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RESEARCH ARTICLE

Enhanced Method for Estimating Unknown Parameters in Single Diode Model for Solar Photovoltaic Cells

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Abstract Three models of equivalent circuit are frequently applied for modelling solar cells/modules: single, double and three diode models. Among these, the single diode (SD) model is currently the most widely applied for solar cell modelling. This model is characterized by five parameters, which can be estimated using various methods. In the present work, the unknown parameters of this model are determined using an improved hybrid method. Our research introduces an innovative approach for this purpose. Our method formulates and resolves the equations defining these critical parameters. Particularly, our main objective revolves around estimating the diode's saturation current (I_0), series resistance(R_s), photocurrent (I_{ph}) and parallel resistance (R_{sh}), ideality factor (n) through these equations. We confirmed our method reliability by thoroughly simulating the I-V curves of six PV cells, showing the credibility and the precision of our approach. This research significantly advances solar cell modelling by offering an improved technique for estimating crucial parameters within the SD model, enhancing the accuracy and reliability of solar cell performance predictions.

Keywords: Photovoltaic, Single diode model, Solar cell, Parameter determination, Modelling.

Introduction

Recently, solar power has become an increasingly attractive renewable source of electricity in the world [1]. This is mainly due to efforts provided to minimize the fossil fuels consumption and to deal with climate changes, the integration of solar photovoltaic (PV) systems stands as a crucial driver in significantly curbing both emissions and reliance on fossil fuels. The main advantages of this energy are it is abundant, free-polluting, low installation and maintenance costs and it becomes more and more efficient. Generally, solar energy is used in different applications, such as solar (PV) systems, water desalination, and electricity generation. For these reasons, industry and researchers are paying more attention in the prospective development of the worldwide energy sector all over the world [2]. This increased attention is mainly driven by the challenges associated with finding alternatives to fossil fuels and mitigating the environmental harm caused by CO_2 emissions. In the literature, numerous works are dedicated to solar photovoltaic research. For instance, the International Energy Agency (IEA) predicts that by 2030, approximately 80% of the electricity produced in the world will originate from renewable sources [3]. Thus, photovoltaic solar energy will be the main driver of this expansion.

In grid-connected and off-grid systems, the power can be efficiently supplied by sustainable energy sources, particularly solar and wind energy [4]. Globally, the percentage of sources of renewable energy in the production of electricity has augmented from 26% in the first quarter of 2019 to almost 28% in the same period in 2020 [4]. Furthermore, according to data from the US Energy Information Administration, the percentage of electrical power produced in the US from renewable sources has increased from 20% in 2020 to 22% in 2022 (“EIA”).

The solar cell produced power is generally small and, to obtain high powers, solar cells will be coupled in series and parallel composing PV panels. To accurately predict the features of a photovoltaic system,

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it is indispensable to use an appropriate model of the equivalent electrical circuit to compute the PV cell characteristics at different operating modes.

In the literature, various models have been proposed for analysing solar cells. The Single Diode (SD) model stands as the commonly used approach [5,6]. While research such as [7,8] highlights the Double Diode model's superiority in specific operational scenarios, the prediction of seven parameters presents notable computational hurdles. Conversely, the SD model provides a rationalised approach, requiring less computation time and predicting only five parameters. Thus, it proves more practical for parameter extraction. Additionally, the Three-Diode model proposed in [9] presents a comprehensive representation of solar cell characteristics but requires the estimation of nine parameters, leading to increased complexity and computational time.

Our choice for the SD model over other alternatives, such as the Double and Three-Diode models, is due to its inherent simplicity, computational efficiency, and ability to accurately capture essential solar cell behaviour. With fewer parameters and simplified execution, the SD model emerges as the optimal choice for our parameter extraction requirements. Despite its simplicity, this model has demonstrated its efficacy in faithfully representing solar cell electrical circuits [7,8], affirming its suitability for our study's objectives. For these reasons, the SD model is applied in the present work.

The electrical circuit corresponding to the single, double, and three diode models are presented in Figure 1. As illustrated in this figure, the circuit of the SD model consists of an ideal diode, mounted with a current-generating component in series, representing the light flow, a series (R_s) and shunt (R_{sh}) resistances representing the losses. Therefore, for SD model, the electrical circuit consists of five unknown parameters which are: the generated photocurrent (I_{ph}) the diode reverse saturation current (I_0), the series resistance (R_s), the shunt resistance (R_{sh}), and the factor of ideality of the diode (n).

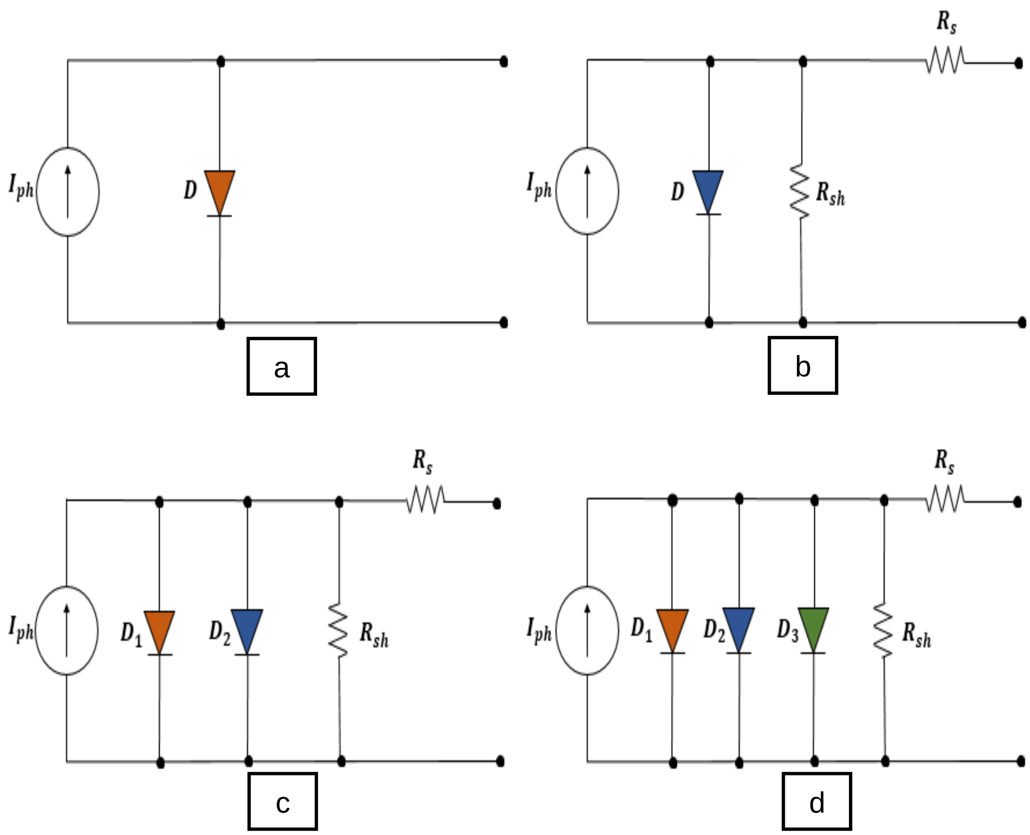

Figure 1. Electrical circuits models: (a) idealized, (b); SD-model (c); Double-diode (DD) model; (d) Three-diode (TD) model

The current-voltage characteristic of the PV cell is illustrated in Figure 2. From this characteristic, we deduce the information required for PV cell modelling, including the open circuit voltage, current, maximum power point voltage, and short-circuit current. This information is necessary for PV cell modelling. However, it is not sufficient to predict the five unknown parameters.

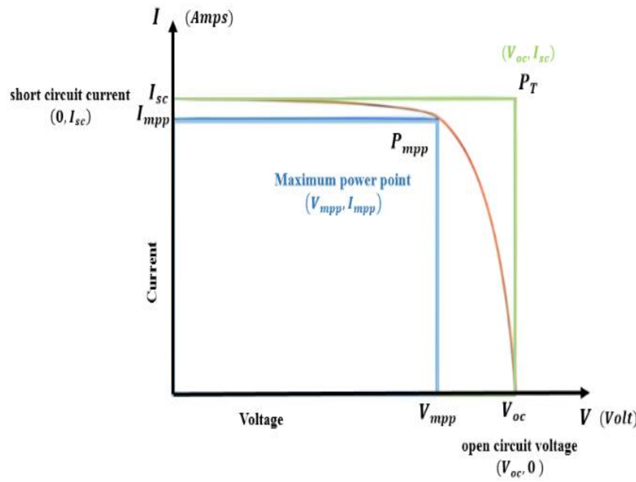

Figure 2. PV cell characteristic: IV curve

To calculate the unknown parameters of the electrical equivalent circuit of the SD model, several methods can be found in the literature. These last can be categorized into three groups: iterative, analytic and hybrid approaches. Each of these methods is distinguished from the others by its efficiency, precision in the identification of the parameters, its complexity, the computation time, and the required experimental input data. A comprehensive review of the different approaches used for the photovoltaic cell performance simulation is presented in [10].

Analytical-based techniques are non-iterative approaches established up on approximations and simplifications. In addition, some experimental data of the I-V curve is needed for the parameter's prediction. The major advantages of these techniques are the computation time and the sufficiently accurate results. Within this framework, several works were published.

In [11], the author proposes a mathematical approach that offers several advantages, notably in terms of results around the maximum power point and precise reproduction of the I-V curve. However, a notable limitation is the assumption of a fixed ideality factor for the diode, which may not accommodate variations due to different photovoltaic technologies.

In [12], another mathematical method is presented, constrained to four equations with a constant ideality factor. However, it shares the disadvantage of assuming a fixed ideality factor, like the approach in [11]. In [13], the Taylor series expansion is applied to calculate the five unknown parameters. However, a significant drawback of this method is that the function must have a convergent power series expansion at the chosen point, which may not always be the case.

Using the Thevenin equivalent circuit, the estimation of the five parameters is facilitated in [14]. This method stands out for its practicality and efficiency in parameter estimation, making it a valuable approach in the context of the study.

In [15], an analytical method is proposed for predicting the five parameters of the SD model. However, it's worth noting that the RMSE value associated with this method tends to be slightly higher compared to other methods.

In [16] an accurate and fast-based analytical method was proposed for the prediction of the parameters. This approach is based on the data provided by the manufacturer. The main objective is the use of a simple calculation technique for the ideality factor evaluation.

In [17], a dynamic modelling of electrical characteristics of a PV module is presented. Simulated I_{pv}-V_{pv} characteristics show precise predictions, with RMSE ranging from 0.0852 to 0.0594. However, the complexity of the model may generate implementation challenges.

In [18], an analytical technique is applied to find the parameters of the PV panel. Then, these parameters are taken as the input values for an optimization procedure based on Gauss-Seidel to obtain more refined parameters.

In [19] an innovative-based analytical and iterative technique was suggested to find the SD model's unknown parameters. This approach is based on electrical information deduced from the voltage of the open-circuit, current and voltage corresponding to the maximum power point (MPPT) and short circuit current. At first, a set of equations is constructed, and a closed-form expression for the five unknown parameters is deduced. The ideality factor is iteratively computed by minimizing the RMSE between observed and simulated results.

In [20], a novel hybrid analytical/iterative approach is introduced for extracting the parameters of the SD model using Lambert's W-function. This method requires explicit equations for each parameter. However, it's important to note that this approach requires a high level of mathematical proficiency and familiarity with complex mathematical functions like Lambert's W-function. This could potentially restrict its accessibility and applicability.

In [21], the SD model five parameters of photovoltaic panels are iteratively estimated. The iterative algorithm follows three stages: (i) from the manufacturer information, the ideality factor is analytically estimated, (ii), three analytical equations are formulated to find R_{sh}, I_0, and I_{ph} as functions of R_s and n, (iii), using an iterative algorithm to minimize the difference between the simulated and the experimental values of the maximum power. However, the author's comparison is restricted to just one other method. Considering both the advantages and drawbacks of method family in determining the five parameters of the Single Diode (SD) model for PV panels, our study aims to achieve the highest possible electrical efficiency by precisely determining the current-voltage characteristic, which is crucial for predicting the parameters of a photovoltaic module.

In this pursuit, an improved form expression for R_s based on four equations as functions of the I_{ph}, I_o, n, and R_{sh} parameters is derived. In contrast, several methods that maintain one of the parameters constant, are used in [11, 22-23], our approach integrates both analytical and iterative methods. This hybrid process adjusts experimental characteristics and model estimates iteratively, allowing the determination of all parameters without prior fixation.

A pivotal innovation in our approach lies in the simultaneous incremental adjustment of both (n) and (R_s). The increment of (R_s) is customized according to the number of solar cells connected in a photovoltaic unit, enabling adjustment of the algorithm convergence speed in correlation with the number of solar cells. Rooted in the single diode model, our method depends on the measured current and voltage data. To evaluate its efficacy, six photovoltaic units were tested.

In our study, we introduce an enhancement for five-parameter estimation by combining analytical and iterative methods. First, we delineate the implementation steps, incorporating analytical parameter expressions and calculation processes. Next, we compare the results obtained with measurements and other state of art methods. Finally, we will conclude by summarizing the concepts explored in this study.

Proposed Approach

Under different operation modes (irradiation and temperature), the SDM enables a very accurate simulation of the electrical behaviour exhibited by various PV cells and modules [25,26]. Moreover, the identification of its five parameters is less complicated compared to other models (double and triple diode), requiring more parameter estimation.

The electrical equivalent circuit of the SD model is illustrated in Figure 1 (a). The law of Kirchhoff is the origin of the specific equation for the SD model's five parameters [11,20]. The current of the cell is expressed as the following:

$$I = I_{ph} - I_D - I_{sh} \quad (1)$$

where

$$I_D = I_0 \left[exp(\frac{V+I\,R_s}{nV_t}) - 1 \right] \quad (2)$$

and

$$I_{sh} = \frac{V+IR_s}{R_{sh}} \quad (3)$$

Thus, Eq. (1) can be replaced in the following way:

$$I = I_{ph} - I_0 \left[exp(\frac{V+I\,R_s}{nV_t}) - 1 \right] - \frac{V+IR_s}{R_{sh}} \quad (4)$$

Where

$$V_t = \frac{KT}{q} \tag{5}$$

where:

- I_{ph}: photocurrent,
- I_0: diode saturation current,
- q: charge of an electron,
- n: factor of ideality of the diode,
- R_s: series resistances,
- R_s: shunt resistances,
- T_k: temperature in Kelvin,
- K: constant of Boltzmann.

As previously mentioned, we apply iterative methods for determining R_s and n. As proposed in [19] the diode ideality factor is iteratively evaluated according to the following equation:

$$n = n_0 + 0.01V_t \tag{6}$$

where $n_0 = 1$.

The series resistance R_s is determined through an iterative process as follows [20]:

$$R_s = R_s + 0.001\,\frac{N_c}{N_p} \tag{7}$$

Photocurrent (I_{ph}):

The generated photocurrent (I_{ph}) is calculated according to the manufacturer's information related to the short circuit at STC by applying the short circuit operating form: ($V=0$ and $I=I_{SC}$). Under this conditions, Eq. (4), becomes:

$$I_{sc} = I_{ph} - I_0\left[exp(\frac{R_s\,I_{sc}}{nV_t}) - 1\right] - \frac{R_s\,I_{sc}}{R_{sh}} \tag{8}$$

Due to the extremely low value of R_s, the exponential term in Eq. 8, can be equal to 1. Therefore, we obtain the following expression:

$$I_{ph} = \frac{R_s + R_{sh}}{R_{sh}} I_{sc} \tag{9}$$

Diode Saturation Current (I_0)

Using the manufacturers data from the open circuit operating conditions ($V=V_{0C}$ and $I=0$) the diode's reverse saturation current (I_0) can be determined. Within the open circuit conditions Eq. (4) becomes:

$$0 = I_{ph} - I_0\left[exp(\frac{V_{oc}}{nV_t}) - 1\right] - \frac{V_{oc}}{R_{sh}} \tag{10}$$

By rearranging Eq. (10), we can determine the equation of I_0.

$$I_0 = \frac{I_{ph} - \frac{v_{oc}}{R_{sh}}}{exp(\frac{v_{oc}}{n\,V_t}) - 1} \tag{11}$$

Parallel Resistance (R_{sh})

To calculate the parallel resistance (R_{sh}), we use the model proposed in [28]. The computation method starts by adding into Eq. (4) the point reaching the maximum power and the short circuit conditions. The following expression is obtained by replacing I_0 with Eq. (11) and the maximum power point conditions ($V=V_{mp}$) and ($I=I_{mp}$) in (Eq. 4):

$$I_{mp} = I_{ph} - I_0\left[exp(\frac{V_{mp} + I_{mp}R_s}{nV_t}) - 1\right] - \frac{V_{mp} + I_{mp}R_s}{R_{sh}} \tag{12}$$

According to [27] and [19], we obtain the following results:

$$R_{sh} = \left[V_{OC}\left(exp\left(\frac{V_{mp} + I_{mp}R_s}{nV_t}\right) - exp\left(\frac{I_{sc}R_s}{nV_t}\right)\right) - V_{mp}\left(exp\left(\frac{V_{oc}}{nV_t}\right)\right) - exp\left(\frac{I_{sc}R_s}{nV_t}\right)\right] / \left[I_{mp}(exp\left(\frac{V_{oc}}{nV_t}\right)) - exp\left(\frac{I_{sc}R_s}{nV_t}\right)) - I_{sc}\left(exp\left(\frac{V_{oc}}{nV_t}\right)\right) - exp\left(\frac{V_{mp} + I_{mp}R_s}{nV_t}\right)\right] - R_s \tag{13}$$

The Series Resistance (R_s)

A preliminary estimation of the series resistance R_s value is required for parameter identification: n, R_{sh}, I_0, and I_{ph}. In our work, we will use experimentally data extracted from the I-V characteristic curve. After that, the value of R_s is iteratively calculated by minimizing an objective function *F.* This objective function corresponds to the mean difference between the experimental and the estimated currents as represented in the following equation:

$$F = \sum_{i=1}^{N} \frac{I_{mes} - I_{cal}}{N} \tag{14}$$

where I_{mes}, I_{cal} and N are respectively the measured current, the estimated current and the number of points *(V(i),* I_{mes} *(i))* measured.

To determinate the series resistance, we initiate the process using this formula:

$$R_s = (n\,V_t) * exp(-V_{oc}/\,(nV_t\,)) \tag{15}$$

This equation is commonly used in diode models to approximate the series resistance [28]. To calculate the effect of series resistance on diode behaviour [29]. This equation considers variables such as the factor of ideality (*n*) and the thermal voltage (V_t). The exponential term of the voltage, corresponding to the open circuit (V_{oc}), is needed to represent the nonlinear properties of the diode. Then, an initial value ($R_{sh,init} = 0.01$) makes it possible to launch the process of computing the other parameters *a*, R_{sh}, I_0, and I_{ph}. Afterwards, these parameter values are used to compute the predicted current value, $I_{cal,\,I}$ corresponding to Eq. 4. Then, the objective function F, is evaluated. At this stage, if the function F is not yet minimal, the stopping criterion is not fulfilled, and the iterative procedure continues by replacing R_S with its new value: $R_s = R_s + 0.001.N_s/N_p$. These steps are repeated unless the stopping criterion becomes satisfied and the value of R_s minimizing the objective function F is found [20].

The tolerance is the lowest value of F provided by the model. According to [20], it can be calculated by analysing the changes of *F* as a function of R_s.

Diode Ideality Factor (n)

Many studies assume that PV technology can be used to determine the value of the ideality factor. According to these studies, this factor is a constant and it depends on the used PV technology. Usually, a value of this parameter between 0 and 1 is taken.

This parameter depends on the number of cells constituting the PV module, the temperature and it varies with voltage and other factors. In this work, we apply an iterative method to calculate this parameter as proposed in [19], hence making the calculation of the ideality factor more reliable and systematic. The diode ideality factor, *n*, is determined based on Eq. 6.

The flowchart algorithm, dealing with five parameters determination and presuming the previously mentioned steps is shown in (Figure 3).

This flowchart begins with collecting input data. Subsequently, all equations including R_{sh}, R_s, I_{ph}, I_o, RMSE, and F are calculated. Subsequently, we compare each value of RMSE and F against a predetermined tolerance (initially set at 1e-5). If both RMSE and F exceed the tolerance, both n and R_s are incremented, and the tolerance will be updated to a new value calculated as tolerance = RMSE / I_{sc}. This iterative process ensures the refinement of parameter values until satisfactory accuracy is attained.

Results and Discussions

To study the effectiveness of the suggested approach and to measure the discrepancy between the obtained results and the measured ones, RMSE [19, 20,24] criterion is applied:

$$RMSE = \sum_{i=1}^{N} \sqrt{\frac{1}{N}(I_{mes,i} - I_{cal,i})^2} \tag{16}$$

To ensure the accuracy of the proposed prediction method, another tool was also applied as an evaluation criterion. This is the Mean Absolute Percentage Error, MAE [24], which is computed as described by the following equation:

$$MAE = \frac{1}{N}\sum_{i=1}^{N} |I_{mes,i} - I_{cal,i}| \tag{17}$$

N denotes the number of the used data points

The proposed method will be evaluated through a comparison of the experimental I-V curves supplied by the manufacturers of various commercial PV modules with the I-V curve generated using our method. This comparative analysis provides a thorough assessment of the suggested strategy.

The I-V curves of the studied different PV modules are simulated. The obtained results are illustrated in figures Figure 4, Figure 5, Figure 6, Figure 7, Figure 8, and Figure 9. The characteristics of the tested PV cells are shown in Table 1:

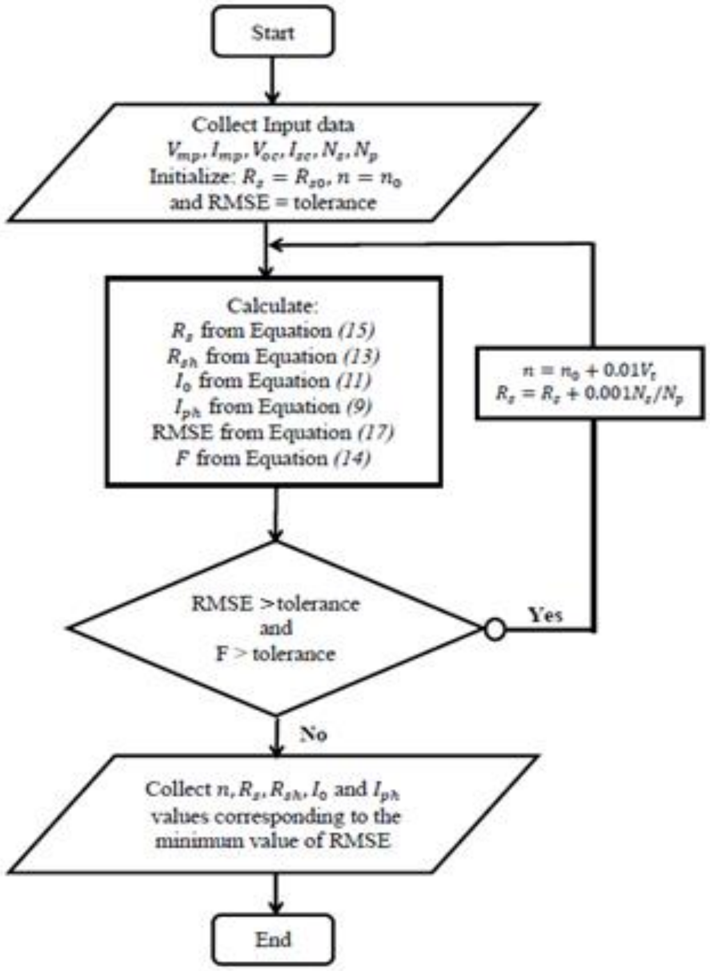

Figure 3. Flow diagram of the suggested approach

Table 1. The characteristics of the tested PV cells

Solar Cell	Type	Number of serie connected	Irradiation W/m^2	Temperature °C
BP 5170 S photovoltaic	monocrystalline silicon cells	72	1000	25
Photowatt-PWP 201	Polycrystalline	36	1000	45
BP MSX120	monocrystalline	1	1000	25
KC200GT	polycrystalline	1	1000	25
RTC France	Thin film	1	1000	25

The experimental data (provided by the manufacturer) [19,20] are compared against results obtained using the proposed method on the studied PV cells. The points on the graphs are comprised of blue, green, and red data points, depicting the voltage (V) and current (I) values retrieved from the module datasheets under standard test conditions (STC).

This analysis will offer comprehensions into the performance and the implementation of the proposed approach. Through this comparison, we can validate the proposed approach against the experimental data, which shows its potential as a reliable tool to characterize the performance of PV module.
The electrical specifications of the considered photovoltaic cells are summarized in Table 2.

Table 2. Electrical features of the considered PV cells/ modules

Electrical feature	BP 517S	BP MSX120	Photowatt-PWP201	R T C France	PVM 752 GaAs	KC200 GT
I_{mp} (A)	4.72	3.56	0.9120	$6.894 .10^{-1}$	$0.937 .10^{-1}$	7.61
V_{mp} (V)	36	33.7	12.649	$4.507 .10^{-1}$	$8.053 .10^{-1}$	26.3
V_{oc} (V)	44.2	42.1	16.778	$5.728 .10^{-1}$	$9.926 .10^{-1}$	32.9
I_{sc} (A)	5	3.87	1.030	$7.03.10^{-1}$	$0.998 .10^{-1}$	8.21
N_s	72	72	36	1	1	54

To verify the correspondence between the generated curves and the experimental data, the RMSE and the non-dimensional standard deviation are used as validation criteria. The results are presented in Tables 3, 4 and 5.

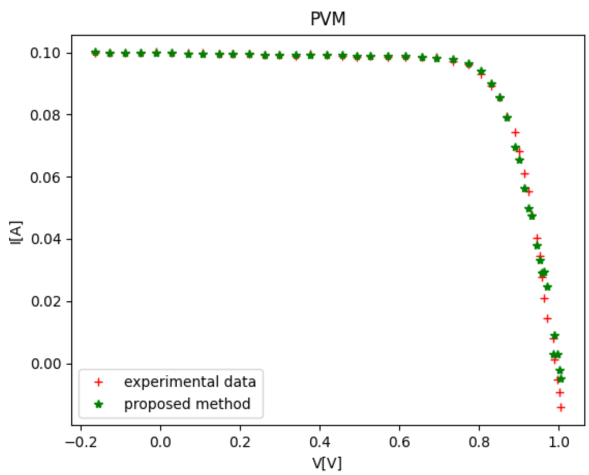

Figure 4. I-V Computed and experimental curves. For the PVM 752 GaAs (T=25 ◦C, G=10^3 W/m^2)

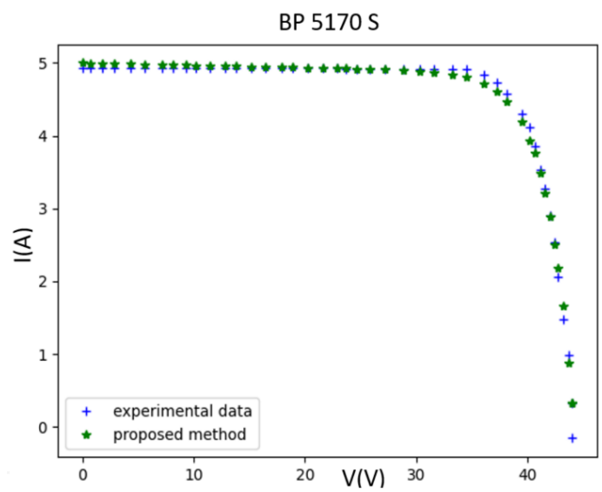

Figure 7.I-V Computed and experimental curves related to BP 5170 S solar cell (T=25 ◦C, G=10^3W/m^2)

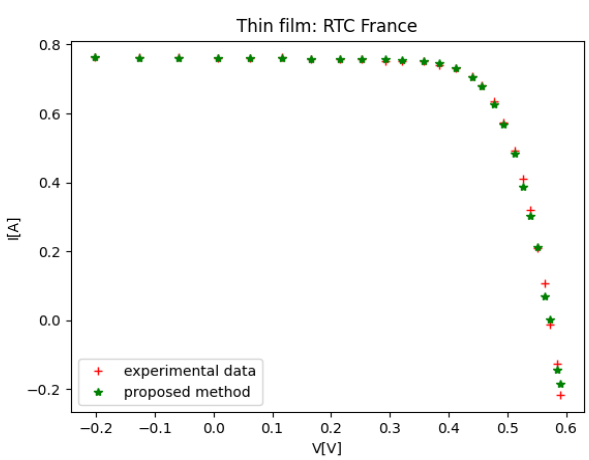

Figure 5. I-V Computed and experimental curves for the RTC France solar cell (T =33 ◦C, G = 10^3 W/m^2)

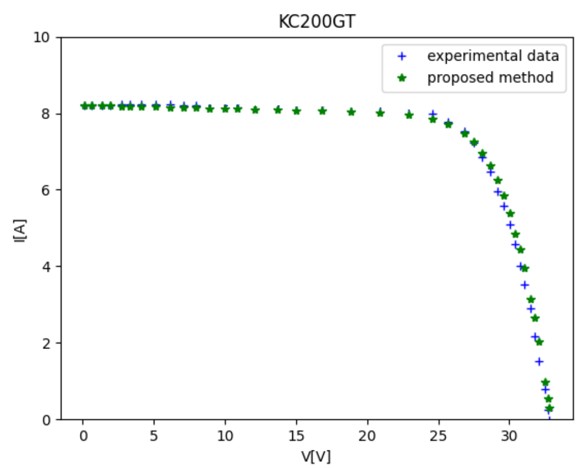

Figure 8. I–V Computed and experimental curves for the KC200GT (T=25 ◦C, G=10^3 W/m^2)

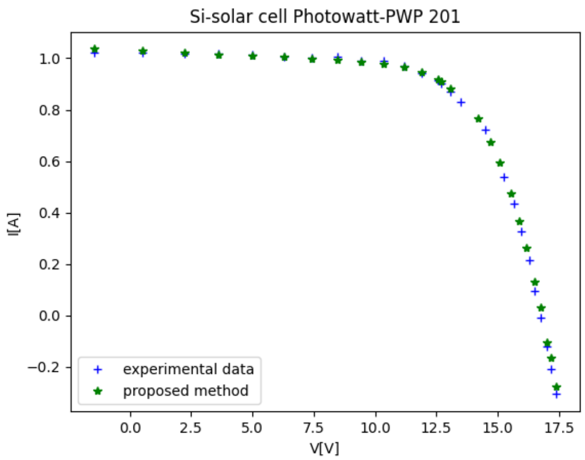

Figure 6.I-V Computed and experimental curves for the Photowatt PWP201 (T=45 ◦C, 10^3 W/m2)

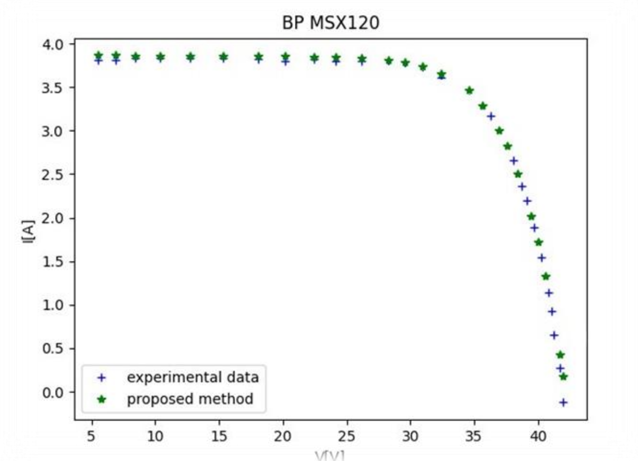

Figure 9. I-V Computed and experimental curves related to BP MSX120 SOLAR Cell (T=25 ◦C, 10^3 W/m2)

The recovered parameters obtained from the proposed approach for the six tested PV cells/modules are provided in the Table 3. These results prove the efficiency and reliability of our method to accurately calculate the crucial parameters for pv systems.

Table 3. Estimated parameters of the considered PV cells/modules

	BP 5170 S	BP MSX120	Photowatt-PWP 201	RTC France	PVM 752 GaAs	KC200GT
R_s(Ω)	0.0800	0.382	0.004500	0.028085	0.02709	0.254
R_{sh}(Ω)	311.1528	1406.7684	127.3007431	8.655413	134.67840	113.51274
I_0(A)	5.269796e-08	1.192641e-06	1.301936e-07	1.346865e-09	3.105327e-7	1.858382e-08
I_{ph}(A)	5.000128	3.870852	1.03	0.762767	0.09982	8.224465
n	1.221067	1.420067	1.010654	1.000285	1.000278	1.1150

Table 4. Computed the RMSE and tolerance ε for the Photowatt-PWP 201

Method	Photowatt-PWP 201	
	RMSE	ε
Suggested	**5,589e-4**	**5,4265e-4**
Choulli Reference [20] (hybrid analytical/iterative)	2.18e-03	-
Pindado Reference [38] (explicit model)	4.27e-3	4.138e-3
Das Reference [37] (explicit model)	2.64e-3	2.558e-3
Cubas Reference [11] (hybrid analytical/iterative)	2,94e-3	2,85e-3
Phang Reference [32] (hybrid analytical/iterative)	35,49e-3	34,4e-3
Lidaighbi Reference [19] (hybrid analytical/iterative)	2,164e-3	2,097e-3
GWO Reference [39] (Meta- heuristic)	5.48 e-3	5.31e-3

Table 5. Computed RMSE and ε for the PVM.752 GaAs

Model	PVM.752 GaAs	
	RMSE	ε
Suggested	5,466e-3	54,73e-3
(ELPSO) Reference [30] (Meta- heuristic)	25,4e-3	254,5e-3
(CPSO) Reference [30] (Meta- heuristic)	25,4e-3	254,5e-3
(BSA) Reference [30] (Meta- heuristic)	2,14e-3	21,44e-3
(ABC) Reference [30] (Meta- heuristic)	2,04e-3	20,44e-3

Table 6. Computed the RMSE and the tolerance ε for the RTC France solar cell

Method	RTCSolar cell	
	RMSE	ε
Suggested	2,537e-4	3,337e-4
Choulli Reference [20] (hybrid analytical/iterative)	7.90740e-04	-
Peng Reference [33] (hybrid analytical/iterative)	3,543e-3	4,65e-3
Louzazni Reference [34] (Analytical)	5,80e-3	7,62e-3
Toledo Reference [35] (Analytical)	0,77e-3	1,01e-3
Akbaba Reference [36] (Explicit model)	23,60e-3	31,03e-3
Das Reference [37] (Explicit model)	31,74e-3	41,73e-3
Pindado Reference [38] (Explicit model)	7,63e-3	10,03e-3
Oulcaid Reference [39] (Explicit model)	031,99e-3	42,06e-3
BSA Reference [30] (Meta- heuristic)	1.44 e-3	1.89 e-3

Table 7. Computed the RMSE and the tolerance ε for each BP 517S, BP MSX120 and KC200GT solar cells

Cell	Values of Suggested methods	
	RMSE	ε
BP 517S	15.395e-3	3.079e-3
BP MSX120	30.607e-3	7.908e-3
KC200GT	33.366e-3	4.064e-3

This study presents a significant advancement in computational methodologies within the field of procedures calculation involving parameters (n) and (R_s). Specifically, this work combines the analytical algorithm proposed by [19] for determining the parameter (n) with an innovative approach for computing (R_s) introduced in [20]. The synergy of these methodologies culminates in the development of a novel hybrid algorithm that notably enhances computational simplicity and efficacy in addressing the challenges posed by the calculation of (R_s).

By utilizing experimental data points, the algorithm continuously adapts these parameters to approximate practical behaviour for predicting solar cell performance. Its iterative aspect not only enhances accuracy but also provides an efficient convergence towards optimal parameter determination. The algorithm's success in minimizing RMSE, a crucial metric reflecting alignment between calculated and measured data.

Our methodology underwent different comparison, are detailed in Tables 4, 5, and 6, with diverse analytical approaches [19, 33-35], explicit models [36-38], and notable metaheuristic strategies like the Grey Wolf Optimizer (GWO) in [39].

The RMSE values were extracted for Enhanced Leader Particle Swarm Optimization (ELPSO), Conventional Particle Swarm Optimization (CPSO), Backtracking Search Algorithm (BSA), and Artificial Bee Colony (ABC) algorithms referenced from [30].

Our method, while demonstrating superior performance and accuracy across various methods, shows a simplicity in implementation. It stands out for its clarity and lack of complexity; also, it achieves best results. This simplicity facilitates the implementation and significantly reduces the required time without compromising its efficiency.

Its particularity relies in the choice of initial values for parameters (n) and (R_s), using an iterative improvement process that radically minimizes RMSE values. These outcomes clearly affirm the effectiveness and superiority of our methodology over existing approaches.

The evaluation, based on RMSE and ε analyses, clearly demonstrates the superior performance of our model. The basis of our method is the concurrent calculation of parameters (n) and (R_s), ensuring their optimization within the algorithm until both equations validate a minimum error within defined tolerance limits.

Conclusions

The development of an enhanced method for estimating parameters in single diode models represents a fundamental step in the optimization of photovoltaic (PV) systems.

Equivalent circuit models like the single diode model serve as essential tools for PV system simulations. Various techniques, both analytical and iterative, have been proposed to estimate crucial parameters within these models. Our work specifically presents an improved method for extracting series resistance (R_s) and the ideality factor (n) within the single diode model, leveraging I-V curves and using an iterative algorithm. This novel approach consistently outperformed existing approaches in terms of accuracy and precision, demonstrating minimal error values($RMSE$).

The comparison between our outcomes and experimental data confirms the reliability and practicality of our proposed model for accurately characterizing solar cells. Indeed, the RMSE value obtained for the solar cells Photowatt-PWP 201, PVM.752 GaAs and RTC solar cell are 5.589e-4,5.466e-3, and 2.537e-4, respectively. While these results are encouraging, further advancements are necessary. Future research could extend the algorithm's applicability across diverse operating conditions and refine its accuracy. Expanding the algorithm by including additional parameters and optimizing the iterative process could significantly enhance its precision. Additionally, integrating machine learning or optimization techniques holds promise for further enhancing the model's efficiency.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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