Comparative Analysis of MPPT Algorithms for PV Systems Under Partial Shading Conditions

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***Abstract*—This paper presents a performance comparison between two kind of maximum power point tracking (MPPT) algorithms for grid-connected photovoltaic (PV) systems under partial shading conditions, one based on conventional methods and the other on artificial intelligence. One of the MPPT algorithms is the Observe, Compare and Perturbed Method (OC&P) which corresponds to an improved version of the conventional Perturb and Observe (P&O) technique. The other algorithm is based on fuzzy logic. The objective of the algorithms is to track the global maximum power point in arrays of PV panels in series connection under the occurrence of partial shading, avoiding non-global maximums. Furthermore, a comparison with the traditional (P&O) technique is also presented. The algorithms performance is evaluated by simulations in MATLAB/Simulink considering a single-phase grid-connected PV system composed of two-stages (DC-DC and DC-AC converters); the MPPT algorithm is applied to the DC-DC converter. The algorithms are compared under the following criteria: convergence time to the point of global maximum power, maximum relative error in steady-state, and its efficiency. The results show that the fuzzy logic controller presents a faster respond to the global maximum power and smaller relative errors than the OC&P technique.**

***Keywords*—Photovoltaic systems, maximum power point trackers, partial shading, fuzzy logic.**

I. Introduction

Nowadays, photovoltaic (PV) technology is one of the fastest growing renewable energy sources in the global market. This technology is based on the conversion of solar irradiance directly to electrical energy through a PV generator which is formed by the interconnection of PV panels. Commercial PV generators exhibits low energy conversion efficiency and nonlinear characteristics between its power and output voltage. Furthermore, its characteristics curves depend on the irradiance and temperature conditions at which the PV generator operates. For certain weather conditions, a PV generator presents an operating point where it delivers the maximum power, called the Maximum Power Point (MPP). Therefore, it is important to ensure the operation of the PV generator in the MPP to achieve maximum efficiency [1].

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Accordingly, to maximize the PV delivered power under changing weather conditions, there are a variety of control techniques known as Maximum Power Point Tracking (MPPT) algorithms which vary in accordance to the complexity, number of sensors, convergence speed, implementation costs, between others [1]–[3]. Conventional MPPT algorithms are generally designed for uniform irradiance and temperature conditions, where the characteristic curve of the PV generator does not present several local MPP. However, under partial shading conditions, due to different factors as cloud cover, trees and buildings, the characteristic curves can present several local maximums and only a global MPP. Under these non-uniform conditions, the conventional MPPT can converge to a local maximum (non-global) in steady state, thus reducing energy production efficiency [2], [4].

To overcome the above disadvantages, there are different proposals focused on tracking the global MPP under partial shading conditions. Some of the proposals are modifications of traditional algorithms [3]–[6]. Others are based on artificial intelligence, such as Artificial Neuron Network and Fuzzy Logic [2], [7]–[10]. The last ones have shown a fast response to achieve the global MPP as a promising feature.

In accordance to the ideas described above, this paper presents a comparative analysis between two kind of MPPT algorithms under partial shading conditions. One of the algorithms is based on a modified version of the traditional Perturb and Observe (P&O) technique, and the other is based on artificial intelligence using fuzzy logic. Furthermore, comparisons of these two algorithms with the traditional (P&O) technique are also presented. The performance of the algorithms is evaluated in a single-phase grid-connected PV system through simulations in MATLAB/Simulink. There are considered as comparison criteria the convergence time to the point of global maximum power, the maximum relative error in steady-state, and the efficiency of the algorithms.

The organization of the paper is as follows. Section II presents a description of the grid-connected PV system and the inverter controllers. In section III, the MPPT algorithms are described. The simulation tests and results are shown in section IV. Finally, the main conclusions are presented.

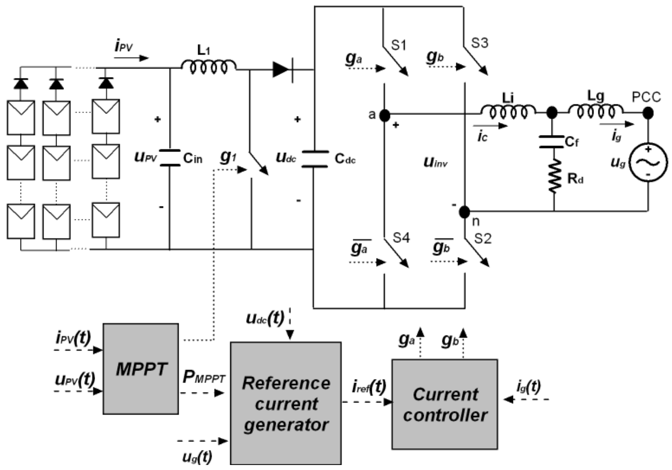

Fig. 1. General scheme of the grid-connected PV system. Source: Authors.

II. Grid-connected PV System

A grid-connected PV system is composed of the following stages: the PV generator, the power conditioning system, the grid-tied filter, and the control stage. A general scheme of this system is presented in Fig. 1, where the following assumptions are taken into account:

- It is considered a centralized architecture for the PV generator which is connected to a unique power conditioning system.
- The power conditioning system is composed of two stages: a DC-DC converter and a power inverter.
- The switching semiconductor devices are modeled as ideal switches.
- It is considered a third order damped LCL filter.
- The equivalent network at the point of common coupling (PCC) is modelled as a single-phase independent voltage source.

A. The PV generator

In a centralized architecture, the PV panels are connected in series forming strings. These strings are commonly protected by a blocking diode that prevents current flow from outside the generator into the string. The strings are interconnected in parallel with each other to form the PV generator (see Fig 1). Each PV panel includes one or more bypass diodes to provide an alternative path for the current under shading conditions. Bypass diodes are connected in anti-parallel with the sub-modules (groups of series cells) of the PV pannel as seen in Fig 2.

B. Power conditioning and control system

As seen in Fig. 1, the power conditioning system is composed of two stages. The first stage corresponds to a DC-DC boost converter. The second stage is the power inverter which topology corresponds to the full-bridge single-phase voltage source converter.

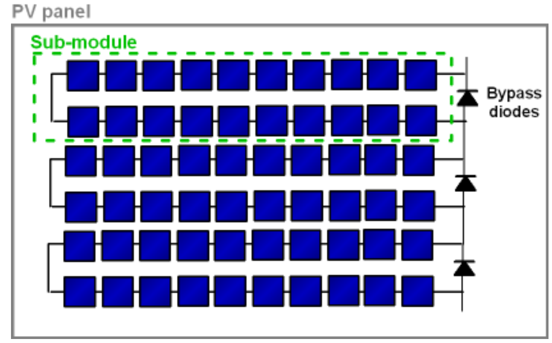

Fig. 2. Connection of bypass diodes in PV panels. Source: Authors.

Regarding its control system, it is composed of three loops (see Fig. 1): the MPPT algorithm, the reference signal generation, and the current controller. The MPPT algorithms control the DC-DC boost converter and they are presented in section III. The other two loops control the power inverter and they are described below.

1) Reference signal generation: This algorithm is based on the power definitions proposed by Fryze considering unit power factor [11]. The reference current i_{ref} is calculated as shown in (1), where u_g is the voltage at the PCC, U_{gRMS} is the RMS value of u_g, P^* is the reference power defined by (2), and P_{PV} is the active power delivered by the PV generator.

$$i_{ref} = \frac{P^* u_g}{U_{gRMS}^2} \tag{1}$$

$$P^* = P_{PV} - P_{dc} \tag{2}$$

To maintain the DC-link nominal voltage U_{dc}^*, P^* includes a corrective power P_{dc} whose value is obtained using the PI control described by equations (3) and (4), where K_p is the proportional gain of the PI and T_i represents the times this gain is being applied in the P_{dc} estimation.

$$P_{dc} = k_p e + \frac{k_p}{T_i}\int e dt \tag{3}$$

$$e = U_{dc}^* - u_{dc} \tag{4}$$

2) Current controller: A Proportional Resonant (PR) damped controller with a PMW technique is used to generate the pulses for the inverter in order that the injected current i_g follows i_{ref}, overcoming the delay response caused by the LCL filter. The gain of a PR damped controller is described by (5) [12], where ω_o is the resonance frequency and ω_c controls the bandwidth around ω_o to avoid stability problems due to an infinite gain.

$$G_{PR}(s) = k_{pr} + \frac{2k_i\omega_c s}{s^2 + 2\omega_c s + \omega_o^2} \tag{5}$$

In this work, ω_o is set as the fundamental grid frequency, ω_c is taking as 10% of ω_o, and the gains for the PR controller are determined applying the Routh Hurwitz stability criterion, obtaining $k_{pr} = 21.62$ and $k_i = 8408.7$.

III. Maximum Power Point Tracking (MPPT) Algorithms

The MPPT algorithms calculate the duty cycle of the DC-DC boost converter to ensure the operation of the PV generator at the MPP. Once the duty cycle is calculated, the firing pulses of the converter are synthesized using a PWM technique. The MPPT algorithms considered in this work are described below.

A. Perturb and Observe (P&O) technique

The P&O technique is one of the traditional algorithms used to track the MPP in PV generators. In this algorithm, the duty cycle (D) of the boost converter is perturbed (increase or decrease in a small quantity) for each iteration. After the execution of each perturbation, the voltage (u_{PV}) and power (P_{PV}) delivered by the PV generator are compared at the current iteration (instant k) with the previous one (instant $k-1$). In this way, depending of the changes in these two variables (du and dP), a duty cycle increase or decrease action is performed in the next iteration, as seen in the flowchart presented in Fig. 3; where U_r is a reference voltage used to modify the duty cycle, C is the perturbation step, and i_{PV} is the current delivered by the PV generator [4].

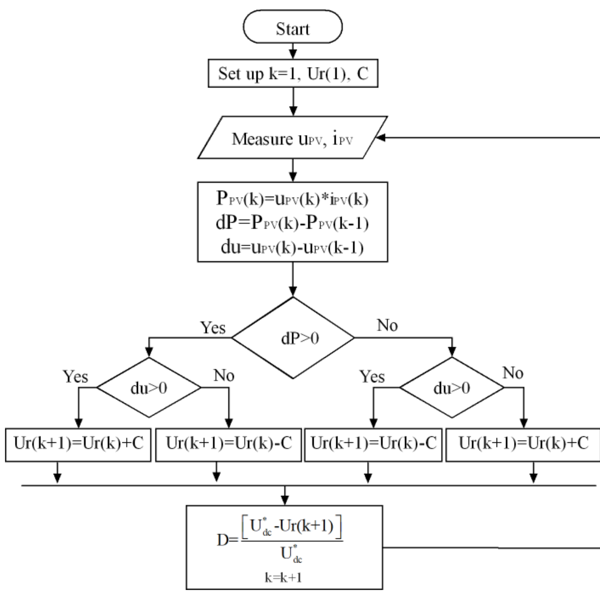

Fig. 3. Iterative process of the P&O algorithm. Source: Authors.

B. Observe, Compare and Perturbed Method (OC&P)

The OC&P technique is a modification of the traditional P&O algorithm. It was proposed in [4] to avoid the convergence to local maximums (non-global) and ensure the tracking of the global MPP under partial shading. In this technique, a previous process is performed before applying the P&O algorithm. This process is used to find an initial reference voltage in the region where the global MPP is located. Then, this resulting voltage $U_r(1)$ is the starting point for the P&O algorithm as seen in Fig. 4.

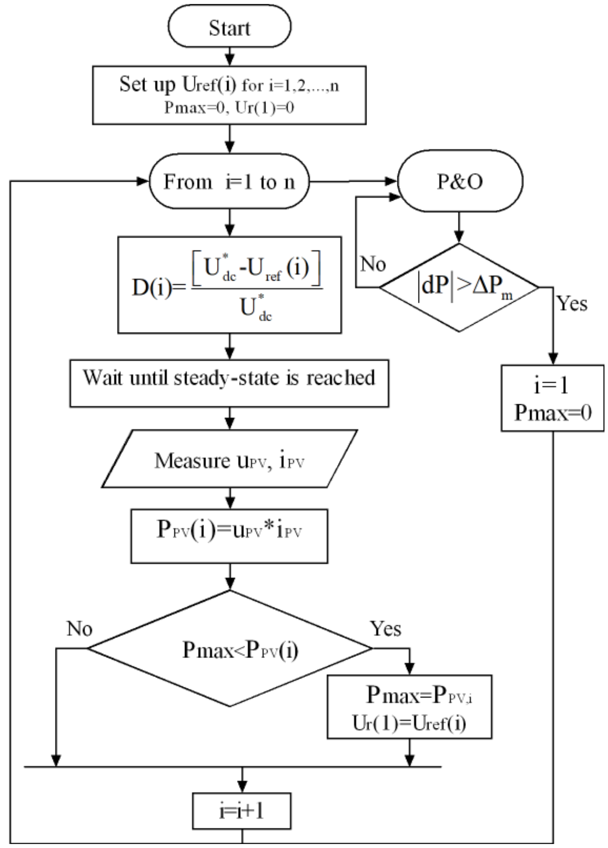

Fig. 4. Iterative process of the OC&P technique. Source: Authors.

The initial search process performs a comparison between the power delivered by the PV generator at different reference voltages previously established ($U_{ref}(i)$ for $i = 1, 2, ..., n$). These reference voltages are defined according to the number of PV panels in series connection in a string, the number of sub-modules per panel with their corresponding bypass diode, and the open circuit voltage of the PV generator. Through the comparison process, the reference voltage that leads to the highest power is selected as the starting point to the P&O, which is then applied to find the maximum global. Furthermore, as seen in Fig. 4, the algorithm restarts if there is a drastic change in the delivered power. A detailed information about this process can be found in [4].

C. Fuzzy Logic Controller

A single-input fuzzy logic controller is considered in this paper. The fuzzy logic controller design is based on the incremental conductancy method [13]. The input of the fuzzy logic controller is the ratio between the relative changes in the output power ΔP and voltage ΔV during the previous time interval. The output of the fuzzy controller is the relative change in the duty cycle ΔD. This output is integrated to obtain the duty cycle (D) as shown in Figure 5.

The rules of the fuzzy controller are obtained by analyzing the PV curve presented in Figure 6. This figure illustrates the variation of the sign of the dP/dV ratio at different positions on the PV curve. When the dP/dV ratio is positive, increasing the output of the PV generator requires increasing the voltage at the PV terminals. Considering the proposed configuration, this requires a reduction in the duty cycle. Similarly, when the dP/dV ratio is negative, the duty cycle should increase to increase the output power. For simulation purposes in this paper, the rules and membership functions are directly taken from [9].

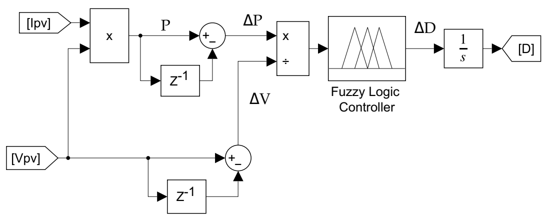

Fig. 5. Fuzzy logic controller structure. Source: Authors.

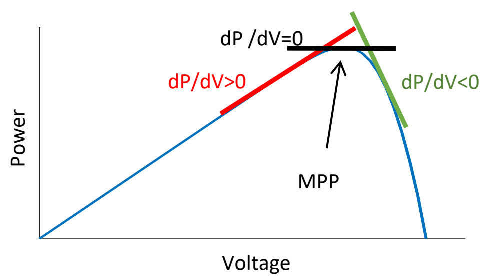

Fig. 6. Sign of the dP/dV at different positions on the PV curve [14].

IV. Simulation Test and Results

The performance of the MPPT algorithms is evaluated under partial shading conditions on the PV generator through simulations in MATLAB/Simulink. It is considered the single-phase grid-connected PV system shown in Fig. 1. The comparison criteria, test conditions, and simulation results are presented below.

A. Comparison criteria

The following criteria are considered to compare the performance of the MPPT algorithms:

- Convergence time: time required to reach the 95% of the final value of the power at the global MPP after the occurrence of a disturbance.
- Maximum relative error in steady-state between the power delivered by the PV generator (P_{PV}) and the power at the global MPP (P_{MPP}), as seen in equation (6).

$$\varepsilon = max\left(\frac{|P_{PV} - P_{MPP}|}{P_{MPP}}\right) \quad (6)$$

- The efficiency of the algorithm in steady-state according to equation (7).

$$\eta(t) = \frac{\int_{t_1}^{t} P_{PV}(\tau)d\tau}{\int_{t_1}^{t} P_{MPP}(\tau)d\tau} \quad (7)$$

B. Test conditions

The tests are carried out for a PV generator composed of four PV panels in series connection, forming a single string as seen in Fig. 7a. It is considered only one bypass diode per panel (one sub-module per panel).

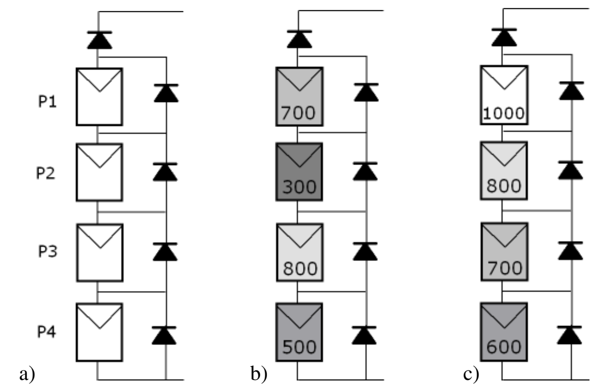

Fig. 7. PV generator and shading conditions for: a) $0 \leq t \leq 4$ [s], b) $4 < t \leq 6$ [s], and c) $6 < t \leq 8$ [s]. Source: Authors.

The parameters of the PV generator under standard test conditions -STC (irradiance of $1000\ W/m^2$, cell temperature of 25^oC, and AM 1.5) are presented in Table I. Additionally, the parameters of the grid-connected PV system (see Fig. 1) are also shown in this table.

TABLE I
Parameters of the PV Generator and Grid-Connected PV System

Parameter	Value
Power at the MPP under STC	1000 W
Voltage at the MPP under STC	120.4 V
Current at the MPP under STC	8.3 A
Input capacitor (C_{in})	10 μF
DC-link capacitor (C_{dc})	2200 μF
Filter capacitor (C_f)	9.2 μF
Filter damping resistor (R_d)	1.5 Ω
Boost converter inductor (L_1)	10 mH
Inverter side inductor (L_i)	3.7 mH
Grid side inductor (L_g)	180 μH
Grid voltage (u_g)	120 V_{rms} / 60 Hz
Switching frequency (f_s)	20 kHz
DC-link reference voltage (U_{dc}^*)	300 V

The algorithms are tested under three cases. The first case study corresponds to uniform irradiance conditions of $1000\ W/m^2$ in the time interval $0 \leq t \leq 4$ [s]. The other two cases consider partial shading conditions on the PV generator in the time intervals $4 < t \leq 6$ [s] and $6 < t \leq 8$ [s] as shown in Fig. 7b. and Fig. 7c, respectively. The irradiance conditions are described in Table II. In all cases a uniform cell temperature of 25^oC is considered.

Fig. 8 and Fig. 9 present the characteristic curve of the PV generator for the two cases of partial shading. As shown in these figures, the global MPP corresponds to $410.3\ W$ and $662.9\ W$ for the time intervals $4 < t \leq 6$ [s] and $6 < t \leq 8$ [s], respectively.

TABLE II
IRRADIANCE CONDITIONS ON THE PV PANELS FOR THE STUDY CASES

Panel	Case I $0 \leq t \leq 4$ [s]	Case II $4 < t \leq 6$	Case III $6 < t \leq 8$ [s]
P1	1000 W/m^2	700 W/m^2	1000 W/m^2
P2	1000 W/m^2	300 W/m^2	800 W/m^2
P3	1000 W/m^2	800 W/m^2	700 W/m^2
P4	1000 W/m^2	500 W/m^2	600 W/m^2

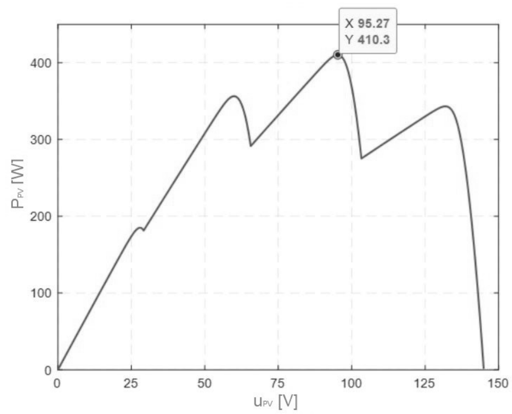

Fig. 8. Characteristic curve of the PV generator for $4 < t \leq 6$ [s]. Source: Authors.

C. Results

Simulation results for the traditional P&O technique, OC&P method, and fuzzy logic controller are presented in Fig. 10, Fig. 11, and Fig. 12, respectively. Each figure shows both the power delivered by the PV generator (blue line) and the power at the global MPP (red line) for the three study cases.

The initialization process of the system is carried out in the first case ($0 \leq t \leq 4$ $[s]$) considering zero initial conditions in $t = 0$ $[s]$. In case I, as seen in figures 10 to 12, all three algorithms reach the global MPP under uniform irradiance conditions. In this case, the fuzzy logic controller presents the slowest response in the tracking of the MPP with a convergence time of around 1.6 $[s]$, however this results only occurs in the startup process.

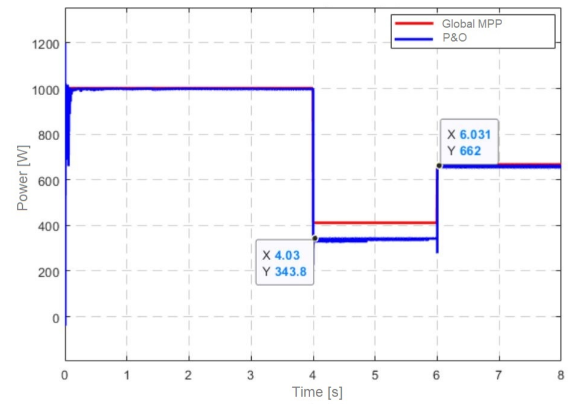

Fig. 10. Results for the traditional P&O technique. Source: Authors.

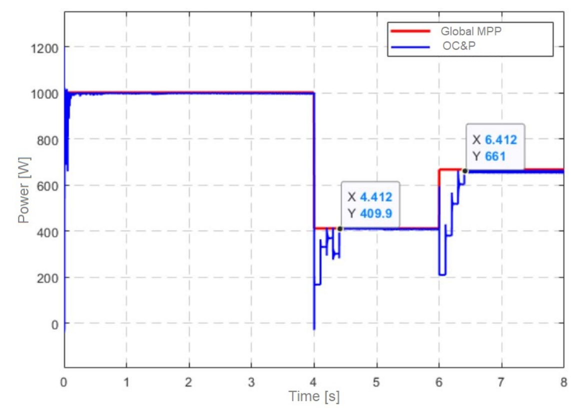

Fig. 11. Results for the OC&P technique. Source: Authors.

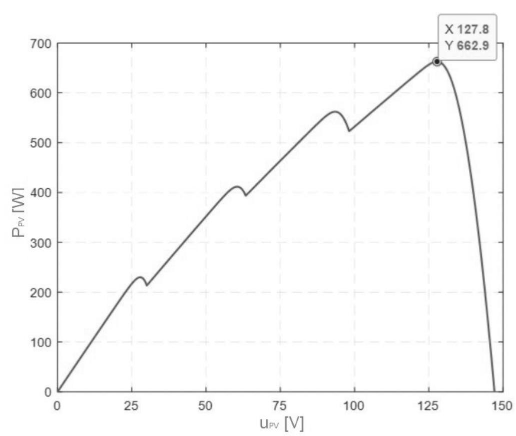

Fig. 9. Characteristic curve of the PV generator for $6 < t \leq 8$ [s]. Source: Authors.

In the second case ($4 < t \leq 6$ [s]), the traditional P&O technique converges towards a non-global maximum, so the PV generator delivers 343.8 W instead of the global maximum power which corresponds to 410.3 W, as seen in Fig. 10. On the other hand, the OC&P method and fuzzy logic controller reach the global MPP under partial shading conditions. In this case, the fuzzy logic controller presents the fastest respond with a convergence time of around 0.03 $[s]$. The convergence time for the OC&P method is around 0.41 $[s]$ due to the initial search process performed by this technique in order to avoid convergence to non-global maximums.

For comparison purposes, table III presents the results of the comparison criteria for the OC&P method and fuzzy logic controller for case II. As seen, the fuzzy logic controller presents the fastest responds and the lowest relative error in steady-state. On the other hand, both algorithms present a efficiency above 95%.

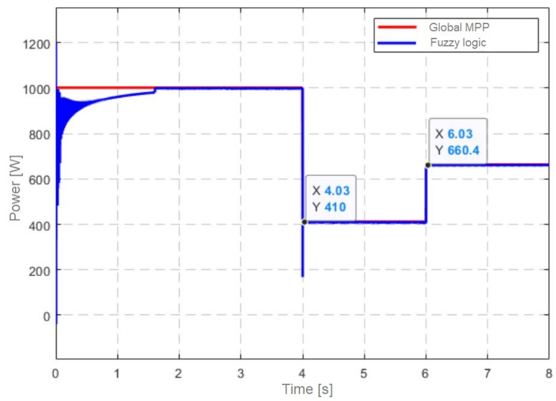

Fig. 12. Results for the fuzzy logic controller. Source: Authors.

Finally in case III ($6 < t \leq 8$ [s]), the three algorithm reach the global MPP under partial shading conditions. The convergence times for the P&O, OC&P, and fuzzy logic controllers are around 0.03 $[s]$, 0.41 $[s]$, and 0.03 $[s]$, respectively. In this case, the good results for the traditional P&O technique are due to the initial value for reference voltage (U_r) which was taken near to the open circuit voltage of the PV generator so it was also near to the global maximum, otherwise it may converge to a non-global maximum.

TABLE III
RESULTS FOR THE COMPARISON CRITERIA - CASE II

Technique	**Convergence time** [s]	**Relative error** [%]	**Efficiency** [%]
OC&P	0,412	0,509	above 95
Fuzzy logic	0,03	0,178	above 95

V. CONCLUSION

A comparative analysis between different kind of MPPT algorithms was presented in this paper. The performance of the algorithms was tested under uniform irradiance and partial shading conditions in the PV generator. Simulation results showed that the traditional P&O technique may converge to non-global maximums under partial shading conditions, which depends on the initial reference voltage value and the location of the global maximum.

On the other hand, the OC&P method and fuzzy logic controller presented an outstanding performance on the tracking of the global maximum under different cases of partial shading conditions with an efficiency above the 95% in steady-state. Between these two algorithms, the fuzzy logic controller presented a faster respond to the global maximum power and smaller relative errors than the OC&P technique once the system has already been initialized. It is important to clarify that the fuzzy logic controller requires a previous algorithm that provides the most suitable ranges for the membership functions, otherwise it could lead to local maximums. Regarding the OC&P method, it presented a convergence time less to 0.5 $[s]$, which is feasible for this application. However, this algorithm requires prior knowledge of the number of PV panels in series connection in the PV generator and the number of sub-modules per panel with bypass diodes.

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