Solar Energy 162 (2018) 403–409

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

A fast modeling of the double-diode model for PV modules using combined analytical and numerical approach

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ARTICLE INFO

Keywords:
PV module
Double-diode model
Modeling
Computational time

ABSTRACT

This paper proposes a fast and accurate method through utilizing combined analytical and numerical approach to determine the five parameters double diode model of photovoltaic (PV) modules. The proposed formulations are developed based on the main points given by the PV datasheets i.e., the open circuit voltage (V_{OC}), the short circuit current (I_{SC}), and the current and voltage at the maximum power point (I_M,V_M). In order to reduce computational time, some approximations and simplifications have been applied to make analytical equations and calculations simpler and manageable. In addition, a rapid and accurate iterative numerical method is proposed to determine the value of series resistance R_S. To validate its accuracy the obtained results from proposed method are compared with experimental data of PV module from different technologies: mono-crystalline, poly-crystalline and thin film. Furthermore, the effectiveness of the model is shown by comparing its accuracy and computational time, against two well-known modeling methods for double diode model. The results show that in the proposed method, in spite of computational time reduction, better precision is provided as well. It is envisaged that the proposed model can be useful for PV designers who require a fast, accurate and simple approach for modeling the PV modules.

1. Introduction

Nowadays, economic growth of countries is highly dependent on energy supplies. As a result, to reduce the usage of finite natural resources and fossil fuels which are harmful to the environment, some activities are raised worldwide in terms of technology to access clean and renewable energy sources instead. From among all renewable energy sources, solar energy is the most promising energy and photovoltaic (PV) systems provide the most direct way to convert solar energy into electrical energy by utilizing the inherent properties of semiconductors (Sheraz Khalid and Abido, 2014).

Due to high investment costs and ensuring optimized utilization of solar energy, accurate and reliable simulation for designed PV systems before installation is highly essential.

PV electrical characteristics can be modeled through representing it with equivalent electrical circuit. It is always desirable to provide a model that closely emulate the behavior of physical solar cells i.e., matches the measured *I-V* data under all operating conditions (Chin et al., 2015a). In order to describe the current-voltage relationship for PV cells/modules, two main equivalent electrical circuit models, namely the single-diode (Majdoul et al., 2015; Villalva et al., 2009; Ding et al., 2014; Cubas et al., 2014; Shongwe and Hanif, 2015; Silva et al., 2016; Park and Choi, 2015; Ayodele et al., 2016; Yildiran and Tacer, 2016; Deihimi et al., 2016) and double-diode (Ishaque et al., 2011; Gupta and et al., 2012; Hejri et al., 2014; Babu and Gurjar, 2014; Adel, 2014; Jacob et al., 2015; Muhsen and Ghazali, 2015; Chin et al., 2015b, 2016) models are widely used by various researchers, which have difference in precision and simplicity. Increasing the number of parameters in double diode model demands a significant challenge to maintain a reasonable computational time. However, due to providing more accuracy in predicting the *I-V* characteristic behavior especially under low irradiation levels conditions, it poses an attractive option in the literature (Chin et al., 2015a; Ishaque et al., 2011).

In general, there are two types of methods to extract the parameters of the solar cell/module models proposed in the literatures, namely: analytical and numerical approach (Chin et al., 2015a). Analytical solution is fast, but due to the nonlinearity and multi-variability in extracting the parameters of solar cells /modules, it is difficult to determine parameters accurately alone with analytical methods without any simplifications and assumptions in it (Majdoul et al., 2015). Therefore, recent numerical approaches use artificial intelligence techniques or the soft computing methods to determine the double diode model parameters, such as: Differential evolution (DE) Chin et al., 2015b, 2016, Artificial Immune System (AIS) Jacob et al., 2015 and

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https://doi.org/10.1016/j.solener.2018.01.047
Received 31 January 2017; Received in revised form 10 November 2017; Accepted 15 January 2018

Hybrid evolutionary algorithms (EA) Muhsen and Ghazali, 2015. However, many of these algorithms are inaccessible and difficult to use. Furthermore, these methods lead to longer computational time compared with common simple iterative numerical approaches. As mentioned above, another aspect that must be considered in double-diode model parameters extraction is about the complexity of the analytical equations. In this case, in order to make it simpler and manageable, some reasonable approximation is required. For example, in Ishaque et al. (2011) both diode saturation current values are considered equal, it contradicts the well-known fact that I_{S2} is at least two orders of magnitude greater than I_{S1} Chin et al. (2016). For double diode models, several authors have also calculated both I_{S1} and I_{S2} parameters with analytical and iterative numerical methods, which leads to complexity of equations (Hejri et al., 2014; Adel, 2014). In (Babu and Gurjar, 2014), in order to simplify the model equations, the effects of both shunt R_{SH} and series R_S resistances are neglected. Ignoring R_S greatly affects the model accuracy, particularly for the data points which are in the vicinity of the V_{OC} region Chin et al. (2016).

To simplify, several authors assumed diode ideality factors a_1 and a_2 equal to 1 and 2 respectively, based on the approximations of the Schokley–Read–Hall recombination in the depletion region in the photodiode. However, this assumption is not always true (Ishaque et al., 2011). The value of "a_1" and "a_2" is considered "1" and "larger than 1.2" respectively in Ishaque et al. (2011). It should be noted that the wrong choice of a_2 yeilds significant error in calculation of other parameters. In (Adel, 2014), the ideality factors are given as $a_1 + a_2 = 3$ for multi-crystalline and thin film solar cells and $a_1 + a_2 = 4$ for amorphous solar cell. However, these relationships do not always lead to reliable convergence and have no physical basis (Chin et al., 2016). Authors in Chin et al. (2015b, 2016) extract the double diode parameters by using Differential Evolution method (DE). It has been found that diode ideality factors a_1 and a_2 obtained from mentioned methods are reliable and give more accurate results in calculation of other parameters which lead to the model, fitting well with the *I-V* curve. Thus, the authors decided to use these values in their computational methods.

The iterative algorithm proposed by Ishaque et al. (2011) which extended the (Villalva et al., 2009) method for double diode model can efficiently extract the series and parallel resistances with a reasonable computational time, but this model is not very accurate in the proximities of the open circuit point region under standard test conditions (STC), due to ignoring the series and parallel resistances during the analytical calculation of the reverse saturation current (Wang et al., 2016). Authors in Babu and Gurjar (2014) have also used the same algorithm, but instead of determining the exclusion R_S and R_{SH}, the values of the diode ideality factors a_1 and a_2 are estimated with the similar conditions. Recently, a combined analytical and numerical method is proposed in Majdoul et al. (2015) to extract the single diode five parameters model. Its iterative numerical algorithm has excellent balance between the calculation time and the accuracy.

In this work, the authors have extended single diode method proposed in Majdoul et al. (2015) and applied it to the double-diode model. In fact, combined analytical and numerical methods have been proposed to extract the parameters of a five-parameter double-diode model of PV modules which only require coordinates of three key points of the *I-V* curves, i.e., the open circuit voltage (V_{OC}), the short circuit current (I_{SC}), and the current and voltage at the maximum power point (I_M, V_M). This method is commonly used due to the fast calculation and requires limited information of the *I-V* curve, which is usually available in datasheets (Hejri et al., 2014). Initially, all the parameters are determined analytically according to the value of the series resistance R_S. In the following, fast and simple iterative algorithm is designed to solve nonlinear equation order to extract the value of R_S. The algorithm reduces the computational time. To validate the model accuracy, the obtained results from proposed method are compared with experimental data of three different PV module technologies, i.e., mono-crystalline, poly-crystalline and thin film. Furthermore, computational time and root mean square error (RMSE) are also calculated. To show the effectiveness of the proposed model, it is evaluated against the popular modeling methods for the double diode model (Ishaque et al., 2011; Babu and Gurjar, 2014).

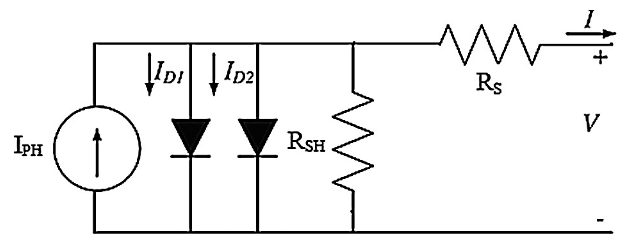

Fig. 1. Equivalent circuit for a double-diode PV model.

2. Extraction of double-diode PV model parameters

2.1. Introducing the double diode PV model

Unlike the single diode model, in the double-diode model, the effect of recombination current losses within depletion region is considered which leads to further improvement in the accuracy (Chin et al., 2015a). The double diode equivalent circuit model is shown in Fig. 1. It is comprised of a current source connected in parallel with two diodes. Additionally, along with parallel and series resistances, two diodes were used in this model; one relates to the diffusion process and the other one associates with the carrier recombination in space-charge region of the junction. Series resistance R_S represents the internal resistive losses and shunt resistance R_{SH} corresponds to the leakage current in the p-n junction and its magnitude varies according to different fabrication methods (Chin et al., 2015a).

Using Kirchhoff's current law, the *I-V* equation or the output current of a PV module, shown in Fig. 1, can be written as:

$$I = I_{PH} - I_{S1}\left[\exp\left(\frac{V + R_S I}{a_1 N_S V_{T1}}\right) - 1\right] - I_{S2}\left[\exp\left(\frac{V + R_S I}{a_2 N_S V_{T2}}\right) - 1\right] - \left(\frac{V + R_S I}{R_{SH}}\right) \tag{1}$$

where I_{PH} is the current generated by the incidence of light, I_{S1} and I_{S2} are the reverse saturation currents of diode 1 and diode 2, respectively, $V_{T1,2}$ are the thermal voltage of the PV module and is given by (kT/q), N_s is the number of cells connected in series, q is the electron charge (1.602×10^{-19} C), k is the Boltzmann constant (1.38×10^{-23} J/K), T is the temperature of the p–n junction in Kelvin. Variables a_1 and a_2 represent the ideality factor of diode 1 and diode 2.

In order to utilize double-diode model, values of circuit's elements should be determined. As mentioned before, double-diode model requires calculating seven parameters, i.e. I_{PH}, I_{S1}, I_{S2}, R_{SH}, R_S, a_1 and a_2. In order to make the double-diode model analytically manageable, seven unknown parameters of this model are reduced to five parameters: I_{PH}, I_{S1}, I_{S2}, R_{SH} and R_S. Values of these five parameters can be calculated using analytical relationships and the proposed numerical algorithm. Diode ideality factors values a_1 and a_2 are assumed to be constant and the values stated in the literature (Chin et al., 2015b, 2016) are used.

Common approach to calculate parameters is to estimate their values using information available in manufacturer's datasheet. Equations are obtained from three operational point conditions of the $I-V$ curve, i.e., Short-circuit point where $V = 0, I = I_{SC}$, Open circuit point where $V = V_{OC}, I = 0$ and Maximum power point where $V = V_M, I = I_M$. This information is always availabled at standard test conditions (STC) of temperature and solar irradiation. STC means radiation level is 1000 W/m^2, with a module temperature of 25 °C (298 °K) and air mass of AM1.5 spectrum (Villalva et al., 2009).

Authors, in Majdoul et al. (2015), proposed combined analytical and numerical approach to determine the parameters of the single diode model. As described earlier, in this paper the mentioned method has been extended for the double-diode model.

2.2. Analytical approach to extract I_{PH}, I_{S1}, I_{S2} and R_{SH}

Eq. (1) is being evaluated at three points of the PV module's *I-V* curve:

The short-circuit point $(0, I_{sc})$:

$$I_{SC}=I_{PH}-I_{S1}\left[\exp\left(\frac{R_SI_{SC}}{a_1N_SV_{T1}}\right)-1\right]-I_{S2}\left[\exp\left(\frac{R_SI_{SC}}{a_2N_SV_{T2}}\right)-1\right]-\left(\frac{R_SI_{SC}}{R_{SH}}\right) \tag{2}$$

The open circuit point $(V_{OC}, 0)$:

$$0=I_{PH}-I_{S1}\left[\exp\left(\frac{V_{OC}}{a_1N_SV_{T1}}\right)-1\right]-I_{S2}\left[\exp\left(\frac{V_{OC}}{a_2N_SV_{T2}}\right)-1\right]-\left(\frac{V_{OC}}{R_{SH}}\right) \tag{3}$$

The maximum power point (V_M, I_M):

$$I_M=I_{PH}-I_{S1}\left[\exp\left(\frac{(V_M+R_SI_M}{a_1N_SV_{T1}}\right)-1\right]-I_{S2}\left[\exp\left(\frac{(V_M+R_SI_M}{a_2N_SV_{T2}}\right)-1\right]-\left(\frac{(V_M+R_SI_M}{R_{SH}}\right) \tag{4}$$

By using (2), (3) and (4), two following equations are obtained:

$$I_{SC}=I_{S1}\left[\exp\left(\frac{V_{OC}}{a_1N_SV_{T1}}\right)-\exp\left(\frac{R_SI_{SC}}{a_1N_SV_{T1}}\right)\right]+I_{S2}\left[\exp\left(\frac{V_{OC}}{a_2N_SV_{T2}}\right)-\exp\left(\frac{R_SI_{SC}}{a_2N_SV_{T2}}\right)\right]+\left(\frac{V_{OC}-R_SI_{SC}}{R_{SH}}\right) \tag{5}$$

$$I_M=I_{S1}\left[\exp\left(\frac{V_{OC}}{a_1N_SV_{T1}}\right)-\exp\left(\frac{(V_M+R_SI_M}{a_1N_SV_{T1}}\right)\right]+I_{S2}\left[\exp\left(\frac{V_{OC}}{a_1N_SV_{T2}}\right)-\exp\left(\frac{(V_M+R_SI_M}{a_2N_SV_{T2}}\right)\right]+\left(\frac{(V_{OC}-V_M-R_SI_M}{R_{SH}}\right) \tag{6}$$

To simplify the handling of equations, the following assumptions are going to be used:

$$X_{OC1,2}\equiv\exp\left(\frac{V_{OC}}{a_{1,2}N_SV_{T1,2}}\right) \tag{7}$$

$$X_{M1,2}\equiv\exp\left(\frac{V_M+R_SI_M}{a_{1,2}N_SV_{T1,2}}\right) \tag{8}$$

$$X_{S1,2}\equiv\exp\left(\frac{R_SI_{SC}}{a_{1,2}N_SV_{T1,2}}\right) \tag{9}$$

It can be seen that in STC condition, $X_{S1,2}$ and $X_{M1,2}$ can be calculated once R_S is estimated. Considering (7)–(9), (5) and (6) can be rewritten as:

$$I_{SC}(1+R_S/R_{SH})=I_{S1}(X_{OC1}-X_{S1})+I_{S2}(X_{OC2}-X_{S2})+\left(\frac{V_{OC}}{R_{SH}}\right) \tag{10}$$

$$I_M(1+R_S/R_{SH})=I_{S1}(X_{OC1}-X_{M1})+I_{S2}(X_{OC2}-X_{M2})+\left(\frac{V_{OC}-V_M}{R_{SH}}\right) \tag{11}$$

It is known that the value of the series resistance is negligible compared to the parallel resistance, thus:

$$1+R_S/R_{SH}\cong 1 \tag{12}$$

Applying this approximation to (10) and (11), the followings are achieved:

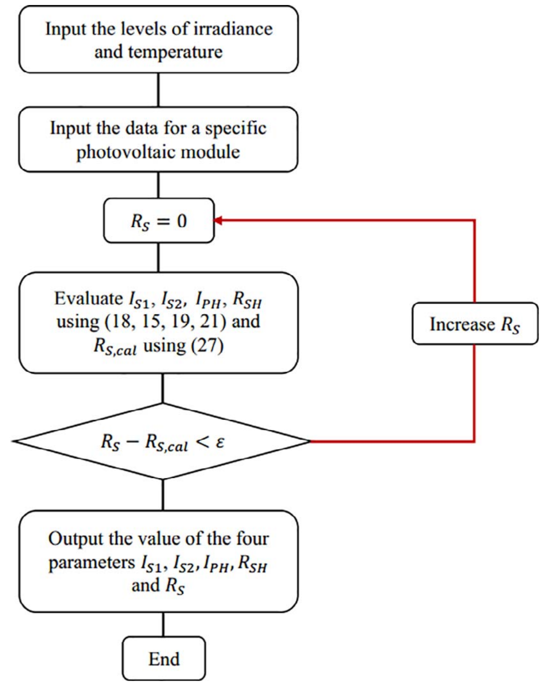

Fig. 2. Flowchart of the proposed iterative algorithm for parameter estimation.

Table 1
PV modules specifications at STC.

Parameters	Mono-crystalline SM55	Multi-crystalline S75	Thin film ST40
I_{SC} (A)	3.45	4.70	2.68
V_{OC} (V)	21.7	21.6	23.3
I_M (A)	3.15	4.26	2.41
V_M (V)	17.4	17.6	16.6
K_V (mV/°C)	−76	−76	−100
K_I (mA/°C)	1.4	2	0.35
N_S	36	36	36

$$I_{SC}=I_{S1}(X_{OC1}-X_{S1})+I_{S2}(X_{OC2}-X_{S2})+\left(\frac{V_{OC}}{R_{SH}}\right) \tag{13}$$

$$I_M=I_{S1}(X_{OC1}-X_{M1})+I_{S2}(X_{OC2}-X_{M2})+\left(\frac{V_{OC}-V_M}{R_{SH}}\right) \tag{14}$$

On the other hand, approximation $X_{OC1,2}\gg X_{S1,2}$ can be considered for PV modules (Hejri et al., 2014). Therefore, $X_{S1,2}$ can be neglected in (10) and (13).

In general, it is found that magnitude of I_{S2} is three to four times greater than I_{S1} Gupta and et al. (2012), and it can be taken as:

$$I_{s2}=\left(\frac{T^{\frac{2}{5}}}{3.77}\right)I_{S1} \tag{15}$$

To simplify and better handling of the equations, the authors assumed the value of I_{S2} in terms of I_{S1}. This relation is presented by "K". So (15) will be shown as: $I_{S2}=KI_{S1}$.

By considering the aforementioned assumptions and simplifications, parameters can be obtained more conveniently. Simplifications include: a_1 and a_2 are taken from diode ideality factors for modules proposed in Chin et al. (2015b, 2016), $X_{OC1,2}\gg X_{S1,2}$ and $I_{s2}=KI_{s1}$.

Therefore, (11) and (12) are modified as following:

$$I_{SC}=I_{S1}X_{OC1}+KI_{S1}X_{OC2}+\left(\frac{V_{OC}}{R_{SH}}\right) \tag{16}$$

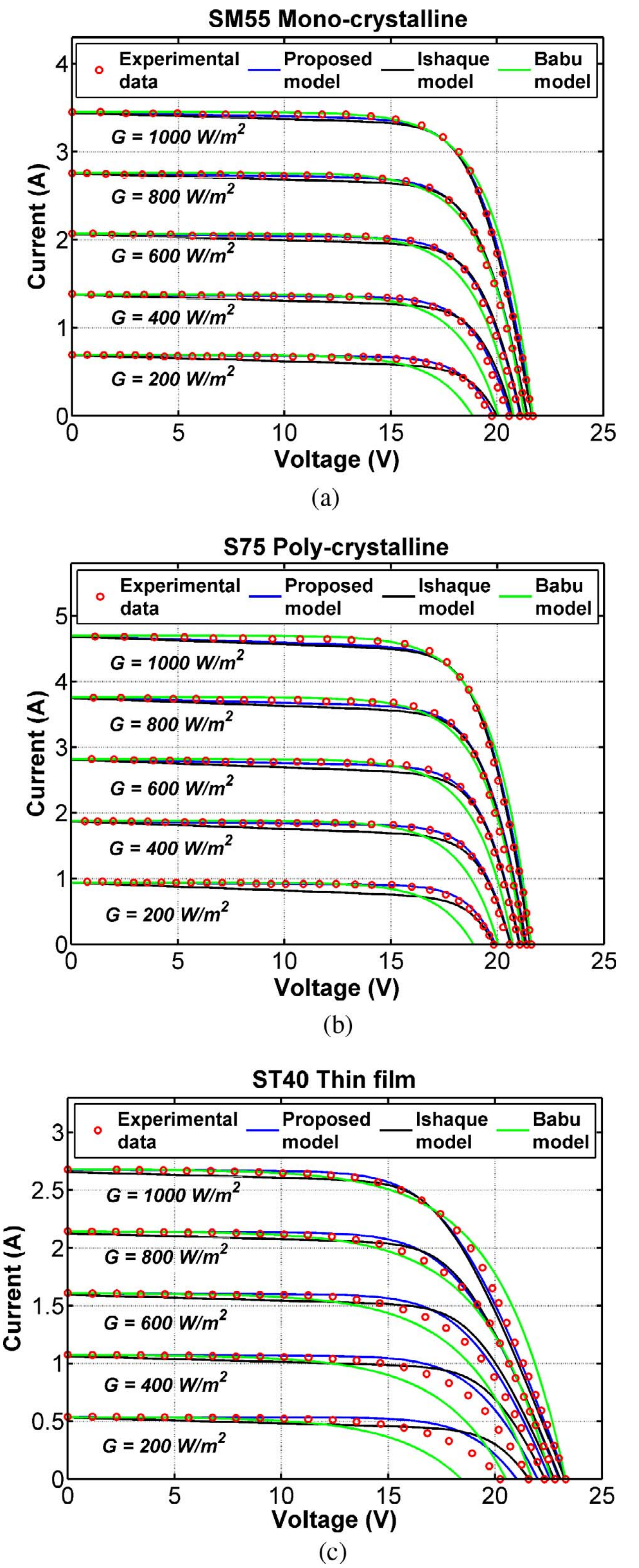

Fig. 3. *I–V* characteristic curves of three double diode model and eperimental data at varying irradiation levels and fixed temperature (25 °C). (a) SM55, (b) S75, (c) ST36.

$$I_M = I_{S1}(X_{OC1}-X_{M1}) + KI_{S1}(X_{OC2}-X_{M2}) + \left(\frac{V_{OC}-V_M}{R_{SH}}\right) \tag{17}$$

From these equations, reverse saturation current of diode 1 (I_{S1}) and diode 2 (I_{S2}) are calculated with (18) and (15) respectively, with only one unknown parameter (series resistanceR_S):

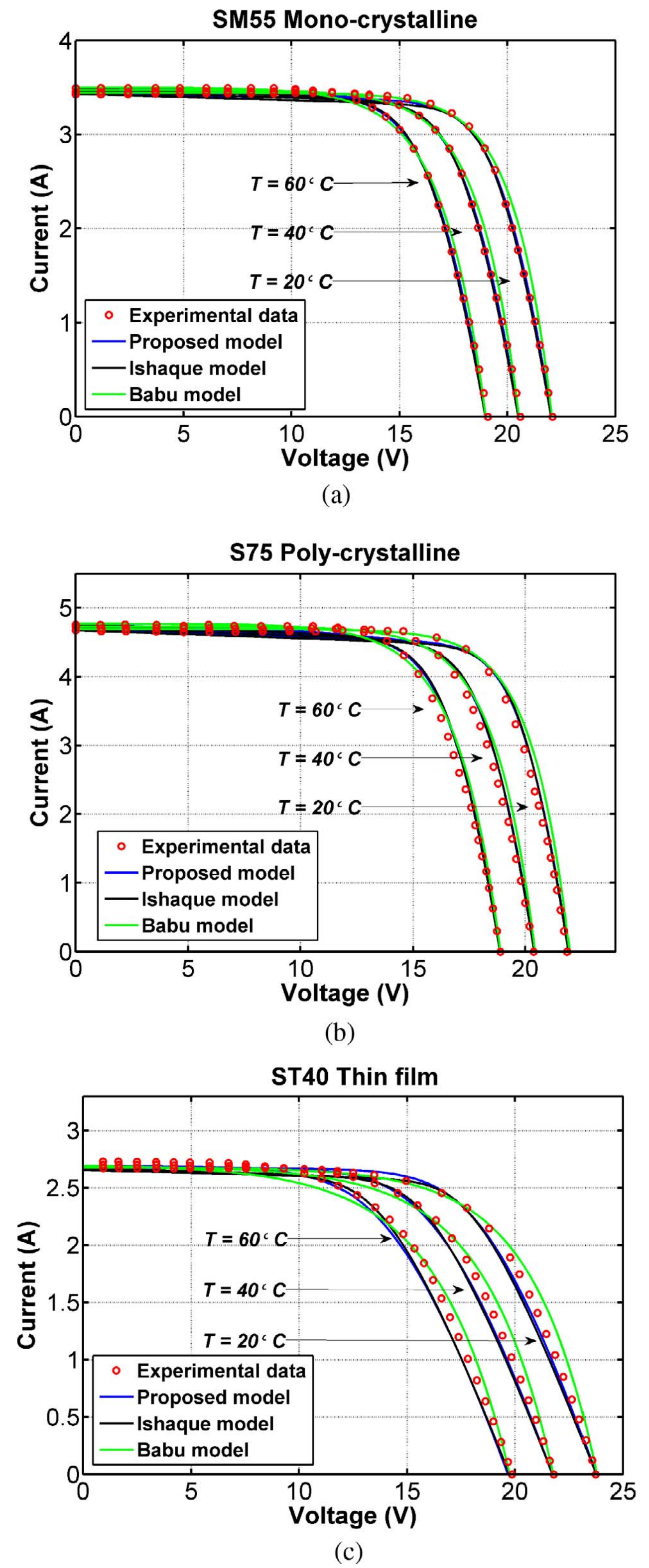

Fig. 4. *I–V* characteristic curves of three double diode model and eperimental data at varying temperature values and fixed radiation (1000 W/m^2). (a) SM55, (b) S75, (c) ST36.

$$I_{S1} = \frac{V_{OC}(I_{SC}-I_M)-V_M I_{SC}}{V_{OC}[X_{M1} + KX_{M2}]-V_M[X_{OC1} + KX_{OC2}]} \tag{18}$$

Using (3) and (18), the expression for photocurrent is given by:

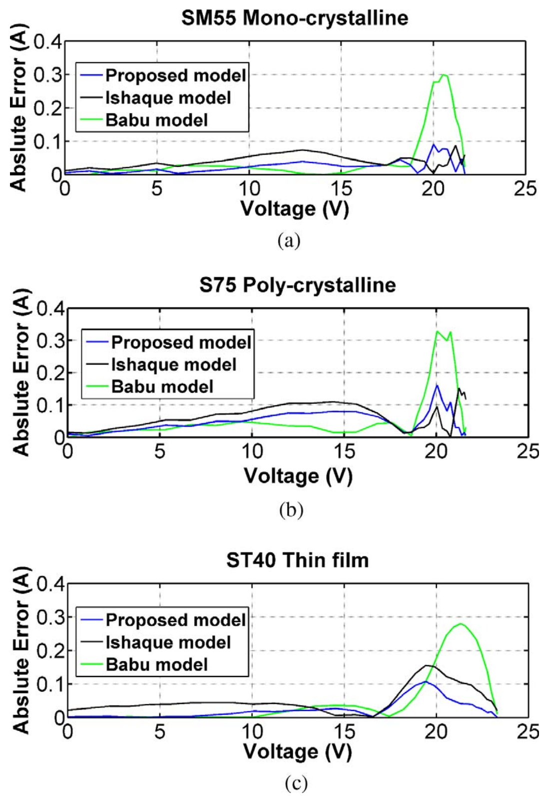

Fig. 5. Comparison of the absolute errors at STC condition (a) SM55, (b) S75, (c) ST36.

$$I_{PH} = \frac{V_{OC} I_M + I_{S1}[V_{OC}(X_{M1} + KX_{M2}) - V_M(X_{OC1} - KX_{OC2})]}{V_{OC} - V_M} \tag{19}$$

From (1) at maximum power point condition, the expression for R_{SH} can be rewritten as:

$$R_{SH} = \frac{V_M + I_M R_S}{\left\{I_{PH} - I_{S1}\left[\exp\left(\frac{V_M + I_M R_S}{a_1 N_S V_T}\right) - 1\right] - I_{S2}\left[\exp\left(\frac{V_M + I_M R_S}{a_2 N_S V_T}\right) - 1\right] - \frac{P_{max,E}}{V_M}\right\}} \tag{20}$$

Eq. (20) is simplified in accordance with the approximation (8) as follows:

$$R_{SH} = \frac{V_M + I_M R_S}{\{I_{PH} - I_M - I_{S1}(X_{M1} - 1) - I_{S2}(X_{M2} - 1)\}} \tag{21}$$

It can be seen that in (18), (15) and (21), only $X_{M1,2}$ are unknown and depend on R_S. Values of $I_{S1,2}$ and R_{SH} can be calculated, if R_S is estimated. In this regard, another expression is required.

The power delivered at each point on the PV module *I-V* curve is expressed as follows:

$$P = VI \tag{22}$$

Next, the derivative of the power with respect to the voltage at the MPP is zero:

$$\left.\frac{dP}{dV}\right|_{(V_M, I_M)} = \left(\frac{dI}{dV}\right)V + I = 0 \tag{23}$$

which leads to the following relationship:

$$\left.\frac{dI}{dV}\right|_{(V_M, I_M)} = \left(-\frac{I_M}{V_M}\right) \tag{24}$$

By taking the derivative of (1) with respect to V at the MPP, there is:

$$\left.\frac{dI}{dV}\right|_{(V_M, I_M)} = -\frac{I_{S1}}{a_1 N_S V_T}\left(1 - R_S\frac{I_M}{V_M}\right)\exp\left(\frac{V_M + R_S I_M}{a_1 N_S V_T}\right) - \frac{I_{S2}}{a_2 N_S V_T}\left(1 - R_S\frac{I_M}{V_M}\right)\exp\left(\frac{V_M + R_S I_M}{a_2 N_S V_T}\right) - \frac{1}{R_{SH}}\left(1 - R_S\frac{I_M}{V_M}\right) \tag{25}$$

The Eq. (26) is obtained according to the (24) and (25):

$$\frac{I_M}{V_M} = \left(1 - R_S\frac{I_M}{V_M}\right)\left[\frac{I_{S1}}{a_1 N_S V_T}X_{M1} + \frac{I_{S2}}{a_2 N_S V_T}X_{M2} + \frac{1}{R_{SH}}\right] \tag{26}$$

From (26), and after some manipulations, (27) can be obtained to compute the value of the series resistance $R_{S,CAL}$:

$$R_{S,CAL} = \frac{V_M}{I_M} - \frac{1}{\left[\frac{I_{S1}}{a_1 N_S V_T}X_{M1} + \frac{I_{S2}}{a_2 N_S V_T}X_{M2} + \frac{1}{R_{SH}}\right]} \tag{27}$$

Eqs. (18), (15), and (21) calculate parameters R_{SH} and $I_{S1,2}$ analytically, if R_S is known. Expression (27) is strongly nonlinear and helps us to calculate the value of the R_S numerically using a simple and accurate iterative algorithm.

2.3. Proposed fast and simple numerical algorithm to extract R_S

The simplified flowchart of the iterative algorithm to determine the final value of R_S is illustrated in Fig. 2. In this algorithm, the series resistance is gradually increments starting from an initial value. For each value, I_{S1}, I_{S2},I_{PH} and R_{SH}, are evaluated using (18), (15), (19), (21), respectively. The algorithm reiterates until the value of $R_{S,CAL}$ calculated by (27) coincides closely with the value of R_S taken at the beginning of each iteration. It should be noted that the value of ε is considered 0.0001 that defines the model precision.

Table 2
Root mean square error (RMSE) at different environmental conditions.

Environmental conditions		SM55 (mono-crystalline)			S75 (poly-crystalline)			ST40 (thin film)		
T (°C)	G (W/m^2)	Proposed method	Ishaque method (Ishaque et al., 2011)	Babu method (Babu and Gurjar, 2014)	Proposed method	Ishaque method (Ishaque et al., 2011)	Babu method (Babu and Gurjar, 2014)	Proposed method	Ishaque method (Ishaque et al., 2011)	Babu method (Babu and Gurjar, 2014)
25 (constant temperature)	1000	0.0378	0.0450	0.1333	0.0658	0.0774	0.1434	0.0435	0.0778	0.1334
	800	0.0299	0.0368	0.0630	0.0896	0.0860	0.1088	0.0359	0.0446	0.0411
	600	0.0357	0.0629	0.1248	0.0493	0.0712	0.2256	0.0609	0.0983	0.1342
	400	0.0353	0.0749	0.1606	0.0455	0.0774	0.2568	0.0724	0.1202	0.1911
	200	0.0153	0.0504	0.1604	0.0231	0.0875	0.2587	0.0701	0.0927	0.1707
20	1000 (constant irradiance)	0.0395	0.0620	0.1232	0.1333	0.1349	0.2857	0.0632	0.0912	0.1039
40		0.0418	0.0621	0.1018	0.1321	0.1369	0.2314	0.0723	0.0893	0.0878
60		0.0425	0.0654	0.0815	0.1227	0.1292	0.1664	0.0968	0.0938	0.0856

Table 3
Calculated model parameters of the proposed and available models for different PV modules.

Model parameters	SM55 (mono-crystalline)			S75 (Poly-crystalline)			ST40 (thin film)		
	Proposed method	Ishaque method (Ishaque et al., 2011)	Babu method (Babu and Gurjar, 2014)	Proposed method	Ishaque method (Ishaque et al., 2011)	Babu method (Babu and Gurjar, 2014)	Proposed method	Ishaque method (Ishaque et al., 2011)	Babu method (Babu and Gurjar, 2014)
I_{SC} (A)	3.45	3.44	3.45	4.70	4.68	4.70	2.68	2.66	2.68
V_{OC} (V)	21.70	21.60	21.60	21.60	21.50	21.50	23.30	23.2	23.20
$I_{M,CAL}$ (A)	3.15	3.15	3.13	4.26	4.26	4.28	2.41	2.40	2.29
$V_{M,CAL}$ (V)	17.40	17.40	17.50	17.60	17.60	17.50	16.60	16.70	17.50
I_{PH}	3.45	3.45	3.45	4.70	4.70	4.70	2.68	2.68	2.68
I_{S1} (A)	2.75E−08	2.23E−10	1.43E−05	5.68E−09	3.39E−10	1.23E−05	1.65E−07	3.07E−11	1.18E−03
I_{S2} (A)	7.11E−08	2.23E−10	3.70E−05	1.47E−08	3.39E−10	3.18E−05	4.28E−07	3.07E−11	3.07E−03
a_1	1.26	1	1.89	1.14	1	1.82	1.52	1	3.26
a_2	2.84	1.3	3.65	2.6	1.3	3.36	2.15	1.3	22.44
R_S (Ω)	0.36	0.48	0.00	0.23	0.27	0.00	1.40	1.71	0.00
R_{SH} (Ω)	233.46	146.43	∞	103.58	84.38	∞	1350.30	198.94	∞

Table 4
The Computational time (s) for the proposed and available methods.

PV module type	Proposed method	Ishaque method (Ishaque et al., 2011)	Babu method (Babu and Gurjar, 2014)
Shell SM55	0.085486	0.188405	1.573582
Shell S75	0.079153	0.145197	1.446574
Shell ST40	0.134452	0.438874	4.117734

3. Results and discussion

The performance of proposed computational method is validated for the PV module of three different technologies such as mono-crystalline (Shell SM55), poly-crystalline (Shell S75) and thin film (Shell ST40). The specifications of these modules are summarized in Table 1. This table contains information about K_V and K_I which represents the temperature coefficients for open circuit voltage and short circuit current, respectively. These PV modules are widely used by different researchers (Chin et al., 2015b, 2016).

The accuracy of proposed model is validated through comparing the results to the experimental *I-V* data extracted from the manufacturer datasheets. For comprehensive comparison, proposed method is evaluated against previously cited authors, namely the work by Ishaque et al. (2011) and Babu and Gurjar (2014) who calculated double-diode model parameters by using analytical and numerical approach.

Fig. 3(a)–(c) shows the calculated and experimental $I-V$ curves of the PV modules in different irradiation levels G, while temperature is fixed at $T = 25$ °C. As it can be seen, at lower irradiance level, model (Ishaque et al., 2011) presents lower accuracy in the left side of MPP or fixed current region. Model (Babu and Gurjar, 2014) is also deviated significantly on right side of MPP. All three models, particularly (Babu and Gurjar, 2014) (due to simplifications applied to calculation of its parameters (Chin et al., 2016) provides poor performance for thin film module, however, the proposed model outperforms two other models. It can be noted that the proposed method is found to exhibit superior accuracy for the variation in irradiance for SM55 and S75 modules.

Performance of the model for different temperatures with fixed irradiance $G = 1000\text{W/m}^2$ is demonstrated in Fig. 4(a)–(c). All three models are in agreement with experimental data at all temperature conditions. In general, results of the proposed model in this case are also closer to experimental data compared to other two models.

Fig. 5(a)–(c) presents the error of the PV current at STC condition ($G = 1000$ W/m^2 and $T = 25$ °C). The error is defined as the absolute difference between the experimental (I_{exp}) and computed (I_{com}) current values for a given voltage point of the $I-V$ curve Chin et al., 2016: $AE = |I_{exp}-I_{com}|$. As it can be seen, compared to other models, the proposed model is more accurate and provides lower error.

Root Mean Square Error (RMSE) of PV current is presented in Table 2 to evaluate accuracy of modeling methods. Results show that the proposed model has the least RMSE value compared to other methods.

Table 3 presents the calculated values of the computed model parameters for the PV modules. Validity of the obtained values from methods (Deihimi et al., 2016) and (Hejri et al., 2014) for selected PV modules are also verified according to the published papers (Park and Choi, 2015) and (Yildiran and Tacer, 2016).

Parallel resistance R_{SH} is usually large and about KΩ. According to Table 3, value of R_{SH} obtained in this research is higher than method proposed in Ishaque et al. (2011). Since value of R_{SH} affects slope of the curve between short curcit point and MPP (Chin et al., 2015a), it can be seen that large value of R_{SH} selected for model (Babu and Gurjar, 2014) and obtained from this model verified better accuracy of these two models in the constant current region.

Value of the series resistance R_S is usually negligible. Resistance R_S affects slope of the curve in regions between open voltage point and MPP. In model (Babu and Gurjar, 2014), R_S is considered zero which reduces accuracy of $I-V$ curve in the proximities of V_{OC}. Value of the R_S in the proposed model is larger and smaller than (Babu and Gurjar, 2014) and (Ishaque et al., 2011), respectively, where trade-off between these two values lead to better accuracy of the proposed model compared to other two models.

In addition, a_1, a_2, I_{S1}, and I_{S2} values obtained for thin film module in model (Babu and Gurjar, 2014) are very large. That is because to apply numerous simplifications made in it, the algorithm is unable to cope with the low fill factor inherent in thin film modules (Chin et al., 2016). The higher value of a_1 and a_2 causes to soften the knee of the *I-V* curve, thus, it is changing the position of MPP. It is clearly visible in model (Babu and Gurjar, 2014), as shown in Fig. 3(a)–(c).

Table 4 shows the computational time of three modeling methods. As it can be seen, computational time of the proposed model, in average, is about two and twenty times less than models presented in Ishaque et al. (2011) and Babu and Gurjar, 2014, respectively. In fact, the proposed model provides less computational time while being accurate due to applying reasonable simplifications and using a fast and simple algorithm for converging to a desired solution.

It should be noted that the computational time for each of the methods was determined by the code timer several times feature of MATLAB 2014b, and the average value of the measurements is recorded. MATLAB has been run on an Asus A53SM notebook with 8 GB RAM and an Intel Core i7- 2670QM CPU, 2.2 GHz processor.

In order to complete this study, dependency of the calculated parameters on temperature and irradiation levels is considered. Information available in PV datasheet is related to STC. Therefore, the calculated parameters are obtained at STC condition. Dependency of PV model's parameters on T and G can be replaced with a set of suitable mathematical equations in the computational model (Majdoul et al., 2015; Ishaque et al., 2011; Hejri et al., 2014) and (Yetayew and Jyothsna, 2016). This dependency can be described as follows:

$$R_S = R_{S,STC} \tag{28}$$

$$R_{SH} = R_{SH,STC}\frac{G}{G_{STC}} \tag{29}$$

$$I_{S1} = \frac{[I_{PH,STC} + K_I(T-T_{STC})]}{\exp[(V_{OC,STC} + K_V\Delta T)/a_1V_T]-1} \tag{30}$$

$$I_{PH} = \frac{G}{G_{STC}}[I_{PH,STC} + K_I(T-T_{STC})] \tag{31}$$

In the above expressions, STC subscript stands for the values of different parameters in STC condition. Note that dependency of parameter I_{S2} to T and G is expressed as (15).

4. Conclusion

In this paper, an improved modeling approach is proposed for the extraction of the double diode model parameters. The values of I_{S1}, I_{PH}, and R_{SH} are calculated analytically according to the value of series resistance R_S. The proposed analytical approach is based on the three remarkable points of the $I-V$ curve namely, the open circuit, the short circuit, and the maximum power point (MPP). The R_S value is also computed with a fast and simple iterative algorithm. The validity of the modeling method is verified using the experimental data of three different types of PV modules, i.e. mono-crystalline, poly-crystalline, thin-film. Furthermore, the performance and effectiveness of the proposed method is evaluated against the popular modeling methods for the double diode model. According to the results, the proposed method offers significant performance and has a good comprise between accuracy and rapidness compared to the two other models. As a consequence, the proposed study can help novices and PV designers who require fast and accurate modeling of the PV module for simulation applications.

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