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Research Article

Characterization and Sensitivity Analysis of a Photovoltaic Panel

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Abstract: The characterization of photovoltaic (PV) panels is crucial both in post-manufacturing quality control and operational phases. To achieve this purpose, models of equivalent electronic circuits are utilized. The modeling of photovoltaic panels can be simulated using single-diode and double-diode models. These models differ in the number of parameters due to the inclusion of one or two diodes, resulting in non-linearity within the mathematical descriptions of these systems. In this study, a single-diode model with 5 parameters has been employed to analyze the system's behavior. Sensitivity analysis and a comparative study of two different numerical methods were conducted to assess the estimation of the maximum power. Furthermore, the internal and external factors influencing the performance of photovoltaic panels were studied and analyzed. To simulate panel degradation, both the serial resistance and temperature were considered as slow time-varying internal and external parameters, affecting the I-V characteristic and the Maximum Power Point. This work presents a comparative study of heuristic search algorithms applied to the two models, accompanied by a simulation of a real-time application.

***Keywords*:** modelling, single-diode model, Maximum Power Point (MPP), instrumentation

1. Introduction

Nowadays, solar energy serves as a convenient alternative for societies that prioritize utilizing durable energy sources over fossil fuels [1]. It is considered one of the most suitable renewable sources to address the global energy crisis and mitigate global warming by reducing greenhouse gas emissions [2]. A photovoltaic system is a technology that directly converts irradiance into electricity. It is frequently employed to generate clean and renewable energy for various applications, including residential, commercial, and utility-scale power generation [3]. Photovoltaic systems offer several environmental advantages, such as producing electricity without emitting greenhouse gases or other harmful pollutants. They help reduce the carbon footprint and air pollution [4-5]. As this technology continues to advance, photovoltaic systems are becoming more efficient, cost-effective, and widely adopted worldwide [6]. They play a significant role in the transition to clean energy and in decreasing reliance on fossil fuels [7-8].

However, the electricity generated by PV systems raises some concerns related to optimization, production, and maintenance challenges [9]. Characterizing PV devices is crucial for comprehending their efficiency, electrical behavior, and overall performance [10]. Photovoltaic characterization plays an essential role in understanding the behavior and performance of solar cells and systems [11-12]. It aids researchers, manufacturers, and system designers in optimizing

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PV technology, improving efficiency, and developing more reliable and cost-effective solar energy solutions [13].

The I-V curve serves as a fundamental tool for PV characterization [14]. It illustrates the relationship between current and voltage across the device or module at various operating points [15]. Through plotting the I-V curve, one can determine parameters like open-circuit voltage, short-circuit current, maximum power point, and fill factor of the PV system. These parameters offer valuable insights into the device's electrical behavior and performance [16-17]. However, not only do the characteristics of the PV panel itself determine PV conversion efficiency, but environmental factors also significantly influence the performance and efficiency of photovoltaic systems [18]. Understanding and accounting for ambient environmental parameters are crucial throughout the design, installation, and operation of photovoltaic systems [19]. Proper site assessment, maintenance practices, and system design considerations can aid in optimizing the performance, efficiency, and long-term reliability of PV systems in various environmental conditions [20]. Two models exist for PV characterization: the single-diode and double-diode models. These models analyze not only the various parameters of PV cells but also their internal and external parameters. These parameters are examined by utilizing the ideal values specified by the industry [21-24].

In the first step of this study, the mathematical equations of the power-voltage characteristic curve of the photovoltaic panel are introduced using two different numerical methods: the Bisection method and the Newton-Raphson algorithm. The five parameters of the single diode model for determining the characteristic P-V curve optimally have been analyzed. In the second step, the influence of temperature and changes in serial resistance are studied, respectively.

2. Materials and methods

Most PV cells consist of thin silicon films that harness the sun's energy and directly convert its rays into electrical energy. Primarily, the electrical output of a single cell is low, so multiple cells are connected in series and parallel configurations to form a module conventionally called a "panel," which generates higher voltage and current.

This technology offers numerous advantages, including silent operation, adaptability to various weather conditions, stable installation in different environments, minimal maintenance requirements, and a long lifespan. One of its strongest points is its environmental friendliness, as it does not produce emissions such as greenhouse gases and CO_2 during electricity generation [25].

2.1 *Mathematical equations for photovoltaic cell*

When photons strike the solar cell, the resulting electric current is termed the photo-generated current, denoted as I_{ph} [26]. The solar cell functions as a diode in the absence of radiation, generating voltage and current [27]. According to the Shockley diode formula, two models exist for accurate solar cell modeling: the single-diode model and the double-diode model [28]. The single diode model, depicted in Figure 1, comprises five parameters: a constant current source I_{ph}, the saturation current I_s, an ideality factor of the diode n, and series and shunt resistances, represented as R_s and R_{sh}, respectively [29]. This model is recognized for its high accuracy [30].

The current supplied by a photovoltaic cell represented by a single diode model is:

$$I = I_{ph} - I_s \left[\exp\left(\frac{q\left(V + IR_s\right)}{nKT} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \tag{1}$$

With Ns representing the number of series-connected cells in the module, V indicating the output voltage, T representing the cell temperature, q representing the electric charge, and K denoting the Boltzmann constant.

A photovoltaic cell exhibits a nonlinear I-V characteristic, expressed by the implicit Equation 1, wherein the output current appears on both sides of the equality, rendering it more challenging to solve. Consequently, the Newton-Raphson method has been employed to determine the roots of Equation 2 in order to derive the characteristics of the PV panel.

$$f(I,V) = I - I_{ph} - I_s\left[\exp\left(\frac{q(V+IR_s)}{nKT}\right) - 1\right] - \frac{V+IR_s}{R_{sh}}. \tag{2}$$

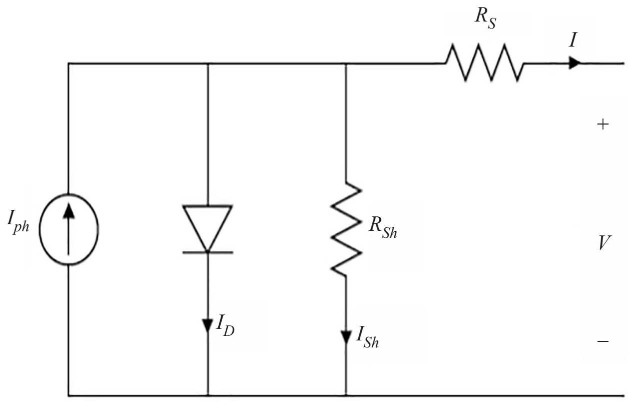

Figure 1. Equivalent circuit with shunt and series resistance

2.2 *The Newton-Raphson method*

The Newton-Raphson method commences with an initial root approximation, denoted as $x_0 \neq x_r$, and employs the tangent of $f(x)$ at x_0 to refine the root estimation. By identifying the point of intersection between the tangent line of $f(x)$ at x_0 and the x-axis, x_1 is calculated. This marks the first iteration of the method and is depicted in Figure 2(a). Conversely, the second iteration employs the tangent line of $f(x)$ at x_1 to determine x_2, as illustrated in Figure 2(b). The direction of the tangent line is determined by the sign of the local gradient of each x_n [31].

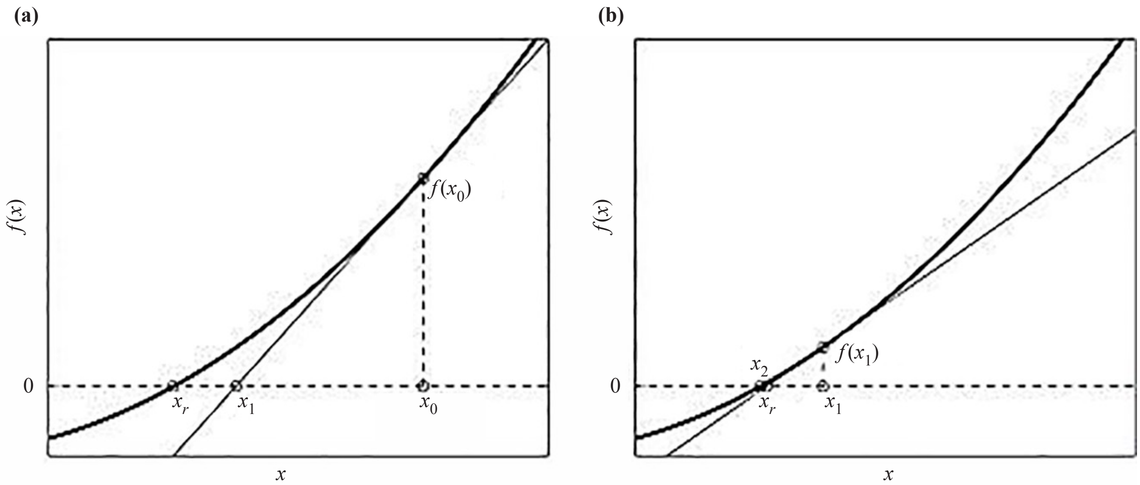

Figure 2. The process of convergence of the Newton-Raphson method

This numerical method primarily relies on a selected initial point x_0, which plays a crucial role in the Newton-Raphson method. The method's convergence to its root or divergence depends on the choice of the point x_0. As a result, the initial estimation can be calculated using the following relationship.

$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)} \tag{3}$$

The Consecutive approximations of this method can be obtained from the following equation:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \tag{4}$$

where $f'(x_n)$ represents the first derivative of the function $f(x)$ at the point x_n.

The advantages of the Newton-Raphson method include high speed, convergence, accuracy, and flexibility. Additionally, this algorithm is reliable and effective for solving systems that operate near voltage drops. However, sometimes the required conditions for convergence are met, but the chosen initial guess falls outside the range of convergence for Newton's method. This situation can occur when, for instance, the variable x approaches positive and negative infinity, and the function's root approaches zero sufficiently. Moreover, in certain functions, specific points selected as the initial guess might lead to circular behavior that prevents convergence. In such cases, a more suitable method like the Bisection method should be used to obtain a more accurate estimate [32-33].

Both the Bisection and Newton-Raphson methods were applied to compare their results and determine the better algorithm for illustrating the current voltage curve. In the Bisection method, the interval [0.00-0.10] was employed with an error of 10^{-8}, while for the Newton-Raphson method, the interval voltage [0.00-32.7] was used. Both methods underwent several iterations until convergence was achieved. The stopping criterion for each iteration step was the absolute deviation of the computed current, which in this research was set to 32 with the same voltage values used in the Newton method.

3. Sensitivity analysis

3.1 *Temperature effect*

There are two key aspects contributing to the good performance of Photovoltaic panels. The first is electrical efficiency, and the second is power output [34]. However, it's evident that electrical efficiency takes precedence, making it the primary focus of the study. The primary factor that can impact electrical efficiency is the cell's material, which is not a subject of doubt in this paper [35]. (It's worth noting that the photovoltaic panel used in this research employs polycrystalline material). The second crucial factor influencing efficiency is temperature, which serves as the main objective of this paper. This factor becomes more significant when photovoltaic panels are used as the primary power source [36]. The temperature of photovoltaic panels is mainly dependent on ambient temperature and the intensity of solar radiation. As anticipated, higher cell temperatures have an adverse effect on efficiency, meaning that an increase in temperature results in decreased efficiency [37].

Typically, the impact of temperature on polycrystalline panels is around 3 percent. This implies that for every degree of rise in temperature, the efficiency decreases by three percent. Conversely, for each decrease in temperature, the efficiency increases by five percent. While the effect of temperature on panel current is imperceptible, it is observable in voltage, leading to changes in panel behavior [38].

The influence of temperature on the electrical efficiency of photovoltaic panels can be described using a fundamental equation [39-40],

$$P_m = I_m V_m = (FF) I_{sc} V_{oc} \tag{5}$$

in which FF represents the fill factor, I_{sc} is the short-circuit current, V_{oc} is the open-circuit voltage and subscript *m* is the maximum power point in the modules I-V characteristic. V_{oc} and FF diminish significantly with temperature [41-42], while I_{sc} rises, but only moderately [43-44].

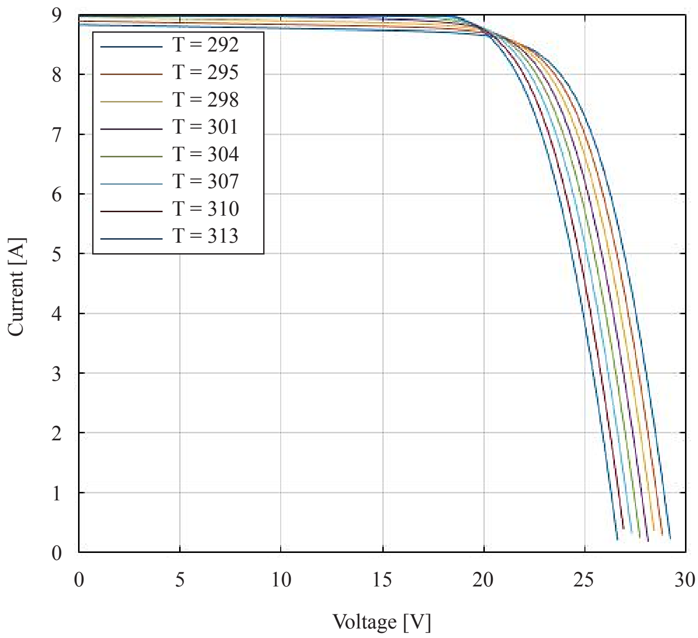

Figure 3. The effect of the temperature on the I-V curve

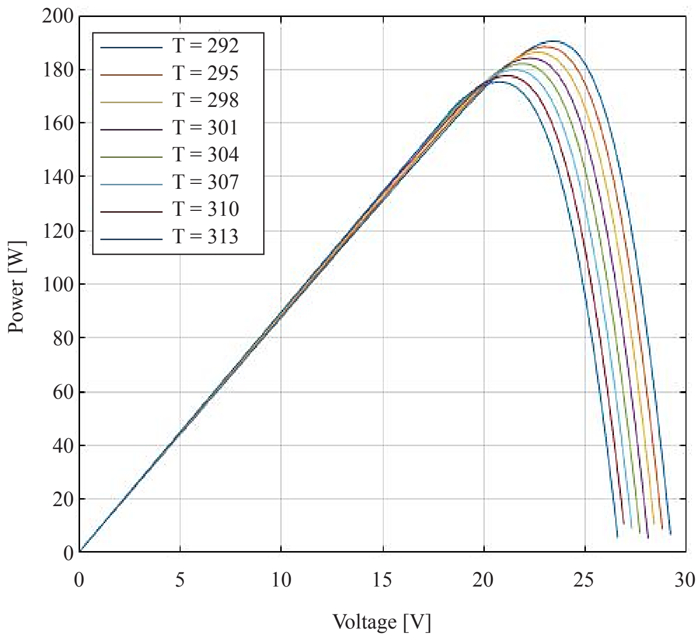

Figure 4. The effect of the temperature on the P-V curve

The conditions used to simulate the effects of temperature on the PV panel were based on a summer day in the region of Evora, Portugal. The temperature was varied between 292 K and 313 K. The results obtained from this study are presented in Figures 3 and 4. As depicted in Figure 3, which shows the impact of temperature on the I-V characteristic, it can be concluded that increasing cell temperature leads to an increase in I_{sc} and a decrease in V_{oc}.

Furthermore, Figure 4 illustrates the effect of temperature on the P-V characteristic. With rising temperature, both V_{oc} and the Maximum Power Point (MPP) decrease. Generally, changes in temperature have a more significant impact on V_{oc} compared to I_{sc}.

Typically, as temperature rises, the amount of absorbed radiation reaching the solar cells and the power of the panel decreases. Temperature plays a critical role in the efficiency of photovoltaic systems. The increase in temperature enhances the conductivity of the semiconductor crystals in the panel, leading to a reduction in voltage. As a result, the system converts only a small portion of the absorbed solar energy into electrical energy, with most of it being dissipated as thermal energy. This thermal energy raises the temperature of the panels and diminishes the system's capacity.

3.2 *Sensitivity analysis toward resistance's changes*

The single-diode model is the most commonly used approach for modeling a solar cell. It can be characterized by a light-dependent current source in a similar manner to a diode. To enhance the model's accuracy, a series resistance is consistently included in the circuit. This addition is necessary as the solar cell is subject to temperature changes that can lead to a loss of accuracy. In order to further improve the model's precision at higher temperatures, a shunt resistor is incorporated into the circuit.

When the series resistance within the cell increases, it results in a greater voltage drop across it, leading to a reduction in current. Consequently, this causes a notable decrease in terminal voltage along with a slight reduction in I_{sc}.

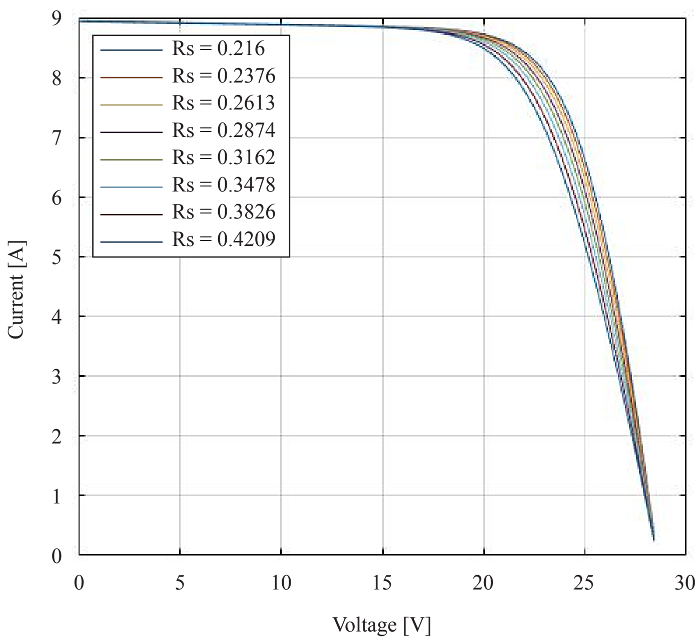

Figure 5. The effect of R_s the on the I-V curve

In general, the series resistance in PV systems is often considered insignificant and has been disregarded in many instances; however, its changes can yield certain effects. With variations ranging from 0.216 Ω to 0.420 Ω, there is a noticeable alteration in I_{sc} while V_{oc} remains constant. According to Figures 5 and 6, the increase in series resistance results in a decrease not only in the current-voltage characteristic but also in the power-voltage characteristic. Consequently, reducing the series resistance influences an increase in both the I-V and P-V, leading to an elevation in MPP. In summary, the series of resistances have a substantial impact on the MPP.

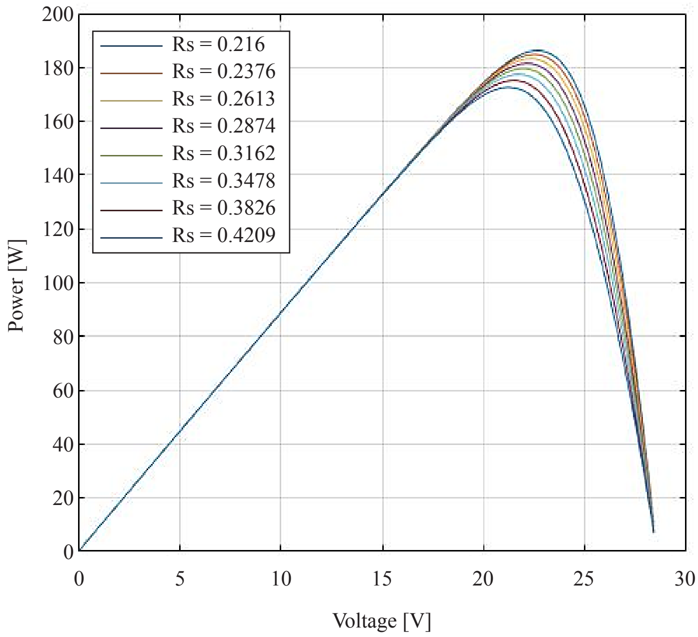

Figure 6. The effect of the R_s on the P-V curve

4. Conclusions

While both the Bisection and Newton-Raphson methods can be applied to the same goal, a major concern is that each of them should be used under specific conditions for optimization and to prevent time wastage. Nonetheless, with initial intervals and complex equations, the Bisection method can be more efficient, but it requires more iterations. On the other hand, the Newton method can save time due to its faster convergence, but it's not always guaranteed, and predicting the initial point can sometimes pose a challenge.

The increase in temperature enhances the conductivity of the semiconductor crystals within the panel. This, in turn, leads to a reduction in voltage, causing the system to convert only a small portion of the absorbed solar energy into electrical energy. The majority of this energy is wasted as thermal energy, which raises the temperature of the panels and decreases the system's capacity.

To enhance the performance of these systems and increase their efficiency, efforts should be made to minimize panel temperature. When the series resistance within the cell increases, it results in a larger voltage drop and reduces the current flow. Consequently, this leads to a significant drop in terminal voltage and a slight decrease in short-circuit current. Thus, the series resistance has an impact on the solar cell's output power. Conversely, increasing the shunt resistance reduces the current passing through it. As a result, the bond voltage increases, leading to a decrease in circuit voltage. Additionally, reducing the cell's output current results in a slight decrease in open-circuit voltage.

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Conflict of interest

The authors declare no competing financial interest.

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