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Numerical analysis of a single-diode photovoltaic cell model using NRM and SET algorithms with perspectives on nanotechnology-enhanced solar cells

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The careful identification of modeling parameters particular to the device under study is necessary for the realistic simulation of a photovoltaic solar cell. Five parameters R_s, R_{sh}, I_{ph}, I_o, and n must be established in the case of the single diode model. In general, these values can be determined using analytical or numerical approaches. Although analytical methods are quick and easy to use, the assumptions and simplifications they incorporate to deal with a solar cell's non-linear properties could lead to inaccurate modeling. This paper describes two numerical strategies for solving an equation for a PV cell with a single diode utilizing two appropriate approximations: the Newton Raphson (NRM) and Householder's (SET) algorithms. Two rounds of the nonlinear function are required in the new suggested technique. The suggested algorithm's progression is based on NRM. The major goal of this project is to create a circuit-based simulation model of a photovoltaic (PV) cell that can be used to predict how the electrical behavior of a real cell would change as a function of variables including open circuit voltage, load resistance, and short current. According to the findings, the output is nonlinear in nature and demonstrates that the proposed technique NRM is more convenient to use, efficient, and accurate than the previous numerical approach provided SET. In parallel with numerical optimization techniques, recent advances in nanotechnology have played a significant role in improving photovoltaic (PV) cell performance. Nanostructured materials, such as quantum dots, nanowires, and thin-film nanolayers, enhance light absorption, charge transport, and overall conversion efficiency. The accurate numerical modeling of PV cells, as presented in this study, is essential for understanding and optimizing the electrical behavior of nanotechnology-enhanced solar cells, thereby supporting the development of high-efficiency next-generation photovoltaic systems.

Keywords: SET; NRM; Zeros; Load resistance.

1. INTRODUCTION

In practical applications and due to the limitations of analytic algorithms have led engineers and scientists in order to improve iterative algorithms; however, the exact algorithms fail in finding roots of some special functions or in solving nonlinear functions. There are several more instances in which analytical procedures fail to generate appropriate findings. Even if analytical solutions exist, they are not amenable to straightforward numerical interpretation [1-5]. Lately, the growing demand for renewable solar energies, such as photo-voltaic (PV), has led to tremendous advancement in photovoltaic technology converting sunlight into power [6,7]. The electrical characteristic of PV cells. To analogy the on their internal parameter, being described would also know by equation can be provided by forecasting and is important in order to simulate it completely modelling these devices [8,9]. They use the complicated mathematical expression has utilized, including a current voltage curve. The Shockley-diode equation is the fundamental model that describes the current-voltage characteristic of a single diode in PV cells [10,11]. Single-diode solar cell equation and model description. The single-diode model equations represent the primary electrical parameters of a solar cell [12]. It has been widely utilized in photovoltaic for calculating the current-voltage (I-V) curves and efficiency of solar cell given different conditions [13]. It is crucial to numerically analyse such-equation systems for optimizing the performance of solar cell systems and interpreting their behaviour in reality [14-16]. For PV cell design and analysis, it is also required to develop accurate but straightforward solutions of the Shockley diode equation [17,18]. The accurate numerical methods which can approximately solve such a nonlinear equation and then have strong step by step convergence to them always are highly desirable for the authors for an extensive time [19,20]. The NRM and the SET algorithms are two such approaches which are suitable to solve the PV cell equation, because they are some of the most widely used in practice for solving nonlinear problems [21]. Approximations and iterations are used to find step by step a good representation of the current voltage characteristic in both approaches [22-26]. The solution of the equations describing the operation of a single diode solar cell is based on computational methods, which are presented in this work [27]. We will review the fundamentals of the physics and mathematics underlying the single diode model, and discuss its relevant parameters [28]. We will also explore various numerical methods such as the NRM and the SET algorithm to solve those system of complex equations that are represented in determining the solar cell operation [29]. Two numerical iteration methods, NRM and SET were implemented by using for Rs (R-value) the values of 1-5 ohms in calculating the zero of one-diode model for photovoltaic electrical circuit, a non-linear function. Our NRM method needs eight times of the contrast function and SET's solution needs nine times as well [30]. These algorithms have been used to attack dozens of nonlinear experiments recently, and tested on hundreds science applications, biology images, signal and engineering problems. The main purpose of this work is to conduct a comprehensive study of the NRM and SET algorithms related to solving an equation for one-diode photovoltaic (PV) cell application. In this work, we investigate the mathematical principles of these algorithms, explore their convergence properties and reveal their advantages and limitations. Prospective researchers, scientists or engineers in the field of photovoltaics will be accorded a valuable wealth while training to optimize designs and characterization of solar cell as well as contributors to ongoing energy change challenge [31,32]. Nanotechnology has emerged as a key enabler in modern photovoltaic technology, offering innovative approaches to overcome efficiency and material limitations of conventional solar cells. The incorporation of nanostructured materials—such as plasmonic nanoparticles, nanostructured anti-reflection coatings, and nanoscale semiconductor layers—has been shown to improve photon absorption and reduce recombination losses. Accurate numerical modelling of PV cell behaviour, including current–voltage characteristics described by the single-diode model, is therefore crucial for analysing and optimizing nanotechnology-based photovoltaic devices. Numerical solvers such as the Newton–Raphson and Householder (SET) methods provide reliable tools for this purpose. The following sections establish the article's strategy: sections two, three, and four examine the analytical model and zero finding of NRM and SET algorithms, respectively; sections eight and nine explore numerical issues, discuss the discussion, and provide the conclusion findings.

2. DEMONSTRATING THE ANALYTICAL MODULE

Kirchhoff's process is applicable to the photovoltaic cell-single-diode electrical arrangement [33,34].

$$I = I_{ph} - I_D \tag{1}$$

where:

$$I = I_{ph} - I_0\left(e^{-V_{pv}/mV_T} - 1\right) \tag{2}$$

$$I_D = I_0\left(e^{-V_{pv}/nV_T} - 1\right) \tag{3}$$

$$V_T = \frac{KT}{q} = 27.5\ mV \tag{4}$$

and $k = 1.38 \times 10^{-23} J/K$= the Boltzmann constant is a constant that exists in all physical systems, I_0 = diode's reverse saturation current= 10^{-12}A, I_{ph} = generated current, m = 1 to 2 imply the factor involved in recombination., $T = p - n$ the junction's temperature, $q = 1.6 \times 10^{-19}C$= charge of an electron [35].

$$I_{ph} = I_{source}\ ,\ I_D = I_s * \left(e^{\frac{V_D}{nV_T}} - 1\right) \tag{5}$$

$$I_{pv} = \frac{V_{pv}}{R};\ P_{pv} = I_{pv} \times V_{pv} \tag{6}$$

where: I_{pv}, V_{pv}, P_{pv} = the cell's current, voltage, and power, respectively.
Put the appropriate value for I, and obtain [36]:

$$(I_{source}) - \left(e^{-V/1.2*0.026} - 1\right) \times 10^{-12} = V\ /\ R \tag{7}$$

2.1. Newton-raphson method (NRM)

The Newton-Raphson method is an iterative numerical technique for finding approximate solutions to real-valued functions. To apply the Newton-Raphson method to solve Eq. 3

1. Start with an initial guess, V_o.
2. Calculate $f(V_o)$ utilizing the given equation.
3. Calculate the derivative $f'(V_o)$ with respect to V_o. To find the derivative, differentiate each term of the equation separately. The derivative $f'(V_o)$ should be computed analytically or numerically.
4. Update the guess for the root [37]:

$$V_1 = V_o - \frac{f(V_o)}{f\prime(V_o)} \tag{8}$$

5. Check if $|V_1 - V_o|$is smaller than your chosen tolerance (a small positive number that

determines the desired accuracy). If it is, you have found an approximate root. Otherwise, set $V_o = V_1$ and go back to step 2.

6. Repeat steps 2-5 until the desired accuracy is achieved $\varepsilon = 10^{-9}$, or until you reach a maximum number of iterations (to prevent infinite loops) utilizing the following equation [38]

$$\sigma = |\mathrm{v}_{\mathrm{n}+1} - \mathrm{v}_{\mathrm{n}}| < \varepsilon \tag{9}$$

As with any numerical method, the success of the Newton-Raphson method can depend on the choice of the initial guess and the characteristics of the function $f(x)$. Ensure that you handle cases where the derivative becomes very close to zero to avoid division by a small number, which can lead to numerical instability. Adjusting the initial guess or using a more robust numerical solver may be necessary in such cases.

2.2. Householder's method (SET)

A root-finding algorithm based on the iteration formula [39]

$$x_{n+1} = x_n - \frac{f(x_n)}{\acute{f}(x_n)}\left\{1 + \frac{f(x_n)\ddot{f}(x_n)}{2\left[\acute{f}(x_n)\right]^2}\right\} \tag{10}$$

1. Start with an initial guess, V_o.
2. Calculate $\mathrm{f}(\mathrm{V_o})$ utilizing the given equation.
3. Calculate the first derivative $\mathrm{f}'(\mathrm{V_o})$ with respect to $\mathrm{V_o}$.
4. Calculate the second derivative $\mathrm{f}''(\mathrm{V_o})$ with respect to $\mathrm{V_o}$
5. Calculate the second derivative $\left[\acute{f}(v_n)\right]^2$
6. Update the guess for the root [40]:

$$V_{n+1} = V_n - \frac{f(v_n)}{\acute{f}(v_n)}\left\{1 + \frac{f(v_n)\ddot{f}(v_n)}{2\left[\acute{f}(v_n)\right]^2}\right\} \tag{11}$$

7. Check if $|\mathrm{V_1} - \mathrm{V_o}|$is smaller than your chosen tolerance (a small positive number that determines the desired accuracy). If it is, you have found an approximate root. Otherwise, set $\mathrm{V_o} = \mathrm{V_1}$ and go back to step 2.
8. Repeat steps 2-5 until the desired accuracy is achieved $\varepsilon = 10^{-9}$, or until you reach a

3. RESULTS AND DISCUSSION

This section details various numerical tests that demonstrate the accuracy and efficiency of the NRM and SET algorithms. The NRM was used to get these findings for determining the roots of a non-linear function with an initial estimate of $\mathrm{v_0} = 1$, and these results were compared to those obtained using the SET with the same starting guesses of $\mathrm{v_0}$. The convergence requirement is 10^{-9}, which indicates that the gap between two successive iterates must be small. Eq. 7 is illustrated with five examples corresponding to resistances ranging from 1 to 5 ohms (load resistance). All accounting is performed with the accuracy specified in Tables and Figures 1 to 5. The findings demonstrate that the NRM formula takes eight iterations to attain convergence, but the SET formula requires nine iterations; hence, NRM is quicker than SET.

Table 1 Approximate solution for solving Eq. 7 corresponding to NRM and SET.

Iterations	**V_{pv}-NRM**	**I_{pv}-NFM**	**P_{pv}-NRM**	**V_{pv}-SET**	**I_{pv}-SET**	**P_{pv}-SET**
1	0.973679416	0.194735883	0.189610321	0.984783017	0.196956603	0.193959518
2	0.953940986	0.190788197	0.182000681	0.96018672	0.192037344	0.184391707
3	0.944493509	0.188898702	0.178413598	0.945924809	0.189184962	0.178954749
4	0.942856039	0.188571208	0.177795502	0.942899047	0.188579809	0.177811723
5	0.942833225	0.188566645	0.177786898	0.942833234	0.188566647	0.177786901
6	0.94283352	0.188566704	0.177787009	0.94283352	0.188566704	0.177787009
7	0.942833516	0.188566703	0.177787008	0.942833516	0.188566703	0.177787008
8	0.942833516	0.188566703	0.177787008	0.942833516	0.188566703	0.177787008

Iterations	**ε- NRM**	**ε-SET**
1	0.022950617	0.026920211
2	0.013920866	0.019258418
3	0.004129452	0.006967045
4	0.000270158	0.000543087
5	7.62628E-07	4.1103E-07
6	5.49375E-09	5.5031E-09
7	0	3.95071E-11
8		0

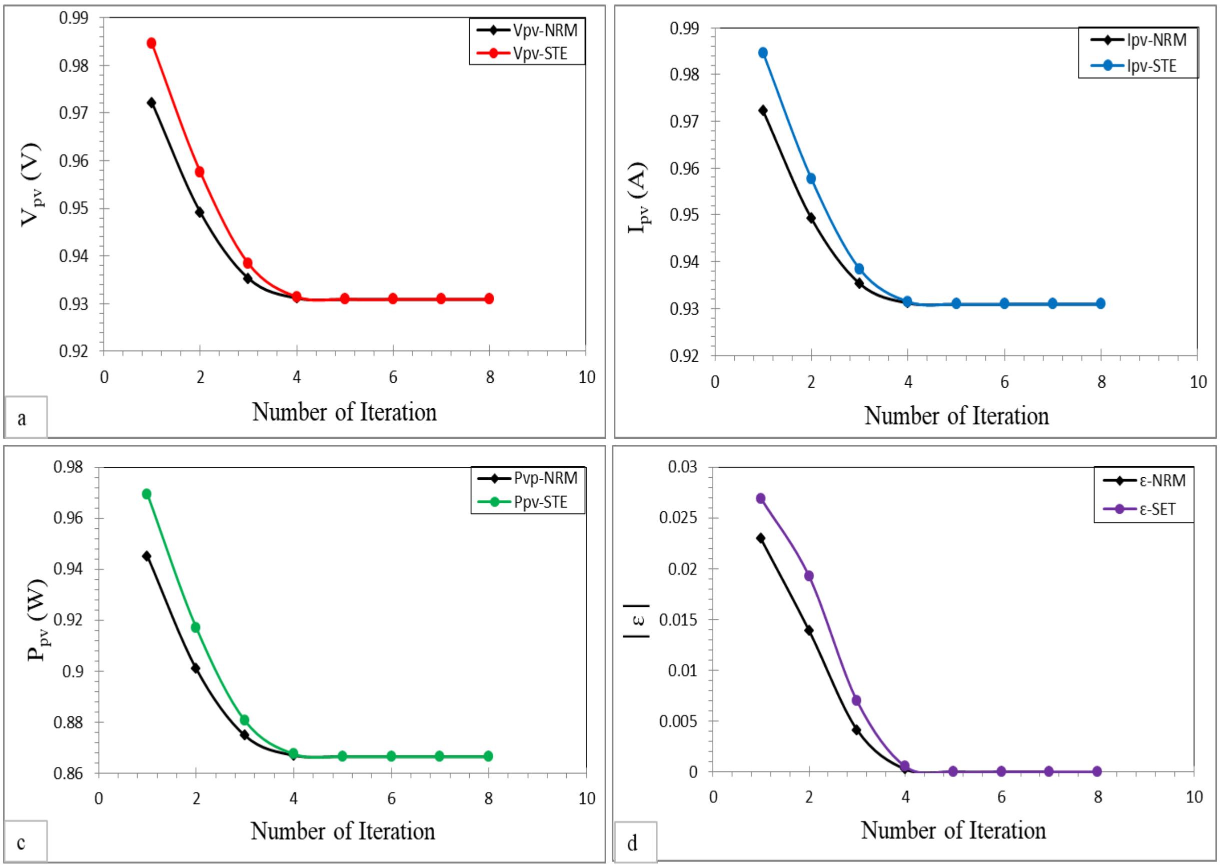

Figure 1 Evaluations of the function in Eq. 7 with various values of R and tolerance of the data.

Table 2 Approximate solution for solving Eq. 7 corresponding to NRM and SET.

Iterations	V_{pv}-NRM	I_{pv}-NFM	P_{pv}-NRM	V_{pv}-SET	I_{pv}-SET	P_{pv}-SET
1	0.972551125	0.486275563	0.472927845	0.984627195	0.492313597	0.484745356
2	0.950445064	0.475222532	0.45167291	0.958279126	0.479139563	0.459149441
3	0.937807092	0.468903546	0.439741071	0.940368483	0.470184241	0.442146442
4	0.934523231	0.467261616	0.436666835	0.934696231	0.467348116	0.436828522
5	0.934362978	0.467181489	0.436517087	0.93436339	0.467181695	0.436517472
6	0.934363810	0.467181905	0.436517865	0.93436381	0.467181905	0.436517865
7	0.934363804	0.467181902	0.436517859	0.934363804	0.467181902	0.436517859
8	0.934363804	0.467181902	0.436517859	0.934363804	0.467181902	0.436517859

Iterations	ε- NRM	ε-SET
1	0.022106061	0.026348069
2	0.012637972	0.017910643
3	0.003283861	0.005672251
4	0.000160253	0.000332841
5	8.32202E-07	4.20171E-07
6	6.4796E-09	6.49071E-09
7	0	5.03629E-11
8	0	0

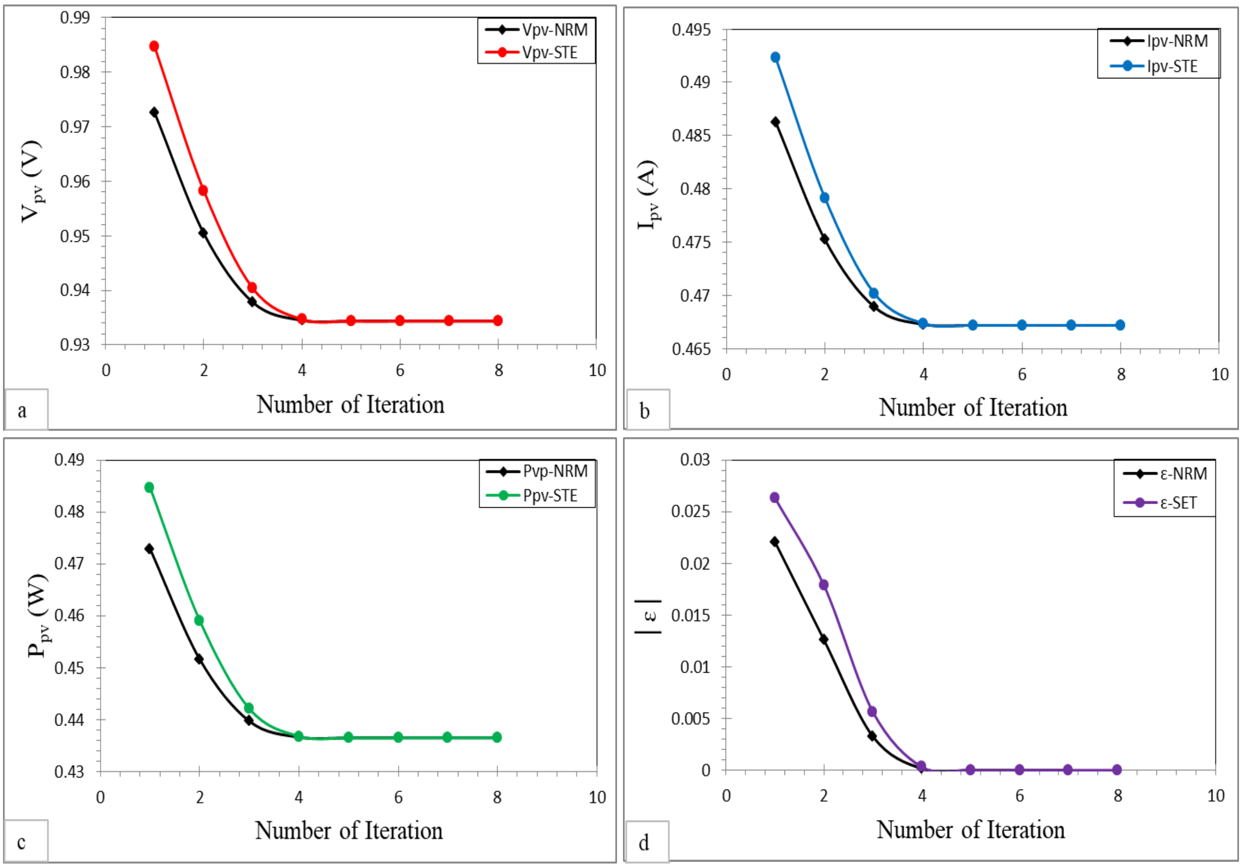

Figure 2 Evaluations of the function in Eq. 7 with various values of R and tolerance of the data.

Table 3 Approximate solution for solving Eq. 7 corresponding to NRM and SET.

Iterations	**V_{pv}-NRM**	**I_{pv}-NFM**	**P_{pv}-NRM**	**V_{pv}-SET**	**I_{pv}-SET**	**P_{pv}-SET**
1	0.972927942	0.324309314	0.315529593	0.984674391	0.328224797	0.323194552
2	0.951633529	0.317211176	0.301868791	0.958902411	0.319634137	0.306497945
3	0.940159126	0.313386375	0.294633061	0.942270298	0.314090099	0.295957772
4	0.937553641	0.31251788	0.293002277	0.937662523	0.312554174	0.293070336
5	0.937463962	0.312487987	0.292946227	0.937464091	0.31248803	0.292946307
6	0.937464712	0.312488237	0.292946695	0.937464712	0.312488237	0.292946695
7	0.937464704	0.312488235	0.292946691	0.937464704	0.312488235	0.292946691
8	0.972927942	0.324309314	0.315529593	0.937464704	0.312488235	0.292946691

Iterations	**ε- NRM**	**ε-SET**
1	0.021294413	0.025771979
2	0.011474403	0.016632113
3	0.002605485	0.004607775
4	8.96791E-05	0.000198433
5	7.49827E-07	6.20833E-07
6	7.35896E-09	7.36798E-09
7	0	7.21322E-11
8	0	0

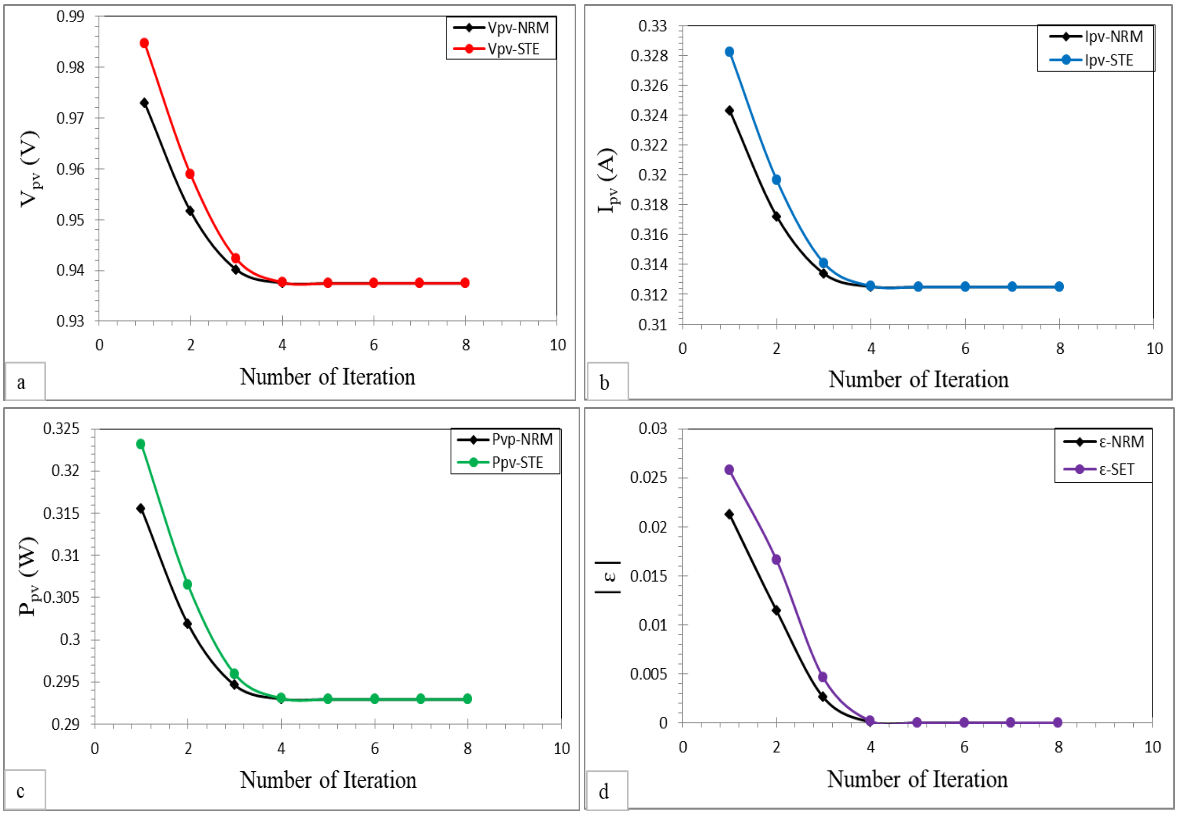

Figure 3 Evaluations of the function in Eq. 7 with various values of R and tolerance of the data.

Table 4 Approximate solution for solving Eq. 7 corresponding to NRM and SET.

Iterations	**V_{pv}-NRM**	**I_{pv}-NFM**	**P_{pv}-NRM**	**V_{pv}-SET**	**I_{pv}-SET**	**P_{pv}-SET**
1	0.973303815	0.243325954	0.236830079	0.984726408	0.246181602	0.242421525
2	0.952798095	0.238199524	0.226956052	0.959538603	0.239884651	0.230178582
3	0.942383958	0.23559599	0.222021881	0.944123038	0.23603076	0.222842078
4	0.940317686	0.235079421	0.221049338	0.940386165	0.235096541	0.221081535
5	0.940270181	0.235067545	0.221027004	0.940270218	0.235067554	0.221027021
6	0.9402707	0.235067675	0.221027247	0.9402707	0.235067675	0.221027247
7	0.940270694	0.235067673	0.221027244	0.940270694	0.235067673	0.221027244
8	0.940270694	0.235067673	0.221027244	0.940270694	0.235067673	0.221027244

Iterations	**ε- NRM**	**ε-SET**
1	0.02050572	0.025187805
2	0.010414137	0.015415564
3	0.002066272	0.003736873
4	4.75043E-05	0.000115947
5	5.18185E-07	4.81992E-07
6	6.05189E-09	6.0562E-09
7	0	7.06286E-11
8	0	0

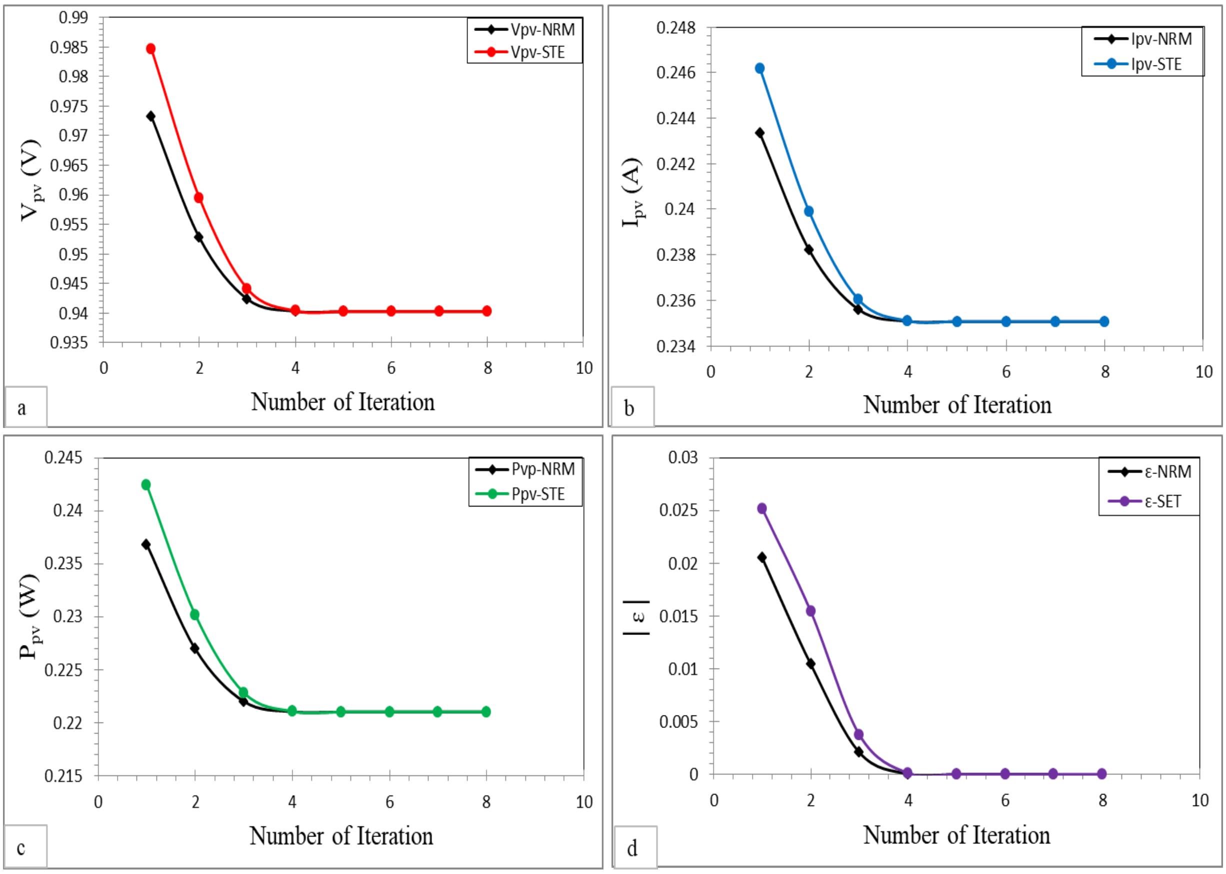

Figure 4 Evaluations of the function in Eq. 7 with various values of R and tolerance of the data.

Table 5 Approximate solution for solving Eq. 7 corresponding to NRM and SET.

Iterations	**V_{pv}-NRM**	**I_{pv}-NFM**	**P_{pv}-NRM**	**V_{pv}-SET**	**I_{pv}-SET**	**P_{pv}-SET**
1	0.973679416	0.194735883	0.189610321	0.984783017	0.196956603	0.193959518
2	0.953940986	0.190788197	0.182000681	0.96018672	0.192037344	0.184391707
3	0.944493509	0.188898702	0.178413598	0.945924809	0.189184962	0.178954749
4	0.942856039	0.188571208	0.177795502	0.942899047	0.188579809	0.177811723
5	0.942833225	0.188566645	0.177786898	0.942833234	0.188566647	0.177786901
6	0.94283352	0.188566704	0.177787009	0.94283352	0.188566704	0.177787009
7	0.942833516	0.188566703	0.177787008	0.942833516	0.188566703	0.177787008
8	0.942833516	0.188566703	0.177787008	0.942833516	0.188566703	0.177787008

Iterations	**ε- NRM**	**ε-SET**
1	0.01973843	0.024596297
2	0.009447477	0.01426191
3	0.00163747	0.003025762
4	2.28133E-05	6.58136E-05
5	2.9464E-07	2.86293E-07
6	3.91459E-09	3.91599E-09
7	0	5.19903E-11
8		0

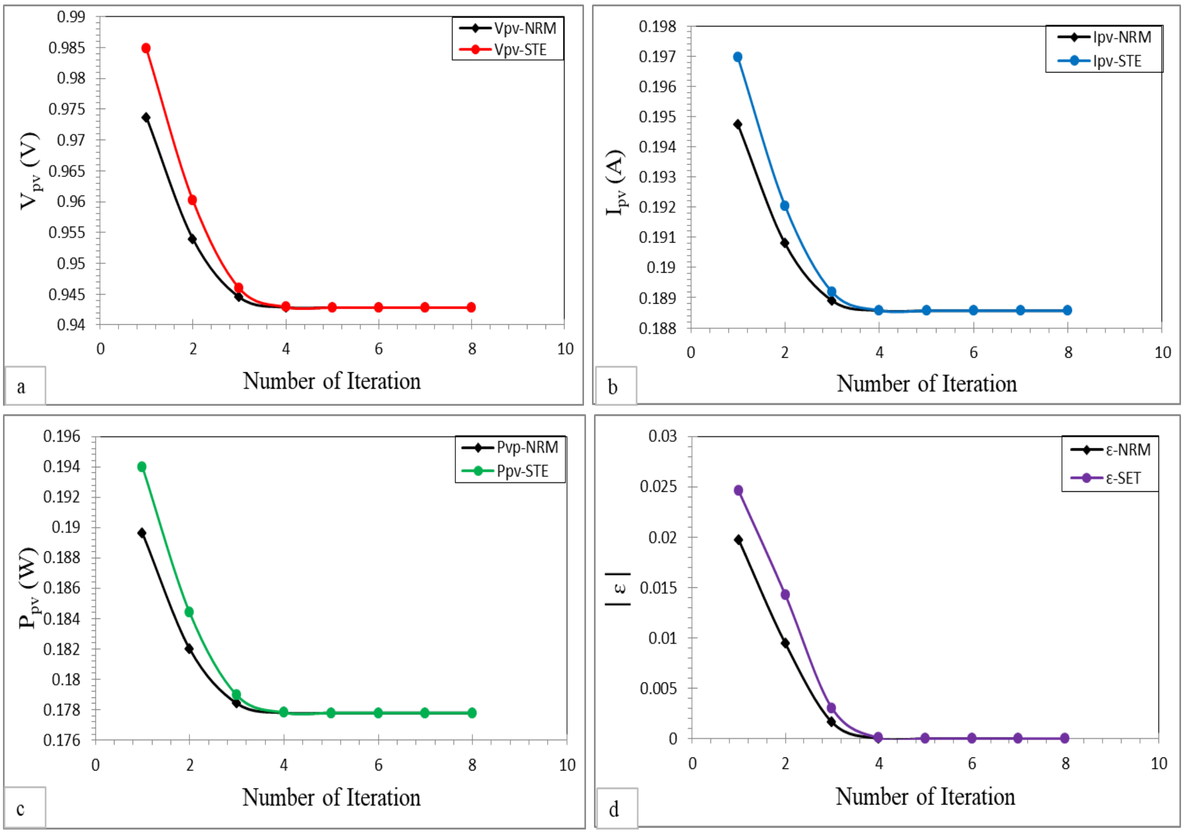

Figure 5 Evaluations of the function in Eq. 7 with various values of R and tolerance of the data.

The observed trend across every example indicates a decrease in the values of V_{pv} (photovoltaic voltage), I_{pv}(photovoltaic current), and P_{pv} (photovoltaic power) as the number of iterations increases in both the NRM and SET methodologies, as shown from the Tables and Figures. One typical behavior seen in iterative numerical approaches, particularly when solving complex non-linear equations such as the Shockley diode equation for a single diode solar cell, is the manifestation of characteristic behaviours. This behaviour may be attributed to several factors, including convergence towards the solution, the influence of initial estimate and updating, convergence criteria, algorithm-specific behaviour, parameter sensitivity, and numerical accuracy. In general, a decrease in values and iteration behaviour are characteristic of numerical techniques [4]. The crucial aspect is in assessing the convergence, precision, and agreement with physical observations in order to evaluate the dependability of the findings. The tolerance values (ε) and their convergence behaviour in the NRM and the SET serve as indications of the proximity of the numerical solutions to the specified accuracy or convergence requirements [42]. The significance of tolerance values and convergence performance for each approach is illustrated in Table 1 and Figure 1, as exemplified. In the case of NRM, the beginning tolerance value was recorded as 0.022950617, and it eventually converged to a final tolerance of 0 after 8 iterations. On the other hand, with SET, the starting tolerance was measured at 0.026920211, and it also achieved a final tolerance of 0 after 9 iterations. The NRM was initiated with an initial tolerance value of 0.022950617, which indicates a sufficient level for error in the obtained solution. Throughout a series of 8 iterations [43], the NRM algorithm continuously exhibited a pattern of error reduction at each stage, ultimately converging to a final tolerance value of 0. A tolerance value of zero indicates that the numerical solution acquired using NRM is now in optimal alignment with the intended solution, signifying a high level of accuracy within the set tolerance threshold [44]. In other terms, NRM has achieved convergence towards a solution characterized by low error. The SET analysis began with an initial tolerance value of 0.026920211. Across six rounds, the SET algorithm continually decreased the error until it ultimately achieved a final tolerance of zero [45]. A SET with a final tolerance of 0 signifies that it has achieved convergence to a solution that satisfies the convergence requirements. This solution is deemed to be very accurate, falling inside the set tolerance threshold [46]. Both the NRM and SET methodologies have effectively achieved convergence towards solutions that satisfy the predetermined requirements for accuracy. The numerical solutions generated by both approaches exhibit a high level of agreement with the intended answer, as seen by the final tolerance values of 0. This indicates that the solutions are very accurate. From a practical perspective, it can be seen that both approaches have shown a notable degree of precision in resolving the equation related to the single diode solar cell. The observation that the tolerance has decreased to zero implies that the solutions have attained a state of near-perfection, exhibiting little residual error. The observed outcome is deemed favourable, suggesting that the used methodologies have yielded outcomes of considerable reliability [47].

The numerical stability and rapid convergence demonstrated by the NRM and SET algorithms are particularly relevant for the modelling of nanotechnology-enhanced photovoltaic cells. Nanostructured PV devices often exhibit increased sensitivity to parameter variations due to nanoscale effects on charge transport and recombination. The accurate extraction of electrical parameters, as shown in Tables 1–5 and Figures 1–5, provides a reliable foundation for simulating PV cells incorporating nanomaterials such as quantum dots, nanowires, or ultra-thin absorber layers [48-50]. Consequently, the numerical methods presented in this study can be effectively applied to optimize the design and performance evaluation of advanced nanotechnology-based solar cells [51-54]. Table 6 summarizes common nanotechnology approaches in photovoltaic systems and highlights their influence on electrical parameters and numerical modelling requirements.

Table 6 Role of nanotechnology in photovoltaic cell performance and numerical modelling.

Nanotechnology approach	Primary function	Impact on PV parameters	Relevance to numerical modeling
Quantum dots absorber layer	Enhanced light absorption through size-dependent bandgap tuning	Increase in photovoltaic current (I_{pv}) and overall conversion efficiency	Introduces strong parameter sensitivity in the single-diode model, requiring accurate root-finding methods
Plasmonic nanoparticles	Localized surface plasmon resonance improving photon trapping	Increase in photovoltaic voltage (V_{pv}) and absorption efficiency	Leads to highly nonlinear I–V characteristics that demand robust numerical solvers
Nanostructured anti-reflection coating	Reduction of optical reflection losses	Increase in output photovoltaic power (P_{pv})	Modifies the current–voltage curve shape, affecting convergence behavior
Nanowire-based junctions	Improved charge transport and reduced recombination	Reduction in recombination losses and improved fill factor	Requires high-accuracy numerical convergence due to nanoscale transport effects

As illustrated in Figure 6, the integration of nanotechnology in photovoltaic devices conceptually enhances conversion efficiency, emphasizing the importance of accurate numerical modelling for performance optimization.

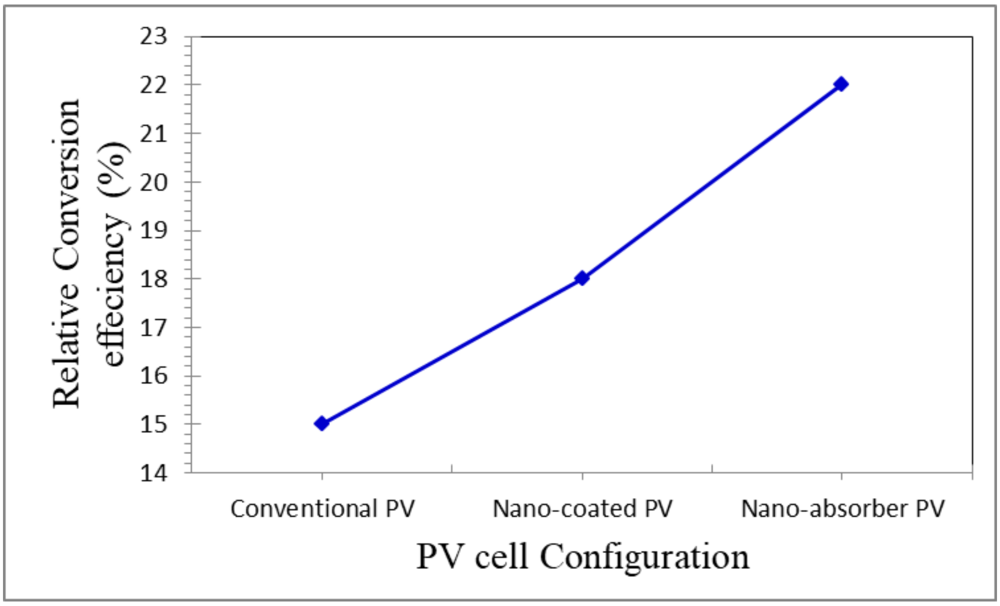

Figure 6 Conceptual impact of nanotechnology on photovoltaic efficiency.

In addition to numerical convergence analysis, nanotechnology has become a critical factor in enhancing photovoltaic performance. As summarized in Table 6 and illustrated in Figure 6, nanostructured materials such as quantum dots, plasmonic nanoparticles, and nanowire junctions significantly influence current–voltage characteristics and power output. These nanoscale effects increase the nonlinearity of PV models, reinforcing the need for robust numerical solvers such as the NRM and SET algorithms presented in this study.

4. CONCLUSIONS

This study presents a further version of the method based on the NRM and SET algorithms, which allows the program to conduct higher order convergence iterative algorithms. A large number of examples demonstrate that the proposed algorithm NRM is superior to SET since the outcomes of the instances approach convergence with the fewest number of evaluations. Beyond conventional photovoltaic modelling, the findings of this study have important implications for nanotechnology-based solar cell development. As nanostructured materials become increasingly integrated into PV devices, robust and efficient numerical solvers are required to accurately capture their electrical behaviour. The demonstrated efficiency and convergence of the NRM and SET algorithms make them well suited for the analysis and optimization of next-generation nanotechnology-enhanced photovoltaic systems, supporting ongoing efforts toward high-efficiency and sustainable solar energy solutions.

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