Study and simulation of MPPT techniques to control a stand-alone photovoltaic system under varying irradiance

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Abstract: The aim of this paper is to analyze and evaluate three different forms of Maximum Power Point Tracking (MPPT) techniques under standard and various atmospheric conditions. In the literature, different MPPT methods are proposed and studied by researchers, let us quote the well known Perturb & Observe (P&O), the incremental conductance, fuzzy logic based MPPT, neural networks based MPPT,etc. The major drawback found is the effectiveness of these techniques under sudden variations in weather conditions such as irradiance and temperature. Another drawback of some MPPT techniques is the response time which is important to achieve the optimum power value. In this sense, optimization of P&O method becomes the objective of our work, to track the point of maximum power in a photovoltaic system under different weather conditions. In this paper, we will improve the P&O technique which makes it possible to react quickly to sudden changes in solar radiation and to follow the maximum power point with very low oscillations. The main idea is to use a PID regulator to make the voltage of the PV panel much closer than the MPP voltage, this method is named indirect P&O. The simulation based comparative study showed that the MPPT indirect P&O technique led to better performance.

Keywords: PV system, DC/DC converter, MPPT, P&O, PID controller, fuzzy logic.

1. Introduction

In recent years, the energy demand increases with the same rate as the population increase as well as the technology development. Besides exhausting of fossil fuels and negative effects of nuclear fuels, the tendency of generating energy nearby location, where it is consumed, aim to decrease the transmission losses and improve the energy reliability which has increased interest on renewable energy sources. In this context, one of the most important forms of renewable energy is the photovoltaic solar energy, which has an impact on our renewable energy production activities. Furthermore, this source of energy appears to be the most promising, non-polluting and inexhaustible. Nevertheless, this energy is produced in a non-linear manner that changes according to irradiance and temperature. As a result, the solar panel's operating point does not necessarily correspond to the maximum power point, therefore we utilize a technique called "Maximum Power Point Tracking", which allows us to search for and track the maximum power point (MPPT).

An important number of MPPT command methods have been developed over the years of the previous century, starting with simple methods such as MPPT controllers based on voltage and current status feedback (Rekioua et al., 2012), the correctness of these methods is not guaranteed for the reason that they approximate constant report of I_{max} and I_{SC} or V_{MPP} and V_{OC}. The study of MPPT command methods is continued to more efficient controllers, such as Perturbation and Observation (P&O) and Incremental conductance (IC) (Hanen et al., 2014); (Kollimalla et al., 2014); (Kwaku Anto et al., 2016); (Ibrahim et al., 2019); (Verma et al., 2016), these methods are simple and easy to apply, but it presents the drawback of large oscillations around the optimum power. In recent years, the researchers intend to use other methods, and also more robust control techniques have been coupled with MPPT command such as fuzzy logic and neural networks in order to increase the efficiency of solar panels (Guellal et al., 2016); (Makbul et al., 2017); (Jyotirmayee, 2018); (Issam et al., 2020); (Hammoumi et al., 2020); (Mohcine et al., 2020). The results generated by these methods are satisfactory and better than the previous methods; however, it is complicated to implement them and take a long response time to follow the maximum power of PV system especially in the case when the irradiance change rapidly.

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In this perspective, we will present the different devices of a photovoltaic system (PV array, DC/DC converter and command MPPT), and we will improve a P&O method by using a PID controller to follow MPPT with fast response time and low oscillations. This method is named: the indirect P&O control and it will be studied, simulated and compared to P&O control and fuzzy logic based MPPT.

2. Objectives of the project

This work addresses the simulation of a complete PV system, the controller is implemented using MATLAB software. The proposed methodology is based on MATLAB/SIMULINK to model, simulate the whole PV system under variable climate conditions.

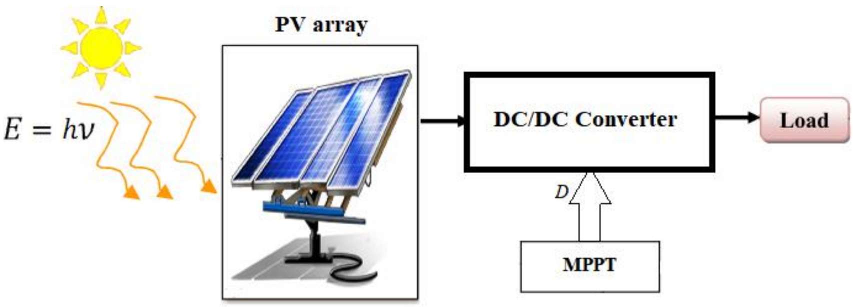


Figure 1. Block diagram of PV system

The objectives intended to be achieved by the end of this work are:

- Model and simulate the PV panel;
- Study the characteristic curves and the effect of variation of environmental conditions such as temperature and irradiation on them;
- Design and implement a DC-DC (Boost) converter and simulate the system overall with a different MPPT controller;
- Extract maximum power from the PV panel using the different MPPT algorithms.

3. Description of photovoltaic system

3.1. Modeling of photovoltaic panel

The fundamental element in a photovoltaic panel is the photovoltaic cell which converts the energy received by solar radiation into electrical energy. A photovoltaic cell can therefore be assimilated to a photodiode in generator convention. There are several electrical models of the PV cell (Faranda & Leva, 2008); (Messalti et al., 2017); (Jyotirmayee, 2018); (Hammoumi et al., 2020), one-diode model and two diode model, we use the simple one-diode model, it is given by the following figure:

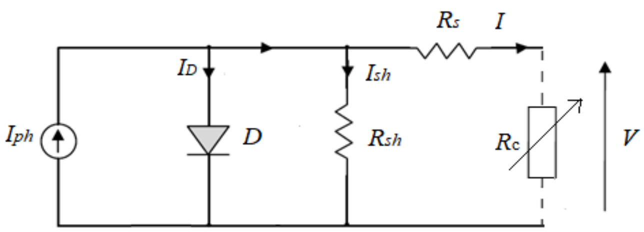


Figure 2. Modeling of a photovoltaic cell

This circuit contains a direct current source and a diode connected in parallel. The current source delivers a current I_{ph}, directly proportional to the irradiance, the diode represents the PN junction of the solar cell. The resistors R_s and R_{sh} respectively represent the resistances of the metal contacts and of the leaks of the PN junction. In general, the R_{sh} resistance is very large and the R_s resistance is very low. The current I as a function of the voltage V is written in the following implicit form:

$$I = I_{sc}\left(\frac{I_r}{1000}\right) - I_s\left[exp\left(\frac{q(V+R_sI)}{\eta kT}\right)-1\right] - \frac{V+R_sI}{R_{sh}} \quad (1)$$

Where :

I_r: sun irradiance (W/m^2)
I_s: reverse saturation current of the diode.
q: charge of electron where: q = 1,6 × 10^{-19} C
k: constant of Boltzmann where: k = 1,38 × 10^{-23} Joule/K
η: is the quality factor of the diode, generally between 1 and 2.
$kT/q \approx 25$ mV at T = 300 K.
I_{sc}: Short-circuit current.
V_{co}: Open circuit voltage.

In general, the PV panel model output current is provided by the following equation (Faranda & Leva, 2008); (KAHLA, Sami et al., 2019) :

$$I = N_p . I_{cc}\left(\frac{E}{1000}\right) - N_p . I_s\left[exp\left(\frac{q\left(\frac{V}{N_s}+\frac{R_sI}{N_p}\right)}{\eta kT}\right)-1\right] - \left(\frac{\frac{N_p}{N_s}V+R_sI}{R_{sh}}\right) \quad (2)$$

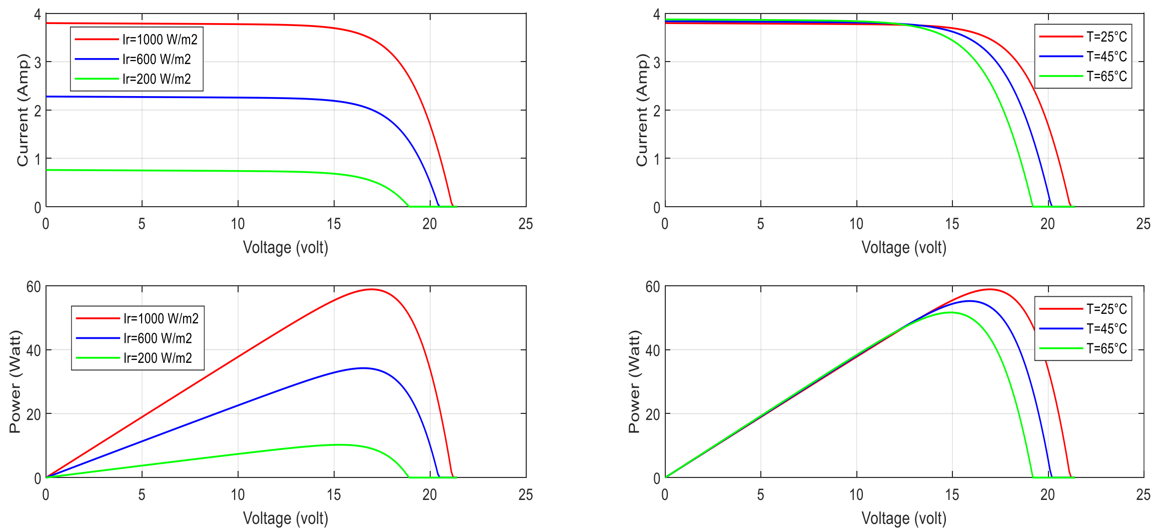
Where: N_p is the number of PV cells connected in series and N_p is the number of PV cells connected in parallel.

The PV panel used in this work is a 'MSX60' type, it is a polycrystalline solar panel, this module is the most cost-effective in the market, and it charges batteries effectively in almost any environment. The parameters of this panel are given by the table below:

Table 1. Electrical characteristics of PV Panel 'MSX60'

Parameters	Value
Maximum Power (P_{max})	58 - 60 W
MPP Voltage (V_{max})	17.1 V
MPP Current (I_{max})	3.5 A
Open circuit voltage (V_{oc})	21.1 V
Short circuit current (I_{sc})	3.8 A
Number of cell (N_s)	36

Figure (3) shows the characteristic $I=f(V)$ and $P=f(V)$ at $T=25^oC$ for different irradiance values; we notice that the current is directly proportional to the irradiance. The voltage on the other hand is not very degraded when the light goes down; but this does not depend on the surface, it is only a function of the material. The optimum power of the module is proportional to the sun irradiance.



(a) (b)

Figure 3. Characteristics of Solar panel for different irradiance and temperature values

The characteristic $I=f(V)$ and $P=f(V)$ at $E=1000W/m^2$ for varying temperatures between 25 and 65 °C, we notice that the temperature has a negligible influence on the value of the short-circuit current. On the other hand, the open circuit voltage drops quite sharply when the temperature increases, while the extractable power consequently decreases.

3.2. DC/DC converters (Choppers)

A DC/DC converter (or choppers) is an electronic device that transforms a changeable DC output voltage from a fixed DC input value (Jyotirmayee, 2018).

- There are different types of choppers:
- If the voltage delivered at the output is lower than the voltage applied at the input, the chopper is said to be step-down or Buck.
- Otherwise, it is said to be step-up or Boost.

There are also choppers capable of working in both ways (Buck-Boost).

In this study, a boost converter was used and it is essentially composed of a switch K (like IGBT or MOSFET) and a diode D. The switch K is controlled by a PWM signal with a fixed chopping period T_d and ratio cyclic variable α. The conduction of the two switches is complementary, therefore when K is closed D is open; and when K is open, D is closed. During each period, K is immediately closed at t=0 to αT_d and open from αT_d to T_d. There are two operating modes depending on whether the current in inductance cancels out (discontinuous conduction mode) or not (continuous conduction mode). We are interested in the second case which is the most important. Figure 4 gives the block diagram of this converter (Priyanka & Vijay, 2016); (Jyotirmayee, 2018); (Abdelilah et al., 2020).

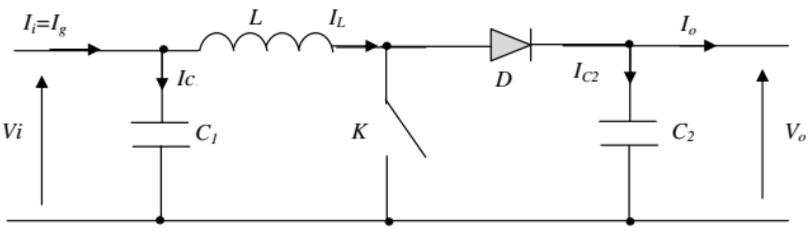


Figure 4. Circuit of boost-converter

The average values of the output voltage V_0 and average cuurent I_0 are given by (Abdelilah et al., 2020) :

$$V_0 = \frac{V_i}{1-\alpha} \quad (2)$$

$$I_0 = I_i(1-\alpha) \quad (3)$$

The DC/DC converters are used in order to provide impedance matching between the PV array and load. These converters are generally employed as a power processing unit with MPPT algorithms by adjusting the duty cycle. This duty cycle is calculated by the MPPT algorithm and varies between 0 and 1.

3.3. Maximum Power Point Traking (MPPT)

The MPPT control delivers the appropriate control action to track the peak power point at all times. This control acts directly on the duty cycle of the DC-DC converter. In the literature, several tracking algorithms have been proposed and studied by researchers to follow the MPP (Rahmani et al., 2013); (Verma et al., 2016); (Makbul et al., 2017); (Messalti et al., 2017); (Bouchiba et al., 2020); (Mohcine et al., 2020). Among which we cite: The "Perturb and Observe" (P&O) algorithm, incremental conductance, the control based on the nouron networks and fuzzy logic algorithm. Each of these techniques has its own advantages and disadvantages from the point of view of simplicity, efficiency and robustness. In our work, we will study P&O methods and fuzzy logic then we will try to improve the P&O method by a PID regulator, this method is called optimized P&O or indirect P&O.

3.3.1. P&O method

The P&O technique is one of the most well-known MPPT techniques; it is widely used because it is simple to implement in comparison to other MPPT techniques. To calculate the actual power delivered by the PV panels, P&O technique requires only the measurement of the terminal voltage and output current of the PV panels The MPP will be achieved after the duty cycle of the DC/DC converter is changed (Rekioua et al., 2012); (Hanen et al., 2014).

The power is observed in the P&O technique by increasing or decreasing the duty cycle with a certain width of the duty cycle defined by the user; the process begins by operating the DC-DC converter with the initial set duty cycle (Faranda et al., 2008); (Verma et al., 2016); (Messalti et al., 2017); (Mohcine et al., 2020).

The P&O technique is based on moving the operating point by increasing V when $\frac{dp}{dv}$ is positive or decreasing V when $\frac{dp}{dv}$ is negative. At the end, the system reaches around the maximum power as it is presented in Figure 5:

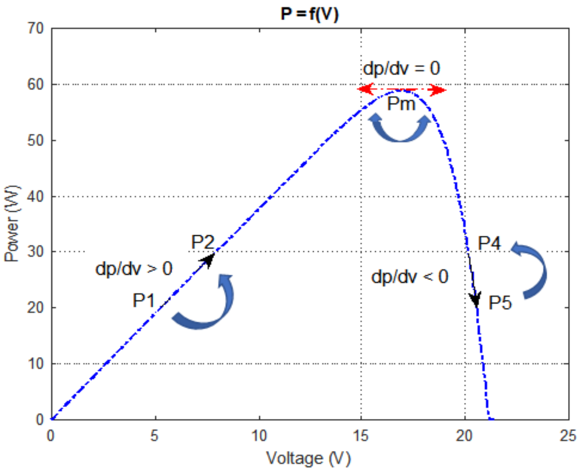


Figure 5. Method of P&O

3.3.2. Indirect P&O method (with PID controller)

This method is based on the comparison between the output voltage of the P&O controller called V_{ref} and the output voltage of PV system: V_{pv}. In controller synthesis step based on the indirect control mode, it is necessary to determine the transfer function that links the output PV voltage model V_{pv} by the input duty cycle to be controlled. The output electrical power is ensured by the two following stages: the first one aims to generate the reference voltage V_{ref} by the P&O-MPPT implementation algorithm using the flow chart of Figure 7. On the other hand, the second stage aims to discrepancy between the output voltage, provided by the PV panel, and the above mentioned reference voltage, provided by the P&O-MPPT algorithm. This goal is reached by a stabilized PID (Proportional-Integral-Derivative) controller, providing thus the desired duty cycle (Faranda et al., 2016); (Chen et al., 2016).

The (PID) controller is the most widely used control algorithm in industry, and it is widely utilized in industrial control. PID controllers' popularity may be ascribed to its strong performance in a wide range of operating conditions, as well as their functional simplicity. The block diagram of the PID controller is shown in Figure 6.

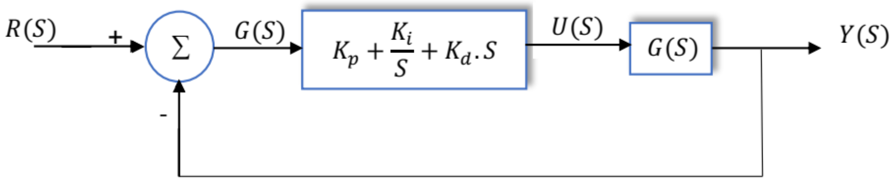


Figure 6. Block Diagram of the PID Controller

The optimal adjusted parameters K_p, K_i, and K_d would be obtained by tuning the digital PID controller and conducting open and closed loop responses. This method would yield the best PID tuning settings for minimizing oscillations around the MPP (Kahla et al., 2019).

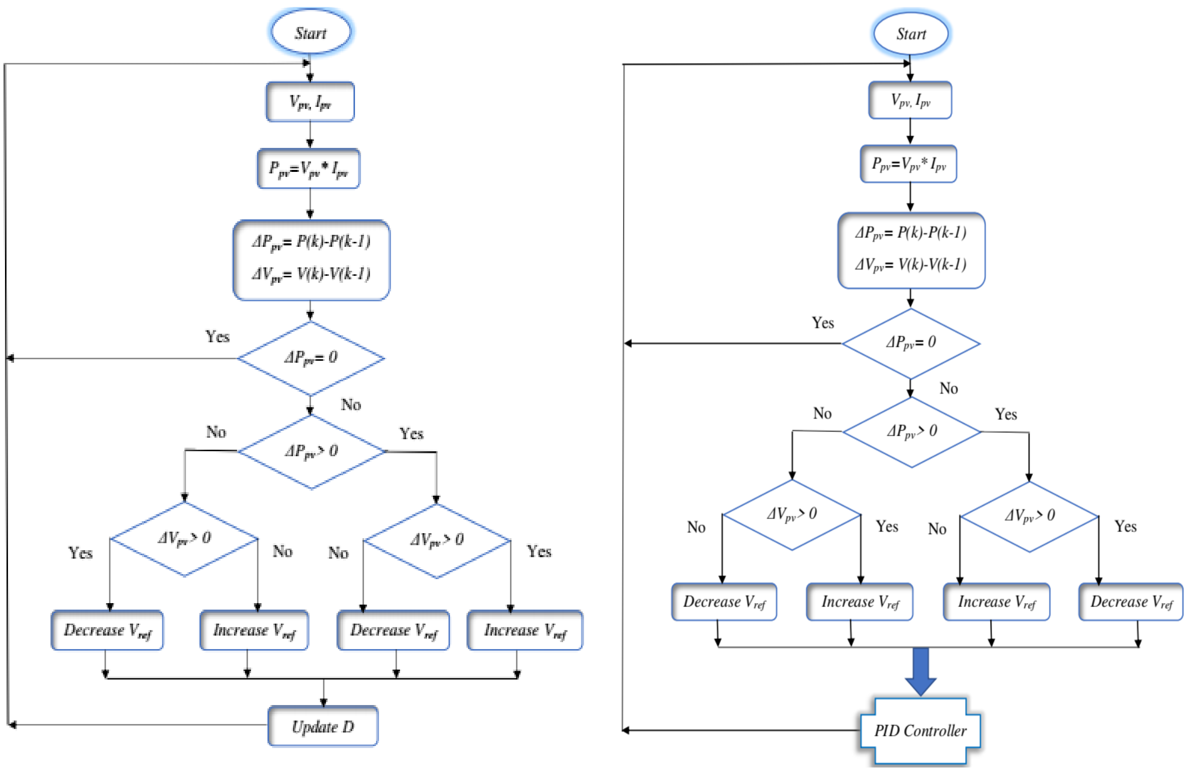


Figure 7. Flowcharts of P&O and indirect P&O algorithm respectively

3.3.3. Fuzzy logic method

Fuzzy logic is an interesting alternative approach today. It has several advantages such as reasoning close to that of humans, it is characterized by its robustness and its insensitivity to the variation of the parameters. The implementation of a fuzzy controller is carried out in three stages, which are: fuzzification, inference and defuzzification (Figure 8) (Chen et al., 2016); (Jyotirmayee, 2018).

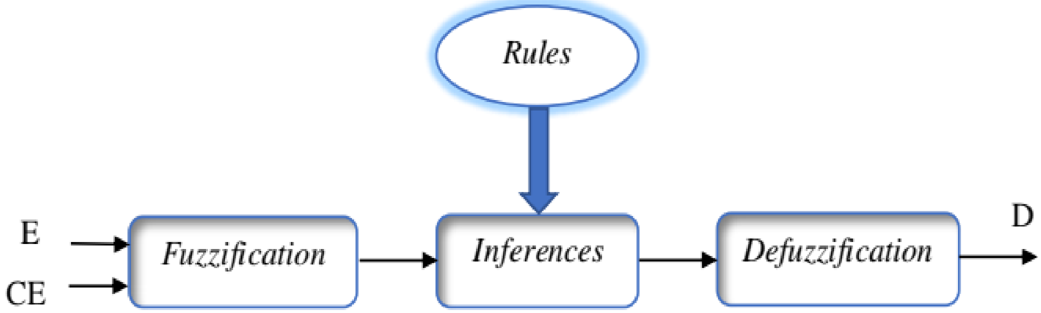


Figure 8. Block diagram of fuzzy logic control

Fuzzification allows to blur the input variables, a preliminary step is to define an interval of maximum variation allowed for the input variables. The aim of fuzzification is to transform input variables into linguistic variables or fuzzy variables. In our case, we have two input variables which are the error *E(k)* and the error variation *ΔE* at the instant *k* which are defined as follows (Hanen et al., 2014); (Guellal et al., 2016); (Makbul et al., 2017):

$$E(k) = \frac{P_{pv}(k) - P_{pv}(k-1)}{V_{pv}(k) - V_{pv}(k-1)} \tag{4}$$

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

Thus its variables will be qualified Negative Big (N.B), Negative Small (N.S), Zero error or Zero (Z), Positive Small (P.S) and Positive Big (P.B)

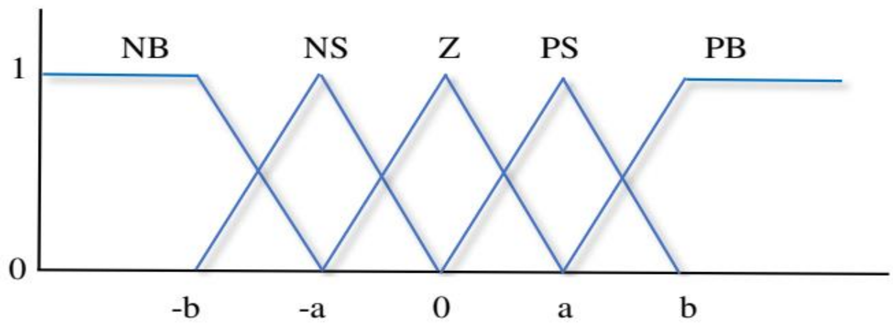


Figure 9. Fuzzy membership functions used in the fuzzification process

Inference is a step of defining a logical relationship between the inputs and the output. Indeed, membership rules will be defined for the output as it was done for the inputs, thanks to these rules an inference table can be drawn up (Table 2) (Issam et al., 2020).

Table 2. Fuzzy logic rule base

E \ ΔE	N.B	N.S	Z	P.S	P.B
N.B	P.B	P.B	P.B	P.B	P.B
N.S	P.S	P.S	P.S	P.S	P.S
Z	P.S	Z	Z	Z	P.S
P.S	N.S	N.S	N.S	N.S	N.S
P.B	N.B	N.B	N.B	N.B	N.B

It is obvious that a good knowledge of the system is required for the development of such a regulator. Indeed, as a general rule, an input value is defined by two fuzzy functions with different degrees, so the output will also be defined by several functions, the question being to know with what degrees of membership. Several methods can answer this question. On our part, we used the MAX-MIN method. Finally, we have to do the reverse operation of fuzzification, here we have to calculate a numerical value understandable by the external environment from a fuzzy definition and this is the purpose of defuzzification.

4. Results and discussion

Figure 9 shows the MATLAB/Simulink model of the proposed model for PV system with a converter DC/DC and different MPPT techniques mentioned above. The MPPT algorithms are applied in the controller to supply the converter with the optimal duty cycle to reach the maximum PV system power for different values of irradiance.

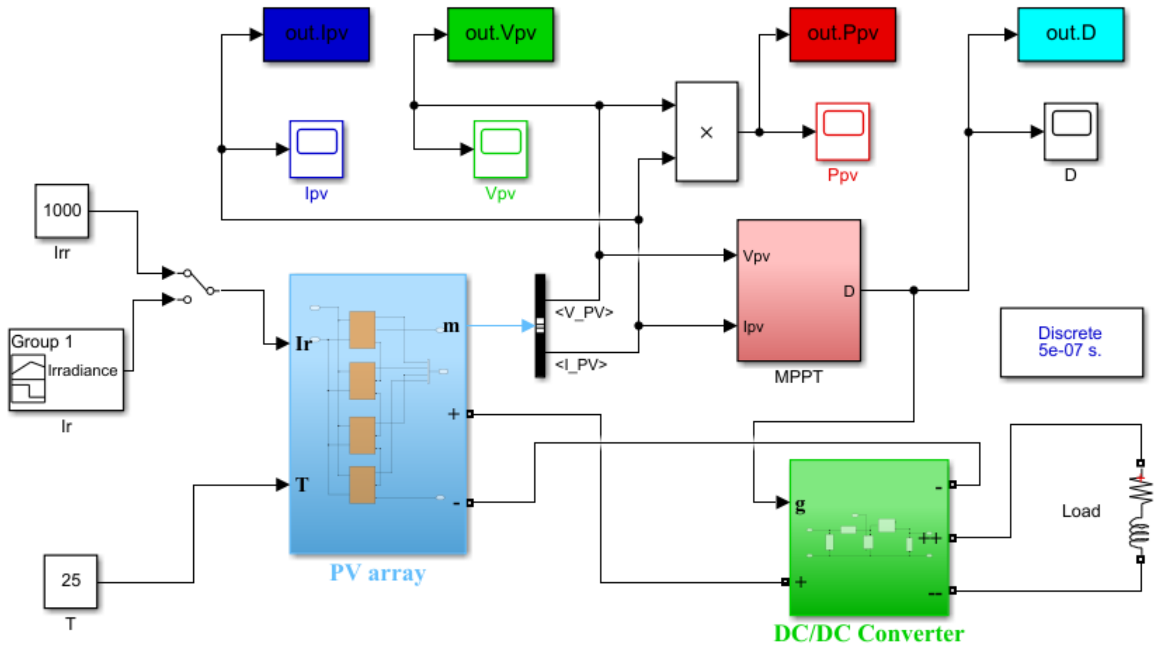
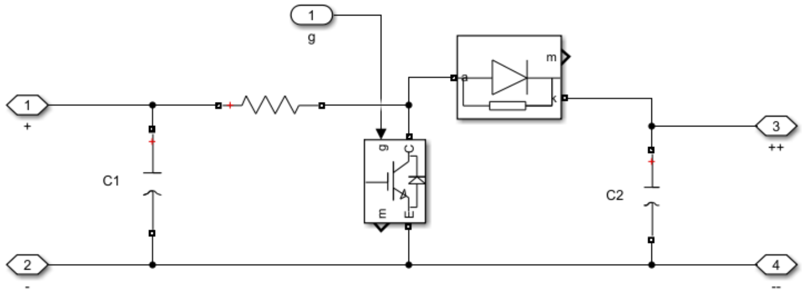
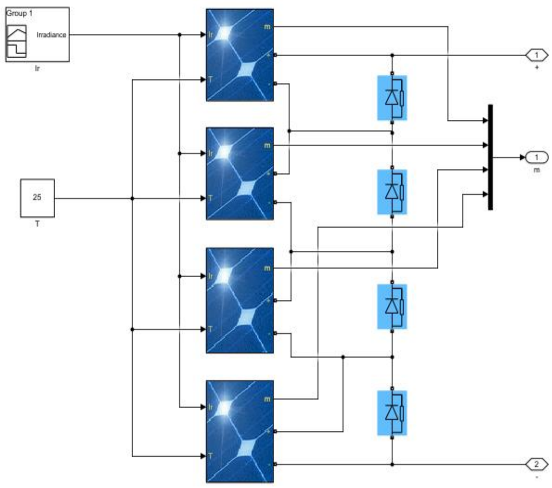


Figure 10. Simulink model for global PV system

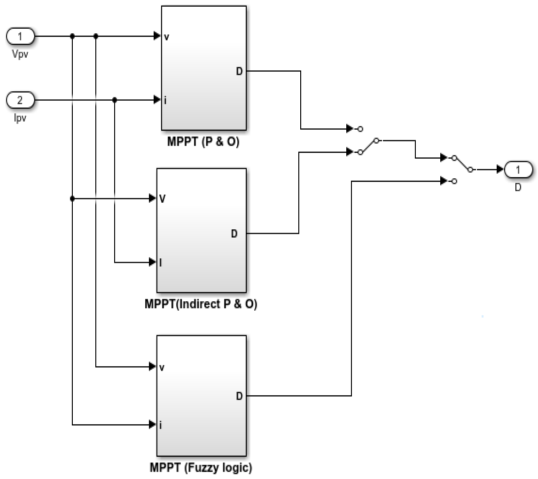
The simulation models of each block: DC/DC converter (Boost), PV array as well as MPPT technique are illustrated in (Figure 11.a, 11.b and 11.c). We change the MPPT technique each time and will see the power curve generated by our system.



(a)



(b)



(c)

Figure 11. (a) DC/DC converter (Boost), (b) Bloc of PV array, (c) Choice of MPPT technique

The simulation results are used to evaluate the performance of the MPPT methods. Our photovoltaic generator is composed of four series-connected PV panels 'MSX60' that generate together 230W under STC (Standard Test Conditions), it is simulated to see how precise and stable it is when the sun irradiance changes suddenly and randomly.

Figures 12 show the power delivered by the system under stable conditions: Irradiance 1000 W/m^2 and Temperature 25 °C.

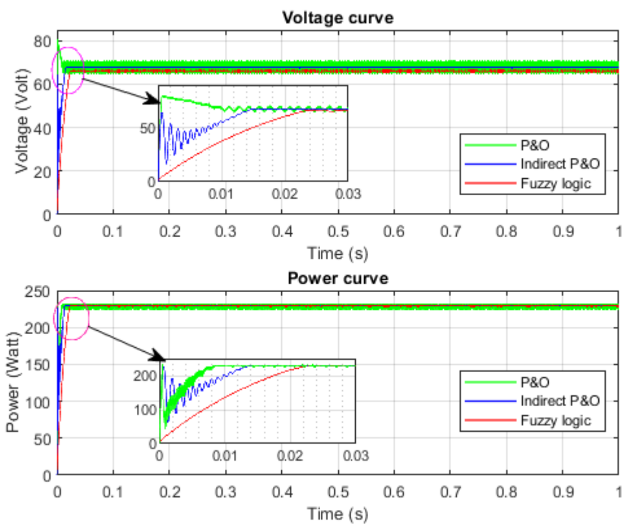


Figure 12.a. Voltage and Power curves of different algorithms under uniform irradiance (1000W/m^2) and temperature (25 °C)

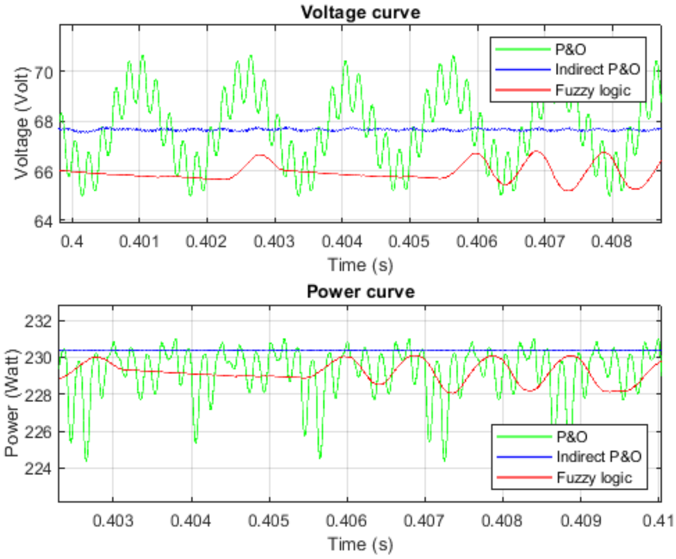


Figure 12.b. Zoom of voltage and power curves

The temporal response of the output voltage and power of the system is shown in Figures 12. We can see that the response time of the MPPT P&O controller is fast compared to other commands, the response time of the indirect P&O technique is a bit fast and the fuzzy logic command is slow, on the other hand the P&O command has low precision and very large oscillations around the theoretical value, the fuzzy control has an acceptable precision, the power values given by the indirect P&O controller are very close to the theoretical value, it has a considerable precision. Therefore, we can say that the proposed indirect P&O algorithm has a very good tracking speed and a good precision in particular around the MPPT point.

Now, we are going to vary the irradiance to several values and keep the temperature constant at 25 °C. This variation allows us to study the robustness and efficiency of our MPPT controls, the irradiance is abruptly reduced from 600 W/m^2 to 400 W/m^2 before rapidly increasing to 800 W/m^2 and 1000 W/m^2 during a disturbance of 1*s*, as illustrated in Figure 13.

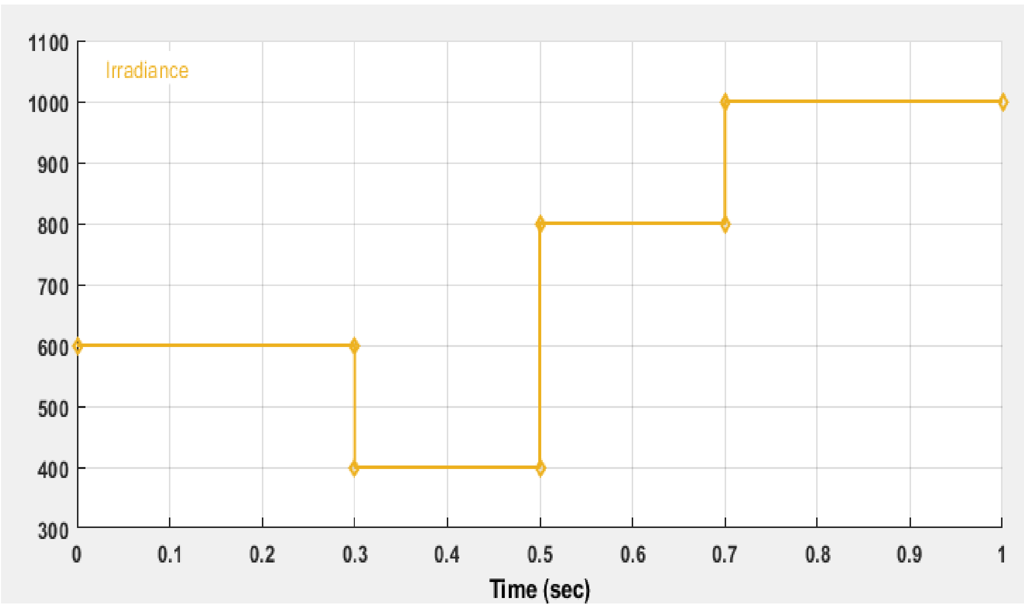
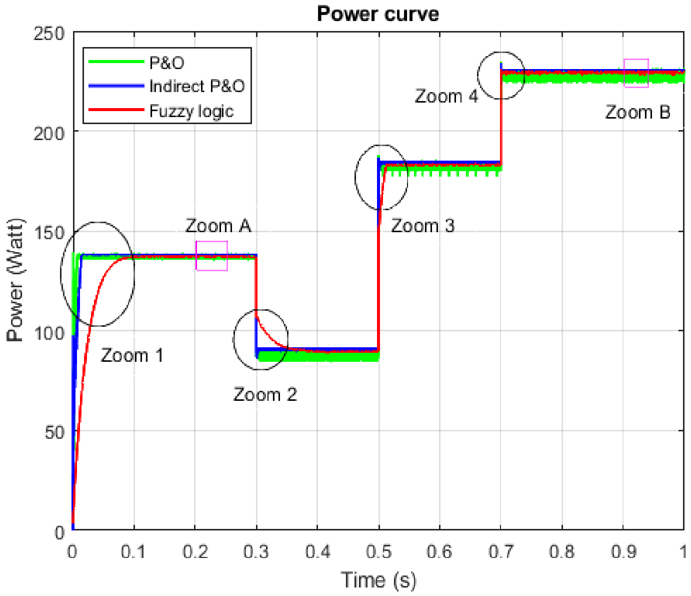


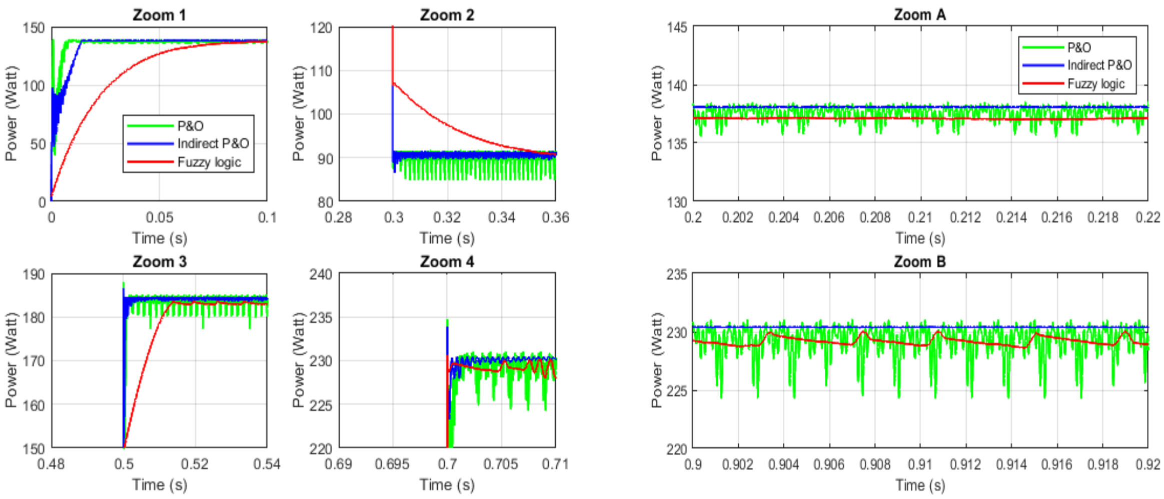
Figure 13. Irradiance profile

The simulation results of different techniques under varying irradiance are shown in Figures 14:



(a)

Figure 14. **(**a) Power curves of different methods under temperature (25 °C) and varying irradiance



(b) (c)

Figure 14. (b) Zoom 1, 2, 3 and 4 of power curves; (c) Zoom A and B of power curves

Zooms 1, 2, 3 and 4 are taken during a sudden change in solar irradiation (transient regime), while zooms A and B are taken in steady state.

We can see that there is a relationship of proportionality between irradiance and power; an increase in irradiation results in an increase in the photovoltaic power generated. In transient mode, we notice that the fuzzy logic controller takes longer than the P&O and indirect P&O controllers to reach the optimum power; i.e., a response time equal to 0.1 *s* for the fuzzy controller, 0.01 *s* for the P&O controller and 0.02 *s* for the indirect P&O controller, which shows that the P&O and indirect P&O controllers are faster than the fuzzy controller. In the steady state and after stability, the P&O control contains very strong oscillations which implies significant power losses, on the other hand, the oscillation is negligible for the fuzzy controller and absent for the indirect P&O controller.

Table 3. Comparison between MPPT techniques

MPPT	P&O	Indirect P&O	Fuzzy logic
Identification of PV array parameters	Necessary	Necessary	Necessary
Complexity	Low	Medium	High
Response time	Very fast	Fast	Slow
Precision	Acceptable	Very good	Good
Oscillations	High	Negligible	Light

From the simulation results obtained and the comparison statistics shown in the table above, we notice that the indirect P&O controller leads to better performance, with the absence of oscillations in the steady state, and a fast response time.

5. Conclusion

Several MPPT commands have been discussed, implemented and compared in this work. The P&O algorithm is a classic and simple algorithm. In general, this algorithm reacts quickly to climate change but it exhibits remarkable oscillations around the optimal value, which causes a significant power loss. The fuzzy logic algorithm appears to be an improvement of the P&O algorithm. Indeed, it behaves better in steady state and has less oscillations around the maximum power point, the major drawback of this algorithm is its bad behavior following a sudden change in irradiance, it takes a long response time to achieve the optimum power. However, this is a more complex algorithm than the previous one. The indirect P&O command is the most reliable compared to other techniques. It is adapted to sudden changes in atmospheric conditions, the indirect P&O controller has a fast response time and exhibits almost no oscillation around the point of maximum power.

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