the five parameter and the two diode models, where it gives the same or better performances. Moreover, it is motivated by the known simplicity of the four parameter model and the small amount of input data requested which can make it as a valuable tool for PV power converter designers and circuit simulator developers.

Keywords: Photovaltaic modeling; Four parameter model; Two diode model; Five parameter model; PV irradiation variation; PV temperature variation

1. Introduction

The photovoltaic module is typically represented by an equivalent circuit whose parameters are calculated using the experimental current voltage characteristic *I–V*. The precise estimation of these parameters remains a challenge for researchers in order to obtain a model which closely emulates the characteristics of photovoltaic cells under specified or no specified irradiance and temperature conditions. Unfortunately, that led to a diversification in models and the differences are mainly in the number of diodes quoted in the model, the shunt resistance infinite or finite, the factor of ideality constant or not and the numerical methods used for determining their parameters (King, 1996; de Blas et al., 2002; Khezzar et al., 2009; Dib et al., 1999; Ma et al., 2014; Gong and Cai, 2013; Ishaque et al., 2011a; Ishaque and Salam, 2011c; Saloux et al., 2011; Van der Heide et al., 2005; Xiao et al., 2004; Chegaar et al., 2001).

In literature, one can find principally the equivalent model with four parameters associated with mathematical modeling of the current–voltage *I–V* curve and which can be considered as the most popular one (Smith and Reiter, 1984; Sera et al., 2008; Eckstein, 1990). In this model the effect of the shunt resistance is neglected because its value is particularly important, especially for Si-crystallin modules (Townsend, 1989; Kuo et al., 2001; Celik and Acikgoz, 2007). The four parameter model offers a good accuracy which reaches the accuracy of the two diode

* Corresponding author.
E-mail address: r-khezzar@hotmail.com (R. Khezzar).

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Nomenclature

$\mu_{I_{sc}}$	temperature coefficient of short circuit current I_{sc}	k	Boltzmann constant
$\mu_{V_{oc}}$	temperature coefficient of open circuit voltage V_{oc}	N_s	number of cells in series
A	diode ideality factor	q	electron charge
I_0	diode saturation current	R_s	series resistance
I_L	photocurrent	R_p	shunt resistance
I_m	current at the point of maximal power	T	cell température
I_{sc}	short circuit current	V_m	voltage at the point of maximal power
		V_{oc}	open circuit voltage

model, if a negative answer for the series resistance is accepted as a model value without a physical meaning (Wagner, 2000; Sera et al., 2008). However, Dongue et al. (2012) reported that the four parameter model which neglects the effects of the shunt resistance is inadequate to fit experimental *I–V* curve (Ma et al., 2014) and presents a serious deficiencies when subjected to high temperature variations because it does not account for the open circuit voltage coefficient, K_V (Ishaque et al., 2011a; Walker, 2001).

The four unknown parameters namely are: I_L (the photocurrent), I_0 (the saturation current), A (ideality factor) and R_s (the series resistance). Zhou (2007) have introduced other parameters for this model to take account of all the non-linear effects of the environmental factors on the PV module performance, especially the solar irradiance and the PV-module temperature. When the shunt resistance is considered in the four parameter model, the number of parameters is increased to five. Using this model, the accuracy is improved, especially at the lower sunlight intensities (Ishaque et al., 2011b,a; De Soto et al., 2006; Celik and Acikgoz, 2007; Chan and Phang, 1987; Hsiao et al., 2010; Bryan, 1999; Sera et al., 2007; Carrero et al., 2007). Although the application of the two diode model that is known to have better accuracy than a single-diode circuit but with more complex computational effort makes it less attractive than the single diode model. (King et al., 1996; Ishaque et al., 2011; Wolf et al., 1977; Gow and Manning, 1999; Chan and Phang, 1987).

The objective of the present paper is to propose some modifications on the four parameter model in order to fit the variation of the current voltage characteristics *I–V*, and this is achieved by modifying the equation which describes the open-circuit voltage. This model takes into consideration the effects of the variation of the equivalent circuit parameters with irradiation and temperature and is motivated by its known simplicity. The accuracy of the simulation results is verified by comparing it with published data provided by manufacturers of seven PV modules of different types (mono-crystalline, multi-crystalline, and thin-film). A comparison between the improved four parameter model with five parameter and two diode ones is also presented which shows that this model combine between simplicity, accuracy and small amount of input data available from the manufacturer.

The simplicity and accuracy of the proposed model are of real importance for the circuit simulator developer and the PV system designer including the different control schemes of power converters, as the max power point tracking MPPT or for fault diagnosis.

2. The four parameter model

The four parameter model is one of the mainly used for modeling solar cells, from which one can describe the cell current–voltage curve as (Fig. 1) (Kuo et al., 2001; De Soto, 2004; Celik and Acikgoz, 2007; Sera et al., 2008):

$$I = I_L - I_0\left[exp\left(q\frac{V + IR_s}{N_sAkT}\right) - 1\right] \tag{1}$$

The four unknown parameters in this model are I_L (the photocurrent), I_0 (the saturation current), A (ideality factor) and R_s (the series resistance). These parameters are estimated from specified measurements of the *I–V* curve (V_{oc} open circuit voltage, I_{sc} short circuit current, I_m and V_m the voltage and current at the maximum power point respectively). These values are usually given by the manufacturer at reference values of irradiance and temperature ($E_{ref} = 1000\ \mathrm{W/m^2}, T_{ref} = 25\ ^\circ$ C, spectrum AM1.5) or from direct measurement on the module (De Soto, 2004; Townsend, 1989).

By using them as three couples of points from the *I–V* curve $(0, I_{sc}), (V_{oc}, 0)$ and (V_m, I_m) in Eq. (1), we obtain

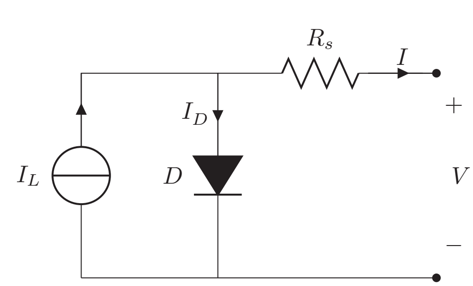

Fig. 1. Equivalent circuit of the four parameter model.

the following set of equations used to identify the unknown parameters:

$$I = I_L - I_0\left[exp\left(q\frac{I_{sc}R_s}{N_sAkT}\right) - 1\right] \tag{2}$$

$$0 = I_L - I_0\left[exp\left(q\frac{V_{oc}}{N_sAkT}\right) - 1\right] \tag{3}$$

$$I_m = I_L - I_0\left[exp\left(q\frac{V_m + I_mR_s}{N_sAkT}\right) - 1\right] \tag{4}$$

2.1. Model parameters estimation

By observing Eqs. (2)–(4), it is clear that we are in front of a problem of three equations with four unknowns and this gives diversification in the choice of the equation to add and the method of resolution to use. Without any convincing proof of the superiority of specified method in the literature, we use the explicit simplified method based on a purely mathematical resolution with some justified simplifications as is shown in references Sera et al. (2008) and Townsend (1989). Eqs. (2)–(4) become:

$$I_{sc} = I_L \tag{5}$$

$$0 = I_L - I_0exp\left(q\frac{V_{oc}}{N_sAkT}\right) \tag{6}$$

$$I_m = I_L - I_0exp\left(q\frac{V_m + I_mR_s}{N_sAkT}\right) \tag{7}$$

From Eqs. (5) and (6) one can deduce the saturation current:

$$I_0 = I_{sc}\left[exp\left(-\frac{q}{N_sAkT}V_{oc}\right)\right] \tag{8}$$

and from that Eq. (1) becomes:

$$I = I_{sc}\left[1 - exp\left(q\frac{V - V_{oc} + IR_s}{N_sAkT}\right)\right] \tag{9}$$

The equation at the point of maximum power at its turn becomes:

$$I_m = I_{sc}\left[1 - exp\left(q\frac{V_m - V_{oc} + I_mR_s}{N_sAkT}\right)\right] \tag{10}$$

where from it, we can deduce the value of series resistance:

$$R_s = \frac{\frac{N_sAKT}{q}ln\left(1 - \frac{I_m}{I_{sc}}\right) + V_{oc} - V_m}{I_m} \tag{11}$$

The last parameter to estimate is the ideality factor A, by exploiting the fact that the power derivative at the maximum point is zero:

$$\frac{dP}{dV} = 0 = V\frac{\partial I}{\partial V} + I\frac{\partial V}{\partial V} \tag{12}$$

and by using Eq. (1) one can find:

$$A = \frac{q(2V_m - V_{oc})}{N_skT\left[\frac{I_m}{I_{sc}-I_m} + ln\left(1 - \frac{I_m}{I_{sc}}\right)\right]} \tag{13}$$

The variation of different parameters versus the variation of irradiance or temperature are usually expressed as (De Soto, 2004; Celik and Acikgoz, 2007; Sera et al., 2008):

For the short circuit current and open circuit voltage cases:

$$I_{sc} = I_{sc}^{ref}\frac{E}{E_{ref}} + \mu_{I_{sc}}(T - T_{ref}) \tag{14}$$

$$V_{oc} = V_{oc}^{ref} + V_t ln\left(\frac{E}{E_{ref}}\right) + \mu_{V_{oc}}(T - T_{ref}) \tag{15}$$

where:

$$V_t = \frac{N_sAkT}{q}$$

and for the current and voltage at the maximum power point cases:

$$I_m = I_m^{ref}\frac{E}{E_{ref}} + \mu_{I_{SC}}(T - T_{ref}) \tag{16}$$

$$V_m = V_m^{ref} + V_t ln\left(\frac{E}{E_{ref}}\right) + \mu_{V_{oc}}(T - T_{ref}) \tag{17}$$

2.2. The four parameter model performance tests

The above model equations are used to simulate Shell SP75 module in order to test its performance in fitting the I–V curve at standard test conditions ($E = 1000\ \mathrm{W/m^2}, T = 25\ ^\circ\mathrm{C}$) (Shell Solar Product Information Sheets, 2014, Table 1) and after that, the authors have attempted to estimate the behavior of a solar panel for different irradiances using the estimated model parameters and the obtained results are compared with those of the manufacturer (Table 2).

One can see in Figs. 2 and 3 that the model fits the I–V curve at the standard test conditions, that is evident as the model is forced to trace a smooth curve through the three couples of points given by the manufacturer (short circuit, open circuit. and maximum power points). However, the differences become apparent when conditions are farther away from the reference conditions. From Table 2 we can underline the inaccuracy in the determination of the parameters V_m and V_{oc} and in order to remove this obvious

Table 1
Electrical characteristic of photovoltaic cell Shell SP75 at standard condition test.

Standard irradiance	E_{ref}	1000 W/m^2
Standard temperature	T_{ref}	25 °C
Maximal power	$p_{m_{ref}}$	75 W
Voltage at maximal power point	$V_{m_{ref}}$	17 V
Current at maximal power point	$I_{m_{ref}}$	4.4 A
Open circuit voltage	$V_{oc_{ref}}$	21.7 V
Short circuit current	$I_{sc_{ref}}$	4.8 A
Temperature coefficient of I_{sc}	$\mu_{I_{sc}}$	2 mA/°C
Temperature coefficient of V_{oc}	$\mu_{V_{oc}}$	−76 mV/°C
Cell number	N_s	36

Table 2
Shell SP75 Cell parameters values for $E = 800\ \mathrm{W/m^2}, E = 400\ \mathrm{W/m^2}$ and $T = 25\ °\mathrm{C}$.

	$I_{sc}(A)$	$I_m(A)$	$V_{oc}(V)$	$V_m(V)$
$E = 800\ W/m^2\ \&\ T = 25\ °C$				
Measured data	3.84	3.52	21.43	17
Calculated values	3.84	3.52	21.3777	16.6777
$E = 400\ W/m^2\ \&\ T = 25\ °C$				
Measured data	1.92	1.76	20.6	17.2
Calculated values	1.92	1.76	20.3764	15.6764

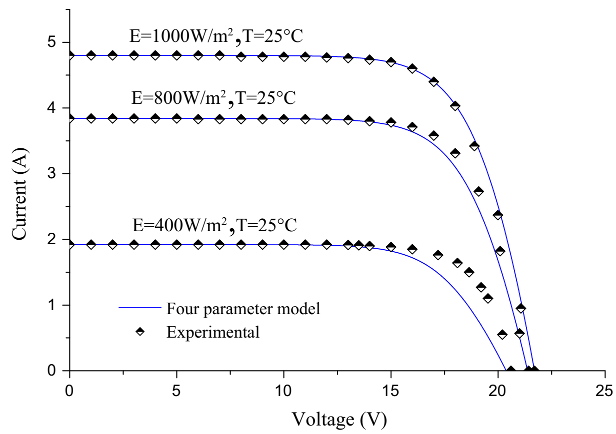

Fig. 2. $I(V)$ characteristic for Shell SP75 module using the explicit method and for various irradiances.

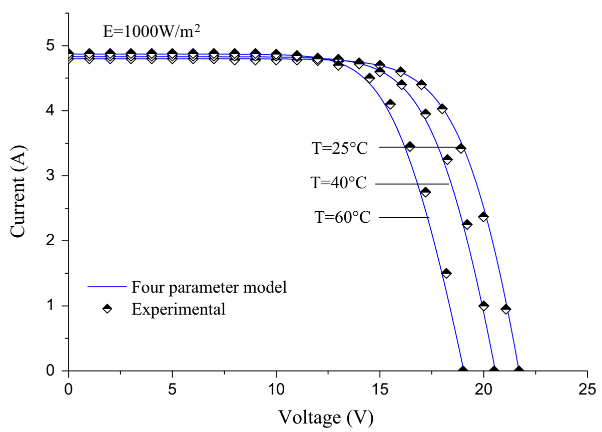

Fig. 3. $I(V)$ characteristic for Shell SP75 module using the explicit method and for various temperatures.

drawback, the authors efforts will focus on its correction in the next section.

3. Proposed improvements for the four parameter model

In order to get the suitable improvements, it is necessary to modify Eqs. (15) and (17) to correct the values of V_{oc} and V_m.

From literature, researchers have proposed many works in order to take into account the irradiance and temperature variation with different models and for different goals. In this section, we focus just on the correction of the voltage Eqs. (15) and (17), using some modifications noticed and justified for other goals in references (Zhou, 2007 and Van Dyk et al., 2002). The voltage equations are proposed to become:

$$V_{oc} = \frac{V_{oc}^{ref}}{1 + \beta_1 \ln\left(\frac{E_{ref}}{E}\right)} \left(\frac{T_{ref}}{T}\right)^{\gamma_1} \tag{18}$$

$$V_m = \frac{V_m^{ref}}{1 + \beta_2 \ln\left(\frac{E_{ref}}{E}\right)} \left(\frac{T_{ref}}{T}\right)^{\gamma_2} \tag{19}$$

where $\beta_1, \beta_2, \gamma_1$ and γ_2 are constant parameters for the PV module.

The values of the $\beta_1, \beta_2, \gamma_1$ and γ_2 parameters can be determined using limited data provided by the PV module manufacturers (Table 3) as:

$$\beta_1 = \frac{\frac{V_{oc}^{ref}}{V_{oc}^1} - 1}{\ln\left(\frac{E_{ref}}{E_1}\right)}, \quad \gamma_1 = \frac{\ln\left(\frac{V_{oc}^{ref}}{V_{oc}^2}\right)}{\ln\left(\frac{T_1}{T_{ref}}\right)} \tag{20}$$

$$\beta_2 = \frac{\frac{V_m^{ref}}{V_m^1} - 1}{\ln\left(\frac{E_{ref}}{E_1}\right)}, \quad \gamma_2 = \frac{\ln\left(\frac{V_m^{ref}}{V_m^2}\right)}{\ln\left(\frac{T_1}{T_{ref}}\right)} \tag{21}$$

Table 4 shows the calculated parameters V_{oc} and V_m obtained using Eqs. (18) and (19) which are in concordance with the measured data from the manufacturer's datasheet. Figs. 4 and 5 show that the improved four parameter model yields good results anf fits very well the I–V PV module curves under different operating conditions.

4. Comparison of the improved four parameter model with other models

In order to verify the accurateness of the proposed improvements for the four parameter model, a comparison is conducted with the five parameter model (Villalva et al., 2009) and the two diode model (Ishaque et al., 2011a) using experimental measurements given by manufacturers of seven photovoltaic cells with different technologies (multi-crystalline, mono-crystalline and thin-film). Eqs. (18) and (19) are also used with the five parameter model and the two diode model to ensure that the comparison is conducted under the best performances of each model.

4.1. The five parameter model

The five parameter model (Fig. 6) is characterized by its cell current–voltage equation:

Table 3
Detailed data requirements for calculation of $\beta_1, \beta_2, \gamma_1$ and γ_2 parameters.

	E_{ref}		E_1	
T_{ref}	V_{oc}^{ref}	V_m^{ref}	V_{oc}^1	V_m^1
T_1	V_{oc}^2	V_m^2		

Table 4
Shell SP75 cell parameters values for $E = 800$ W/m^2, $E = 400$ W/m^2 and $T = 25$ °C considering the improved four parameter model.

	$I_{sc}(A)$	$I_m(A)$	$V_{oc}(V)$	$V_m(V)$
$E = 800\ W/m^2$ & $T = 25\,°C$				
Measured data	3.84	3.52	21.43	17
Calculated values	3.84	3.52	21.4213	17.0483
$E = 400\ W/m^2$ & $T = 25\,°C$				
Measured data	1.92	1.76	20.6	17.2
Calculated values	1.92	1.76	20.5996	17.2002

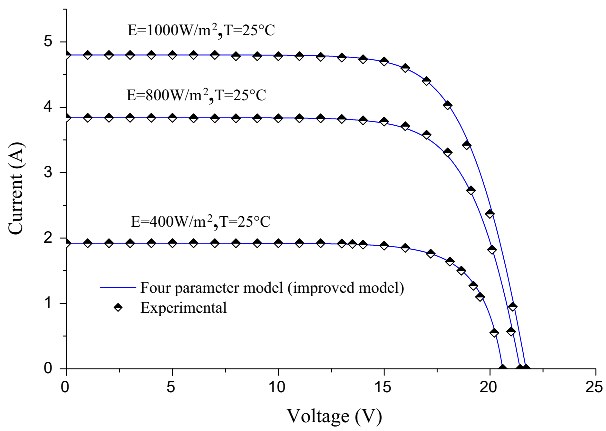

Fig. 4. $I(V)$ characteristic for Shell SP75 module using the explicit method and for various irradiances (improved model).

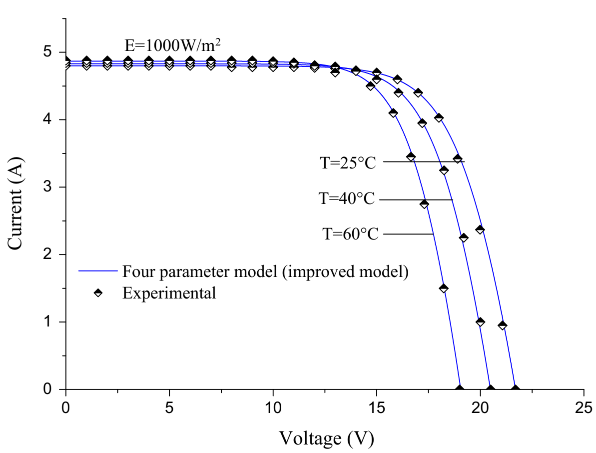

Fig. 5. $I(V)$ characteristic for Shell SP75 module using the explicit method and for various temperatures (improved model).

$$I = I_L - I_0\left[exp\left(q\frac{V + IR_s}{AkT}\right) - 1\right] - \left(\frac{V + IR_s}{R_p}\right) \tag{22}$$

The unknown parameters are I_L, I_0, R_s, R_P and A where the photo current is equal to the short circuit one $I_L = I_{sc}$ and the value of the diode quality factor A may be arbitrarily chosen, usually $1 \leqslant A \leqslant 1.5$ (Villalva et al., 2009).

The saturation current is expressed by:

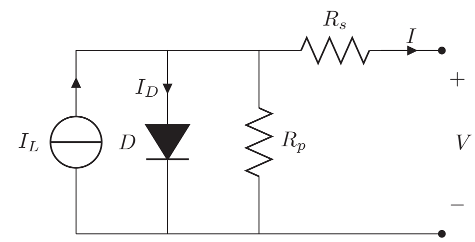

Fig. 6. Equivalent circuit of the five parameter model.

$$I_0 = \frac{(I_{sc} + \mu_{I_{sc}}\Delta T)}{exp\left[q\left(\frac{V_{oc}+\mu_{V_{oc}}\Delta T}{AkT}\right)\right] - 1} \tag{23}$$

The R_s and R_p resistances are calculated by iterative methods. The relation between R_s and R_p, 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, Rs must be slowly incremented starting from Rs = 0 and for every iteration, the value of R_p is calculated simultaneously:

$$P_{max,m} = V_m \times \left\{I_L - I_0\left[exp\left(q\frac{V_m + I_mR_s}{AkT}\right) - 1\right] - \left(\frac{V_m + I_mR_s}{R_p}\right)\right\} = P_{max,e} \tag{24}$$

$$R_p = \frac{V_m + I_mR_s}{I_L - I_0\left[exp\left(\frac{q(V_m+I_mR_s)}{AkT}\right) - 1\right] - \frac{P_{max,e}}{V_m}} \tag{25}$$

The initial condition for the shunt resistance R_p can be found when considering the initial value of $R_s = 0$ (Villalva et al., 2009; Ishaque et al., 2011a),

$$R_{p,\,min} = \frac{V_m}{I_{sc} - I_m} - \frac{V_{oc} - V_m}{I_m} \tag{26}$$

4.2. The two diode model

The two diode model (Fig. 7) equation of the I–V curve is expressed as (Ishaque et al., 2011a):

$$I = I_L - I_{01}\left[exp\left(q\frac{V + IR_s}{A_1kT}\right) - 1\right] - I_{02}\left[exp\left(q\frac{V + IR_s}{A_2kT}\right) - 1\right] - \left(\frac{V + IR_s}{R_p}\right) \tag{27}$$

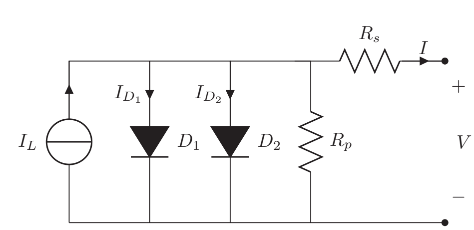

Fig. 7. Equivalent circuit of the two diode model.

where the diode factors $A_1 = 1$ and A_2 can be derived from:

$$\frac{A_1 + A_2}{p} \geqslant 1 \tag{28}$$

where p can be chosen greater than 2.2.

The rest of parameters can be deduced from the following equations (Ishaque et al., 2011a):

$$I_L = I_{sc} \tag{29}$$

$$I_{01} = I_{02} = \frac{I_{sc} + \mu_{I_{sc}} \Delta T}{exp\left[\frac{q\left(V_{oc}+\mu_{V_{oc}}\Delta T\right)}{KT(A_1+A_2)/p}\right] - 1} \tag{30}$$

R_s and R_p are calculated by iterative method, similar to the procedure proposed by (Villalva et al., 2009), where the relation between R_s and R_p 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.

The R_s value is found by a slow incrementation by the same manner as the above subsection.

The expression of R_p can be written as:

$$R_p = \frac{V_m + I_m R_s}{I_L - I_{01}\left(exp(q\frac{V_m+I_m R_s}{k\,T}) + exp(q\frac{V_m+I_m R_s}{(p-1)k\,T}) + 2\right) - \frac{P_{max,e}}{V_m}} \tag{31}$$

4.3. Comparison and discussion

In this section the improved four parameter model proposed in this paper is compared with both the five parameter and the two diode models for different photovoltaic cell technologies (Monocristalline, polycristalline and Thin-film). Table 5 shows the data obtained from the manufacturers datasheets for different cell types at 25 °C and 1000 W/m^2 and the calculated parameters for each model.

Figs. 8–19 compare some of the results obtained at different operating conditions using the five parameter and two diode models versus those obtained using the

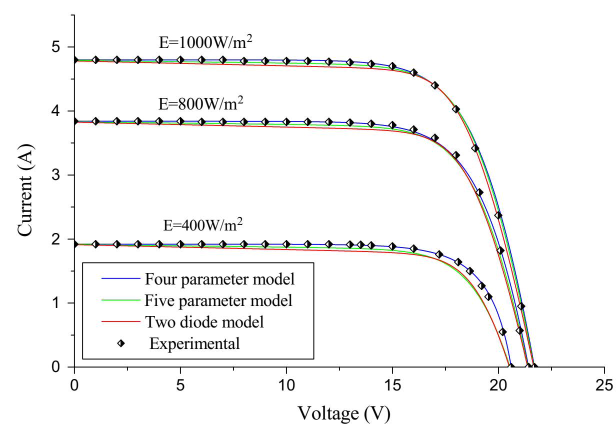

Fig. 8. $I(V)$ characteristic for SP75 monocrystalline PV module using the different models and for various irradiances.

Table 5
STC specifications for the used modules and the calculated parameters of the three models.

	Monocrystalline		Polycrystalline			Thin-film	
	Shell SP75	Shell SQ150	SST 230-60P	Shell S70	MSX-60	GxB-340	Shell ST40
I_{sc} (A)	4.8	4.8	8.52	4.5	3.8	9.3	2.68
V_{oc} (V)	21.7	43.4	36.7	21.2	21.1	51.4	23.3
I_m (A)	4.4	4.4	7.83	4.12	3.5	8.5	2.41
V_m (V)	17	34	29.4	17.0	17.1	40	16.6
$\mu_{I_{sc}}$ (mA/°C)	2	1.4	3.83	2	3	0.06	0.35
$\mu_{V_{oc}}$ (mV/°C)	−76	−161	−128	−76	−80	−0.27	−100
N_s	36	72	60	36	36	72	36
Calculated parameters for the four parameter model							
I_L (A)	4.8	4.8	8.52	4.5	3.8	9.3	2.68
A	1.5619	1.5619	1.6230	1.6535	1.5519	1.8922	1.6144
R_s (Ω)	0.2524	0.5048	0.1293	0.1020	0.1017	0.3311	1.3582
I_0 (A)	1.4356×10^{-6}	1.4356×10^{-6}	3.6230×10^{-6}	4.2889×10^{-6}	1.5662×10^{-6}	3.8926×10^{-6}	4.4734×10^{-7}
Calculated parameters for the five parameter model							
I_L (A)	4.8	4.8	8.52	4.5	3.8	9.3	2.68
A	1.3	1.3	1.3	1.3	1.3	1.5	1.3
R_s (Ω)	0.33	0.67	0.2	0.25	0.2	0.37	1.52
R_p (Ω)	236.7684	466.46	152.6382	311.8126	304.83	132.5701	284.1
I_0 (A)	6.9570×10^{-8}	6.975×10^{-8}	9.4629×10^{-8}	9.886×10^{-8}	9.094×10^{-8}	8.3667×10^{-8}	1.0264×10^{-8}
Calculated parameters for the two diode model							
I_L (A)	4.8	4.8	8.52	4.5	3.8	9.3	2.68
R_s (Ω)	0.45	0.9	0.34	0.39	0.35	0.6	1.76
R_p (Ω)	129.5295	275	118.9356	173.1676	176.4	91.7557	211.7
$I_{01} = I_{02}$ (A)	3.0958×10^{-10}	3.1068×10^{-10}	3.8877×10^{-10}	4.9837×10^{-10}	4.70×10^{-10}	7.9358×10^{-12}	3.0641×10^{-11}

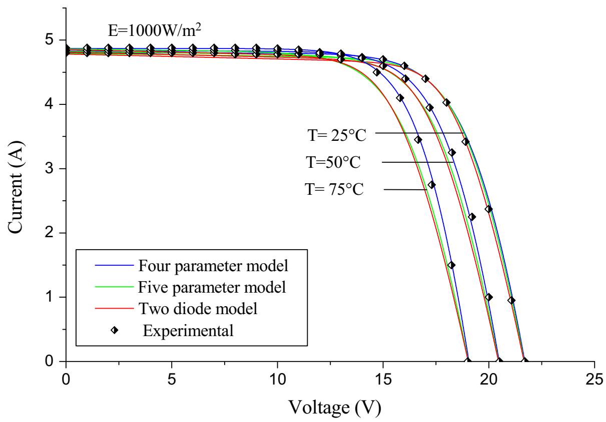

Fig. 9. $I(V)$ characteristic for SP75 monocrystalline PV module using the different models and for various temperature.

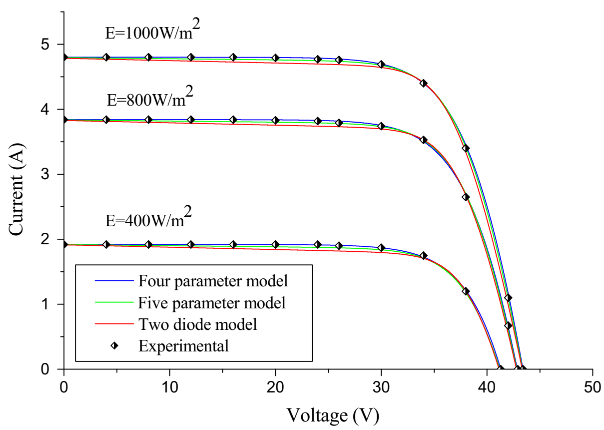

Fig. 10. $I(V)$ characteristic for SQ150 monocrystalline PV module using the different models and for various irradiances.

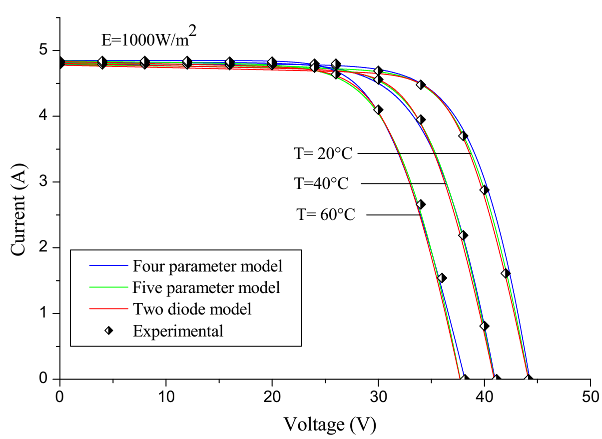

Fig. 11. $I(V)$ characteristic for SQ150 monocrystalline PV module using the different models and for various temperatures.

improved four parameter model. The obvious conclusion from these figures is that the I–V curves generated by the improved four parameter model are the more accurate ones in fitting the measured data given by the corresponding modules manufacturers.

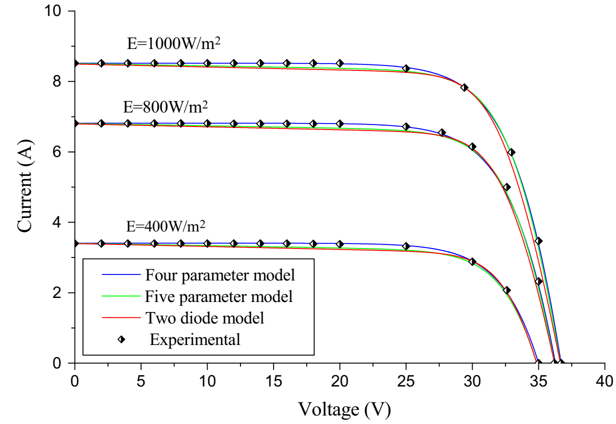

Fig. 12. $I(V)$ characteristic for SST 230 polycrystalline PV module using the different models and for various irradiances.

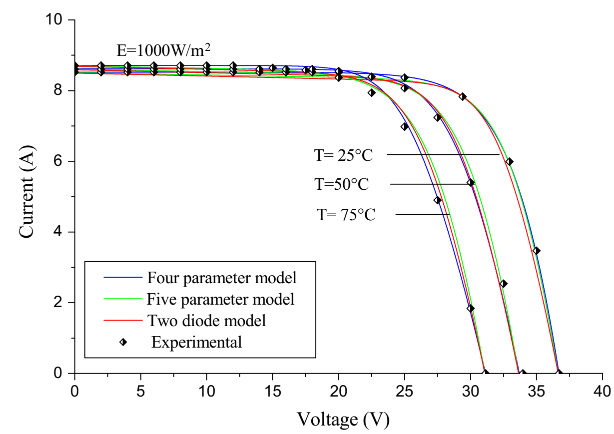

Fig. 13. $I(V)$ characteristic for SST 230 polycrystalline PV module using the different models and for various temperatures.

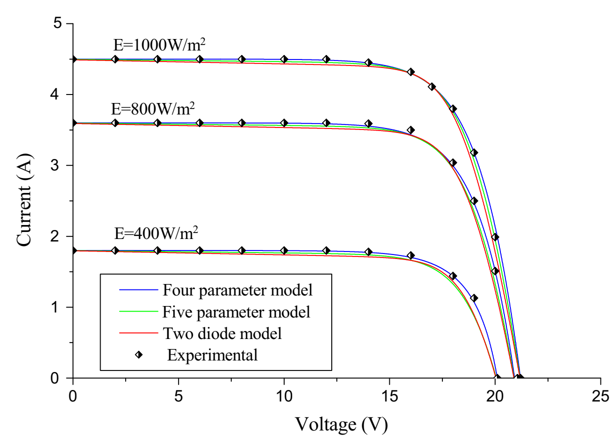

Fig. 14. $I(V)$ characteristic for Shell S70 polycrystalline PV module using the different methods and for various irradiances.

Moreover, the time-varying operating point is as close as possible to the time-varying maximum power point (MPP), especially during peak solar radiation periods. Therefore, the comparison of the predicted maximum power with the measured one over a wide range of

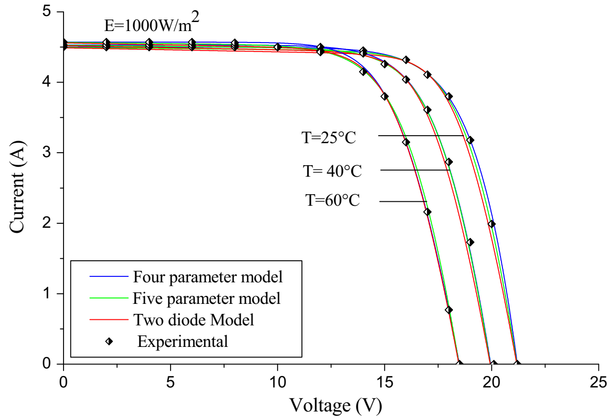

Fig. 15. $I(V)$ characteristic for Shell S70 polycrystalline PV module using the different methods and for various temperatures.

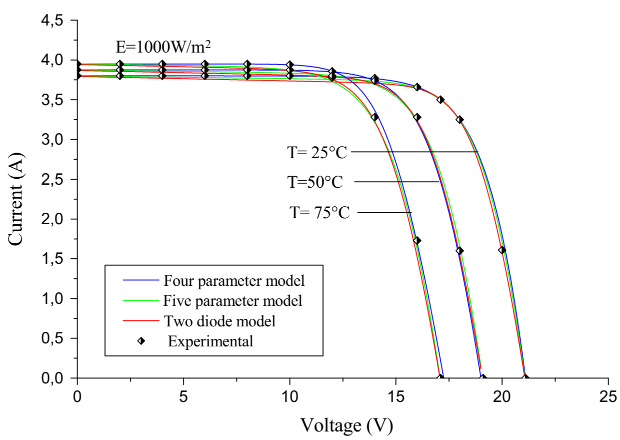

Fig. 16. $I(V)$ characteristic for MSX 60 polycrystalline PV module using the different methods and for various temperatures.

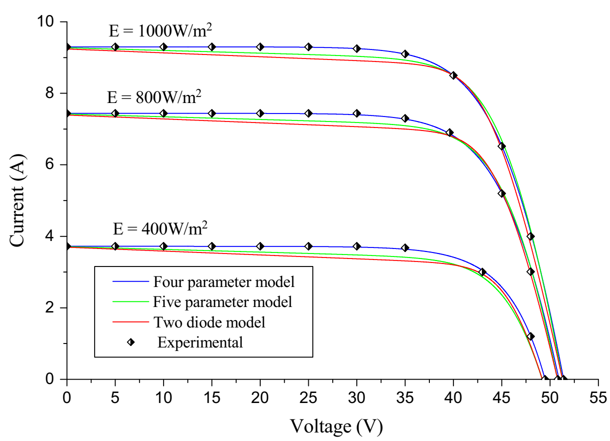

Fig. 17. $I(V)$ characteristic for GxB-340 thin film PV module using the different methods and for various irradiances.

operating conditions provides a stringent test of the I–V model's accuracy.

Tables 6 and 7 show the computed relative errors between the measured and predicted maximum power for

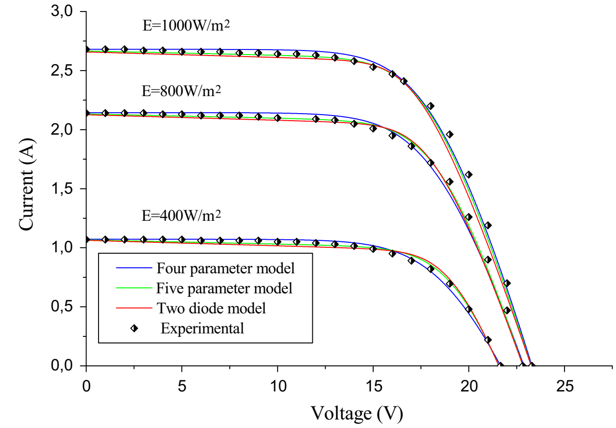

Fig. 18. $I(V)$ characteristic for ST 40 thin film PV module using the different models and for various irradiances.

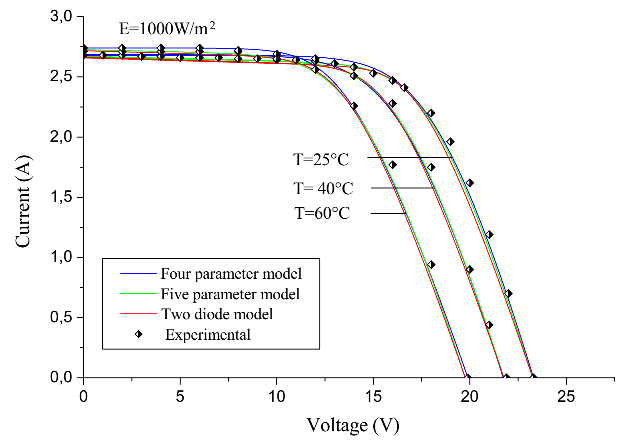

Fig. 19. $I(V)$ characteristic for ST 40 thin film PV module using the different models and for various temperatures.

different test conditions for the SQ150 module. The choice of the SQ150 module is motivated by the fact that the five parameter model and the two diode model give the best I–V fitting (Figs. 10 and 11) and that allows us to underline a correct conclusion when comparing them with the improved four parameter model.

The differences between measured and predicted values for all of the models are close to zero and the improved four parameter model gives the same accuracy in predicting the MPP for the SQ150 module and is more accurate when considering the other modules (Figs. 8–19). The similarities in the prediction of the maximum power point accuracy is due to the fact that the three models consider this point of particular importance and take it as a particular solution for the three models equations.

The accuracy of predicting the maximum power point by the improved four parameter model remains generally under 1% for the different type of cell modules and under different conditions of irradiances and temperatures.

The comparison based on the error that makes use of only the maximum power point for the different models is more useful in applications where the PV cell is expected

Table 6
Relative errors on the MPP of four parameter, five parameter and two diode models at different irradiances ($T = 25\,^{\circ}$C) for SQ 150 module.

Irradiance (W/m^2)	Measured data	4-P model	5-P model	2-D model	Error 4-P model (%)	Error 5-P model (%)	Error 2-D model (%)
1000	$P_{max} = 149.6$ $V_m = 34$	$P_{max} = 149.6$ $V_m = 34$	$P_{max} = 149.877$ $V_m = 34.05$	$P_{max} = 149.87$ $V_m = 34.06$	0.0000 at P_{max} 0.0000 at V_m	0.1851 at P_{max} 0.1470 at V_m	0.1804 at P_{max} 0.1764 at V_m
800	$P_{max} = 120$ $V_m = 33.9$	$P_{max} = 119.2$ $V_m = 33.85$	$P_{max} = 119.7$ $V_m = 34.05$	$P_{max} = 120.1$ $V_m = 34.25$	0.6666 at P_{max} 0.1474 at V_m	0.2500 at P_{max} 0.4424 at V_m,	0.0833 at P_{max} 1.0324 at V_m
400	$P_{max} = 59.5$ $V_m = 33.45$	$P_{max} = 58.8$ $V_m = 33.4$	$P_{max} = 58.2$ $V_m = 33.55$	$P_{max} = 58.01$ $V_m = 34.1$	1.1764 at P_{max} 0.1494 at V_m	2.1848 at P_{max} 0.2989 at V_m	2.5042 at P_{max} 1.9431 at V_m

Table 7
Relative errors on the MPP of four parameter, five parameter and two diode models at different temperatures ($E = 1000$ W/m^2) for SQ 150 module.

Temperature (°C)	Measured data	4-P model	5-P model	2-D model	Error 4-P model (%)	Error 5-P model (%)	Error 2-D model (%)
20	$P_{max} = 153$ $V_m = 34.8$	$P_{max} = 153.6$ $V_m = 34.99$	$P_{max} = 153.15$ $V_m = 34.86$	$P_{max} = 153.5$ $V_m = 34.88$	0.3921 at P_{max} 0.5459 at V_m	0.0980 at P_{max} 0.2216 at V_m	0.3267 at P_{max} 0.2298 at V_m
40	$P_{max} = 140$ $V_m = 31.58$	$P_{max} = 136.4$ $V_m = 31.4$	$P_{max} = 138.2$ $V_m = 31.65$	$P_{max} = 138.9$ $V_m = 31.65$	2.5714 at P_{max} 0.5699 at V_m	1.2857at P_{max} 0.2216 at V_m,	0.7857 at P_{max} 0.2216 at V_m
60	$P_{max} = 126$ $V_m = 28.35$	$P_{max} = 125.2$ $V_m = 28.15$	$P_{max} = 123.3$ $V_m = 28.47$	$P_{max} = 124.4$ $V_m = 28.45$	0.6349 at P_{max} 0.7054 at V_m	2.1428 at P_{max} 0.4232 at V_m	1.2698 at P_{max} 0.3527 at V_m

to operate at this point. The proposed model is suitable also to operate at different points and in order to determine whether this model is a good approximation of measured data or not, the percentage root mean square (RMS) errors were calculated using five important points:

- $V = 0$ voltage equals zero.
- $V = 0.5V_{oc}$ voltage equals half of the open circuit voltage.
- $V = V_m$ voltage equals the voltage at the maximum power point.
- $V = 0.5(V_{oc} + V_m)$ voltage equals half of the sum of the open circuit voltage and the voltage at the maximum power point.
- $V = V_{oc}$ voltage equals the open circuit voltage.

The percentage RMS errors were calculated using the following equation:

$$\%RMS = \frac{\sqrt{\frac{\sum_{i=1}^{5}(I_{measured\ data} - I_{model\ data})^2}{5}}}{I_{measured\ data,SC}} \times 100 \qquad (32)$$

Table 8 shows the RMS errors obtained when using the above five important points for the different models and for three types of solar cell with different technologies (mono-crystalline, multi-crystalline, and thin-film). One can notice that the improved four parameter model provides the best match with experimental data and this is due to the fact that the improved four parameter model does not guess any value and all parameters are expressed by analytical formulas. In plus, the proposed improvements are used to overcome the known weakness of the four parameter model when subject to climatic varying conditions.

On the other hand, the five parameter model proposed by (Villalva et al., 2009) and the two diode model proposed by (Ishaque et al., 2011a) focus on three remarkable points, the short circuit current I_{sc}, the open source voltage V_{oc} and the maximum power point MPP which are assured by forcing the choice of R_s and R_p to fit them. The particular obvious weakness of these two models is the arbitrarily choice of the values of diodes ideality factors, A for the five parameter model, A_1 and A_2 for two diode model. It is well known that the ideality factor affects the curvature of the I–V curves and decreases the I–V fitting accuracy of the model undoubtedly. Moreover, the choice that generally $1 \leqslant A \leqslant 1.5$ (Villalva et al., 2009) for the five parameter model is not the best interval for all modules. For instance, when taking $A = 1.9$ for the GxB-136 module that gives best I–V fitting than when considering $A = 1.5$ (see Fig. 20). Using the percentage RMS errors for the five parameter model as a criteria to choose A iteratively can

Table 8
RMS Errors calculated using five points ($T = 25\,^{\circ}$C) for SQ150, ST40 and SST230 modules.

Irradiance (W/m^2)	RMS error four parameter model (%)			RMS error five parameter model (%)			RMS error two diode model (%)		
	SQ150	ST40	SST 230	SQ150	ST40	SST 230	SQ150	ST40	SST 230
1000	**0.3125**	**1.7421**	**0.1082**	0.3313	2.2239	0.76651	0.8283	3.0928	2.0278
800	**0.3005**	**1.8300**	**1.6553**	0.8523	2.1550	1.6819	1.7345	2.1851	2.2392
400	**0.3827**	**1.6951**	**0.9864**	1.5111	2.2515	2.1280	2.6557	2.8436	2.6743

Bold values indicates the best obtained results.

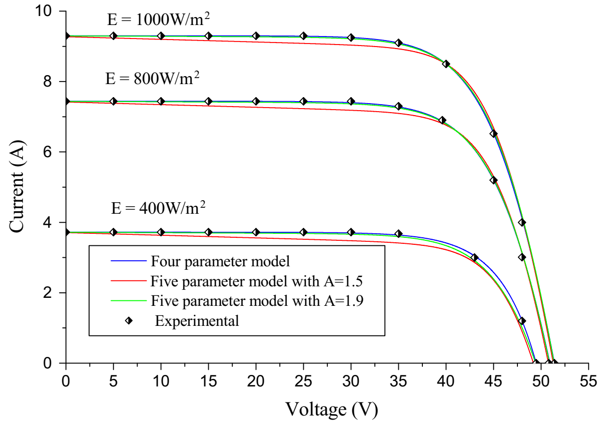

Fig. 20. Influence of diode ideality factor on the accuracy of the five parameter model.

be considered as a good optimization even that increases the calculation complexity. In the case of two diode model optimizing the choice of the two diodes factors is more complicated to realize.

5. Conclusion

The present paper has proposed new improvements to the four parameter model of photovoltaic solar cells under varying operating conditions (solar radiation and temperature). It has been shown that when correcting only the open and maximum voltage equations in the four parameter model gives more accuracy than the five parameter or the two diode models in fitting the PV current–voltage characteristics. These improvements are confirmed with different cell types (mono-crystalline, multi-crystalline, and thin-film) from various manufacturers.

It is envisaged that the proposed model can be used as a potential tool for PV power converter designers and circuit simulator developers. In plus, to validate the different control schemes as the MPPT or fault diagnosis.

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