# Practical Performance Evaluation of Maximum Power Point Tracking Algorithms in A Photovoltaic System

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**ABSTRACT**

This paper addresses a performance evaluation of maximum power point tracking techniques (MPPT) in a photovoltaic system. This research work finds its applications in photovoltaic systems producing electric power with a better energy efficiency, which will lead to an improved relationship between the cost and the amount of the produced power. The importance of this work resides on the one hand in the evaluation of the performances of the different MPPTs according to three criteria instead of one or two criteria in other works of the literature and on the other hand in the study of Four algorithms in one paper and their comparisons. This paper discusses the performance evaluation of the MPPT algorithms called P&O, Inc-Cond, Hill-Climbing and Fuzzy algorithms based simulation results and practical validation. The performances of these algorithms are evaluated according to the following criteria: The response time, the amplitude of the oscillations around the optimal point and the accuracy. The objectives in this article are summarized in the following points: (a) modeling the photovoltaic systems, (b) presenting and detailing each MPPT algorithm (c) pressenting and discussing the simulation results in Matlab/Simulink and practical validation (d) evaluating the performance of each algorithm. This paper is completed by a summary on the areas of use for each algorithm and conclusions.



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## 1. INTRODUCTION

Actually, the production of electric power from renewable energy is among the most recommended solutions non-polluting energy source. These solutions have many advantages. On the one hand, these sources allow the preservation of the environment, as they are eco-friendly. On the other hand, the use of these sources is related to the production competing with fossil sources. For the production of electric power from renewable resources, recourse to sources for basic photovoltaic energy is essential, however, the power supplied by a solar panel is related to three parameters: irradiation, temperature and the load. hence, PV systems suffer from relatively low conversion efficiency. To maximize the output power of PV array and to continuously track the maximum power point (MPP), several MPPT algorithms are proposed in the literature; Comparing the performance of these techniques seems a very interesting spot to determine which one is most suitable and efficient for a given PV system. Numerous works have addressed the comparison of MPPT algorithms. In some papers, this comparison is generally limited to a theoretical study and lacks of practical implementation [1]-[2]. Other articles have compared different MPPT by choosing a few criteria related to the algorithms performance regardless the response time or the convergence rate of MPPT.

In this paper, we study the performance evaluation of some MPPT algorithms. The evaluation is based on criteria related to response time, accuracy, oscillation around MPP and Simplicity of implementation. Throughout this work, each algorithm is presented and explained and a theoretical validation is established in Matlab/Simulink. The experimental validation of the proposed algorithms with a performances comparison are given at the end of this paper. This assessment will be beneficial to researchers and practitioners in PV systems given that it can serve as a suitable reference for selection, understanding different ways and means of MPPT. The rest of the paper is organized as follows. While section 2 deals mainly with the modeling of the studied photovoltaic system, a presentation of each algorithm is detailed in Section 3. Simulation results are presented with comments in Section 4. Section 5 is devoted to practical validation and results with application areas of each MPPT algorithm. Section 6 presents the conclusions drawn from this study.

## 2. RESEARCH METHOD

The power circuit consists of a PV array module, dc-to-dc boost converter and a load as shown in Figure 1. The boost chopper is the circuit that adjusts the power extracted in the power demanded by the load. It allows operation at maximum power of photovoltaic panel [3]-[4].

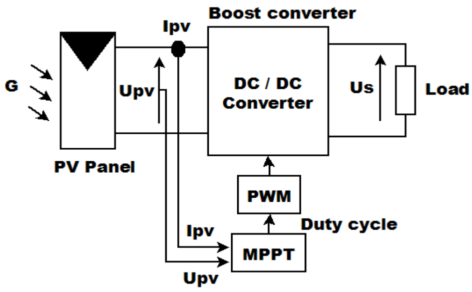



Figure 1. Photovoltaic power circuit

### 2.1. PV model

The equivalent model of a solar panel consists of a current source that depends on the solar irradiation in parallel with a diode and two resistors, the first in the series and the second is a parallel which represent the internal joule losses [5]-[7]. The equivalent-circuit model of PV is illustrated in Figure 2.

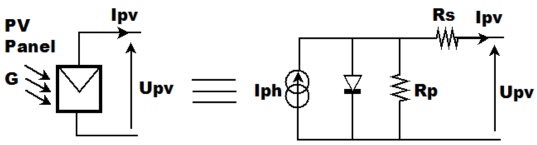



Figure 2. Equivalent model of the PV panel

Using the equivalent model of the PV panel (Figure 2, the photovoltaic current is expressed as a function of the voltage by the following relation:

$$I_{pv} = I_{ph} - I_{sat}\left(\frac{U_{pv} + R_s I_{pv}}{\frac{k.T.A}{q}} - 1\right) - \frac{U_{pv} + R_s I_{pv}}{R_p} \quad (1)$$

Where Iph is the PV output current (A), Upv is the PV output voltage (V), q is the charge of an electron, k is Boltzmann’s constant in J/K, A is the p–n junction ideality factor, T is the cell temperature (K), and Isat is the reverse saturation current.

### 3.1. BOOST model

The dynamics model of the adaptation circuit illustrated in Figure 3 is expressed by the following equations:

$$\frac{U_s}{r_c} - \frac{U_c}{r_c} = (1-u).I_L - I_s \tag{2}$$

$$L.\dot{I}_L + r.I_L = U_{pv} - (1-u).U_s \tag{3}$$

Where $L$ and $I_L$ represents the storage inductance and the current across it, Us is the output voltage and $u$ is the control signal.

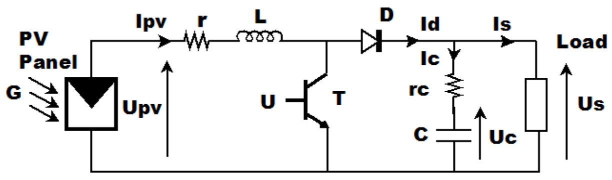



Figure 3. Photovoltaic system

The minimum inductance is calculated from the maximum permissible ripple of the current IL. It is expressed by the following relation:

$$L_{min} = \frac{U_{pv}.\alpha}{f_s.\Delta I_{L\_max}} \tag{4}$$

Where Upv is input voltage, D is a duty cycle, fs is a switching frequency of the converter and L is a selected inductor value. The minimum capacitor is calculated from the maximum permissible ripple of the output voltage. It is expressed by the following relation:

$$C_{min} = \frac{I_s.\alpha}{f_s.\Delta U_{s\_max}} \tag{5}$$

## 3. PROBLEM OVERVIEW

As illustrated in Figure 4, the power characteristic of a photovoltaic module shows that the power is maximum according to value of irradiation or temperature at a determined point of the curve. Called MPP (maximum power point), this point is characterized by an extraction of the maximum power of the PV module is a single point of the power curve. To operate the photovoltaic generator at this point, it is necessary to use an algorithm called MPPT (maximum power point tracking) whose function is to collect the variations in current and voltage to determine the MPP. Then, the control unit produces the adequate duty cycle to the power converter to operate the PV module at the MPP. This process continues to search the MPP since the weather can change. Which implies that the optimal point moves whenever there is a change in temperature or irradiation.

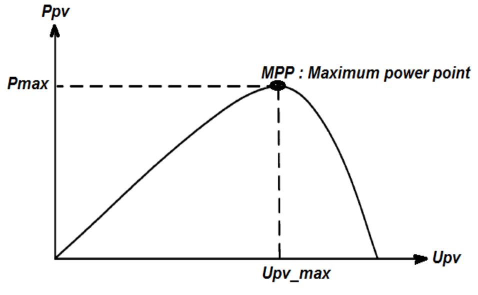



Figure. 4. Power curve of PV panel

## 4. MAXIMUM POWER POINT TRACKING (MPPT) ALGORITHMS

To determine the maximum power point, several algorithms are discussed in the literature. This paper study is limited to P&O, Inc-Cond, fuzzy and Hill-climbing MPPT algorithms.

### 4.1. Hill climbing

The principle of the algorithm called Hill climbing is illustrated in Figure 5. This algorithm is based on the continuous-measuring variations in the power of the PV module and increase or decrease the duty ratio according to this change. If the power change is positive, which implies that the optimum point is right working point. In this case, the control unit adjusts the duty cycle to increase the voltage of the photovoltaic module. If the change in power is negative, which implies that the optimum point is to the left of the operating point. In this case, the control adjusts the duty cycle to decrease the voltage of the photovoltaic module. When the system finds the optimal point, it oscillates around that point. To minimize these oscillations, the control unit must use a variable step to adjust the duty cycle [8]-[9].

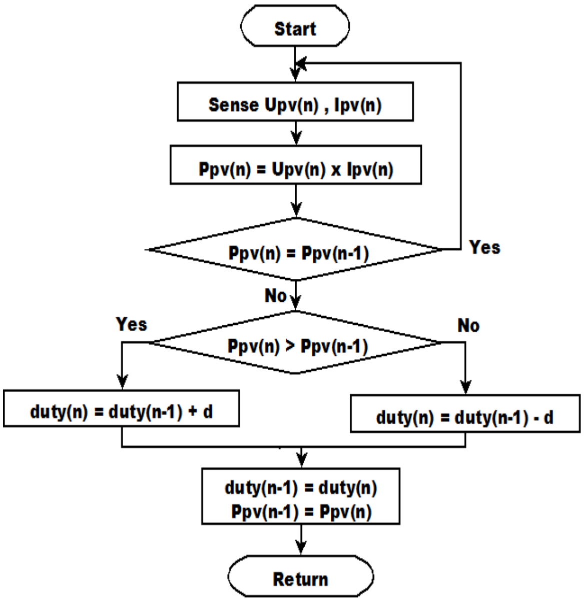



Figure 5. The flowchart of hill climbing algorithm

### 4.2. P&O (perturb and observ)

The principle of the P&O algorithm is illustrated in Figure 6. This MPPT algorithm is based on the continuous-measuring variations in the power and voltage of the PV module. If the power change is positive and the voltage change is positive which implies that the optimal point is right of the operating point. Then the reference voltage is adjusted to coincide with the optimum point. If the power change is negative and the voltage change is positive which implies that the optimal point is left of the operating point. In this case, the reference voltage is adjusted to the optimum point. Once the reference voltage that corresponds to the optimal point is found, the control unit regulates the PV voltage by adjusting the duty cycle. This process is repeated continuously according to temperature or radiation change which has repercussions on the position of the MPP. When the MPPT algorithm finds the optimal point, it oscillates around it. To minimize these oscillations, It is necessary to use a variable step size to adjust the voltage reference [10]-[11].

### 4.3. Incremental conductance

The MPPT algorithm called Inc-Cond is based on the calculation of the conductance that is defined by the current change divided by the voltage change. If the conductance is greater than the ratio (-Ipv / Upv) implies that the optimal point is to the left of the operating point otherwise the optimal point is to the right. When the conductance and the term (-Ipv / Upv) are equal, the system operates at the optimal point. The control must maintain this operation until the detection of a change in climatic conditions. Figure 7 summarizes the principle of the Inc-Cond MPPT algorithm [12]-[13].

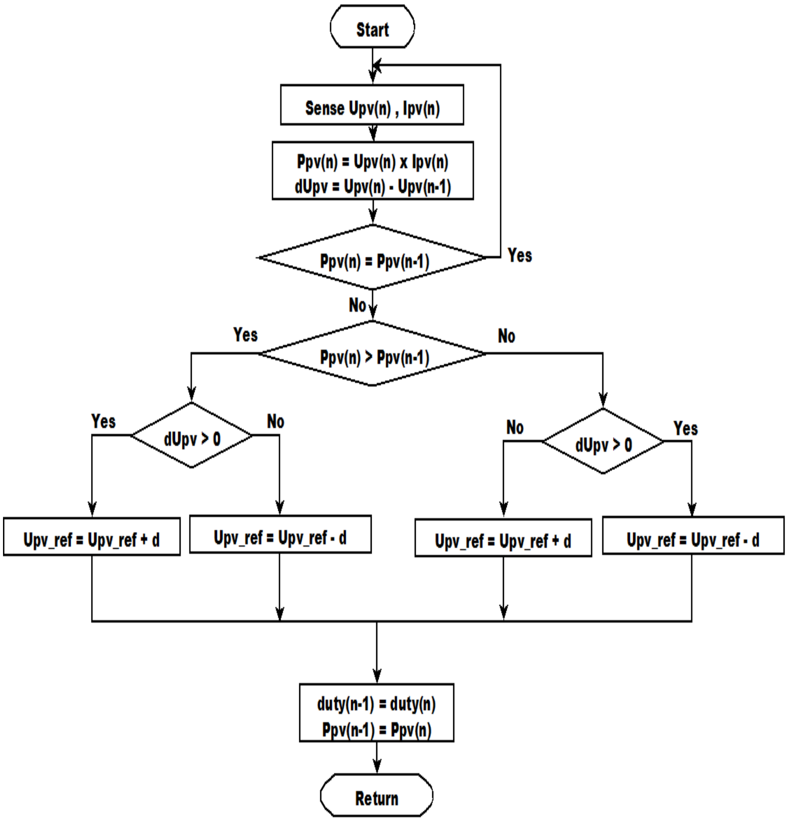



Figure 6. The flowchart of P&O algorithm

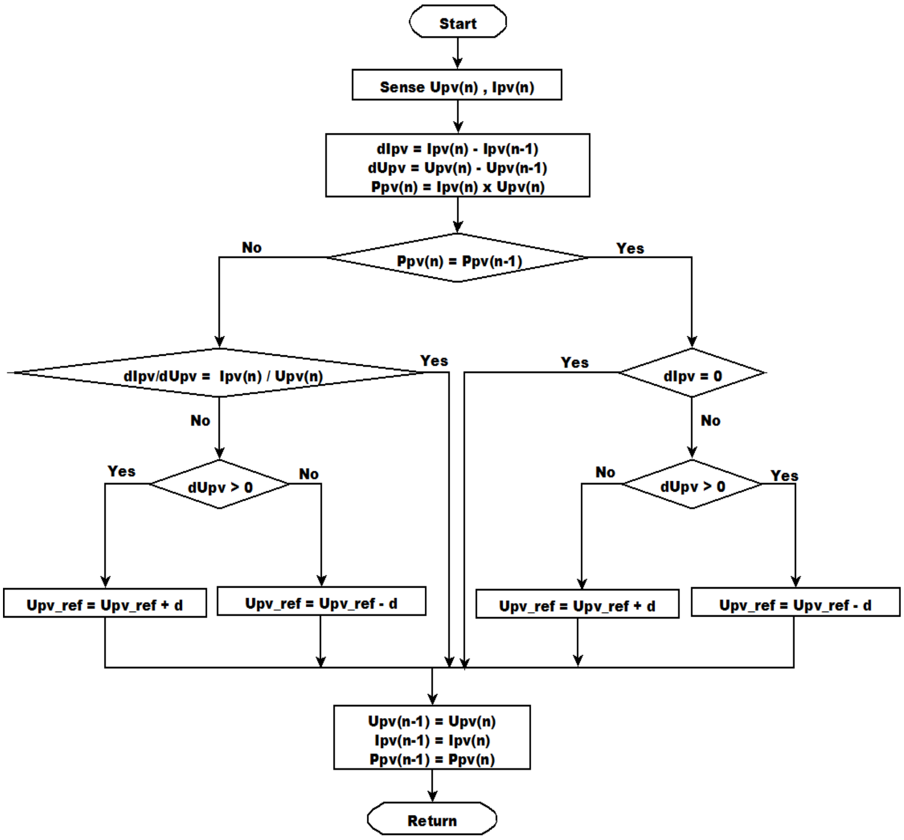



Figure. 7. The flowchart of Inc-cond algorithm

### 4.4. Fuzzy logic MPPT

This MPPT algorithm is based on the Fuzzy logical theory. The Fuzzy MPPT consists of three internal steps: fuzzification, inference and difuzzification. The input variables are the error and the error change. These variables are defined according to the equation 3 and equation 4 respectively. The input variables are converted in the fuzzification stage of a digital form to a language form. A membership function is set up to perform the fuzzification of the inputs. The Fuzzy controller determines from rule table what adjustment should be done on the duty cycle. The output of Fuzzy-MPPT is the duty change dα variable that represents the change need to perform on the duty cycle [14]-[15]. Equations 3 and 4 describe the input variables of the fuzzy MPPT. Figure 8 shows how to choose membership functions in a fuzzy MPPT algorithm.

$$e(n) = \frac{p_{pv}(n) - p_{pv}(n-1)}{u_{pv}(n) - u_{pv}(n-1)} \tag{3}$$

$$de(n) = e(n) - e(n-1) \tag{4}$$

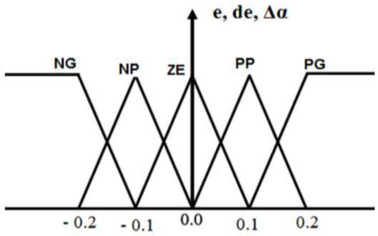



Figure 8. The membership functions

## 5. SIMULATION RESULTS

The model of photovoltaic module, power boost converter model and the MPPT algorithm are implemented in Matlab/Simulink. In this study, the PV panel provide a maximum power of 1 KW. The PV module is based on RSM-60 that deliver a maximum power of 60 Watts. The specification of the control parameters and the main characteristics of the PV module are summarized in Table 1 and Table 2 respectively. Our goal is to evaluate the performance of the MPPT algorithms. In this context, the PV power system is subject to an echelon of solar irradiation. The evaluation is based on the response time, accuracy and the oscillations around the optimal point. In the simulation test, the temperature is kept equal to 25 °C. Figure 9 shows simulation results in response to a step change of irradiation of 500 to 1000W/m$^2$ as shown in Figure 9.a

Figure 9.b illustrates the response of the photovoltaic system in case of the P&O algorithm. It seen that the PV voltage reaches the optimum point after 0.2 second. Once the optimum point is found, the algorithm performs oscillations around the MPP whose amplitude does not exceed 1 volt. When applying of the irradiation step change, the MPPT algorithm finds the new optimal point after 0.001 second and continues to oscillate around this point. Other algorithms are validated under the same conditions mentioned above. Figure 9.c, Figure 9.d and Figure 9.e show the response of the PV system in case of Hill-climbing, Fuzzy and Inc-Cond MPPT.

Table 1. Control Parameters Used in the Simulation

| Parameters | Value | Unit |
|---|---|---|
| $R_L$ | 10 | Ω |
| $c_1$ | 2 | µF |
| $c_2$ | 4700 | µF |
| L | 0.002 | H |

Table 2. Main Characteristics of the PV Panel

| | | |
|---|---|---|
| Maximum power | $P_{max}$ | 60W |
| Maximum power | $V_{max}$ | 16V |
| Output voltage at Pmax | $V_{oc}$ | 21.5V |
| Open-circuit voltage | $I_{cc}$ | 3.8A |
| Short circuit | $P_{max}$ | 60W |

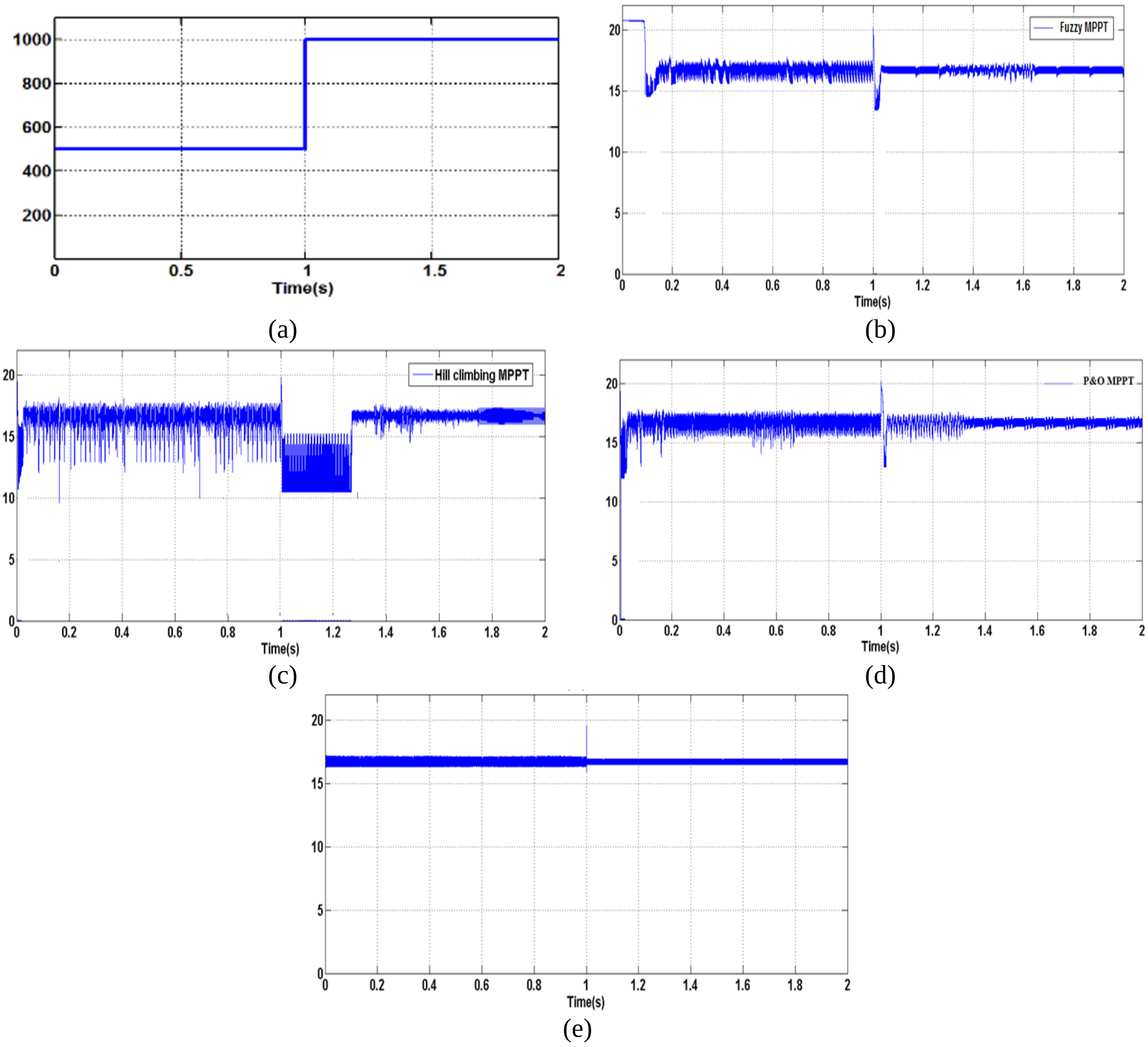



Figure 9. (a) Step irradiance, (b) Fuzzy, (c) Hill Climbing, (d) P&O, (e) IncCond

The evaluation of the performances of the studied MPPT algorithms is performed in case of a high and low irradiation. The criteria are the response time, accuracy and the amplitude of the oscillation around the optimum point. In the case of high irradiation (Figure 10, Figure 11 and Figure 12), the oscillations around the MPP in the Fuzzy and Inc-Cond MPPT are small compared to P&O and Hill-climbing MPPT while the response time of P&O, Inc-Cond and Hill-Climbing MPPT is a better than Fuzzy MPPT. According to Figure 12, the error from the theoretical value in Inc-Cond algorithm is important compared to the others algorithms. In the case of low irradiation (Figure13, Figure 14 and Figure 15) the same remarks are recorded.

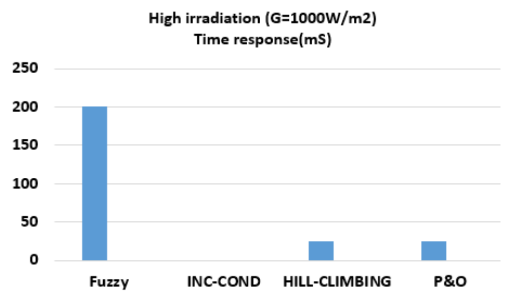



Figure 10 . Comparative graph of time response (mS)

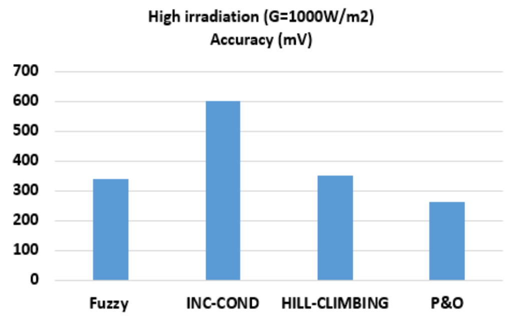



Figure 11 . Comparative graph of accuracy (mV)

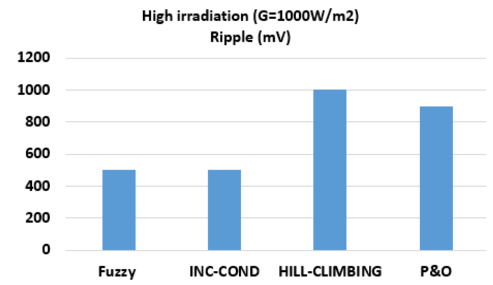



Figure 12 . Comparative graph of ripple (mV)

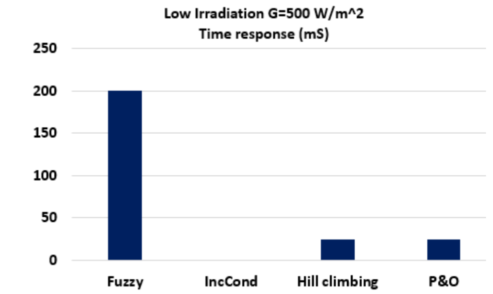



Figure 13 . Comparative graph of time response (mS)

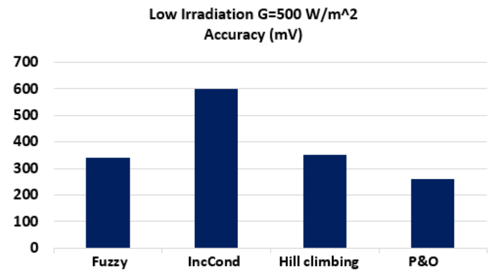



Figure 14 . Comparative graph of accuracy (mV)

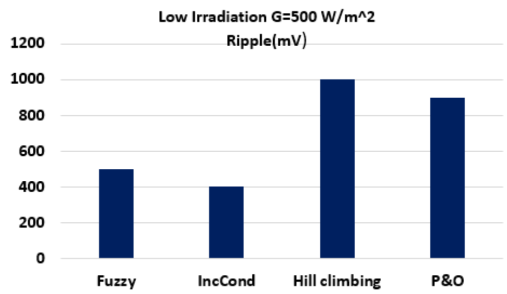
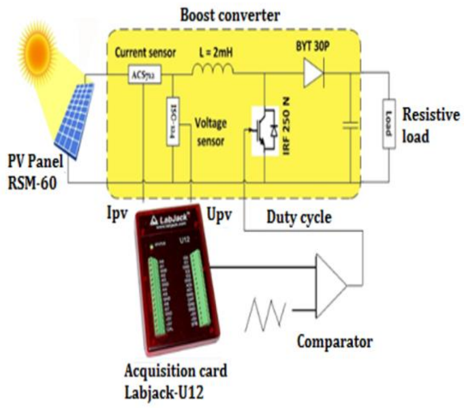


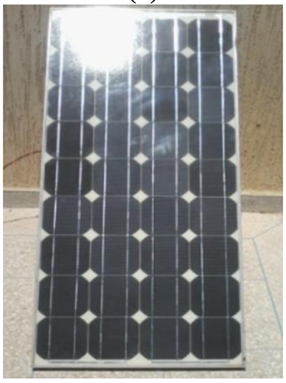

Figure 15 . Comparative graph of ripple (mV)




(a)

(b)

(c)



(d)

Figure 16. Practical implementation, (a) Boost control across Labjack U12 Card, (b) Boost converter card, (c) PWM Card, (d) RSM-60 PV Panel

## 6. PRACTICAL VALIDATION

The evaluation in the simulation phase remains insufficient because the simulation study are performed based on many simplifications in the model and several parameters are overlooked. Include for example, the time of acquisition of current and voltage sensors, the internal resistor of the coil, the switching time of the MOSFET and the acquisition time of the command card. To develop a performance evaluation with a better precision, the boost chopper and the current and voltage sensors of a PV panel are experimentally realized. The MPPT algorithms are implemented in Matlab/ Simulink. The Figure 16 shows the diagram of the practical validation. A Labjack-U12 card is used as an interface for the acquisition through the analog to digital conversion of PV current and voltage. This card is characterized by a 12-bit resolution and a possibility of conversion of 8 analog channels. To measure the PV current and voltage, the ACS712 and ISO-124 are used. To modulate the duty cycle a PWM card is realized. The frequency of the PWM control is set to 20KHZ and the step size is equal to 0.01. To ensure decoupage function in the switching power converter, the IRF250 MOSFET is used. The power switch is characterized by a maximum current of 30Amps and supports a voltage equal to 200 Volts. The MPPT algorithms are implemented in Matlab/Simulink. Good knowledge of optimum point requires knowledge of the panel power curve. The first step is to identify the power curve of the photovoltaic panel. Figure 17-19 show the power curves plotted for various irradiations. In terms of practical tests, the measured temperature is almost constant equal to 30 °C.

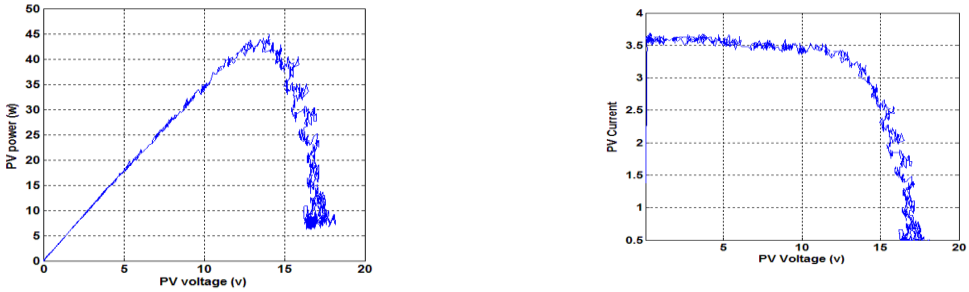



Figure 17. Practical identification of the power curve and the current-voltage characteristic of the PV module in climatic conditions ( G = 700W/m$^2$ and T = 30°C )

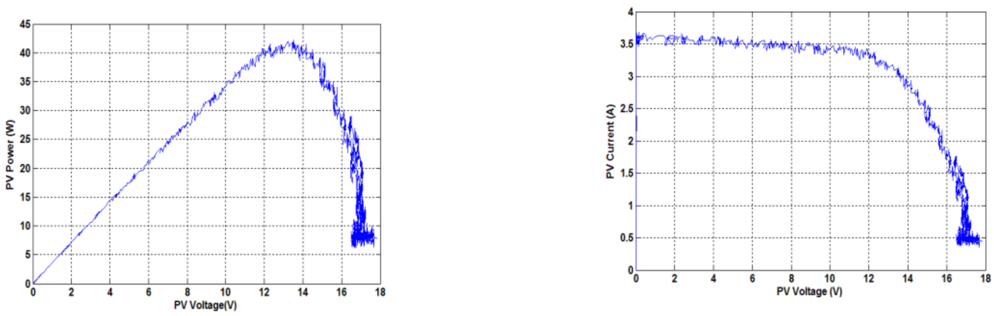



Figure 18 Practical identification of the power curve and the current-voltage characteristic of the PV module in climatic conditions ( G = 650W/m$^2$ and T = 31°C )

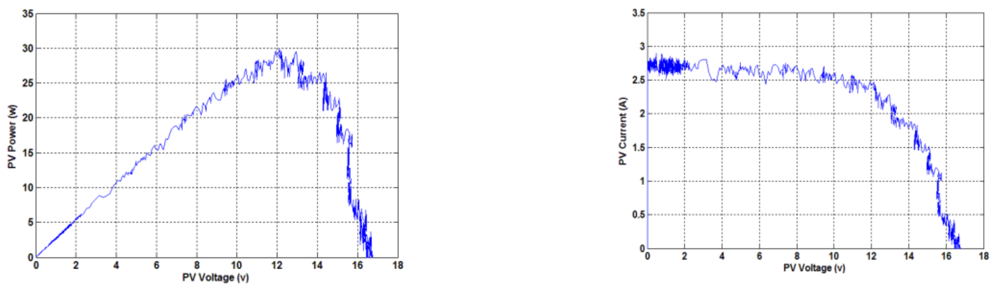



Figure 19. Practical identification of the power curve and the current-voltage characteristic of the PV module in climatic conditions ( G = 460W/m$^2$ and T = 30°C )

Practical validation is conducted at three levels of solar irradiation. According to the power curve illustrated in Figure 17-19, the maximum power point (MPP) is strongly dependent on the irradiation level and moves with each change of the light intensity. At the time of practical validation of P&O algorithm, solar irradiation was about 700W/m$^2$ and a temperature is 30 °C. Figure 20-23 shows the power of PV module, the PV voltage and the load voltage according to the time change. In the previously mentioned weather conditions, it finds that the average PV power is 44 watts and the PV voltage performs oscillation around 13 Volts. The amplitude of the oscillations is 2 volts. It can be noticed that the PV voltage reaches the MPP after 2 seconds according to Figure 20.b. Based on the power curve given in Figure 17, the optimal point is characterized by a voltage of 13 volts and a power of 44 Watts, which coincides with the identification power curve under the same test conditions. Hence, it can be concluded that the optimal point is found and the P&O algorithm is validated.

The next step is to validate the Hill-Climbing algorithm. According to Figure 21, the measured irradiation is equal to 600 Watts/m$^2$. The measured voltage is 15 Volts and the average power is equal to 37.5 Watts. It is found that the PV voltage reaches the optimal value in less than 1 second and oscillates around the MPP with an average amplitude of 0.5 Volt. These results show that the Hill-climbing algorithm tracks the MPP. In the following test, the Fuzzy MPPT algorithm is validated. The climatic conditions are characterized by a sudden transition of the irradiation from 600Watts/m2 to 680Watt/m2. The step change is a challenge which shows the ability of the MPPT algorithm to track the MPP. According to Figure 22, it is found that the measured value of the voltage is equal to 15.2 Volts and the power value is equal to 36 Watts and passes to 42Watts at time t=115 Seconds.

Based on Figure 22, the PV voltage reaches the desired value after 10 Seconds. It can be noticed that the Fuzzy MPPT algorithm is able to find quickly the new optimal point in 5 seconds. When the system finds the MPP it remains there and oscillates around the MPP with an amplitude of 0.5 Volt. The practical validation results of the Inc-Cond MPPT algorithm are illustrated in Figure 23. The PV system is exposed to irradiation change from 600 Watts/m$^2$ to 900 Watts/m$^2$. At the MPP, the PV voltage reaches the corresponding value of 14 Volts in a 1 Second. The results given by Figure 23 demonstrate that the Inc-Cond MPPT is able to find the optimum point.

Logically, the practical results do not allow to judge which of these approaches is the best. Each MPPT algorithm has different performance than the other one. It was found that the conventional MPPT (P&O and Hill-climbing) are efficient to search the MPP even in the presence of the most important oscillations than the others MPPT algorithms. If the oscillations are disadvantages, the P&O and Inc-Cond algorithms are easy and simple to implement practically. It is important to note that the response time and the oscillations of the P&O and Inc-Cond algorithms are greater than the others MPPT algorithms. There is a compromise between response time and the oscillations around the MPP. The MPPT algorithm based on Fuzzy logic takes a longer time to find the optimal point but has smaller oscillations. In addition, this approach presents a more complicated algorithm and very difficult in its implementation. The Inc-Cond MPPT algorithm is simple in its implementation and has smaller oscillations around MPP but finds difficult to carry out requested equal.

According to this comparative study, the application areas of the proposed MPPT algorithms are as follows:

a. In the fields of satellites space, looking for maximum power point must be as shortest time as possible. It is interesting in this context to use the P&O techniques, RCC algorithm or Hill-climbing approach.
b. In the solar vehicles applications, looking for maximum point must be efficient. It is recommended to use the MPPT based on fuzzy logic.
c. The field of public lighting with solar power, the battery must be charged during the day to work the night. A less complex MPPT eg Hill Climbing or P&O or others techniques discussed in the literature will be more suitable.

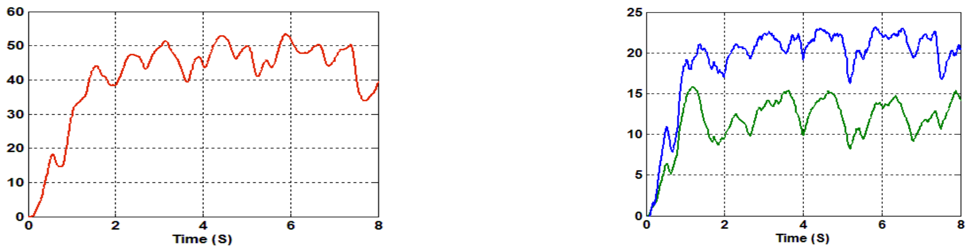



Figure 20 Practical validation results of the P&O MPPT, (a) PV power (b) PV voltage and output voltage

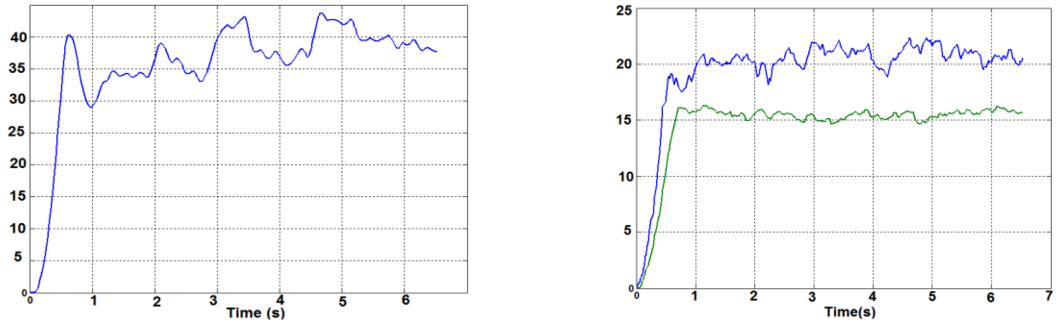



Figure 21 Practical validation results of the Hill-Climbing MPPT
(a) PV power (b) PV voltage and output voltage

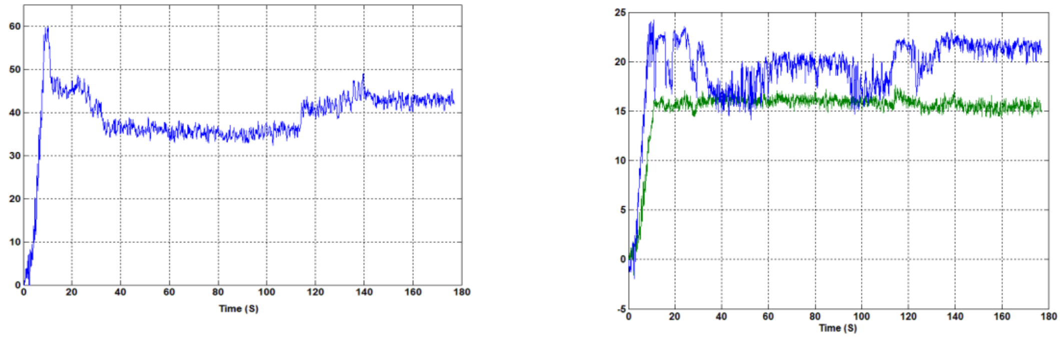



Figure 22 Practical validation results of the Fuzzy MPPT,
(a) PV power (b) PV voltage and output voltage

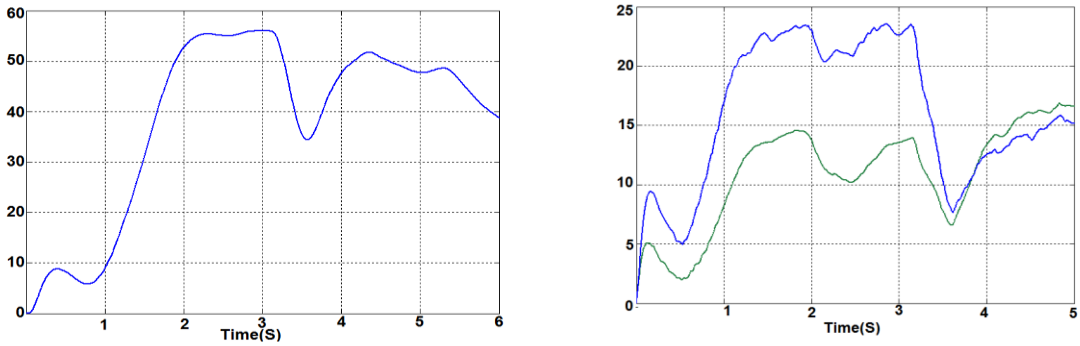



Figure 23 Practical validation results of the Inc-Cond MPPT,
(a) PV power (b) PV voltage and output voltage

## 7. CONCLUSION

According to the simulation results and practical validations, the P&O and Hill-Climbing MPPT allow the tracking of maximum power point but have a greater amplitude of the oscillations around MPP than the other methods. This oscillation constitutes a disadvantage since the grid connected PV system will pollute the electrical grid by the injection of the harmonics of greater amplitudes. The method based on the fuzzy logic has a more interesting precision than the other approaches. This method can be integrated into applications aimed at injecting the extracted energy with a better efficiency and therefore a better price per unit ratio of the power produced. In regions where climatic conditions change is very fast, the need for a faster MPPT is paramount. The MPPT called Inc-Cond is the optimal choice among the algorithms presented, because it will find quickly the optimal point that is difficult with Fuzzy MPPT.

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