Identification and Extraction of Parameters from Photovoltaic Panels using the Newton-Raphson Method

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Abstract - Photovoltaic electricity (PV) is obtained through the direct conversion of sunlight into electricity using photovoltaic cells. The operation of these optoelectronic components is often described by the I-V characteristic, which depends on several electrical parameters [1-3]. Accurately determining these parameters remains a challenge for researchers, as this determination is crucial for simulating, quality control, and implementing photovoltaic devices that meet specific specifications [4].
In this work, a new numerical method for extracting the electrical parameters of these PV cells for a single-diode model (I_{ph}, I_0, A, Rs, R_{sh}) has been developed. This method is based on solving a system of nonlinear equations obtained by utilizing the full current-voltage measurements directly from a PV module using a modified Newton-Raphson formula [8]. The results obtained demonstrate a high agreement between experimental and simulated characteristics.

Keywords – I-V characteristics, degradation, Photovoltc parameters, Newton-Raphson, modules.

I. INTRODUCTION

Photovoltaic electricity has generated significant scientific and economic interest in recent years. This interest is due to the growing demand for energy in most industrial sectors and environmental obligations. Photovoltaic cells are at the heart of the electricity production chain. Competition to optimize and increase the efficiency of photovoltaic cells has led researchers to seek methods for determining the intrinsic parameters of these cells [2].

In the literature, several methods have been proposed for parameter extraction. Each of these methods has its drawbacks, either in terms of complexity of use and precision or in terms of convergence and speed [6]. They can be categorized as follows :

- Graphical Methods
- Analytical Methods
- Numerical Methods

To address the challenges in this field, this work presents a new and efficient numerical method for the very precise estimation of electrical parameters for the single-diode model. The method has been tested using a graphical interface specially developed for this purpose within the MATLAB environment.

II. MODELING OF SINGLE-DIODE PV MODULES AND NUMERICAL METHOD.

In order to calculate the unknown parameters of a PV cell, it is essential to have an equivalent circuit or model of a PV cell. There are numerous PV cell models available in the literature. Despite the various equivalent circuits for PV cells, for the sake of accuracy and simplicity, we have opted to work with a single-diode model incorporating both series and parallel resistance. The single-diode model with series and shunt resistance is depicted in Figure (1).

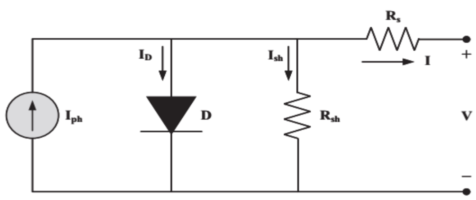

Fig. 1. Equivalent circuit of a PV cell with a diode.

The theoretical model selected to describe the I-V characteristic of the photovoltaic module is the single-exponential model (or single-diode model) as introduced in the first chapter. The current generated by the module is determined by the following equation :

$$I = I_{ph} - I_s\left(e^{\frac{q(V_T+IRs)}{mKT}} - 1\right) - \frac{V_T+IR_s}{R_{sh}} \quad (1)$$

In the case of PV modules with multiple cells connected in series, equation (1) becomes:

$$I = I_{ph} - I_s\left(e^{\frac{q(V_T+IRs)}{NsmKT}} - 1\right) - \frac{V_T+IR_s}{R_{sh}} \quad (2)$$

The above model has five unknowns: I_{ph}, I_s, V_T, R_s, and R_{sh}, which need to be estimated. Here, Iph represents the photovoltaic current flowing through the circuit due to irradiation. As a result, the photovoltaic cell acts as a current source since it doesn't depend on the load attached to the PV cell.

I_s is the saturation current, V_T is the thermal voltage, and R and R_{sh} are the series and shunt resistances, respectively.

The Newton-Raphson method is an iterative technique used to approximate a given function f(x) using an initial estimation. The method is derived from the Taylor series expansion around $(x - x_0)$, as shown below :

$$f(x) = f(x_0) + f'(x_0)(x - x_0) + \frac{1}{2}f''(x_0)(x - x_0)^2 + \cdots = 0 \quad (3)$$

Let's assume that the initial estimation is very close to the real root of the equation. In this case, $(x - x_0)$ is quite small, and only the first terms become significant in estimating the root's value, given X_0.

By truncating the series after the second term, we obtain the general Formula of the Newton-Raphson method [4].

$$x_1 = x_0 \frac{f(x_0)}{f'(x_0)} \quad (4)$$

So, given xn, the point x(n+1) will be obtained by intersecting the tangent to f(x) at xn with the x-axis. This can be illustrated mathematically using equation (4) and graphically as shown in figure 3.

$$x_{n+1} = x_n \frac{f(x_n)}{f'(x_n)} \quad (5)$$

The convergence of the Newton-Raphson method is guaranteed for a certain interval [a, b] containing the root of f(x), as long as f(x) and f'(x) are continuous within that interval and f(α) = 0, where α is the root of f(x) [5].

To estimate the five unknowns of the single-diode model, five equations are derived from the circuit in figure (1). The equations are provided below.

$$f_1 = I_{sh} - I_{ph} + I_s\left(e^{\frac{IscRs}{V_T}} - 1\right) + \frac{IscR_s}{R_{sh}} \quad (6)$$

$$f_2 = I_{ph} - I_s\left(e^{\frac{Voc}{V_T}} - 1\right) - \frac{Voc}{R_{sh}} \quad (7)$$

$$f_3 = I_{mp} - I_{ph} + I_s\left(e^{\frac{(Vmp+ImpRs)}{V_T}} - 1\right) + \frac{(Vmp+ImpR_s)}{R_{sh}} \quad (8)$$

$$f_4 = I_{mp} - (Vmp + ImpR_s)\left(\frac{I_s}{V_T}\left(e^{\frac{(Vmp+ImpRs)}{V_T}}\right) + \frac{1}{R_{sh}}\right) \quad (9)$$

$$f_5 = \frac{R_s}{R_{sh}} - \frac{I_s}{V_T}\left(e^{\frac{IscRs}{V_T}}\right)(R_{sh} - R_s) \quad (10)$$

Where I_{sc} is the short-circuit current, V_{OC} is the open-circuit voltage, V_{MP} is the voltage at maximum power, and I_{MP} is the current at maximum power. These details are provided with the photovoltaic cell upon purchase. In this chapter, we have discussed the Newton-Raphson method, which is employed to estimate the five unknown parameters. The method utilizes equations (6) to (10).

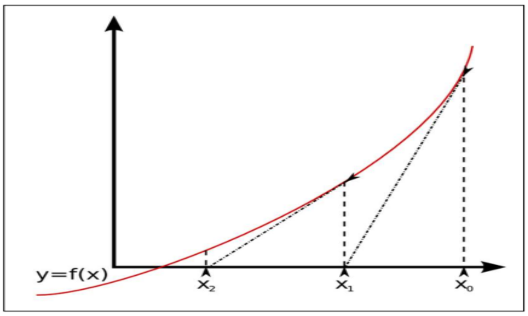

Fig. 2. Illustration of the Newton-Raphson method.

III. PARAMETER ESTIMATION TECHNIQUES

This section is divided into three subsections, with each subsection explaining an existing technique. The first subsection is based on a numerical approach, while the last two subsections utilize an evolutionary approach.

A) Photovoltaic Panel Electrical Characteristics

The proposed estimation method was implemented within the MATLAB environment using the single-diode equation (1). A monocrystalline PV module type JW-G2000 with 72 cells connected in series was chosen for testing the method. The parameters provided by the manufacturer under STC (Standard Test Conditions) for an irradiation of 1000W/m^2 and a temperature of 25°C, which are utilized in the proposed method, are presented in Table (1). Table (2) represents the initial values integrated into the Newton-Raphson method.

Table 1. Technical specifications of JW-G2000 monocrystalline under STC.

Cell Type	Value
Short-circuit current of the cell (STC) I_{SC}	5.92 A
Nominal temperature T_n (k)	298°K
Electron charge (C)	1.6×10^{-19}
Boltzmann constant (J/K)	$1.38\,e^{-38}$ (J/K)
Number of cells in series N_s	72
Number of cells in parallel (shunt) N_{sh}	1
Nominal power	200 W
Maximum voltage V_{mpp}	36.5 V
Maximum current I_{mpp}	5.48 A
Open-circuit voltage V_{CO}	44.5 V

Table 2. Inital parameters.

Parameters	Initial values
Photocurrent I_{ph}	5A
Saturation current Is	1E-8 A
Ideality factor V_T	1.5
Series resistance R_S	0. 3 Ω
Shunt resistance R_{sh}	1000 Ω

In order to characterize the solar cell, we utilized the presented models to provide values for voltage (V), generated current (I) as illustrated in Fig. 3, and generated power (P) as shown in Fig. 4, under standard test conditions to validate our work in the end.

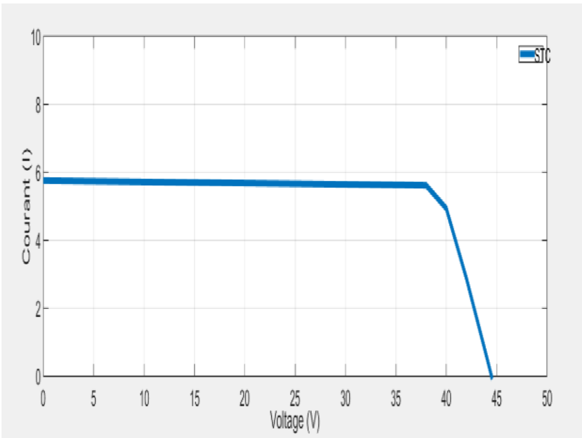

Fig. 3. Characteristic I(V) under standard test conditions.

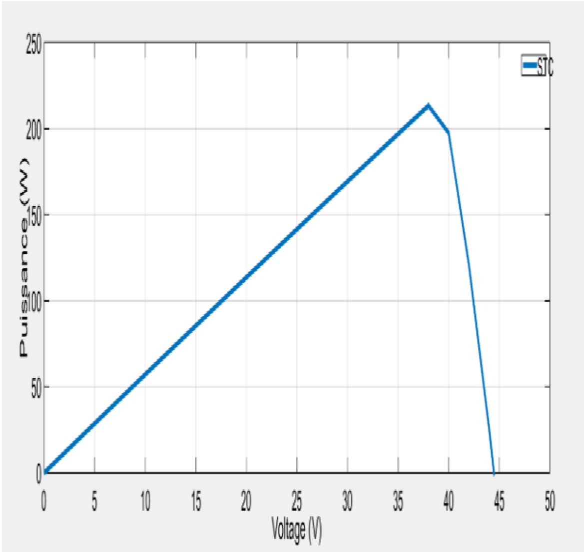

Fig. 4. Characteristic P(V) under standard test conditions.

After obtaining the photovoltaic panel's specifications plate, which allowed us to extract manufacturer values and results, we entered them into the simulation and obtained the following results. These results include two curves, I-V and P-V, as depicted in Figures 3 and 4. In the first curve, I-V, it illustrates the evolution of electric current I(A) in terms of voltage V(V). Here, we observe that the curve remains stable up to a maximum value of 5.92 A. The second curve, P-V, represents changes in power P (W) in terms of V(V). It's noteworthy that the curve increases to a value of 210 W.

Based on the experimental I-V characteristic of the photovoltaic module, it is essential to identify the optimal parameter configuration to align the simulated results (implicit expression) accordingly Modifying the parameters can be specified while keeping in mind the error reduction associated with optimization. Consequently, we conducted experiments using the photovoltaic panel located at the Renewable Energy Laboratory of Salhi Ahmed University Center in Naâma. This photovoltaic panel has been in operation since 2018. The results obtained have been presented in Figure 5 and Figure 6.

Thus, through this study and the analysis of the two curves, we have determined that the photovoltaic panel's values have changed due to degradation factors.

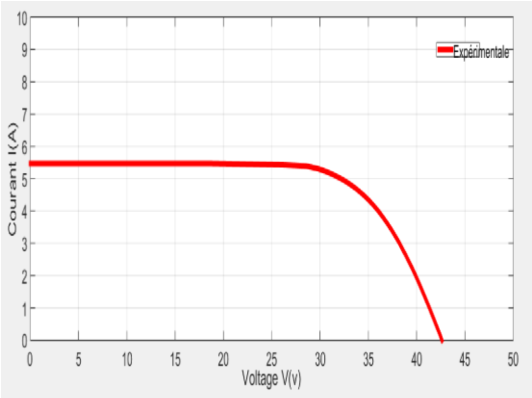

Fig. 5. Current-voltage characteristic I(V).

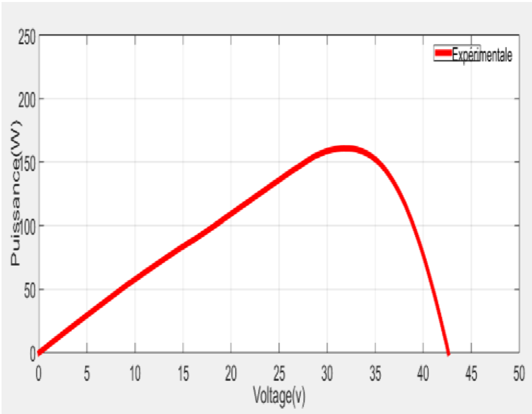

Fig. 6. Power-voltage characteristic P(V).

After approximately five years of operating the photovoltaic panel, we conducted a test on (06-03-2023) by studying the current voltage and power provided to the photovoltaic panel (jw_G1950) under 1000 watts/m2 irradiation and 25 degrees Celsius temperature. We extracted specific values that enabled us to obtain results, leading to the generation of two curves: I(V) and P(V). These curves depict variations of current I(A) and power P(W) in relation to voltage V(V). In the first curve (5), we observed the variation in electric current I(A) with respect to voltage V(V), with the curve remaining stable at a maximum value of 5.5. The second curve showcases changes in power P(W) values with respect to voltage V(V), and we noticed that curve (6) increases up to a maximum value of 165 W.

After extracting these values for the photovoltaic panel, which we found to be degraded due to the factors mentioned in chapter II, we proceeded to diagnose these panels using the Newton-Raphson method through simulation.

To apply the numerical Newton-Raphson method to the proposed problem, it's necessary to use multiple points sampled from the curve. In the case of a diode model, five parameters need to be extracted (I_{ph}, I_s, R_s, R_{sh}, V_T), and it's essential to formulate five equations (f_1, f_2, f_3, f_4, f_5) (Equations 6 to 10) to make the problem solvable. Therefore, it's necessary to extract four points from the real curve, which will be used to solve the problem.

In this work, the following points were used: the first corresponds to the initial point of the curve, being the maximum voltage V_{mp}, the second point is the maximum current Imp, the third point is the open-circuit voltage V_{oc}, and finally, the fourth point is the short-circuit current Isc. With these equations, it's possible to set up the system to solve the problem.

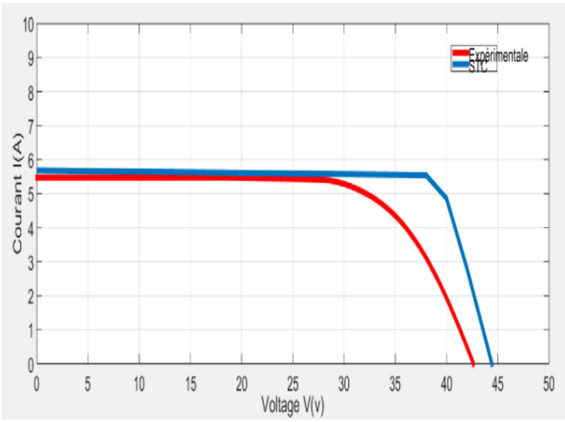

Fig. 7. Comparison of current-voltage characteristics I(V).

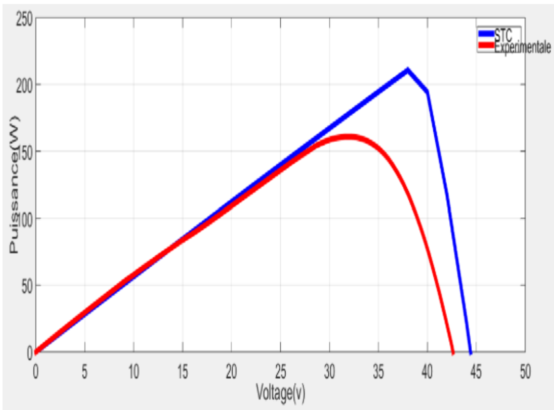

Fig. 8. Comparison of power-voltage characteristics P(V).

B) Calculating the Jacobian matrix [JV]

The Jacobian matrix [J^V], is written in the same form as the matrix mentioned above, and for this purpose, we need to differentiate each equation with respect to the five unknown parameters and place them accordingly.

In our case, the derivative of each equation with respect to the five unknown parameters results in the Jacobian matrix having five rows and five columns.

$$\begin{bmatrix} x_{1,k+1} \\ x_{2,k+1} \\ x_{3,k+1} \\ x_{4,k+1} \\ x_{5,k+1} \end{bmatrix} = \begin{bmatrix} x_{1,k} \\ x_{2,k} \\ x_{3,k} \\ x_{4,k} \\ x_{5,k} \end{bmatrix} - \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \frac{\partial f_1}{\partial x_3} & \frac{\partial f_1}{\partial x_4} & \frac{\partial f_1}{\partial x_5} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \frac{\partial f_2}{\partial x_3} & \frac{\partial f_2}{\partial x_4} & \frac{\partial f_2}{\partial x_5} \\ \frac{\partial f_3}{\partial x_1} & \frac{\partial f_3}{\partial x_2} & \frac{\partial f_3}{\partial x_3} & \frac{\partial f_3}{\partial x_4} & \frac{\partial f_3}{\partial x_5} \\ \frac{\partial f_4}{\partial x_1} & \frac{\partial f_4}{\partial x_2} & \frac{\partial f_4}{\partial x_3} & \frac{\partial f_4}{\partial x_4} & \frac{\partial f_4}{\partial x_5} \\ \frac{\partial f_5}{\partial x_1} & \frac{\partial f_5}{\partial x_2} & \frac{\partial f_5}{\partial x_3} & \frac{\partial f_5}{\partial x_4} & \frac{\partial f_5}{\partial x_5} \end{bmatrix} \begin{bmatrix} f_{1(x_k)} \\ f_{2(x_k)} \\ f_{3(x_k)} \\ f_{4(x_k)} \\ f_{5(x_k)} \end{bmatrix} \quad (11)$$

When using the Newton-Raphson method, it's essential to have an approximate value in mind that one intends to obtain because the initial estimation must be close to the problem's solution. Otherwise, the method might not converge to the solution. This understanding is necessary as the inverse of the Jacobian matrix ((J^V)-1) calculated at each iteration must be non-singular, which means its determinant should be nonzero.

C) Flowchart of the Newton-Raphson Method

The flowchart below summarizes the various equations used for the extraction of photovoltaic cell parameters, as presented in Fig. 9.

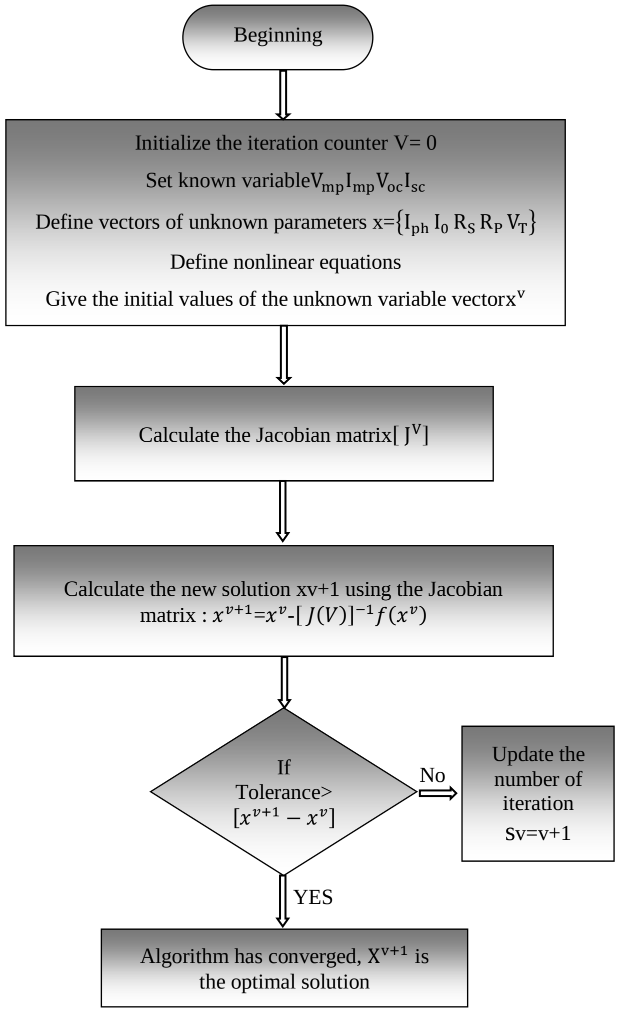

Fig. 9. Flowchart of the Newton-Raphson Method Calculation.

IV. RESULTS AND DISCUSSIONS

Table (3) displays the results of the five photovoltaic parameters obtained using the Newton-Raphson method through MATLAB software calculations, concerning the monocrystalline JW-G2000 panel.

Table 3. Results of Parameter Extraction using the Newton-Raphson Method.

I_{ph}(A)	I_S(A)	V_T	R_S	R_{sh}
5.7119	**1.7017E-8**	**1.8606**	**0.2172**	**951.927**

After obtaining the numerical iteration values using the MATLAB program, the number of iterations that provided us with approximate solutions was 46. These values should be input into Simulink to plot the I(V) and P(V) curves.

A) Block Diagram

The following figure illustrates the internal diagram of the Simulink simulation block.

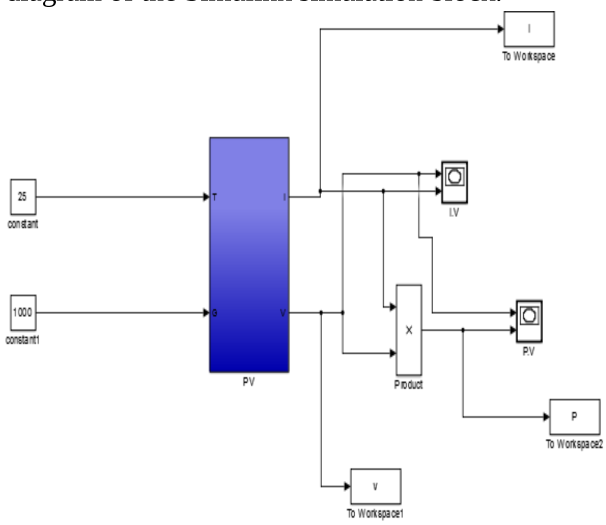

Fig. 10. Photovoltaic Generator Simulation Block.

B) Current-voltage and power-voltage characteristics of the model

Figures 11 and 12 represent respectively the current-voltage characteristics I(V) and power-voltage characteristics P(V) of a photovoltaic panel using the Newton-Raphson method, which was applied to solve the system of five nonlinear equations representing the exact value of each parameter.

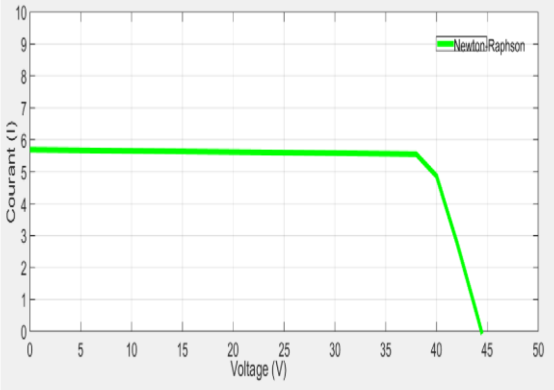

Fig. 11. I(V) Characteristics.

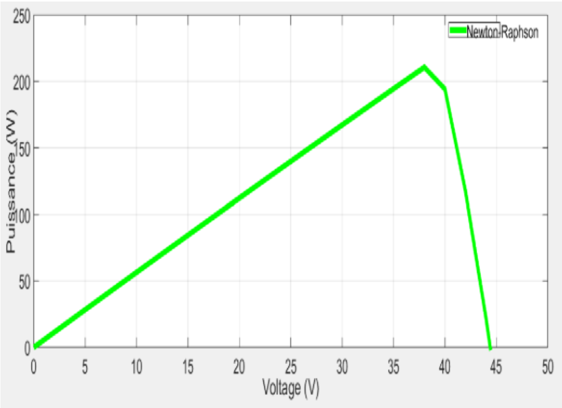

Fig. 12. P(V) Characteristics.

The results obtained through the I (V) and P(V) characteristics shown in Figures 11 and 12 reveal that the values of the five parameters $\overrightarrow{I_{ph}}$ $\overrightarrow{I_0}$ $\overrightarrow{R_S}$ $\overrightarrow{R_P}$ $\overrightarrow{V_T}$ obtained using the Newton-Raphson method provide a performance equivalent to what is provided by the manufacturer. This demonstrates the effectiveness of this method.

The proposed method allows us to more easily perform a comprehensive diagnosis to understand the reasons for degradation and the lifespan of the solar panel, ultimately leading to improved photovoltaic panel efficiency.

To validate our Newton-Raphson obtained model, we compared it with the experimental model, achieving a good agreement. This confirmation reinforces the validity of the proposed model. It's worth noting that the maximum power point calculated by the Newton-Raphson method closely matches the one measured under standard conditions and is significantly higher than the experimental result. This is demonstrated in Figures 13 and 14.

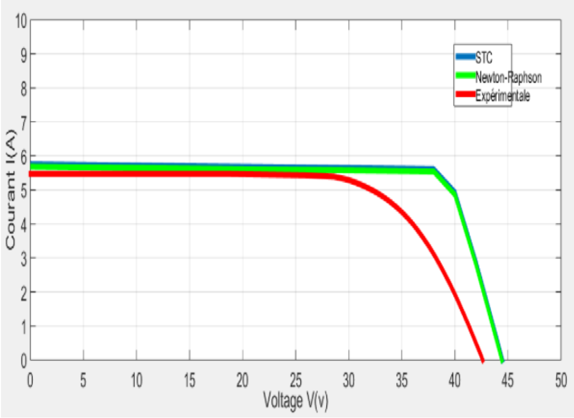

Fig .13. Validation of the N-R Method I(V) Characteristics.

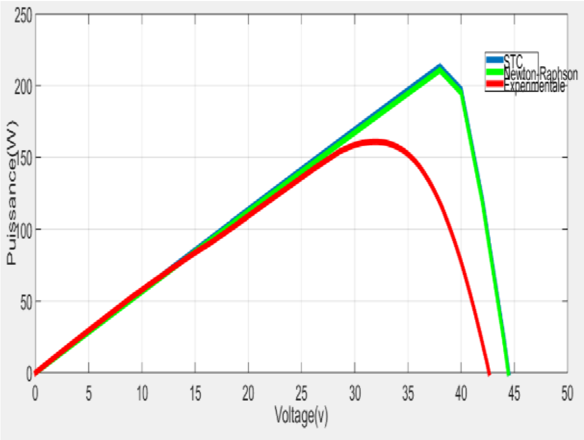

Fig. 14. Validation of the N-R Method, P(V) Characteristics.

V. CONCLUSION

There is a growing focus on solar energy worldwide, with solar cells frequently used to harness energy from sunlight, especially when electrical power is required. This is because the analysis and accurate prediction of solar cell behavior under various operating conditions are of great practical importance.

In this paper, a general approach to modeling photovoltaic (PV) cell modules using the single-diode five-parameter models was presented. The model was implemented in the MATLAB software, and the results were compared with datasheet values and PV module characteristics under standard test conditions (STC) (25°C, 1000 W/m^2). The parameter values were extracted using the Newton-Raphson method from experimental current-voltage (I(V)) and power-voltage (P(V)) characteristics of the monocrystalline JW-G2000 module. The obtained results exhibited good agreement with the data provided by the manufacturer for standard test conditions. This approach can be highly beneficial for researchers and engineers in rapidly and easily assessing the performance of any photovoltaic module.

VI. REFERENCES

[1] A. Wagner, 'Peak-Power and Internal Series Resistance Measurement under Natural Ambient Conditions', Euro Sun Conference, 2000 Copenhagen, June 19-22, 2000.

[2] [2] J.H. Smith and L.R. Reiter, 'An In-Depth Review of Photovoltaic System Performance Models', The American Society of Mechanical Engineers, 84-WA/Sol-12, 8 p., 1984.

[3] Revue des Energies Renouvelables Vol. 13 N°3 (2010) 379 – 388.

[4] F. ZOUACHE, "Etude de la concentration solaire sur les performances des systèmes photovoltaïques", Mémoire de Magister, Université Mentouri Constantine, 2009.

[5] Michael Boxwell. "Solar Electricity Handbook", 2012.

[6] R. Irkettou, A. M. Taj, C. E. Hadi, A. Abouhilal, et A. Malaoui, « « Nouvelle méthode d'extraction des paramètres électriques d'une cellule solaire ». Revue de l'Entrepreneuriat et de l'Innovation, Vol 1, N°3, pages 1-6, 2017. », Art. no 3.

[7] Abdessamad Malaoui, EL Mahdi BARRAH, and Jilali ANTARI, 'Implementation of a new approach for modeling and determining the electrical parameters of solar cells,' International Journal of Innovation and Applied Studies, vol. 15, no. 2, pp. 329–338, April 2016

[8] Abdessamad Malaoui, 'New method for improving the quality of electrical measurements: application to the extraction of the intrinsic parameters of the photovoltaic cells,' International Journal of Innovation and Applied Studies, vol. 15, no. 2, pp. 375–386, April 2016.

[9] Nsulwa John Mlazi 'Mathematical modeling and extraction of parameters of solar photovoltaic module based on modified Newton–Raphson method,' Results in Physics 57 (2024) 107364.

[10] Patrick Juvet Gnetchejo'A Self-adaptive Algorithm with Newton Raphson Method for Parameters Identification of Photovoltaic Modules and Array,' Transactions on Electrical and Electronic Materials, 2021.