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THE PERFORMANCE OF SOLAR PHOTOVOLTAIC PANELS IN DIFFERENT ENVIRONMENTAL CONDITIONS

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This article presents a comprehensive analysis of a solar photovoltaic (PV) panel performance using simulation techniques implemented in MATLAB/Simulink. While measurements under standard test conditions (STC) provide valuable insights, understanding how PV panels operate under varying environmental conditions (solar irradiance and temperature) is essential for their real-world applications. By utilizing both numerical methods as well as a fuzzy logic (FL) based maximum power point tracking (MPPT) algorithm, in this study we investigate the effects of different environmental conditions on the maximum power point (MPP) of solar panels, providing valuable information for systems optimization and design.

Keywords: photovoltaic; dynamic simulation; maximum power point tracking; irradiance; operating temperature;

1. Introduction

Economic development, industrial progress, and societal growth are strongly linked to the fundamental requirement of access to affordable and sustainable electric power for any country. This interdependence forms the backbone of modern civilization and plays a major role in shaping the trajectory of nations [1]. In recent years, the PV industry has experienced a remarkable surge in growth, transforming the landscape of energy production and consumption. This burgeoning sector has witnessed the widespread adoption of PV systems, spanning a diverse range of practical applications that extend from modest off-grid setups to entire solar power stations [2,3].

One of the key reasons behind the increasing popularity of PV panels is their ability to harness energy from a renewable and infinite source: the Sun. Solar energy usage is also significantly tied to the ongoing efforts to decrease worldwide carbon emissions, a pressing concern that has taken center stage in the global environmental, social, and economic discourse in recent times [4].

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The process of modeling, simulating, and analyzing solar PV generators plays an important role in the preliminary stages of deploying them in any specific location. This phase provides valuable insights into the performance and attributes of the PV system under the actual climatic conditions prevailing in that area. Through thorough modeling, simulation, and analysis, engineers and researchers can gain a comprehensive understanding of how the PV system will behave and respond to environmental factors, such as irradiance and temperature.

2. Simulation of a photovoltaic panel under Standard Test Conditions

In the field of PVs, assessing the performance of solar cells is a fundamental step in understanding their capabilities and potential for energy generation. This assessment is typically conducted under a set of standardized conditions [5] known as STC. Under these conditions, several key parameters are controlled to provide a consistent basis for comparing different solar cell technologies and designs.

Table 1.

Standard Test Conditions (STC*)

irradiance G_{STC}	1000 W/m^2
cell temperature $t_{c,STC}$	25 °C
Air mass AM	1.5

In this article the modeling approach adopted relies on the specification data provided in manufacturers' datasheets (as presented in Table 2). These datasheets contain information about the solar panel’s characteristics, efficiency, and performance metrics under STC. By using the manufacturer-provided data as the basis for their modeling, the aim is to accurately predict and analyze the behavior of the reference solar panel, taking into account the standardized conditions that are essential for meaningful comparisons and assessments.

The single diode model, illustrated in Fig. 1, stands as the prevailing and widely adopted model for simulating the behavior of solar panels [6,7]. This model describes the current-voltage relationship and considers the effects of factors like parasitic resistances, diode behavior, and enviromental factors. By incorporating these factors into its calculations, it captures the real-world complexities that solar panels encounter during their operation [8,9].

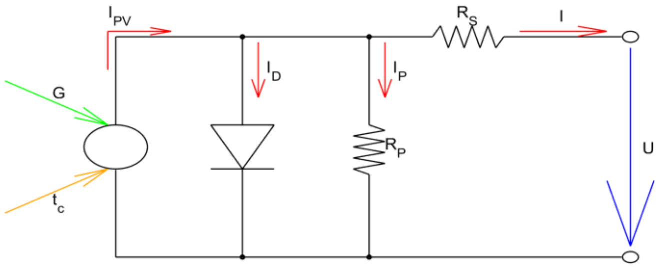

Fig. 1. Equivalent circuit of the solar panel (single diode model)

Integrating the single-diode model into the analysis and design of solar panels requires the use of a set of mathematical equations that describe the electrical behavior of the solar panel. These equations provide a framework for understanding how various parameters influence the Current-Voltage (I–V) and Power-Voltage (P–V) characteristics of the solar panel:

$$I = I_{PV} - I_D - I_P \quad (1)$$

$$I = I_{PV} - I_0 \cdot \left(e^{\frac{q \cdot (V + I \cdot R_S)}{N_S \cdot k \cdot T_C \cdot \alpha_D}} - 1\right) - \frac{V + I \cdot R_S}{R_P} \quad (2)$$

$$P = V \cdot I \quad (3)$$

I	output current [A]
I_{PV}	light-generated current [A]
I_D	diode current [A]
I_P	current through the shunt resistance [A]
I_0	diode saturation current [A]
q	electron charge $1.6 \cdot 10^{-19}$ C
V	output voltage [V]
R_S	series resistance [Ω]
N_S	number of cells connected in series
k	Boltzmann constant $1.38 \cdot 10^{-23}$ J/K
T_c	operating cell temperature [K]
α_D	diode ideality factor
R_P	shunt resistance [Ω]
P	output power [W]

Equation (2) establishes the I-V characteristic of the solar panel, illustrating the connection between the output current (I) and the output voltage (V). Equation (2) is:

- Transcendental: The mathematical complexity is due to how the output current (I) interacts within the equation: it appears both within an exponential term and linearly on the right side, which defies simplification into a form where it can be directly isolated using algebraic operations.

- Consisting of a total of five parameters that exert a substantial influence on the overall performance and functionality of the solar panel. These parameters shape the behavior of the solar panel, ultimately determining its efficiency in converting sunlight into electrical energy. These parameters are: light-generated current (I_{PV}), diode saturation current (I_0), series resistance (R_S), shunt resistance (R_P), and diode ideality factor (α_D).
- Lacking an analytical solution: the complexity of this equation makes it challenging to find a simple, closed-form analytic solution for the output electrical current (I) as a function of output voltage (V). In those cases, numerical techniques or iterative methods are employed to approximate the solution.

One such powerful tool employed for solving complex equations and conducting simulations is MATLAB/Simulink. As it is known, MATLAB/Simulink [10] is a versatile programming environment and software package that excels in numerical analysis, scientific computing, and data visualization. With its extensive capabilities, it serves as a reliable platform for implementing a wide range of numerical methods and algorithms. It empowers researchers and engineers to address equations that lack analytical solutions, enabling them to explore solutions to real-world problems with high precision and efficiency.

For this article, the LG350N1C-V5 solar panel has been selected as the reference model for conducting simulations and analyses. This particular solar panel serves as the point of comparison, enabling assessments of various parameters, behaviors, and outcomes. By adopting a reference model, we establish a standardized framework that allows for thorough and systematic investigations, facilitating a complete exploration of the subject matter at hand. The properties and specifications of the LG350N1C-V5 solar panel [11], as outlined in its datasheet, have been organized for reference in Table 2.

Certain parameters necessary for fine-tuning PV models are notably absent from the manufacturers' provided data sheets [12]. However by using Simulink, particularly leveraging the PV Array Block [13], it becomes possible to accurately compute the nominal values of parameters associated with the single diode model tailored to the LG350N1C-V5 solar panel. The parameter values derived from the PV Array Block for the LG350N1C-V5 solar panel are presented in Table 3.

Table 2.

LG350N1C-V5 solar panel properties [11]

Electrical Characteristics (under STC*)	
MPP Voltage (V_{MPP})	35.3 V
Open Circuit Voltage ($V_{oc,n}$)	41.3 V
MPP Current (I_{MPP})	9.92 A
Short Circuit Current ($I_{SC,n}$)	10.61 A
Maximum Power (P_{MPP})	350 W

Module Efficiency (%)	20.4 %	
Operating Temperature Range	-40 ~ +90 °C	
Mechanical Characteristics		
Number of cells N_S	60 Cells (6 x 10)	
Cell Type	Monocrystalline/N-type	
Temperature Characteristics		
Nominal Operating Cell Temperature NOCT		42 ± 3 °C
Maximum Power/Temperature Coefficient (γ_P)		-0.360 %/°C
Open-circuit Voltage/Temperature Coefficient (β_V)		-0.260 %/°C
Short-circuit Current/Temperature Coefficient (α_I)		0.030 %/°C

Table 3.

PV Array parameter values for the LG350N1C-V5 solar panel

Parameter	Value
light-generated current (I_{PV})	10.68 A
diode saturation current (I_0)	$5.92 \cdot 10^{-12}$ A
series resistance (R_S)	0.13 Ω
shunt resistance (R_P)	97.57 Ω
diode ideality factor (a_D)	0.95

Moreover, these datasheet properties and parameters can be utilized by the PV Array Block to plot the PV characteristics of the reference solar panel, containing the I-V and P-V curves under STC conditions (as presented in Fig. 2).

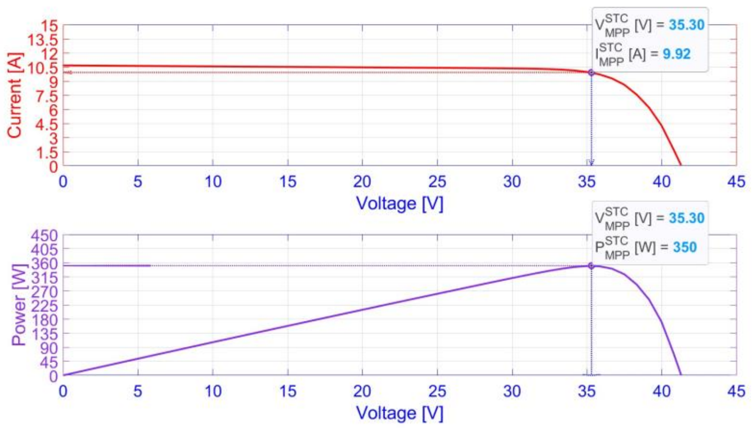

Fig. 2. PV characteristics of the LG350N1C-V5 solar panel
(I–V curve – top / P–V curve – bottom)

The STC serve as an essential benchmark for rating solar panels, however they represent a highly controlled and idealized environment that rarely mirrors the conditions encountered in practical applications. Moreover, it's imperative to recognize that the location of the MPP is not static at the STC value.

3. Simulation of photovoltaic panels for real-world values of irradiance and temperature

When evaluating the performance of PV panels in real-life scenarios, it is essential to consider multiple factors, with solar irradiance and operating temperature being the two most important [14,15]. Moreover, the determination of the MPP is influenced not only by the immediate operating conditions but also by the internal characteristics of the used solar panel. In contrast to irradiance and operating temperature, which exhibit rapid fluctuations throughout the day due to sunlight exposure, the series resistance, shunt resistance, and the diode ideality factor remain relatively constant over time. These particular parameters are tied to the inherent construction and design of the PV device itself, making them largely impervious to the short-term variations experienced during daily sunlight exposure.

The PV Array Block can be used to plot the PV characteristics of the reference solar panel, under various conditions of irradiance and temperature. This capability is necessary for understanding how different environmental conditions affect the performance of the solar panel. The PV Array Block also provides the position of the MPP. By identifying the MPP, the PV Array Block enables users to determine the most efficient operating point of the solar panel under different conditions of irradiance and temperature [13]. This functionality is essential for optimizing the performance and efficiency of PV systems, as it allows for precise adjustments and control to maintain operation at or near the MPP, thereby ensuring maximum energy harvest and overall system efficiency.

The PV characteristics of the reference solar panel are illustrated in several figures to demonstrate its performance under varying environmental conditions. Fig. 3 presents the I-V and P-V curves for the solar panel at different levels of irradiance.

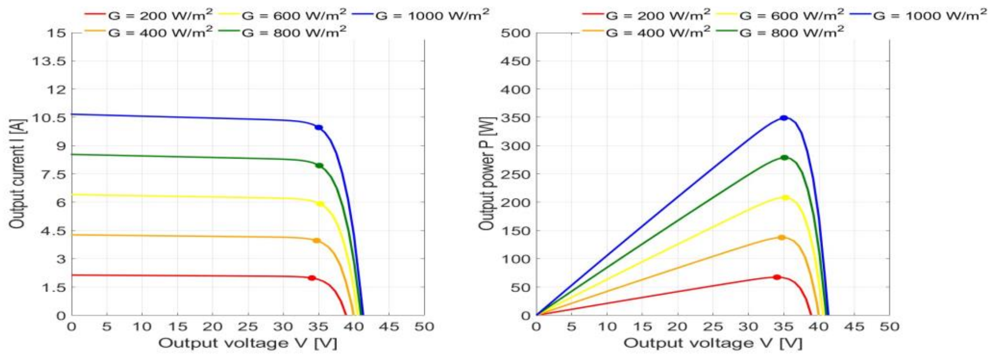

Fig. 3. PV characteristics of the LG350N1C-V5 solar panel for different levels of irradiance (I–V curves – left / P–V curves – right)

These curves illustrate how the current and power outputs change with varying sunlight intensities, providing a clear visualization of the panel’s behavior for different irradiance levels ranging from 200 W/m² to 1000 W/m².

It is clear that the irradiance level significantly impacts the light-generated current (I_{PV}) in the solar panel. As irradiance increases, more sunlight is available for conversion into electrical energy, leading to higher current/power output.

In Fig. 4, the PV characteristics are shown for different operating temperatures. This figure highlights the impact of temperature on the panel's performance, illustrating how higher temperatures typically reduce the voltage output and overall efficiency of the solar panel. The figure illustrates how temperatures ranging from 25°C to 65°C affect both current and power outputs.

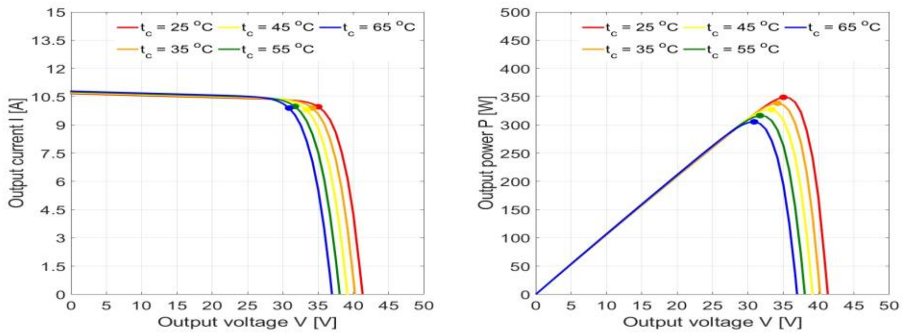

Fig. 4. PV characteristics of the LG350N1C-V5 solar panel for different operating temperatures (I–V curves – left / P–V curves – right)

The operating temperature affects the diode saturation current (I_0) and, consequently, the overall efficiency of the solar panel. Higher temperatures reduce the voltage output, thereby affecting the power output.

Fig. 5 presents the MPP coordinates as determined by the PV Array Block in Simulink for the entire range of irradiance and operating temperature. This figure provides an overview of how the MPP changes under different environmental conditions, allowing for an understanding of the panel's efficiency and performance optimization.

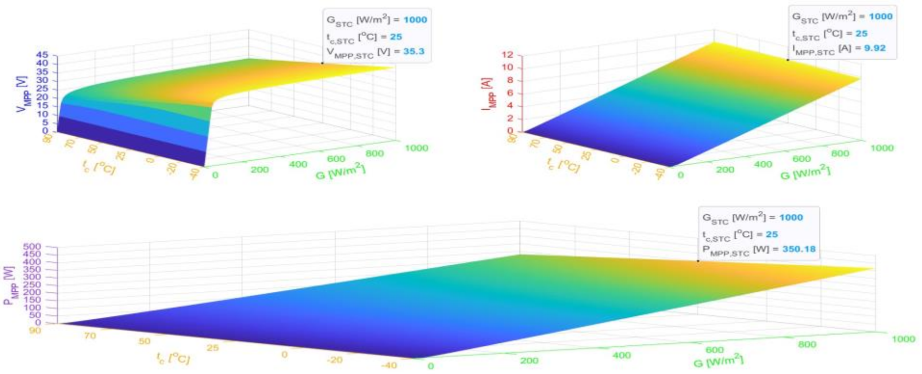

Fig. 5. MPP coordinates of the LG350N1C-V5 solar panel
(Voltage at MPP – top right / Current at MPP – top left / Maximum power – bottom)

Each figure within our study serves a specific purpose, collectively aimed at elucidating the intricate relationship between irradiance levels, and operating temperature, and how these two factors intricately impact the power generation capabilities of the reference solar panel. The first key insight derived from Fig. 3 and 5 is the clear trend that as irradiance levels increase, the maximum power output of the solar panel also increases. Furthermore, Fig. 4 and 5 highlight a contrasting trend with operating temperatures as they show that as the operating temperature of the solar panel increases, the maximum power output decreases. In practical terms, it means that solar panels tend to perform more efficiently when they are cooler and exposed to higher levels of irradiance.

4. Implementation of a maximum power point tracking algorithm

Achieving optimal performance in PV systems is a significant objective, and a key strategy to enhance their efficiency is to operate them as closely as possible to the MPP. The nonlinearity illustrated in Fig. 2, 3, and 4 manifests in the way both current and power output of the PV array are intrinsically intertwined with the operating voltage. Changes in voltage significantly impact the current and, consequently, the power output of the system. Therefore, pinpointing the precise operating point that maximizes power output requires a dynamic approach, one that adapts to varying conditions.

MPPT algorithms are essential in PV systems for optimizing the power output of solar panels. These algorithms can vary significantly based on factors such as speed, cost, and accuracy [16]. One advanced MPPT algorithm is the fuzzy logic control (FLC) method that can be considered highly effective due to its quick response to changing conditions, independence from specific system parameters, and robustness in handling nonlinearities and uncertainties. These attributes make it a powerful tool for optimizing the performance of PV systems under diverse and dynamic environmental conditions. The inputs to the FL controller are the error (E) and the change in error (CE), which help in adjusting the operating point to track the MPP (as presented in Table 4).

$$E(k) = \frac{\Delta P}{\Delta V} = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{4}$$

$$CE(k) = E(k) - E(k-1) \tag{5}$$

Table 4.

The rule table for FLC [16]

E/CE	PB	PM	PS	ZE	NS	NM	NB
PB	ZE	ZE	ZE	NB	NB	NB	NB
PM	ZE	ZE	ZE	NM	NM	NM	NM
PS	ZE	ZE	ZE	NS	NS	NM	NM
ZE	NS	NS	ZE	ZE	ZE	PS	PS
NS	PM	PM	PS	NS	ZE	PS	ZE
NM	PM	PM	PM	PB	ZE	ZE	NS
NB	PM	PM	PM	PB	ZE	ZE	ZE
NB = negative big				PB = pozitive big			
NM = negative medium				PB = pozitive medium			
NS = negative small				PB = pozitive small			
ZE = zero							

Implementing this MPPT algorithm in Matlab/Simulink via the fuzzy logic toolbox [17] enables the effective tracking of power output for the reference solar panel under varying irradiance and temperature conditions. The MPPT algorithm dynamically adjusts the operating point of the solar panel to ensure it consistently operates at or near its MPP. By doing so, the algorithm maximizes the energy harvested from the solar panel regardless of changes in environmental conditions.

Fig. 3 and 4 showcase the static PV characteristics of the reference solar panel. These figures provide a visualization of the panel's performance at different levels of irradiance and temperature without considering the dynamic changes that occur in real-world scenarios. However, to thoroughly evaluate the effectiveness of the MPPT algorithm, it is essential to consider scenarios where irradiance and temperature change rapidly. In real-world conditions, solar panels are subjected to fluctuating environmental factors such as passing clouds, shading, or sudden changes in ambient temperature. These conditions pose a significant challenge for maintaining optimal power output. The following scenarios presume rapid changes in irradiance and temperature to test the MPPT algorithm's performance. By simulating these rapid variations, we can assess how well the algorithm adapts to changing conditions and maintains the solar panel's operation at or near its MPP. This dynamic testing is imperative for validating the robustness and responsiveness of the MPPT algorithm, ensuring that it can effectively maximize energy in real-time applications despite environmental fluctuations.

The first scenario (illustrated in Fig. 6) presumes a rapid variation of irradiance, starting from 1000 W/m² and decreasing to 200 W/m², while the temperature stays constant at 25°C. This scenario is designed to test the MPPT algorithm's ability to handle swift changes in sunlight intensity. The second scenario presumes an increase in temperature, from 25°C to 65°C, while the irradiance stays constant at 1000 W/m². This scenario (illustrated in Fig. 7) is designed to test the MPPT algorithm’s ability to adapt to rapid changes in operating temperature, which can occur due to factors such as sudden changes in ambient conditions or heat dissipation issues.

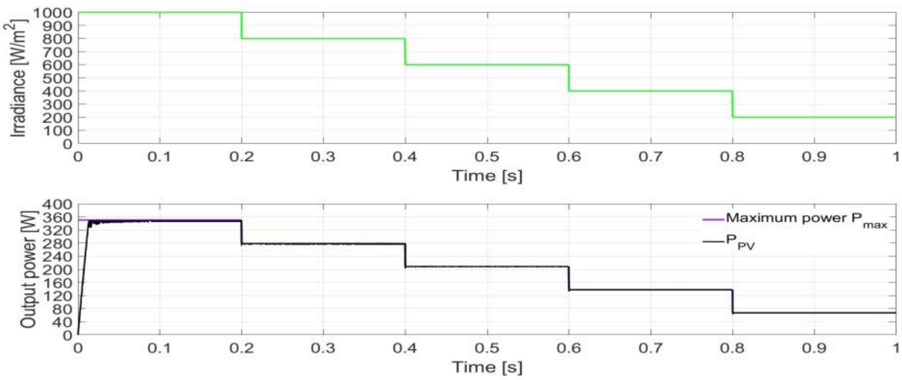

Fig. 6. Scenario 1 for MPPT – rapid irradiance decrease
(irradiance – top / maximum power – bottom)

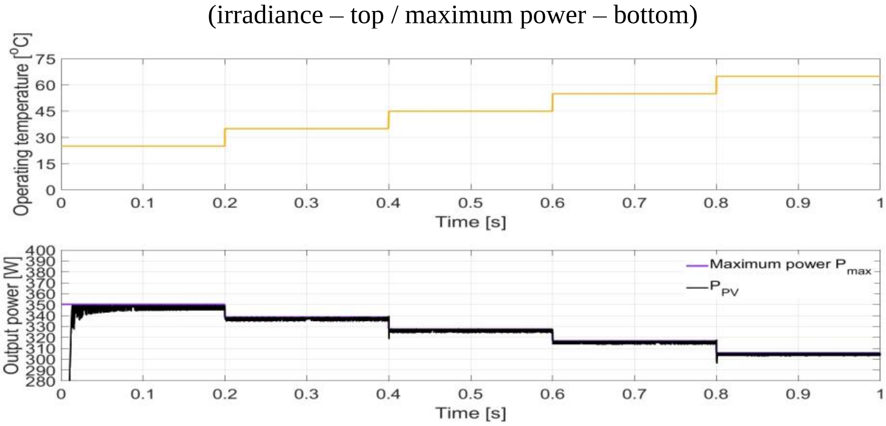

Fig. 7. Scenario 2 for MPPT – rapid temperature increase
(operating temperature – top / maximum power – bottom)

5. Conclusions

Achieving peak efficiency in PV systems is a complex and evolving challenge due to the intricate interplay of factors such as the nonlinear behavior of photovoltaic characteristics, which are highly dependent on external conditions like temperature and irradiation. Through Matlab/Simulink simulations, we have analyzed these influences and concluded that maintaining optimal performance in PV systems requires adaptive control strategies.

To ensure that the PV system consistently operates at/near maximum power, we’ve implemented a FLC MPPT algorithm. In both considered scenarios, the convergence of the output power to the maximum power attainable occurs within a remarkably short duration of half a cycle (0.01 seconds) and a mean MPPT efficiency of 99.67% indicating an efficient MPPT algorithm. This rapid alignment signifies that the algorithm swiftly detects and adjusts to changes in irradiance and temperature, ensuring that the solar panel operates at or near its MPP almost instantaneously. Such efficiency is fundamental for maximizing the energy harvest from the solar panel under dynamic environmental conditions, demonstrating the algorithm's effectiveness in optimizing power output with minimal loss and high responsiveness.

To enhance the reliability of these simulations, future research should integrate measured data, ensuring accurate representation of real-world conditions. Additionally, the research could extend to the integration of photovoltaic panels/arrays within the power grid, addressing challenges related to intermittency, grid stability, and optimizing the efficiency of power inverters. Lastly, although this study carried out refers to the case of a concrete panel, the conclusions obtained and the methodology implemented can be generalized for most types of photovoltaic panels on the market.

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