Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2019) 27: 3026 – 3039
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doi:10.3906/elk-1805-161

A new approach for parameter estimation of the single-diode model for photovoltaic cells/modules

Bilge Kaan ATAY[1], **Ulaş EMİNOĞLU**[2,*]
[1]Graduate School of Natural and Applied Sciences, Gaziosmanpaşa University, Tokat, Turkey
[2]Department of Electrical and Electronics Engineering, Gaziosmanpaşa University, Tokat, Turkey

Received: 23.05.2018 • **Accepted/Published Online:** 15.04.2019 • **Final Version:** 26.07.2019

Abstract: Solar energy has become a popular renewable energy source, leading to wide use of photovoltaic (PV) cells/modules in energy production. For this reason, realistic modeling of PVs and determining the equivalent circuit parameters is of great importance in terms of planning and operation. Hence, in this study, an analytical model for identifying the single-diode equivalent circuit parameters; series resistance (R_s), shunt resistance (R_p), diode ideality factor (a), diode reverse-saturation current (I_o), and photon current (I_{pv}) for PV cells/modules is developed without neglecting any term. In order to test the accuracy of the model, a number of PV modules from different manufacturers are taken into account and the results are compared with those obtained by using such analytical models given in the literature. Current-voltage (I-V) characteristics of the PV modules, which are studied here, are also simulated by comparing with the experimental I-V curves provided by the manufacturers. Results show that the values of the parameters obtained for the PV modules are consistent with those extracted by using other analytical models. In addition, I-V curves created by using the obtained parameters are in full agreement with the experimental data. The curves also show a high degree of compatibility with the ones created by using the optimal parameters of the two-diode models given in the literature. Moreover, the proposed model provides a great advantage in estimating equivalent circuit parameters in terms of ease of use, requirements for input data, dependency on initial conditions as well as considering the parameters which are neglected in such methods given in the literature.

Key words: Photovoltaic cells/modules, mathematical modeling, parameter extraction, single-diode model

1. Introduction

The ever-decreasing production costs of solar panels have made PV modules a preferred energy source to be used in an off-grid or on-grid system. In this context, accurate modeling of PV modules plays quite an important role in the effective assessment and quality control. In addition, the characterization of the output current and power (I-V and P-V) curves of the system, based on the equivalent circuit parameters, is of great importance in terms of design and sizing [1]. Therefore, numerous studies have been conducted in the literature, especially on determining the equivalent circuit parameters for PVs. In the literature, we see that particularly two types of models, i.e. the single-diode five-parameter model and the two-diode seven parameters model, are used. For instance, in a study by Chan and Phang [2], a PV cell has been presented with the single-diode and the two-diode models using analytical techniques based on experimental data. For both models, there are analytical and numerical solutions, in which various methods can be applied. In another study, Shongwe and Hanif have

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[*] Correspondence: ulas.eminoglu@gop.edu.tr

compared different methods developed for the extraction of the parameters of PV modules using the single-diode five-parameter circuit model on two commercial PV modules [3]. The single-diode model has been improved by adding a shunt resistor and a resistor in series. In a similar study [4], the authors have created a model with a shunt and serial resistors at the standard test conditions (STC) by taking into account the temperature-dependent saturation current; however, they have neglected some terms in the set of equations. Due to the nonlinearity of the equations and the number of unknown variables, it is necessary to use iterative solutions for these types of systems. Accordingly, Reis et al. formulated the parameters for the single-diode five-parameter model [5]. The set of equations was solved using the Newton–Raphson method, and it was demonstrated that the extraction of the five unknown parameters can easily be determined by this method. A new set of equations for the determination of the equivalent circuit parameters based on Kirchhoff's laws at STC was proposed in [6], and the validity of the model was evaluated on some commercial PV modules using the Gauss–Seidel method. In this study, the initial values of the unknown parameters were also determined by using approximate analytical models since the performance of the Gauss method is significantly affected by the initial conditions. For the single-diode model, however, a set of equations were created and solved for different commercial PV cells/modules [7]; the shunt resistor, which is one of the main parameters of the equivalent circuit, was selected as an input parameter. In other words, it is claimed that the value of the shunt resistor can be determined by experimental measurements and hence the parameter is assumed to be known. Similarly, an analytical model based on the equivalent circuit was developed by Javier et al. in [8] and tested on two well-known commercial PV modules comparing the results with those available in the literature. Despite the reasonable results obtained using this model, one main parameter in the equation set, namely the diode ideality factor was defined as an input parameter and its range was kept between 1 and 1.5. As is well known, the Newton–Raphson method has good accuracy, but it becomes disadvantageous as the number of iterations increase. Accordingly, Patel, who created a new method by synthesizing an analytical and numerical solution, used Lambert W-function to reduce the execution time [9]. In addition to these models, it is also possible to determine the parameters using temperature-dependent models; however, manufacturer's data, I-V and P-V characteristics, and solar temperature become very important in this type of approach [10].

The main difference between the two main models in the literature is the accuracy and the number of unknown parameters. A comparative study on both models was conducted by Shannan et al. [11]. In their study, the differences between the models were analyzed in terms of accuracy and execution time, and it has been concluded that the two-diode model has better accuracy, but it also has a longer execution time. Similarly, in another study [12], the authors solved both models using a numerical solution on a PV module simulated in a hybrid system. In addition, the authors stated that the single-diode model has fewer parameters so that the unknowns can be calculated in a shorter time, and that the two-diode model is more consistent in terms of accuracy. Since the determination of initial values in numerical studies is quite difficult, the approximate analytical solutions have been proposed by Hejri et al. to determine the values needed for the numerical solution of the two-diode model, and this method was verified with experimental data of different commercial PV models [13]. The authors have also analyzed the single-diode five-parameter model [1]. In their study, some terms have been neglected and the saturation current of the diode has been eliminated to decrease the number of unknown parameters in the set of equations.

Metaheuristic methods are widely used to obtain the optimum solution for multiparametric complex systems. Consequently, there are studies in the literature [14–17] conducted to obtain the parameters of PV module using such optimization techniques namely genetic algorithm (GA) [18], particle swarm optimization

(PSO) algorithm [19], and differential evaluation (DE) method [20]. In order to calculate the unknown parameters on a single-diode model, Zagroube et al. [14] used GA, and the method was quite effective for such a problem. In another study [15], the authors used the PSO algorithm for the first time to determine the value of the parameters for the double-diode models by using the data for practical PV modules provided by the manufacturers. A similar approach has also been used in a study for parameter extraction of the single-diode model [16]. Another technique, called differential evaluation algorithm, was used by Ishaque and Salam for identifying the parameters of the single-diode model [17]. The proposed model has been evaluated on the experimental data and the results obtained have been found to be more reliable as compared with the single diode R_s-model. In addition, parameter estimation by using different approaches such as multiple optimization-based method [21], search algorithm based on the reduced form of the equations set [22], hybrid form of the Nelder–Mead and modified PSO algorithm [23], partly search-based method using diode ideality factor (a) for the single-diode model [24] and series resistance (R_s) for the double-diode model [25] as an independent variable, tool/software solution-based method [26] are also available in the literature. In [21], the authors proposed an algorithm based on the hybrid GA-PSO to extract the parameters of the single-diode model for PV modules, and hybrid approach was shown to be more advantageous than the method based on the GA. Bencherif and Benouaz reduced the number of parameters to be calculated only to two and reached a solution using the graphical method based on the search algorithm [22]. A hybrid method based on the combination of the Nelder–Mead and modified PSO algorithm was developed for extracting the double-diode equivalent circuit parameters for PV modules [23]. The proposed model was validated on a commercial solar cell comparing the results with those obtained by using such metaheuristic approaches. In order to extract the parameters of the single-diode equivalent circuit model, the authors in [24] developed a partly search-based algorithm in which the diode ideality factor (a) was defined as an independent variable. In the method, the values of the remaining parameters are obtained analytically at each step by using the numerical solution of the equation reduced only to the series resistance (R_s). The algorithm is terminated based on the error value defined between the calculated output current and empirical data of I-V curves. A similar approach was also implemented for a double-diode model of PV modules in [25]. The series resistance (R_s) was used as an independent parameter and the remaining ones were determined based on the selected R_s in each iteration. In this method, the procedure is reiterated until the selected value of R_s coincides closely with its calculated value. In [26], the authors created five basic nonlinear equations from the equivalent circuit and solved by using a solution technique of MATLAB for one practical PV module. The reliability of the model was validated on an experimental system and the results were also compared with those obtained by two different methods available in the literature. Detailed information about the methods developed for extracting equivalent circuit parameters of PV cells/modules based on the analytical and/or numerical solution techniques are given in [27].

The single-diode five-parameter model is widely studied in the literature since it is an adequate method for modeling the equivalent circuit of PV cells/modules. Accordingly, in this study, a mathematical model is proposed for estimating the parameters of the single-diode model for PV cells/modules. The model is validated on several commercial PV cells/modules at different temperature and solar radiation values including standard test conditions. A number of analytical methods available in the literature are also taken into account for comparison purposes. Results show that our model, which has been developed without neglecting any terms, extracts the equivalent circuit parameters of PV modules in a more accurate manner. In addition, it is not sensitive to the initial conditions as compared to such methods available in the literature. The rest of this study is structured as follows: The formulation of the proposed model is presented in Section 2. In Section 3, the set of equations developed are validated on some practical PV cells/modules by comparing with those obtained by using such models and the results of the studies given in the literature. Finally, the advantages of the proposed model are emphasized in Section 4.

2. Mathematical formulation of the single-diode model of PV cells/modules

Since they have no moving parts, PV cells/modules are one of the most convenient systems in terms of maintenance in energy production. In addition, their life cycle is longer than that of other renewable energy conversation systems [6, 16]. In their electrical modeling, the single-diode five-parameter model shown in Figure 1 is commonly used [1, 2].

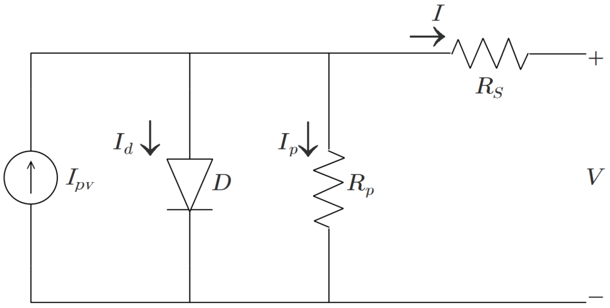

Figure 1. Single-diode five-parameter model.

As shown in Figure 1, the photon current generated by a PV cell is modeled with I_{pv} with a parallel diode. R_p and R_s denote shunt and serial resistor, respectively. V_t refers to the thermal voltage on the diode ($V_t = kN_sT/q$), where N_s denotes the number of PV cells in series, k is the Boltzmann's constant, which is $1.38x10^{-23}J/K$, and q is the electron charge ($1.6x10^{-19}C$). The last term, T, is the cell temperature in Kelvin. Applying Kirchhoff's current law to the system, we can get the output current as:

$$I = I_{pv} - I_d - I_p, \tag{1}$$

$$I = I_{pv} - I_o(e^{\frac{V+IR_s}{aV_t}} - 1) - \frac{V + IR_s}{R_p}. \tag{2}$$

At $(I_{sc}, 0)$,

$$I_{sc} = I_{pv} - I_o(e^{\frac{I_{sc}R_s}{aV_t}} - 1) - \frac{I_{sc}R_s}{R_p}. \tag{3}$$

At $(0, V_{oc})$,

$$0 = I_{pv} - I_o(e^{\frac{V_{oc}}{aV_t}} - 1) - \frac{V_{oc}}{R_p}. \tag{4}$$

At (I_{mpp}, V_{mpp}),

$$I_{mpp} = I_{pv} - I_o(e^{\frac{V_{mpp}+I_{mpp}R_s}{aV_t}} - 1) - \frac{V_{mpp} + I_{mpp}R_s}{R_p}. \tag{5}$$

The generated power by the PV module is given by:

$$P = IV. \tag{6}$$

where V and I refer to the terminal voltage and current, respectively. If the power is differentiated with respect to the output voltage at its maximum point (I_{mpp}, V_{mpp}), Eq. (9) is obtained as follows:

$$\frac{dP}{dV} = I + \frac{dI}{dV}V, \tag{7}$$

$$0 = I_{mpp} + \frac{dI}{dV}V_{mpp}, \tag{8}$$

$$\frac{dI}{dV} = -\frac{I_{mpp}}{V_{mpp}}. \tag{9}$$

and then Eq. (2) can be differentiated with respect to output voltage:

$$\frac{dI}{dV} = -I_o[(\frac{1}{aV_t} + \frac{R_s}{aV_t}\frac{dI}{dV})e^{\frac{V+IR_s}{aV_t}}] - \frac{1}{R_p} - \frac{R_s}{R_p}\frac{dI}{dV}, \tag{10}$$

$$\frac{dI}{dV} = -\frac{I_o}{aV_t}(1 + R_s\frac{dI}{dV})e^{\frac{V+IR_s}{aVt}} - \frac{1}{R_p}(1 + R_s\frac{dI}{dV}). \tag{11}$$

Substituting Eq. (9) into Eq. (11), we get the ratio of output current to the voltage at maximum power point as given in the following equations.

$$-\frac{I_{mpp}}{V_{mpp}} = -\frac{I_o}{aV_t}(1 - R_s\frac{I_{mpp}}{V_{mpp}})e^{\frac{V_{mpp}+I_{mpp}R_s}{aVt}} - \frac{1}{R_p}(1 - R_s\frac{I_{mpp}}{V_{mpp}}), \tag{12}$$

$$\frac{I_{mpp}}{V_{mpp}} = \frac{I_o}{aV_t}(1 - R_s\frac{I_{mpp}}{V_{mpp}})e^{\frac{V_{mpp}+I_{mpp}R_s}{aVt}} + \frac{1}{R_p}(1 - R_s\frac{I_{mpp}}{V_{mpp}}). \tag{13}$$

Rearranging Eq. (3) by taking into account Eq. (4), we get the short circuit current equation as follows:

$$I_{sc} = I_o(e^{\frac{V_{oc}}{aV_t}} - e^{\frac{I_{sc}R_s}{aV_t}}) + \frac{V_{oc} - I_{sc}R_s}{R_p}. \tag{14}$$

Similarly, by substituting Eq. (4) into Eq. (5), we get the following equation:

$$I_{mpp}(1 + \frac{R_s}{R_p}) = I_o(e^{\frac{V_{oc}}{aV_t}} - e^{\frac{V_{mpp}+I_{mpp}R_s}{aV_t}}) + \frac{V_{oc} - V_{mpp}}{R_p}. \tag{15}$$

It is seen in Eqs. (13)–(15) that we have four unknown parameters (R_s, R_p, a, and I_o) but three equations. For this reason, a fourth equation is needed to determine these parameters. On the other hand, at short circuit situation $(I_{sc}, 0)$, we can write the following equality [1]:

$$\frac{dI}{dV} = -\frac{1}{R_{p0}}. \tag{16}$$

By substituting the last equation into Eq. (11), for the short circuit case, we get the equation for R_{p0} as given in the following equations:

$$-\frac{1}{R_{p0}} = -\frac{I_o}{aV_t}(1-\frac{R_s}{R_{p0}})e^{\frac{I_{sc}R_s}{aV_t}} - \frac{1}{R_p}(1-\frac{R_s}{R_{p0}}), \tag{17}$$

$$R_{p0} = \frac{\frac{I_o}{aV_t}R_s e^{(\frac{I_{sc}R_s}{aV_t})} + \frac{R_s}{R_p} + 1}{\frac{1}{R_p} + \frac{I_o}{aV_t}e^{(\frac{I_{sc}R_s}{aV_t})}}. \tag{18}$$

It can be inferred from [1] and [2] that $R_{p0} = R_p$ and therefore Eq. (18) can be rewritten as follows:

$$R_p = \frac{\frac{I_o}{aV_t}R_s e^{(\frac{I_{sc}R_s}{aV_t})} + \frac{R_s}{R_p} + 1}{\frac{1}{R_p} + \frac{I_o}{aV_t}e^{(\frac{I_{sc}R_s}{aV_t})}}. \tag{19}$$

Now, the set of equations given in Eqs. (13)–(15) and (19) can be solved by applying a numerical solution method, such as the Newton–Raphson method, to analytically calculate the values of unknown parameters for the PV cells/modules. However, as stated in [1], convergence problem may occur when such numerical solution methods are used. This is due to the fact that the saturation current of the diode (I_o) has a very small value, and as a result, the Jacobian Matrix converges to singularity. In order to overcome this problem, a new set of equations can be obtained by eliminating I_o as shown in the following procedures.
Eq. (14) can be rewritten as follows:

$$I_o = \frac{I_{sc} - \frac{V_{oc}-I_{sc}R_s}{R_p}}{e^{\frac{V_{oc}}{aV_t}} - e^{\frac{I_{sc}R_s}{aV_t}}}. \tag{20}$$

Then, substituting the last equation into Eqs. (13), (15), and (19), we obtain a new set of equations, only dependent on the shunt, series resistors, and the ideality factor of the diode (R_p, R_s and a) as given in the following equations:

$$0 = \frac{I_{sc} - \frac{V_{oc}-I_{sc}R_s}{R_p}}{aV_t(e^{\frac{V_{oc}}{aV_t}} - e^{\frac{I_{sc}R_s}{aV_t}})}(1-R_s\frac{I_{mpp}}{V_{mpp}})e^{\frac{V_{mpp}+I_{mpp}R_s}{aV_t}} + \frac{1}{R_p}(1-R_s\frac{I_{mpp}}{V_{mpp}}) - \frac{I_{mpp}}{V_{mpp}}, \tag{21}$$

$$0 = \frac{I_{sc} - \frac{V_{oc}-I_{sc}R_s}{R_p}}{e^{\frac{V_{oc}}{aV_t}} - e^{\frac{I_{sc}R_s}{aV_t}}}(e^{\frac{V_{oc}}{aV_t}} - e^{\frac{V_{mpp}+I_{mpp}R_s}{aV_t}}) + \frac{V_{oc}-V_{mpp}}{R_p} - I_{mpp}(1+\frac{R_s}{R_p}), \tag{22}$$

$$0 = \frac{\frac{I_{sc} - \frac{V_{oc}-I_{sc}R_s}{R_p}}{aV_t(e^{\frac{V_{oc}}{aV_t}} - e^{\frac{I_{sc}R_s}{aV_t}})}R_s e^{\frac{I_{sc}R_s}{aV_t}} + \frac{R_s}{R_p} + 1}{\frac{1}{R_p} + \frac{I_{sc} - \frac{V_{oc}-I_{sc}R_s}{R_p}}{aV_t(e^{\frac{V_{oc}}{aV_t}} - e^{\frac{I_{sc}R_s}{aV_t}})}e^{\frac{I_{sc}R_s}{aV_t}}} - R_p. \tag{23}$$

3. Test cases

The last three independent equations allow us to extract the value of three unknown parameters; R_p, R_s, and a for PVs by taking into account the technical data given by the manufacturers or obtained experimentally. Technical data of the PV modules to be used for the validation of the proposed model are presented in Table 1. In order to solve this set of equations, the Newton–Raphson method widely used for solving this type of nonlinear equations [2, 5, 13, 22] is utilized in MATLAB environment. The numerical solutions are found for varying initial conditions and the results obtained for the BP-MSX120 PV module are listed in Table 2. The results obtained by using the model developed in [1] and [4, 6–8, 26] are also presented in the table for comparison purposes. In this context, first of all, it should be noted that the initial conditions do not have an effect on the parameter values as one expects. In addition, the relative error used for terminating the numerical solution is defined as follows:

$$Error = |x^i - x^{i+1}| < 10^{-6} \tag{24}$$

where x_i shows the value of the parameter in the previous iteration. The remaining two parameters (I_o and I_{pv}) are then computed using Eqs. (20) and (4), respectively. As shown in the table, the values of the parameters for PV module are in close agreement with the solutions given in [1] and those determined by the models proposed in [4, 6–8, 26]. It is clear that the proposed model allows getting more realistic results without any prior knowledge except technical data. A similar situation is also observed for the model given in [6]. Even though the models proposed in references [4, 7, 8, 26] give consistent results, these models have some handicaps. For example, in the model proposed in [7], the parallel resistor is considered to be known and taken as an input parameter. Similarly, in the model developed in [8], the diode ideality factor is taken as an input parameter. For both models, the values of these parameters obtained by using the proposed method, which is marked in the table, were used to find the solution. In addition, the performance of the models given in [4] and especially given in [26] is highly dependent on the initial conditions. In other words, realistic results can only be obtained as the initial conditions converge to the actual values. The model in [26] also requires a powerful tool/software for the iterative solution of its nonlinear equations. In this study, *Isqnonlin* command based solution technique in MATLAB program is used and the objective function is chosen as given in [26]. Therefore, it is quite possible to say that these methods are not favorable for parameter extraction of PV cells/modules in terms of application. Moreover, the results given in [1] cannot be obtained when the Newton–Raphson method applied to solve the set of equations given in [1]. The model gives unrealistic results. For this reason, an accuracy analysis was performed for the set of equations due to some noteworthy terms that should not be contained in the model. Table 3 shows the values of equations calculated by substituting the solutions given in Table 2 into the set of equations for both models. It is quite clear from the table that the solutions (roots) do not verify the equations formulated by Hejri et al. in [1], at any degree.

It is well known that metaheuristic methods have been successfully applied to solve various types of large-scale optimization problems. Therefore, in [21], the authors extracted the equivalent circuit parameters

Table 1. Manufacturers' data for PV modules at $T = 25\ ^{\circ}C$.

PV module\ Parameters	MSX60 [10]	KL070 [21]	BP-MSX120 [1]	BP-SX150 [24]	KC200GT [8]	SW255 [7]
V_{oc} (V)	21.1	21.5	42.1	43.5	32.9	38
I_{sc} (A)	3.8	4.59	3.87	4.75	8.21	8.88
V_{mpp} (V)	17.1	17.1	33.7	34.5	26.3	30.9
I_{mpp} (A)	3.5	4.1	3.56	4.35	7.61	8.32
N_s	36	36	72	72	54	60
P_m (W)	60	70	120	150	200	255

Table 2. Equivalent circuit parameters obtained for BP-MSX120 PV module.

PV module\ parameters	BP-MSX120 (BP Solar Global Marketing)							
	Ref. [1]	The proposed model	Model in [1]	Model in [4]	Model in [6]	Model in [7]	Model in [8]	Model [26]
R_s (Ω)	0.473	0.472	Na	0.473	0.472	0.472	0.472	0.472
R_p (Ω)	1365	1365	Na	1366	1365	1365	1364	1360
a	1.396	1.398	Na	1.396	1.396	1.396	1.398	1.398
I_o (μA)	0.323	0.322	Na	0.323	0.322	0.322	0.322	0.325
I_{pv} (A)	3.871	3.871	Na	3.871	3.871	3.871	3.871	3.871

Table 3. The values of the set of equations for BP-MSX120 PV module after the solutions.

PV module\ related parameters	BP-MSX120 (BP Solar Global Marketing)	
	Set of Eqs. (The proposed model)	Sets of Eqs. (Given in [1])
R_s	Eq. (22) $= 8.8x10^{-16}$	Eq. (20) $= -1.02x10^{-3}$
R_p	Eq. (23) $= 0$	Eq. (21) $= 529.17$
a	Eq. (21) $= -2.6x10^{-16}$	Eq. (19) $= 2.2x^{-4}$
I_o	Eq. (20) $= -2.1x10^{-17}$	Eq. (18) $= -8.1x10^{-9}$
I_{pv}	Eq. (4) $= 2.5x10^{-10}$	Eq. (12) $= 9.93x10^{-2}$

of the KL070 PV module by applying metaheuristic methods, namely GA and hybrid GA-PSO algorithms. Thus, the reliability of the proposed method is tested in this section by comparing the values with the ones obtained by such applications. For comparison purposes, other methods are also taken into consideration, and the values of the parameters extracted are presented in Table 4. One can see that the results obtained by the proposed model and the metaheuristic methods slightly differ. This is due to the diode saturation current neglected in the study cited in [21]. In other words, the saturation current has not been taken into account in the equivalent circuit parameters and the analysis has been performed for four parameters. On the other hand, the parameters extracted by using the proposed model are closely in agreement with those obtained by using the existing methods. However, the significant dependency on initial conditions [4, 26], requirement of a functional tool/software to solve the set of its nonlinear equations [26], and the use of the parallel resistor [7] or diode ideality factor [8] as an input parameter are still among the limitations of the existing methods. Additionally, the result obtained by using the equation given in [1] is unrealistic.

Table 4. Equivalent circuit parameters of KL070 PV module.

PV module\ parameters	KL070 (KL solar PV module)								
	Ref. [21] (GA)	Ref. [21] (Hybrid GA-PSO)	The proposed model	Model in [1]	Model in [4]	Model in [6]	Model in [7]	Model in [8]	Model in [26]
R_s (Ω)	0.10	0.28	0.124	Na	0.123	0.123	0.123	0.124	0.124
R_p (Ω)	108.6	97.88	156.2	Na	156.2	156.2	156.2	156.1	156.2
a	1.242	1.292	1.712	Na	1.712	1.712	1.712	1.712	1.712
I_o (μA)	-	-	5.61	Na	5.61	5.61	5.60	5.59	5.60
I_{pv} (A)	4.6	4.6	4.593	Na	4.593	4.593	4.593	4.593	4.594

In this section, as an example for the application of the proposed model, the equivalent circuit parameters of four commercial PV modules; MSX60, KC200GT, SW255, and BP SX-150 were extracted at standard test conditions, i.e. air temperature of 25 $^{\circ}C$ and solar radiation of 1000 W/m^2. Results are given in Tables 5 to 8 together with those obtained using existing methods. Although there are no satisfactory agreements between the parameters extracted for MSX60 PV module by using the proposed model and quantum particle swarm optimization algorithm [16], in Table 5, the results are close to each other. However, this is not the case for the KC200GT parameters given in Table 6. This is due to the fact that the solutions were obtained for a fixed value of the diode ideality factor $(a = 1.3)$ in [8]. The similar situation is also seen in the results obtained for SW255 PV module given in Table 7. This is because the value of parallel resistor (R_p) has been assumed to be in the range of $6.3 - 7.7\ k\Omega$ in the study conducted in [7]. However, the proposed model and the ones given in [4, 6–8, 26] indicate that this value is around 2.5 $k\Omega$. In Table 8, the results identified for BP SX-150 PV module are presented with those given in [24]. For the PV module, the experimental data at standard test conditions were taken from [24]. Considering the first two columns in the table, it is clear that the values of parameters do not match each other. In this case, first of all, it should be noted that the results (solutions) given in [24] do not provide their own equations. This is due to some noteworthy terms that should not be contained in the formula based on R_s. For this reason, the results obtained by rearranging the equation related to R_s are given in the third column in the table and they are close to those determined by the proposed method to a great extent. Hence, it is possible to say that both models are reliable but the requirement of experimental *I-V* curves for PV modules creates a great handicap for the model in [24] in terms of implementation.

Table 5. Equivalent circuit parameters extracted for MSX60 PV module.

PV module\ parameters	MSX60 (Solarex)							
	Ref. [16]	The proposed model	Model in [1]	Model in [4]	Model in [6]	Model in [7]	Model in [8]	Model in [26]
R_s (Ω)	0.146	0.169	Na	0.169	0.169	0.169	0.169	0.178
R_p (Ω)	561.6	637.5	Na	637.8	637.6	637.5	637.8	649.9
a	1.331	1.404	Na	1.405	1.404	1.404	1.404	1.386
I_o (μA)	0.150	0.329	Na	0.329	0.329	0.329	0.330	0.263
I_{pv} (A)	3.802	3.801	Na	3.801	3.801	3.801	3.801	3.800

Table 6. Equivalent circuit parameters extracted for KC200GT PV module.

PV module\ parameters	KC200GT (Kyocera Solar)							
	Ref. [8]	The proposed Model	Model in [1]	Model in [4]	Model in [6]	Model in [7]	Model in [8]	Model in [26]
R_s (Ω)	0.231	0.217	Na	0.217	0.217	0.217	0.217	0.217
R_p (Ω)	594.85	951.92	Na	951.93	951.93	951.93	948.93	899.90
a	1.3	1.342	Na	1.342	1.342	1.342	1.342	1.341
I_o (μA)	0.096	0.171	Na	0.171	0.171	0.171	0.170	0.168
I_{pv} (A)	8.213	8.211	Na	8.211	8.211	8.211	8.211	8.212

In order to further investigate the reliability of the proposed model, the output current-voltage $(I\text{-}V)$ characteristics of two PV modules and a solar cell are examined and the results are compared with the experimental

Table 7. Equivalent circuit parameters extracted for SW255 PV module.

PV module\ parameters	SW255 (SolarWorld)							
	Ref. [7]	The proposed model	Model in [1]	Model in [4]	Model in [6]	Model in [7]	Model in [8]	Model in [26]
R_s (Ω)	0.2039	0.21	Na	0.21	0.21	0.21	0.21	0.21
R_p (Ω)	6300	2570.3	Na	2570.6	2570.3	2570.3	2568.5	2499.9
a	1.2647	1.2484	Na	1.2484	1.2484	1.2484	1.2484	1.2457
I_o (nA)	0.3041	23.176	Na	23.177	23.176	23.176	23.168	22.204
I_{pv} (A)	8.88	8.8807	Na	8.8807	8.8807	8.8807	8.8807	8.8803

Table 8. Equivalent circuit parameters extracted for BP SX-150 PV module.

PV module\ parameters	BP SX-150 (ABC Solar)		
	Ref. [24]	The proposed model	The corrected model in [24]
a	1.64	1.4851	1.4851 (fixed)
R_p (Ω)	1799.3	960.06	782.52
R_s (Ω)	0.3125	0.4543	0.4415
I_o (μA)	2.8016	0.6166	0.6155
I_{pv} (A)	4.7508	4.7522	4.7527

data. Figure 2 demonstrates the consistency between the experimental data and predicted data for Solarex MSX-60 PV module. Experimental data were taken from [16] and the *I-V* curve was plotted using the results of the model given in Table 5. *I-V* characteristics predicted using the results given in [16] are also used for comparison. It is clear from the figure that the calculated values are in good agreement with the experimental data provided by the manufacturer. On the other hand, the data predicted using the value of equivalent circuit parameters given in [16] do not exactly match the experimental data. Similarly, Figure 3 shows the *I-V* curves for BP Solar MSX120 PV module, plotted by using the equivalent circuit parameters which were determined by the proposed model and those given in [22] at an air temperature of 40 $^{\circ}C$ and solar radiation of 300 W/m^2. The experimental data were taken from [22]. The parameters determined by the proposed model and the ones given in [22] are presented in Table 9. Results show that the value of equivalent circuit parameters do not match each other, but it is quite clear in Figure 3 that the *I-V* curve based on the proposed model exactly match the experimental data at all points. Hence, it is possible to say that the parameters extracted by using the proposed model are more realistic than those given in [22]. Figure 4 shows *I-V* curves of a 57 mm-diameter commercial (R.T.C. France) silicon solar cell plotted using the optimal values of single-diode equivalent circuit parameters identified by the proposed model and the optimal values of two-diode equivalent circuit parameters given in [23]. The experimental *I-V* characteristic is also presented in the figure to make a comparison. For the solar cell, the experimental data were taken from [23] and the identified parameters are given in Table 9. As can be seen in the figure, *I-V* curves constructed with the optimal parameters determined by the model and the two-diode hybrid model (model-1) in [23] are exactly coincident with each other. Although there is a slight difference as the output voltage increases, the curves created using the results of both methods are also consistent with the experimental data. On the other hand, it is clear in the figure that *I-V* characteristics created with the results in [23] which were determined by using the pattern search algorithm (model-II) do not coincide with experimental data at a satisfactory level. Consequently, all three comparisons suggest that the model extracts equivalent circuit parameters in a more accurate manner, and as a result, it is well-suited for characterizing *I-V* curves.

Table 9. Extracted parameters for BP-MSX120 PV module and R.T.C France solar cell.

PV module\ parameters	MSX120 (BP Solar Global Marketing)		Solar cell (R.T.C France)		
	Ref. [22]	The proposed model	Model - I Ref. [23]	Model - II Ref. [23]	The proposed model
R_s (Ω)	1.769	1.4922	0.0367	0.032	0.0389
R_p (Ω)	2438.65	4288.2	55.529	81.3	52.252
a	1.1592	1.2472	1.45-1.99	1.6-1.19	1.4582
I_o (nA)	28.164	100.14	224.7-755.2	988.9-1	253.83
I_{pv} (A)	1.1713	1.1709	0.7607	0.7602	0.7611

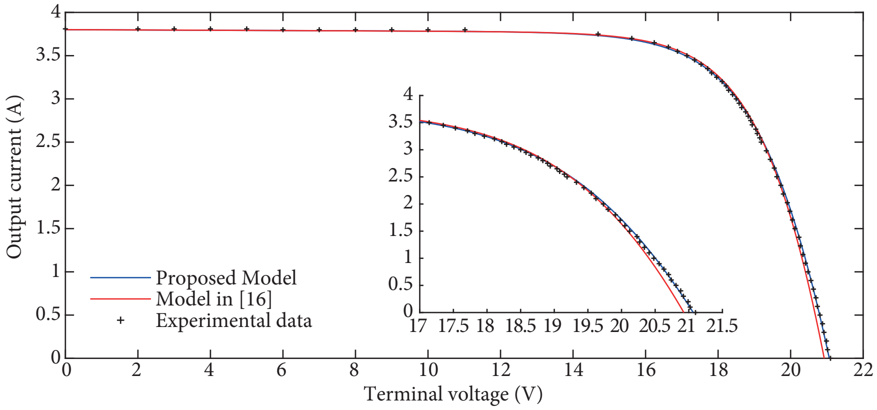

Figure 2. *I-V* curves for Solarex MSX60 PV module ($T = 25\ ^{\circ}C$)

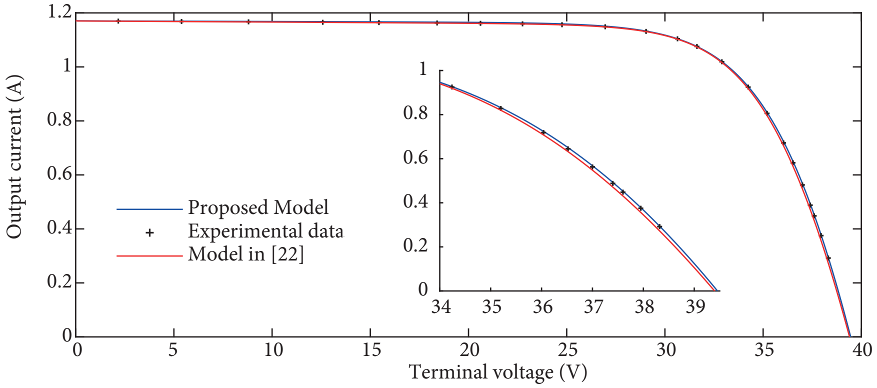

Figure 3. *I-V* curves for BP Solar MSX120 PV module ($T = 40\ ^{\circ}C$)

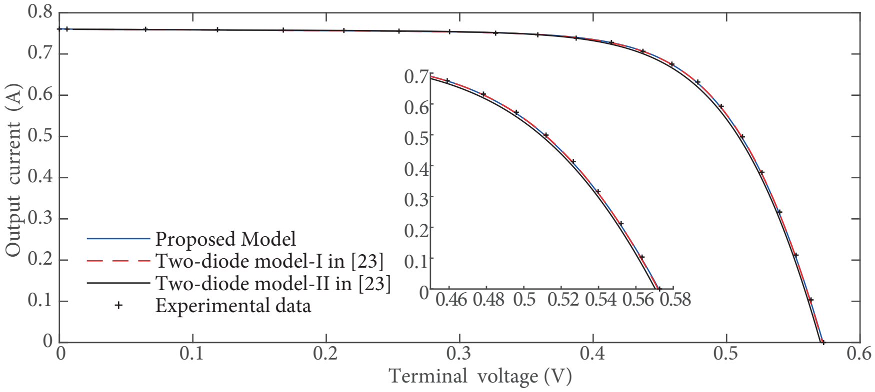

Figure 4. *I-V* curves for R.T.C France solar cell ($T = 33$ °C)

4. Conclusions

In this study, an analytical model for extracting unknown parameters of PV cells/modules using the single-diode model was developed without neglecting any of the valuable terms. It was tested on six well-known commercial PV modules by comparing the results with those obtained by using such analytical methods presented in [1, 4, 6–8, 26]. The results given in [16, 21–24] were also taken into account for comparison. In addition, the accuracy of the extracted parameters was verified by experimental *I-V* curves and also those created by using the parameters of the two-diode models given in [23]. All applications suggest that the proposed method allows to determine all unknown parameters of the single-diode equivalent circuit in a more accurate manner. It requires only the main data points of the *I-V* characteristic; open circuit, short circuit, and the maximum power point as input data which make it a fast and low-cost parameter identification approach. Although the computation time was not undertaken comprehensively, the results from MATLAB environment indicate that the model has the same execution time as the other analytical models given in [1, 4, 6–8, 26] and it is negligible. On the other hand, it is quite clear that the models given in [1] and [24] were developed incorrectly. Additionally, other models considered for comparison have several drawbacks. For instance, the parallel resistance (R_p) or diode ideality factor (a), which are of great importance in the realization of *I-V* curves for PV modules, are considered to be known and used as an input parameter in [7] and [8], respectively. This makes these models dependent on the empirical data from the literature, except for the main data points of the *I-V* characteristics. Moreover, the solution of their equations is highly dependent on the initial values of the parameters [4, 26]. The model proposed in [26] also requires a functional tool/software for solving the set of its nonlinear equations. Additionally, the model developed in [24] is a partly numerical-based method, and as a result, it requires experimental *I-V* curves of PV modules which are not provided by most manufacturers.

5. Future work

The proposed method will be improved to extract equivalent circuit parameters of two-diode seven-parameter model of PV cells/modules.

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