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Research Article

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Several of Numerical Methods to Solving Nonlinear Object Function Used in Parameters Extraction Problem of one Diode Photovoltaic Cell Model

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ABSTRACT

This paper presents an analysis of the output characteristics of a photovoltaic model using numerical methods. The study focuses on the single diode model and examines various methods to solve the associated non-linear equation. The study provides a comparative analysis of these methods, shedding light on their efficiency and accuracy.

The mathematical modeling of solar cell device is used to demonstrate the equivalent circuit of single-diode solar cell model operating under environmental conditions. In this work, Newton Raphson method, Bisection method, Secant method currently exists to demonstrate the non-linear electrical behavior of this device.

The main idea of the present work is to calculate the PV current numerically using different methods with the comparison between them. The results showed that bisection method is the best because it has least iteration to obtain the optimal values of the PV parameters.

This paper presents an analysis of the output characteristics of a photovoltaic model using numerical methods. The study focuses on the single diode model and examines different approaches for solving its associated nonlinear equation. A comparative evaluation of these methods highlights their efficiency and accuracy in parameter estimation.

The mathematical modeling of the solar cell is based on the equivalent circuit of the single diode model under varying environmental conditions. To capture the nonlinear electrical behavior of the device, three numerical techniques are applied: the Newton–Raphson method, the Bisection method, and the Secant method.

The main idea of the present work is to calculate the PV current numerically using these methods and to compare their performance. The results showed that Bisection method provides the most reliable outcome, requiring least iterations to obtain optimal values of the PV parameters compared to Newton–Raphson method and Bisection method.

Keywords: Parameter Estimation, Single-diode Model, Bisection Method, Secant Method, Newton Raphson Method.

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Introduction

The increasing demand for renewable energy sources has led to significant advancements in photovoltaic (PV) technology [1]. PV systems convert solar energy into electrical energy, making them a vital component of sustainable energy solutions [2]. However, the performance of PV systems heavily depends on the accurate estimation of their parameters, which are often nonlinear and complex [3].

To simulate and study the behavior of the PV systems, several mathematical models have been developed, including single-diode model (SDM), double-diode model (DDM) and three-diode model (TDM) [4]. SDM is the most widely used and studied electrical

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circuit models with five unknown parameters [5].

Regardless of the model type, the extraction of optimal PV parameters is crucial for the effective design of PV systems6.

The PV parameter estimation (PVPE) methods fall into two categories: analytical methods and numerical methods [6]. The analytical methods extract parameters by solving the mathematical equations of the PV systems. They have the advantages of less time and data consumption, but can only be applied for the SDM model [7].

Traditional methods for parameter estimation face challenges due to the intricate characteristics of PV models. To address these challenges, researchers have developed numerical methods that offer robust and efficient solutions [8].

Numerical methods used a metaheuristic iterative algorithm, such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE), are powerful tools for estimating parameters in complex systems like photovoltaic (PV) models. These algorithms start by initializing a population of candidate solutions, each representing a potential set of parameters. The fitness of each candidate is evaluated using an objective function, typically the sum of squared errors between measured and modeled data. The algorithms then iteratively update the candidates through specific operators. This process continues until a predefined number of iterations is reached or convergence criteria are met [9,10].

Currently the most common method is to compare the simulated current data obtained by the extracted parameters with the measured current dataset. If the two are closer, the more accurate the extracted parameters are, nonlinear properties of measured current require numerical methods for solve them and compare with measured current, in this topic we will discuss a set of most used numerical methods (Newton Raphson method, Bisection, Secant method) used to evaluated the object function used for estimate the parameters of one diode cell model (used the RTC France solar cell in this research) [11,12].

The study provides a comparative analysis of these methods, shedding light on their efficiency and accuracy to calculate the object function used to evaluate the estimated parameters of SD PV cell model.

The results showed that bisection method is the best because it has least iteration to obtain the optimal values of the PV parameters.

Material and Method

Photovoltaic Modeling and Problem Formulation

To mimic the performance of a solar PV panel, the most commonly used models in the literature are the single-diode, double-diode, and triple-diode models.

The SDM, is the most basic and often used model. It consists of a single diode, series resistance (R_s), shunt resistance (R_{sh}), and a current source (I_{ph}), the equivalent circuit of the single diode model is shown in Figure 01 and the relationship of the I-V characteristics is described as follows [13,14]:

$$I = I_{ph} - \frac{V + I.R_s}{R_{sh}} - I_0\left[\exp\left(\frac{q(V + R_s.I)}{a.k.T}\right) - 1\right] \tag{1}$$

Where (a) is ideality factor of the diode. The I_0 and I_{ph} stand for saturation diode and the diode currents respectively. Also, k=1.381×10^{-23} (J/K) is the Boltzmann constant and T is the cell temperature (K) and q=1.6×10-19 C denotes the electron charge.

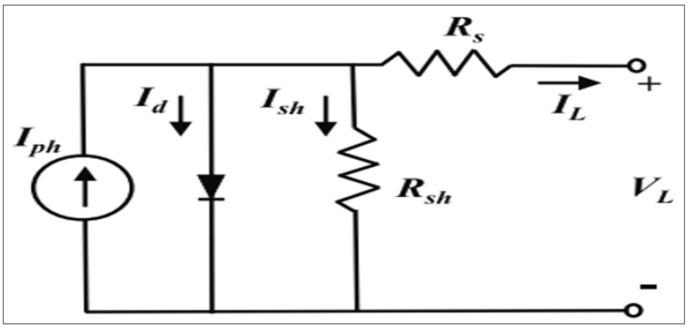

Figure 1: Circuit configuration of solar cell single-diode model [15].

For the single diode model have five unknown parameters (I_{ph},I_o,R_s,R_{sh},a) he is extract based an analytical and numerical methods, and the most goal of these methods to minimize the error between the experimental data and simulated data [6,16]. The overall error between measured and calculated current data is defined as follows:

$$\mathrm{RMSE(x)} = \sqrt{\frac{1}{N}\sum_{C=1}^{NE}\big(fsd(V,I,X)\big)^2}$$

Where N is the number of experimental data, and X is a vector that contains the parameters to be identified.

The objective functions of one diode PV models can be calculated as follow [17,14]:

$$\begin{cases} \mathrm{fsd}\,(V,I,X) = I_{exp} - I_{ph} + I_o\left[e^{\frac{q(V_{exp} + I_{clc}.R_s)}{a.K.T}} - 1\right] - \frac{V_{exp} + I_{clc}.R_s}{R_{sh}} \\ X = (I_{ph}, I_o, R_s, R_{sh}, a) \end{cases}$$

The values of V_{exp} and I_{exp} are measured values from a real solar cell, and the calculated current I_{clc} for every iteration was obtained by using numeric method (NM) to solve them, the most commonly methods used in this study is detailed in next section and has been studied on estimate the parameters of the R.T.C France solar cell.

Numerical Methods

The nonlinear nature of the objective functions in the single diode photovoltaic cell model makes it difficult to solve using traditional analytical algorithms.

To overcome this challenge, several numerical methods were applied to solve the non-linear equation of the single diode model, the most commonly methods used in this study is Newton Raphson method, Bisection method, Secant method and has been studied on estimate the parameters of the RTC France solar cell.

The Newton-Raphson Method

The Newton Raphson method, also known as Newton's method, is named after Isaac Newton and Joseph Raphson [18]. Its elegance lies in transforming nonlinear problems into sequences of linear approximations, making it one the most widely used techniques for root-finding [19]. This method is particularly well known for its fast rate convergence and for improving the convergence properties of iterative solution.

As an iterative technique, the Newton–Raphson method estimates the roots of a given function f(x) starting from an initial guess [20]. The iterative formula is expressed as [21]:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$$

Where $f'(x_n)$ is the derivative of the function f evaluated at x_n. The process continues until a predefined convergence criterion is met.

The algorithm of the Newton-Raphson method can be described as following steps

Algorithm 1: Newton-Raphson method

1	**Start**	
2	**Input**	Define function as f(x), Define derivative of function as $f'(x_n)$, Initial guess (x_0), Tolerance of Error (e), Maximum Iteration (N)
3	t=1	
4	**Do**	
5		If $f'(x_0)$= 0
6		Print "Mathematical Error"
7		Stop
8		**End If**
9		$x_1=x_0 - f(x_0))/(f'(x_0)$
10		$x_0 = x_1$
11	t=t+1	
12		**If** t > N
13		Print "Not Convergent"
14		Stop
15		**End If**
16	**While** abs $f(x_1) > e$	
17	Print root as x_1	
18	**Stop**	
19	Display the required root as x_2	

Bisection Method

In mathematics, the bisection method is a root-finding algorithm which repeatedly divides an interval in half and then selects the subinterval in which a root exists. This method can be used for any continuous function f on in the domain [a, b] [22]. According to Intermediate Value Theorem, if $f_{(a)}.f_{(b)}$ have opposite signs, there is at least one root in this range. To find this root, the interval [a, b] is divided into two parts at the midpoint c, calculated as:

$$c = \frac{(a+b)}{2}$$

If $f_{(a)}.f_{(c)}$ <0, the domain will be restricted by [a, c]. Otherwise, it is replaced by [a, c]. In each iteration, the length of the distance, which contain root is halved, progressively narrowing down the location of the solution [23].

This iterative process continues until the interval length becomes small, and providing the desired approximation of the root.

The algorithm of the Bisection Method can be described as following steps [24]:

Algorithm 2: Bisection method.

1	**Start**
2	**Input** Define function f(x), Lower and Upper of the given interval a and b, tolerance error (e), Maximum Iteration (S)
3	t =1
4	**While** t ≤ S **do**
5	Compute c = (a+b)/2
6	**If**
7	**$\lvert f_{(c)} \rvert$<e**
8	Go to step 2
9	**End if**
10	**If** $f_{(a)}.f_{(c)}$ >0
11	Set a=c
12	**Else**
13	Set b=c
14	End
15	t=t+1
16	**End while**
17	Stop
18	Display the required root as ***c***

Secant Technique

Secant method is an effective approach for finding the root of a nonlinear function. It is a generalized from the Newton-Raphson method but does not require the derivative of the function. One of its main advantages is that it only requires two initial values, x0 and x1, to begin the iteration process. This makes it particularly useful in cases where the derivative of the function is difficult or impossible to obtain [25].

The algorithm of the secant method can be described as following steps:

Algorithm 3: Secant method.

1	**Start**
2	**Input** Define function f(x), two initial values x0, x1 and tolerance error (e), Maximum Iteration (T)
3	t =1
4	**While** t ≤ T **do**
5	Compute $f(x_0)$ and $f(x_1)$
6	Compute $x_2 = x_1 - f(x_1) \times (x_1 - x_0) / f(x_1) - f(x_0)$
7	**If**
8	$\lvert x_{i+1} - x_i \rvert >$ **e** set $\mathbf{x_0 = x_1}$ and $\mathbf{x_1 = x_2}$
9	**End if**
10	t = t+1
11	End while
12	**Stop**
13	Display the required root as x_2

Results and Discussion

The numerical methods in this study were implemented in the Matlab® software, version 8.6 R2023a (MATLAB, 2023), and the computer simulations were realized in the Core i5 7200U HP PROBOOK computer with 8GB RAM Memory. In this section, numerical tests of nonlinear equation systems are presented to validate the effectiveness of the compared methods. The numerical techniques ware adapted to the structural problem and are applied to solve the nonlinear equation of the PV cell objective function.

This study evaluates the parameter extraction performance of the Single Diode Model (SDM) using numerical methods, based on experimental data from the RTC FRANC CELL. The standard datasets used are adopted from, where the measurements are carried out on a 57 mm diameter commercial silicon (R.T.C. France) solar cell operating at 33°C [26]. This sets of measured I–V data is very representative, because there have been extensively adopted in literature as the benchmarks to test and compare the performance of various algorithms for parameter extraction. The measurement of current and tension for standard datasets of RTC France solar cell are detailed in Table 1.

Table1: Terminal I-V measurements of RTC FRANCE solar cell

RTC FRANCE SOLAR CELL	
Current I (A)	**Tension V(v)**
0.7640	-0.2057
0.7620	-0.1291
0.7605	-0.0588
0.7605	0.0057
0.7600	0.0646
0.7590	0.1185
0.7570	0.1678
0.7570	0.2132
0.7555	0.2545
0.7540	0.2924
0.7505	0.3269
0.7465	0.3585
0.7385	0.3873
0.7280	0.4137
0.7065	0.4373
0.6755	0.4590
0.6320	0.4784
0.5730	0.4960
0.4990	0.5119
0.4130	0.5265
0.3165	0.5398
0.2120	0.5521
0.1035	0.5633
-0.010	0.5736
-0.123	0.5833
-0.210	0.5900

The five unknown parameters of SDM as identifier previously used metahurstic algorithm to put at the nonlinear equation of current, the value of current are nonlinear so he calculated used study numerical methods, then are evaluated and compared with experimental current based RMSE object function, the value of Iph, Io, Rs, Rsh, a, were adopted from the datasheet of the R.T.C France solar cell and are presented in Table 2:

Table 2: Values of the five unknown parameters of the SDM for the R.T.C France solar cell

Parameters	**Iph (A)**	**Io (uA)**	**Rs (Ω)**	**Rsh (Ω)**	**A**
Value	0.7608	0.3223	0.0364	53.7634	1.4837

An analysis of the results obtained from the Single Diode Model (SDM) using different numerical methods has been carried out. Figure 2 illustrates the convergence trends of the objective function (RMSE) for the R.T.C. France solar cell when applying the Newton–Raphson, Bisection, and Secant methods. This comparison highlights the differences in convergence speed and stability among the three approaches.

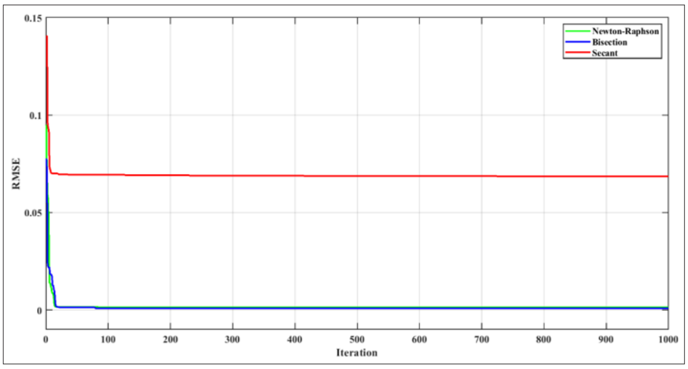

Figure 2: The convergence trends of the objective function (RMSE) for the R.T.C. France solar cell based on the three numeric methods for the SDM model.

Figure 3 presents the I–V curves of the R.T.C. France solar cell, showing a comparison between the experimental current data and the estimated current data obtained using the three numerical methods applied to the nonlinear equation of the single diode model. The figure demonstrates how closely each method reproduces the experimental I–V characteristics, thereby providing insight into their accuracy and reliability for PV parameter estimation.

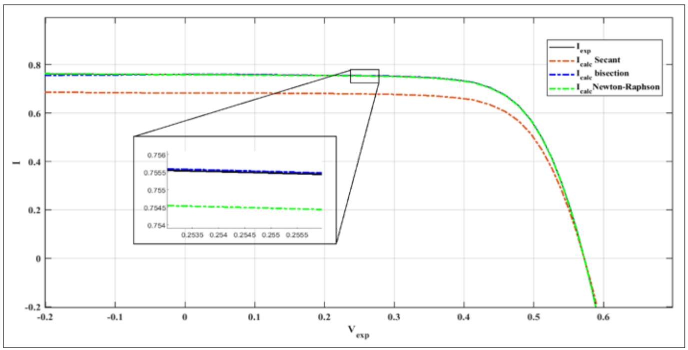

Figure 3: Comparison between the measured and simulated I-V data obtained by three different numerical methods.

Table 3: Comparative the performance of the numerical methods

Numerical method	**Newton-Raphson**	**Bisection**	**Secant**
Number of iterations	100	100	100
Initial guess	I_{exp}	I_{exp}	I_{exp}
Run time	0.606501 seconds	0.352019 seconds	4.7951041 seconds
RMSE error	0.0014483	0.00096054	0.068532

From Figure 2, it is evident that the convergence curve of the SDM achieves the lowest RMSE value among the three numerical methods. Figure 3 illustrates the I–V characteristics of the R.T.C. France solar cell. The estimated data obtained using the Newton–Raphson and Bisection methods closely match the experimental I–V curve, showing almost negligible error. In contrast, the Secant method exhibits noticeable deviation, confirming its lower accuracy in this application.

Table 3 compares the performance of the three numerical methods. The Bisection method achieves the smallest RMSE error (0.00096) and the shortest runtime (0.352 s), while Newton–Raphson provides competitive accuracy but requires derivative evaluation, increasing computational complexity. The Secant method, although derivative free, shows higher error and significantly longer runtime.

All presented tables and figures confirm that the Bisection method is the most efficient and robust technique for calculated nonlinear equation used to estimating SDM parameters. It consistently provides the smallest RMSE, shortest runtime, and closest agreement with experimental I–V data, making it the preferred choice for accurate photovoltaic modeling.

Conclusion

Our comparative study reveals significant differences in the performance of the numerical methods. While the Newton-Raphson method provides rapid convergence, it requires the calculation of the derivative, increasing its computational complexity. On the other hand, the Secant method, although slower, guarantees convergence and has lower computational complexity. Bisection method proves to be the most effective approach in this context, offering reliable convergence with minimal iterations and without the need for derivative calculations. This makes it particularly advantageous for photovoltaic modeling where robustness and precision are critical.

Furthermore, this study contributes to the selection of appropriate numerical methods for solving the nonlinear equation of the Single Diode Model (SDM). It also provides further evaluation of the optimized algorithm used for parameter estimation in photovoltaic (PV) systems.

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