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Mathematical modeling and extraction of parameters of solar photovoltaic module based on modified Newton–Raphson method

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ABSTRACT

This paper presents a numerical method for estimating four physical parameters of a single-diode circuit model based on manufacturer's datasheet. A system of four non-linear equations are formed based on three key points of PV characteristics. The photocurrent, saturation current, ideality factor and the series resistance are solved iteratively using the proposed method. The suggested method is validated using RTC France solar cell, Chloride CHL285P and Photowatt PWP210 modules and the results are verified with respect to the in-field outdoor measurements. The proposed method shows a good agreement with the experimental data. Lastly, The model chosen is simulated under MATLB environment to assess the effects of external physical weather conditions, that is, temperature and solar irradiance. The advantage of the proposed method with respect of existing numerical techniques is that it converged faster than the widely used Newton method. Modeling of PV cell/module is essential in predicting performance of photovoltaic generators at any operating condition.

Introduction

Energy, the lifeblood of economic progress and a fundamental necessity for maintaining our quality of life and supporting all aspects of our economy, has witnessed a significant growth in demand over the past two decades [1], largely fueled by our heavy reliance on fossil fuels. However, the significant growth in energy demand has posed significant environmental challenges on a global level, emphasizing the need for immediate and decisive measures to address and mitigate its impact [2]. To address these challenges, it is imperative to adopt sustainable development strategies that offer long-term solutions. Among these strategies, renewable energy resources have emerged as highly efficient and effective alternatives [3]. In contrast to finite fossil fuel reserves, renewable energy sources like solar, wind, and hydropower have minimal adverse effects on the environment. Solar energy, in particular, has gained immense popularity worldwide due to its numerous benefits, including affordability, widespread availability, and a reduced ecological footprint [4]. This is primarily attributed to the capability of photovoltaic (PV) cell technology to directly convert sunlight into electricity [5,6], making solar energy a promising and viable option for sustainable energy generation [7]. Despite the numerous advantages, the performance of photovoltaic (PV) modules is significantly impacted by external environmental conditions. These include solar intensity [5], ambient temperature [8], relative humidity [9,10], wind speed [11], panel dust accumulation [12], and the tilt angle of the panel [13–15]. In light of this reality, the actual performance of PV module systems in real working environments often falls short of expectations [16]. To overcome this challenge, researchers have explored alternative methods for predicting the output characteristics and maximum power output of PV modules without relying on extensive experimental measurements. One such approach involves utilizing the manufacturer's data, which provides information about the module's electrical characteristics under standardized test conditions (STC) [17]. This data includes parameters like the maximum power point voltage, current, and temperature coefficients of the module. However, it is important to acknowledge that relying solely on manufacturer's data for performance predictions may have limitations. Real-world operating conditions for PV modules can significantly differ from the standardized test conditions used to generate the manufacturer's data [18]. Therefore, while predictive models based on manufacturer's data can offer valuable insights, it is crucial to validate their accuracy through field measurements to ensure reliable performance predictions in actual working environments.

Efforts have been made by researchers to improve the performance of solar panels, leading to the development of various PV models. Based

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on equivalent circuit, the models are classified as single and double diodes. While single diode model consists of five, four or three unknown parameters, double diode model has seven unknown parameters. The five parameters of sinlge diode model are the photocurrent (Iph), reverse saturation current (I_o), series (R_s) and shunt (R_{sh}) resistances, and the ideality factor (α). The four parameter model of a single diode assumes the shunt resistance infinity and its effect is ignored [19–21]. The three parameter model proposes that the series resistance is zero and shunt resistance is infinity leading to their neglect. On the other hand the seven estimated parameters of double diode model includes the five parameters of the single parameter model with additional of second reverse saturation current and ideality factor for the second diode [22,23].

There are various methods developed in literature for parameter extraction of PV circuit models. These approaches can be categorized into analytical, numerical (deterministic and stochastic) and hybrid methods [22]. For example, Jakhrani et al. [23] used numerical method to determine the output current and voltage of a five-parameter model for a single diode equivalent circuit. This method however, required extensive mathematical computations. Similarly, [24] proposed a numerical approach to extract the physical parameters based on single diode model. The ideality factor and series resistance were solved numerically using only two points, at short circuit point and at maximum power point. The method proposed showed good agreement with experimental values. In addition, El Achouby et al. [25] proposed numerical method to extract the five physical parameters at standard test conditions (STC). This ideality factor was made to vary and a system of four nonlinear equations was solved. The drawback of this approach is the suitable choice of initial values of the parameters. Moreover, Elkholy and Abou El-Ela [26] took an analytical approach by solving the parameters of a single diode model based on in-field outdoor data, demonstrating good agreement between simulated and experimental measurements. However, this method was complicated due to the requirement of extensive experimental data. [27] proposed a simple fitting method for estimating parameters of a single diode model, but its validity was limited to constant solar irradiance, making it impractical for real working environments. Rasheed et al. [28] presented the Chebyshev numerical method as an alternative to the Newton–Raphson method for solving the voltage of PV cells, but the increased computational burden from calculating second derivatives posed challenges. Currently, [29] introduced a new simplified method for the iterative estimation of the five PV module parameters. This method uses some approximations to determine the values of series resistance and ideality factor. The accuracy of this method was a bit challenge due to approximations while computing series resistance and ideality factor. [30] presented a numerical method for solving the series and shunt resistances using the Newton–Raphson approach and the Lambert W- function. However, this method needs a lot of assumptions to simplify the problem in order to extract the five parameters. Lastly, Manuel Godinho Rodrigues et al. [31] conducted a comparative study using numerical simulations to evaluate the five-parameter single diode model and the more advanced seven-parameter double diode model. The double diode model accounted for additional energy losses associated with charge carrier recombination in the depletion layers, but its high complexity level limited its practicality.

As per literature review, numerical iterative methods have been widely applied in solving the non-linear, multi-parameter and transcendental equation of PV model. Of many iterative approaches, Newton–Raphson method is the most popular in this field due to its simplicity, accuracy and quadratic convergency rate [28,32,33]. Despite this dominance, Newton–Raphson has convergence shortcomings especially when the initial inputs are far from the actual roots [34,35].

In this work, we present a modified Newton–Raphson Method proposed by [36] to estimate the parameters of single diode model. We first choose to use a simplified four parameter model of a single diode equivalent circuit. Next, we develop the corresponding mathematical equation of the model. Then, basing on three key points from manufacturer's catalog, a system of four non-linear equations is formed and solved iteratively using the proposed method. This method advantageous than the standard Newton–Raphson one because its rate of convergence is enhanced to the order of $1 + \sqrt{2}$. Thus, it offers a quick and accurate analysis of PV module performance. Circuit modeling of PV cells, as discussed by El Achouby et al. [25], Batzelis and Papathanassiou [37], enables PV cell simulation and performance evaluation under varying conditions, aiding in monitoring system operation, forecasting power output, calculating power losses, and developing maximum power point tracking algorithms [38]. This paper is organized as follows: Section "Introduction" presents an introductory part of the study and the reviews of different approaches of solving mathematical models of PV module. Method part is found in Section "Method" in which the model formulation procedures and parameter extraction processes are discussed. Results and Discussion are presented in Section "Results and Discussion". Lastly, conclusion is declared in Section "Conclusion".

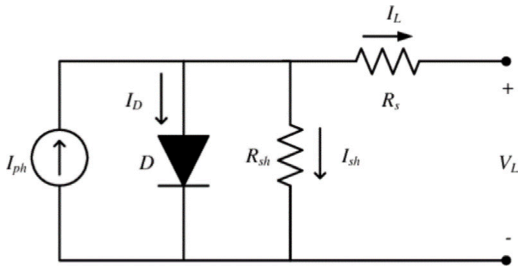

Fig. 1. Equivalent Circuit Diagram for single diode five-parameter model [40].

Method

Model formulation

PV cell is modeled as p–n junction diode because their working principle are similar. The equivalent circuit of the single diode model consists of the real diode connected in parallel with the ideal current source (I_{ph}), the series and the parallel resistors (R_s and R_{sh}) as shown in Fig. 1. Referring Fig. 1, the Kirchhoff's law is represented by the following equation:

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

Where; I is the current output, I_{ph} is the photocurrent from the source, I_D is the current through the diode and I_{sh} is the current through the shunt resistance. The photocurrent I_{ph} is the function of solar irradiation and temperature as shown in the equation [39]

$$I_{ph} = \frac{G}{G_{ref}}\left[I_{ph,ref} + K_i\left(T - T_{ref}\right)\right] \tag{2}$$

Where; G is the solar irradiance, G_{ref} is the solar irradiance at reference point, $I_{ph,ref}$ is the photocurrent at reference point, K_i is the temperature coefficient at short circuit, T is an operating temperature and T_{ref} is the temperature at reference point The diode current is given by Shockley equation as follows [26]

$$I_D = I_0\left[\exp\left(\frac{q(V + IR_s)}{K\alpha T_c}\right) - 1\right] \tag{3}$$

Where:

q – Charge of an electron (1.602×10^{-19} C)
α – Diode ideality factor
K – Boltzmann constant (1.381×10^{-23} J/K)
T_c – Temperature of a cell (K)
V – Voltage output (V)

I_0 – Diode reverse saturation current

The reverse saturation current depends on ambient temperature as shown in the equation [41]

$$I_0 = I_{0,ref}\left(\frac{T_c}{T_{ref}}\right)^3 \exp\left[\frac{qE_g}{K\alpha}\left(\frac{1}{T_{ref}} - \frac{1}{T_c}\right)\right] \tag{4}$$

Where

$$I_{0,ref} = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{\alpha N_s KT}\right) - 1} \tag{5}$$

The series (R_s) and shunt (R_{sh}) resistances can be estimated from $V - I$ curve as follows:

$$R_s = -\frac{dV}{dI}\bigg|_{I=0,V=V_{oc}} - \frac{V_T}{I_{sc}} \tag{6}$$

Where $V_T = \frac{\alpha KT_c}{q}$, and

$$R_{sh} = -\frac{dV}{dI}\bigg|_{I=I_{sc},V=0} \tag{7}$$

The current through the shunt resistance is given by the following equation [42]

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \tag{8}$$

The ideality factor (α) is given by [43,44] as follows:

$$\alpha = \frac{V_{mpp} + I_{mpp}R_{so} - V_{oc}}{V_T\left[\ln\left(I_{sc} - I_{mpp} - \frac{V_{mpp}}{R_{sho}}\right) - \ln\left(I_{sc} - \frac{V_{oc}}{R_{sh}}\right) + \frac{I_{mpp}}{I_{sc} - \frac{V_{oc}}{R_{sho}}}\right]} \tag{9}$$

Under varying physical conditions, [26,45] presents the analytical formulas to determine series R_s and shunt R_{sh} resistances, and the ideality factor α as follows:

$$R_s = R_{s,ref}\left(\frac{T_c}{T_{ref}}\right)\left[1 - \beta_{oc}\ln\left(\frac{G}{G_{ref}}\right)\right] \tag{10}$$

Where, $R_{s,ref}$ is the series resistance at reference conditions and R_s is the corresponding parameter at the real experimental weather conditions. β_{oc} is the temperature coefficient at open circuit whose value is about $0.217K$.

$$R_{sh} = R_{sh,ref}\left(\frac{G_{ref}}{G}\right) \tag{11}$$

Where, $R_{sh,ref}$ is the shunt resistance at reference conditions and is the parameter at the real outdoor conditions [26].

$$\alpha = \alpha_{ref}\left(\frac{T_c}{T_{ref}}\right) \tag{12}$$

Where, α_{ref} is the ideality factor of the diode at reference conditions and α is the ideality factor at the real outdoor conditions [26]. Therefore, the final equation of a single diode five-parameter model is given as follows [25,26,46–49]

$$I = I_{ph} - I_0\left[\exp\left(\frac{q(V + IR_s)}{K\alpha T_c}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \tag{13}$$

[21] claims that the PV cell is not sensitive to shunt resistance and that it can be considered to be infinity without generating earth current leakage. In addition, a comparative study performed by [20] for different models of PV cell reveals that the effect of shunt resistance at low voltage and solar illumination is negligible. Moreover, a study by [19] shows that for higher power yield and fill factor, the shunt resistance should be large enough because low shunt resistance leads to high power loss. Therefore, the shunt resistance in this study is assumed to be infinity, hence the last term of the model equation is disregarded. By omitting this final component of the model, the influence of shunt resistance on PV module performance is ignored. The model equation remains only with four parameters (I_{ph}, I_o, R_s, α). This helps to reduce the complexity of the model as given below:

$$I = I_{ph} - I_0\left[\exp\left(\frac{q(V + IR_s)}{K\alpha T_c}\right) - 1\right] \tag{14}$$

For N cells, Eq. (14) becomes:

$$I = I_{ph} - I_0\left[\exp\left(\frac{q(V + IR_s)}{N\alpha KT_c}\right) - 1\right] \tag{15}$$

Determination of parameters of the model

The model consists of four unknown parameters (I_{ph}, I_0, a, and R_s) whose values are required to be determined. To solve for these parameters, four equations are required. The three basic operating points on $I - V$ curve of the PV cell/module give the first three equations which are Eqs. (16)–(18)

(a) At the open circuit, $V = V_{oc}$ and $I = 0$

$$0 = I_{ph} - I_0\left[\exp\left(\frac{qV_{oc}}{N\alpha KT_c}\right) - 1\right] \tag{16}$$

(b) At the short circuit, $V = 0$ and $I = I_{sc}$

$$I_{sc} = I_{ph} - I_0\left[\exp\left(\frac{qI_{sc}R_s}{N\alpha KT_c}\right) - 1\right] \tag{17}$$

(c) At the maximum power point, $V = V_{mpp}$ and $I = I_{mpp}$

$$I_{mpp} = I_{ph} - I_0\left[\exp\left(\frac{q(V_{mpp} + I_{mpp}R_s)}{N\alpha KT_c}\right) - 1\right] \tag{18}$$

(d) At maximum power point $\left(I_{mpp}, V_{mpp}\right)$ the slope, $\frac{dP}{dV} = 0$, where the power $P = VI$. Thus, we have the fourth equation as shown in Eq. (19) below

$$\frac{I_{mpp}}{V_{mpp}} = \frac{qI_0}{N\alpha KT_c}\left(1 + R_s\frac{I_{mpp}}{V_{mpp}}\right)\exp\left(\frac{q(V_{mpp} + I_{mpp}R_s)}{N\alpha KT_c}\right) \tag{19}$$

If we let $I_{ph} = x_1$, $I_0 = x_2$, $\alpha = x_3$, $R_s = x_4$ and $\frac{q}{NKT_c} = \lambda$, then the system of equations can be written as follows

$$\begin{cases} f_1(X) = x_1 - x_2\left[\exp\left(\frac{\lambda V_{oc}}{x_3}\right) - 1\right] \\ f_2(X) = x_1 - x_2\left[\exp\left(\frac{\lambda I_{sc}x_4}{x_3}\right) - 1\right] - I_{sc} \\ f_3(X) = x_1 - x_2\left[\exp\left(\frac{\lambda\left(v_{mpp} + x_4 I_{mpp}\right)}{x_3}\right) - 1\right] - I_{mpp} \\ f_4(X) = \frac{\lambda x_2}{x_3}\left(1 + \frac{x_4 I_{mpp}}{V_{mpp}}\right)\exp\left(\frac{\lambda\left(v_{mpp} + x_4 I_{mpp}\right)}{x_3}\right) - \frac{I_{mpp}}{V_{mpp}} \end{cases} \tag{20}$$

To obtain the values of model parameters, the system (20) is solved simultaneously by first plugging the values of I_{sc}, V_{oc}, I_{mpp} and V_{mpp} which are always given in manufacturer's catalog. The proposed method, modified Newton–Raphson, is used to solve this system.

Modified Newton–Raphson method

The modified Newton–Raphson algorithm as proposed by [36] is given as follows:

$$x_0^* = x_0 - \frac{f(x_0)}{f'(x_0)} \tag{21}$$

$$x_1 = x_0 - \frac{f(x_0)}{f'(\frac{1}{2}[x_0 + x_0^*])} \tag{22}$$

This algorithm follows predictor–corrector rule in which Eq. (21) is a predictor step and Eq. (22) forms a corrector step. To start iteration two initial values, x_0 and x_0^* are required. Given an initial value x_0, the second starting value, x_0^* is obtained simply by standard Newton–Raphson method (NRM) (Eq. (21)). The iteration then proceeds with the corrector step (Eq. (22)) in which the value of the derivative is evaluated at $\frac{1}{2}(x_0 + x_0^*)$, which is a more appropriate value to use than that at x_0. For $k \geq 1$:

$$x_k^* = x_k - \frac{f(x_k)}{f'(\frac{1}{2}[x_{k-1} + x_{k-1}^*])} \tag{23}$$

Table 1
Manufacturer's catalog for CHL285P module, France Solar cell (RTC) and Photowatt PWP210.

Specification	CHL285P	France solar (RTC)	PWP210
Cell type	Polycrystalline	NA	Polycrystalline
V_{oc} [V]	41.25	0.5728	16.778
I_{sc} [A]	9.54	0.76	1.03
V_{mpp} [V]	32.76	0.45	12.60
I_{mpp} [A]	9.13	0.691	0.898
P_{max} [W]	300	11.315	0.311
Ref. temp. [°C]	STC	33	45
No. of cells	60	1	36
Dimensions	1640 × 992 × 35 mm	57 mm diameter	–

$$x_{k+1} = x_k - \frac{f(x_k)}{f'(\frac{1}{2}[x_k + x_k^*])} \tag{24}$$

The initial values were carefully selected with the help of physical analytical formulas developed by Elkholy and Abou El-Ela [26]. The system Eq. (20) was then implemented in MATLAB under standard settings, and the findings are discussed in the next section.

Results and discussion

In order to verify the proposed method, an outdoor experiment was performed at Arusha Technical College Solar Center using polycrystalline PV module (CHL285P) connected to a PROVA 210 module analyzer. The output current and voltage were obtained at different temperatures and solar irradiances including the standard conditions (irradiation level 1000 W/m^2, Air Mass of 1.5 and cell temperature 25 °C). For more validation, two extra experimental case studies, Silicon solar cell RTC France at 33 °C and Silicon Module PWP201 operating at 45 °C, were selected. The accuracy of the proposed approach and the degree of precision of the applied mathematical model were evaluated using two statistical indicators. These are Absolute Error ($\varepsilon_{\text{absolute}}$) and the Root Mean Squared Error (RMSE) as defined by [25,50,51].

$$\varepsilon_{\text{absolute}} = |I_{\text{measured}} - I_{\text{model}}| \tag{25}$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(I_{i,\text{measured}} - I_{i,\text{model}})^2} \tag{26}$$

Table 1 summerizes the datasheet of each experimental case study used in this study in order to validate the method presented [22,24].

Chloride CHL285P PV module

The proposed iterative method is executed in MATLAB to extract the four unknown parameters (I_{ph}, I_o, α, R_s) of presented model using the information provided in Table 1. The results obtained are then compared with values from standard Newton–Raphson method and another current numerical approach by [24] as shown in Table 1. It can be observed from Table 1 that the proposed method has least value of root mean squared error (RMSE) and less number of iterations than the rest in comparison. This implies that the modified Newton–Raphson method is quicker and accurate than the widely used standard Newton method (see Table 2).

Using the values of four calculated parameters of the model in discussion, it was possible to plot $I-V$ and $P-V$ characteristic curves. The output calculated characteristics of a test PV module obtained at standard conditions were then compared with experimental curves at reference condition as shown in Figs. 2 and 3. It was discovered from these curves that the model curve passes through the points of the experimental curve. This demonstrates good agreement between theoretically estimated and experimental results. Fig. 4 shows the plot of absolute error for output current versus output voltage for three methods in comparison.

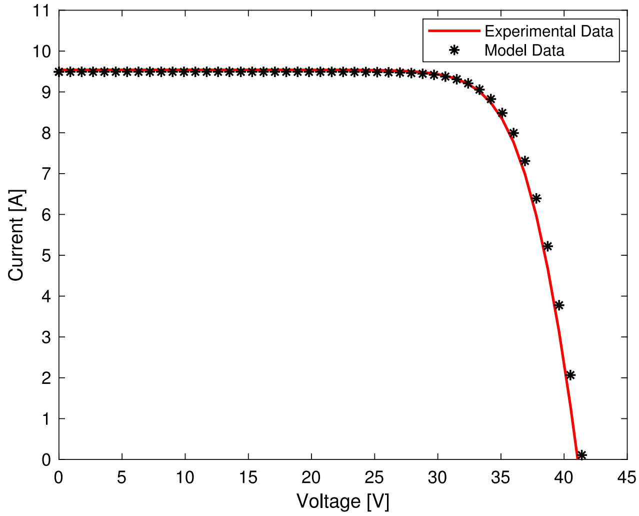

Fig. 2. Illustrates the $I-V$ theoretical Values Compared with its actual measured values.

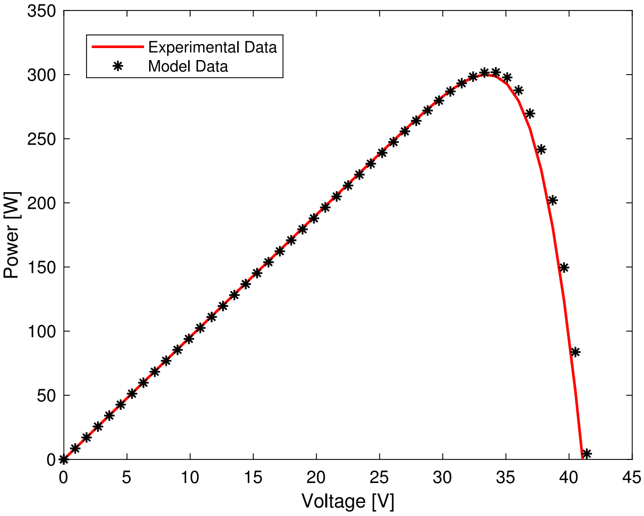

Fig. 3. Demonstrates the theoretical Values of $P-V$ Compared with its Actual Measured Values.

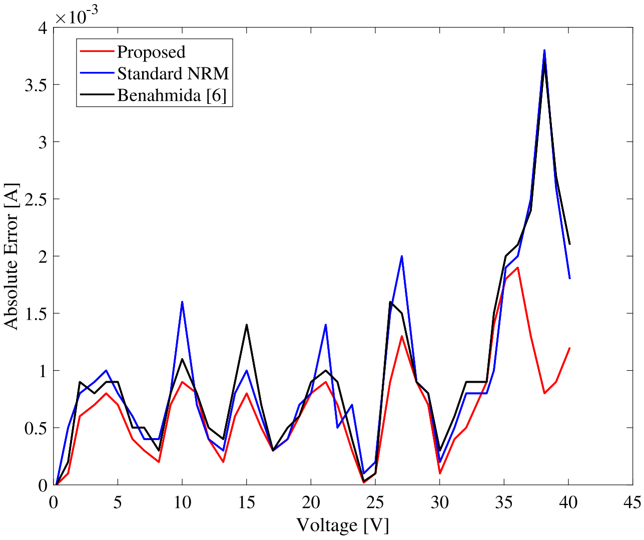

Fig. 4. Plot of absolute error of output current versus output voltage for CHL285P at STC.

Table 2
Comparison of proposed method with other numerical approaches.

Parameters	Proposed	Standard NRM	Benahmida [24]
I_{ph} (A)	9.257012	9.257011	9.257009
I_o (μA)	3.3193	3.3190	3.3191
α	1.206302	1.206301	1.206302
R_s (Ω)	0.355201	0.355201	0.355202
Iterations.	8	10	9
RMSE	0.02	0.028	0.032

Table 3
Parameter values using two methods for RTC France solar cell.

	Standard NRM	Benahmida [24]	Proposed method
I_{ph} [A]	0.7611	0.7611	0.7611
I_o [μA]	0.3479	0.3477	0.3469
R_s [Ω]	0.0348	0.0349	0.0347
α	1.4876	1.4877	1.4875
RMSE	0.004015	0.004938	0.003417
Iterations	7	7	6

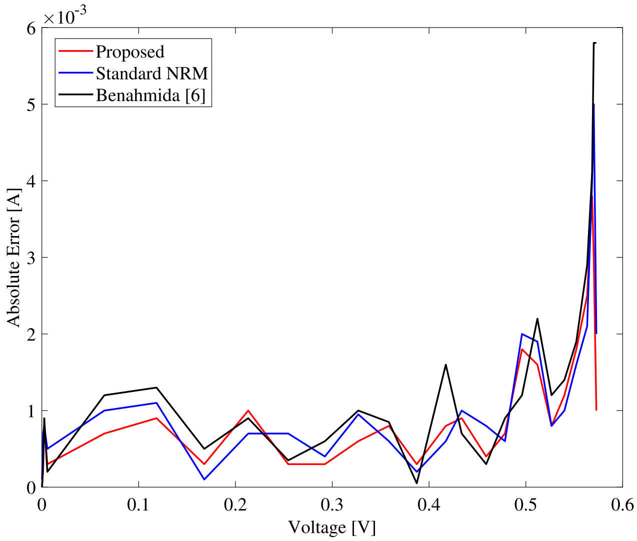

Fig. 5. Plot of absolute error of output current versus output voltage for RTC solar cell at 33 °C.

RTC France solar cell

For RTC solar cell, the optimal parameters obtained using different numerical techniques are presented in Table 3. The cell parameters estimated using modified Newton–Raphson method have the least RMSE value giving its superiority over others in comparison.

Photowatt PWP201

The proposed method is again applied to the PWP201 module to extract the module parameters. The extracted values are then compared to the standard Newton–Raphson method (NRM) and the work [24]. Table 4 shows the results attained for each approach. As it is be seen, the proposed numerical method gives lower RMSE value compared to other methods (see Figs. 5 and 6).

Analysis of output characteristics

Effects of irradiation on PV module

In order to investigate the impact of variations of solar irradiation, a proposed model was simulated under MATLAB/Simulink environments using information given in a test polycrystalline (CHL285P) module described in Table 1. Simulation model that calculates photocurrent was built based on Eq. (2) to obtain the theoretical characteristics. Simulations were performed at five different solar irradiances while keeping temperature constant (25 °C). Both Current–Voltage ($I - V$) and Power–Voltage ($P - V$) curves were plotted and compared with experimental measurements at different irradiances. From Fig. 7 it was observed that, PV module current is proportional to variation of solar illuminance. A significant decrease of short-circuit current was observed on decreasing the solar irradiance. It was further noticed that, open-circuit voltage also decreases on reducing irradiance value, but the decrease is slight. Fig. 8 shows that the maximum power is also directly proportional to solar irradiance. A huge fall of power generated is observed on reducing the sun intensity while the open-circuit voltage change is minimal.

Table 4
Parameter values using two methods for Photowatt PWP210 solar module.

	Newton–Raphson method	Benahmida [24]	Proposed method
I_{ph} [A]	1.033	1.034	1.033
I_o [μA]	2.5671	2.7253	2.2989
R_s [Ω]	1.2316	1.2092	1.1958
α	1.3132	1.3249	1.3043
RMSE	0.002621	0.002410	0.001934
Iterations	9	9	8

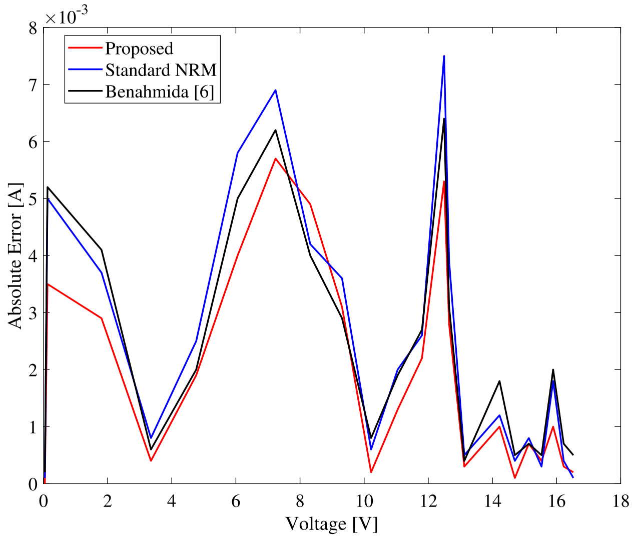

Fig. 6. Plot of absolute error of output current versus output voltage for PWP module at 45 °C.

Effects of temperature on PV module

Simulation of the proposed model was performed under MATLAB/Simulink to study the impact of temperature variation at constant solar illumination level of 1000 W/m^2. A simulating model block was constructed based on Eq. (4) in order to obtain the theoretical characteristics. The inputs of simulating model were obtained from manufacturer's catalog of a test module described in Table 1. Current–Voltage ($I - V$) and Power–Voltage ($P - V$) curves were obtained at five different temperatures and the resulting curves were compared with in-field characteristics. It was observed from Fig. 9 that as temperature of the module increases, the open-circuit voltage decreases significantly whereas short-circuit current increases slightly. Significant decrease in open-circuit voltage is due to the decrease in bandgap of PV material that is caused by increase in temperature as reported by [52]. In Fig. 10, it was observed that the increase in temperature of the PV module lowered the power produced, and thus it was concluded that, raise in temperature reduces the efficiency of PV panel as argued by [25]. Therefore, variation of temperature is inversely proportional to open-circuit voltage and output power.

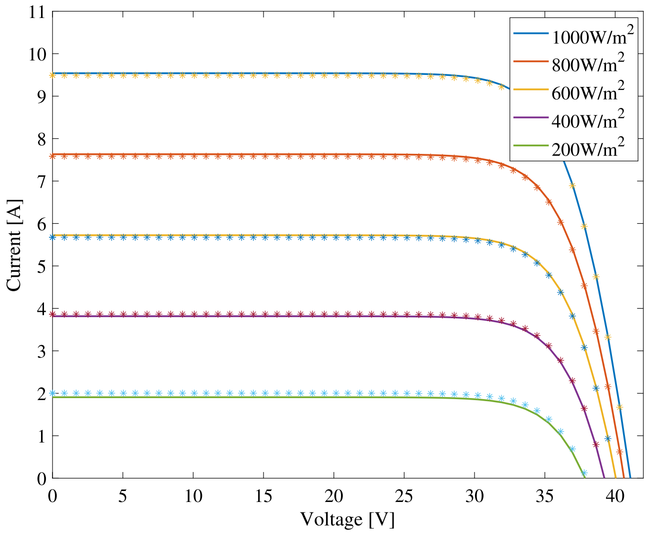

Fig. 7. Experimental (dots) and theoretical (solid line) $I-V$ curve under varying Irradiation.

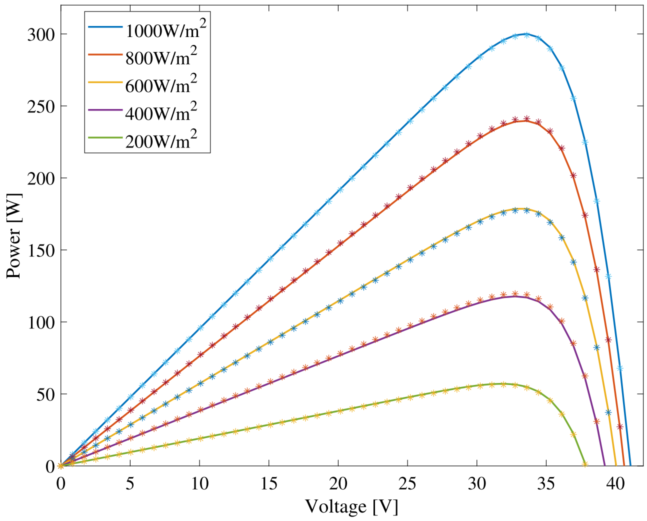

Fig. 8. Demonstrates experimental (dots) and theoretical (solid line) $P-V$ Curves under varying Irradiation.

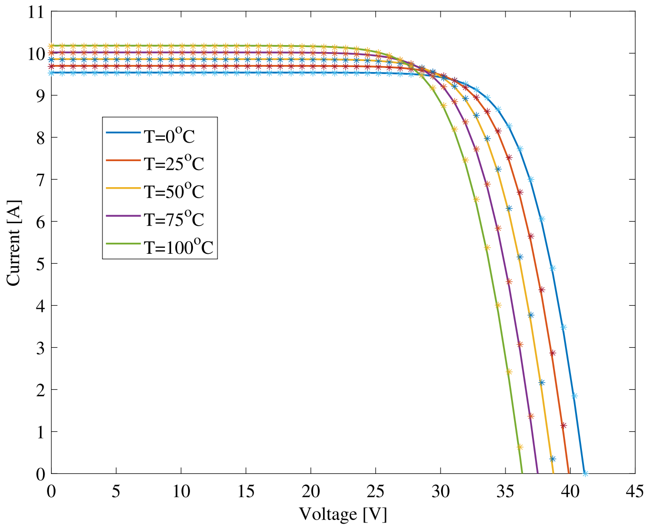

Fig. 9. Illustrates the experimental (dots) and theoretical (solid line) $I-V$ Curves under varying temperature.

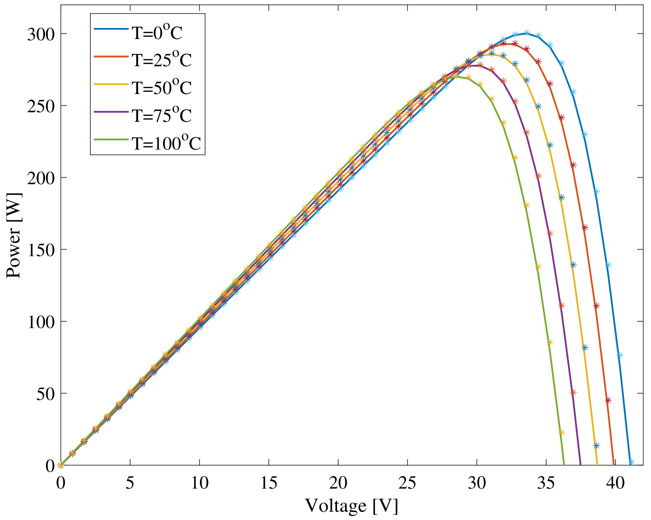

Fig. 10. Demonstrates the experimental (dots) and theoretical (solid line) $P-V$ Curves under varying Temperature.

Conclusion

This paper has presented a modified Newton–Raphson method to extract and evaluate the physical parameters of photovoltaic generators. The equivalent single-diode circuit with four parameters was applied for modeling the electrical behavior of the PV module. This method follows predictor–corrector rule in which two initial values are required. The first starting value is carefully selected whereas the second one is evaluated using standard Newton–Raphson method. The suggested iterative method converges faster than the normal Newton–Raphson method with order of $(1+\sqrt{2})$. The application of this method for the RTC France solar cell, PWP201 and the CHL285P panels returned less error and a good agreement with the experimental measurements. The paper offers a significant contribution to the prediction of photovoltaic module performances, which is a critical stage in the analysis of any PV system. The suggested method can turn it into an alternative tool for designers looking for a simple and effective model for modeling PV devices linked with power converters. Therefore, our contribution could serve as a starting step toward constructing a full solar PV power conversion system for a high grid application.

CRediT authorship contribution statement

Nsulwa John Mlazi: Writing – original draft, Validation, Software, Methodology, Investigation, Conceptualization. **Maranya Mayengo:** Writing – review & editing, Supervision. **Geminpeter Lyakurwa:** Writing – review & editing, Supervision. **Baraka Kichonge:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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