Comparative study and simulation of advanced MPPT control algorithms for a photovoltaic system

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ABSTRACT

A photovoltaic (PV) system uses solar radiation and converts it into electrical energy. An energy management system consisting of a maximum power point tracking (MPPT) charge controller is then necessary. In the present work, for the optimization of the electrical energy delivered by the solar PV panel we will compare four types of controls explained below, namely "MPPT-P&OM", "MPPT-IncM", "MPPT-PI-P&OC" and "MPPT-FOPI-P&OC". Based on these comparisons, for different values of solar irradiance, the four methods seem to perform quite similarly; all four are fast and show small oscillations around the optimal value; nevertheless, the MPPT-IncM method performs slightly better than the others. This is due to the fact that it is slightly faster and has fewer oscillations. The simulation is implemented numerically using the MATLAB/Simulink development tool.

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1. INTRODUCTION

The demand for energy in all its forms has increased since the beginning of the industrial revolution, forcing scientists to research and develop new solutions to optimize energy use [1]. Solar energy is one of the most modern energies and has a bright future, because it is clean and ecological compared to other energies [2]. There are several ways to use this energy to produce electricity [3], but the most important method and the one that concerns us in this work is the method based on the principle of photovoltaics which has the advantage of being non-polluting, flexible and reliable. The photovoltaic (PV) technology transforms part of the solar energy into electricity [4]. This transformation is done without noise, without gas emission, and is therefore by nature totally clean [5].

To overcome the efficiency problem of solar PV panels and achieve maximum efficiency, it is necessary to optimize the design of all parts of the PV system. In addition, it is necessary to optimize the DC/DC converters used as an interface between the PV generator (GPV) and the load, in order to extract the maximum power and thus operate the GPV at its maximum power point (MPP) using a maximum power point tracking controller (MPPT). This will allow to obtain a maximum electrical current under the variation of the load and the atmospheric conditions (illumination and temperature).

The abbreviations "MPPT-P&OM", "MPPT-IncM", "MPPT-PI-P&OC" and "MPPTFOPI-P&OC" stand for: Modified perturbed and observed, modified incremental inductance, MPPT using PI corrector, MPPT using fractional order PI corrector. This paper is organized as follows: after the introduction, section 2 is reserved for the mathematical description of a PV panel using the one-diode model. In section 3, the methods of MPPT control are discussed by dealing with the four modified algorithms, namely; "MPPTP&OM", "MPPT-

IncM", "MPPT-PI-P&OC" and "MPPT-FOPI-P&OC". In section 4, the simulation results are presented and discussed in order to evaluate the presented algorithms and deduce the best performing technique. Finally, we conclude with a conclusion.

2. PHOTOVOLTAIC SYSTEM

Photovoltaic (solar electric) panels contain semiconductors such as silicium that directly convert solar radiation into electricity. A PV system consists of four blocks as shown in Figure 1. The first block represents the energy source (PV panel), the second block is a static DC-DC converter, the third block represents the control system and finally the fourth block is a load [6].

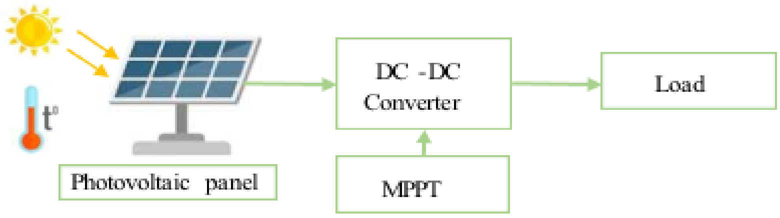


Figure 1. Concentrations block diagram of a PV system

2.1. Photovoltaic panel

The PV panel or module, is composed of small PV cells that are connected together in series and/or parallel, as shown in Figure 2. The PV cell is an electronic device designed to convert light into electricity. Its structure is based on the resulting PN junction of two layers: one doped P and the other N, as shown in Figure 3 [7]. PV solar cells consist of a P-N junction fabricated in a thin layer of semiconductor, often of the silicon type [8].

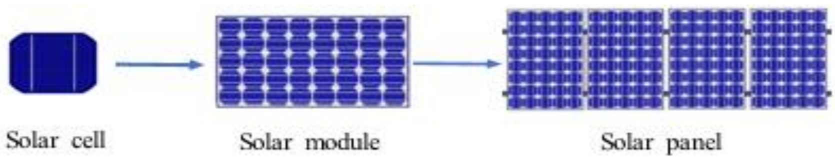


Figure 2. Block diagram of a PV system

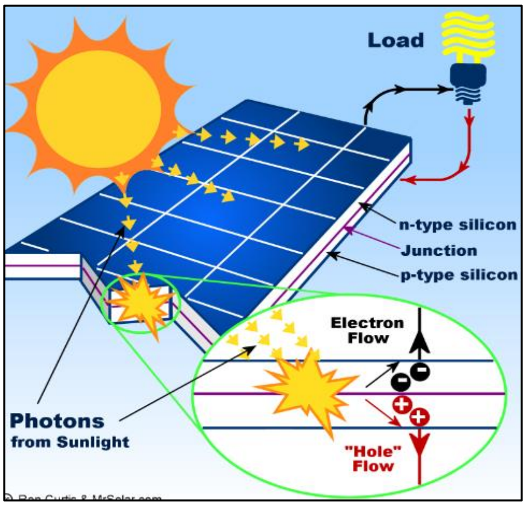


Figure 3. Diagram of a photovoltaic cell

Electronic transitions from the valence band to the conduction band of the semiconductor are generated by the absorption of photons of appropriate energy (Eph) [6], which must be at least equal to the energy gap of the material. This energy is absorbed by the semiconductor, generating electron-hole pairs. With the front and back metal contacts, an electric current flow across the external circuit. The electron-hole pair quickly returns to the most stable equilibrium with energy dissipation in the form of heat. This results in an increase in its temperature in proportion to the solar energy received [7].

2.2. Solar cell mathematical model

The basic unit of a PV module is the PV cell. To generate the required current and voltage, several PV cells are connected in parallel and/or in series. It produces a direct current as a result of the energy transported by the light landing on the PV cells composing it [9]. PV systems are directly impacted by solar radiation and temperature. The performance and cost of these solar systems are influenced by outdoor working conditions and other variable conditions affecting the operation of the system components [10]. The relationship between the output voltage and current of a PV cell is modeled, as shown in Figure 4, by the single diode model circuit. In the latter, there is a current source (I_{ph}), a diode saturation current (I_0), a parallel diode, a shunt or parallel resistor (R_{SH}), and a series resistor (R_S) connected in series with the load.

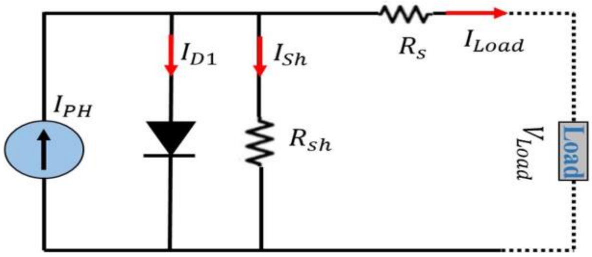


Figure 4. Equivalent diagram to a PV cell-single diode case [11]

For a PV module consisting of Ns and Np PV cells, connected in series and parallel respectively, the output current in the case of this single diode model is given by the expression [11]:

$$I = N_p \times (I_{ph} - I_{01} \left[exp \left(\frac{N_p V + N_s R_s I_{pv}}{n V_{th} N_p N_s} \right) - 1 \right] - \frac{N_p V_{pv} + N_s R_s I_{pv}}{N_s R_{sh}}) \quad (1)$$

with:
N_s : Nombre de cellules PV connectées en série.
N_p : Nombre de cellules PV connectées en parallèle.
I_{ph} : Photo-generated current (A).
I_{pv} : Solar cell terminal current (A).
I_{01} : Reverse saturation current of diode D1 in conventional model (A).
n : Ideality factors.
R_s : Series resistance (Ω).
R_{sh} : Shunt resistance (Ω).
V_{pv} : Solar cell output voltage (V).
$V_{th} = kT/q$: Thermal voltage (V) [12].
In this equation, we find the modeling of a PV cell called simple diode with 5 parameters (I_{ph}, I_{01}, R_s, R_{sh}, I_{ph} and n).

2.3. Boost converter

When we want to increase the voltage of a DC source, we can use a BOOST type static converter called step-up or parallel, because of its high reliability and flexibility compared to other converters [13]. The block diagram of this type of converter is shown in Figure 5. The BOOST direct converter with its MPPT control is interfaced between the PV panel and the load to improve the efficiency of a solar PV system [14]. This power electronics device is a DC-DC converter (DC-DC) that allows the voltage at the terminals of the PV panel to be adapted to that of the load, thanks to a control strategy that allows operation at the maximum power point (MPP).

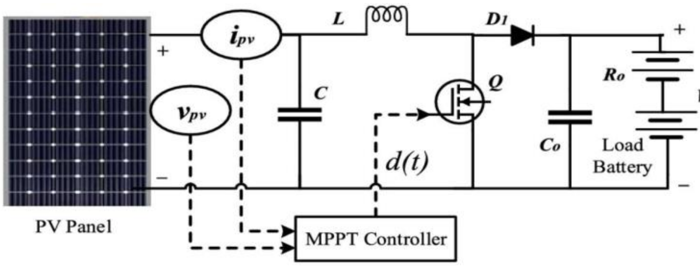


Figure 5. Electrical diagram of a boost converter

3. MPPT TECHNIQUES

There are many conventional and scalable MPPT techniques cited in the literature. They are based on the cyclic ratio control technique applied to the boost converter control circuit acting on its output voltage [15]. MPPT control is an essential control for the optimal operation of a PV system. The principle of this control is based on the automatic variation of the duty cycle to its optimal value in order to maximize the power delivered by the PV panel. For simulation purposes, the PV system under test is composed, on the one hand, of a PV module of type XXR-SFSP-H50-62W [16], whose specifications are summarized in Table 1, and on the other hand of a DC-DC converter and a battery whose parameters are reported in Tables 2 and 3 respectively.

When designing controllers for PV systems, MPPT algorithms are commonly used. To ensure that the PV system delivers maximum power at all times, the algorithms take into account variations in temperature and essentially irradiance, This is shown in the Figure 6. During our simulations, the irradiation profile used for the interval of 0.3 s and for a fixed temperature of 25 ºC is represented in Figure 6(a). While the profit of the maximum power supplied by the PV panel under test and corresponding to the irradiation profile considered is presented in Figure 6(b).

Table 1. PV panel electrical characteristics used in MATLAB/Simulink

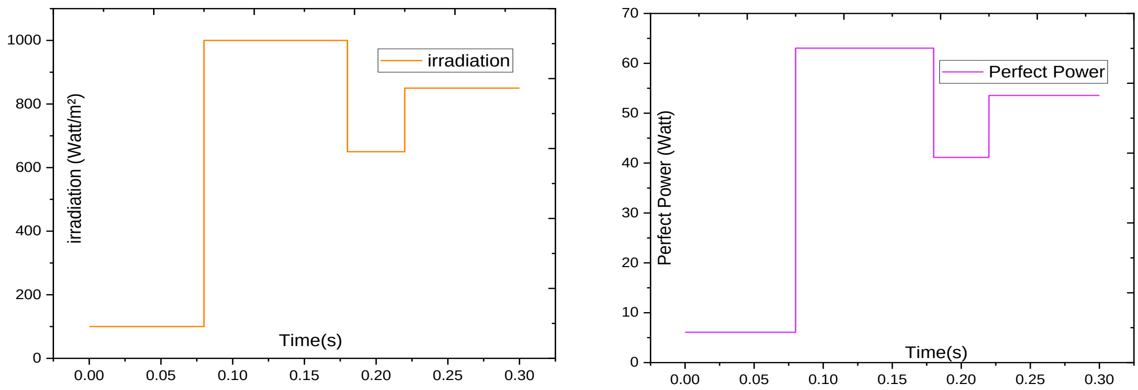
Parameter	Symbol	Value
Maximum power (W)	P_{mp}	62
Open circuit voltage (V)	V_{OC}	21
Short circuit current (A)	I_{SC}	3.8
Voltage at maximum power point (V)	V_{mp}	18
Current at the maximum power point (A)	I_{mp}	3.5
Number of PV cells per module	N_{cell}	18

Table 2. Boost converter specifications

Parameters	Symbol	Value
Switching Frequency (kHz)	F	30
Booster Inductance (μH)	L	330
Input Capacitor (μF)	C	100

Table 3. Battery specifications

Parameters	Symbol	Value
Nominal voltage (V)	V_n	48
Nominal capacity (Ah)	C_n	10
Initial state of charge (%)	SOC	10



(a) (b)

Figure 6. Profiles of irradiation (a) maximum electrical power and (b) used during the simulations under MATLAB

In the following, we will expose, concerning the MPPT, the following algorithms "MPPT-P&OM", "MPPT-IncM", "MPPT-PI-P&OC" and "MPPT-FOPI-P&OC". As well as the simulink block diagrams used for the simulations under MATLAB. This will allow us, after comparing the results, to evaluate the performance of each of these algorithms and to extract the best performing technique.

3.1. Control with the P&OM method noted here "MPPT- P&OM"

The algorithm oscillates the operating point at three points around the MPP. Drift problems occur as illuminance increases and are exacerbated when solar radiation changes rapidly; the results typically occur on cloudy days. Drift can occur from any of the three equilibrium points, as shown in Figure 7.

The problem of drift is due to the fact that it is not known whether the increase in power (dP > 0) is due to the disturbance or to a sudden increase in irradiance. Assuming that the irradiance increases during operation at point 1, the operating point is shifted from point 1 to the new point 4 when $dP = P_2 - P_1 > 0$ and $dV = V_2 - V_1 > 0$, and as a result the algorithm decreases the duty cycle causing a drift towards point 5 of a new curve thus moving away from the true MPP. As shown in Figure 7, with the rapid increase in radiation, the drift problem will become more accentuated and complex for control [17]. Figure 7 shows the I (V) characteristics of the PV modules and the operating point drifts due to solar irradiance fluctuations. The positive value of dP due to an increase in solar irradiance can be detected using the additional parameter dI corresponding to the variation of the PV module output current.

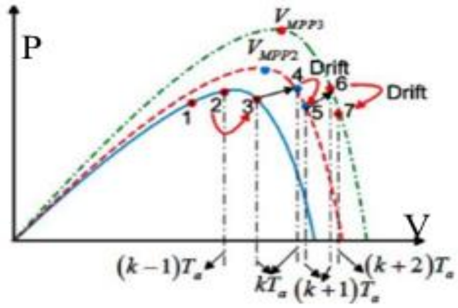
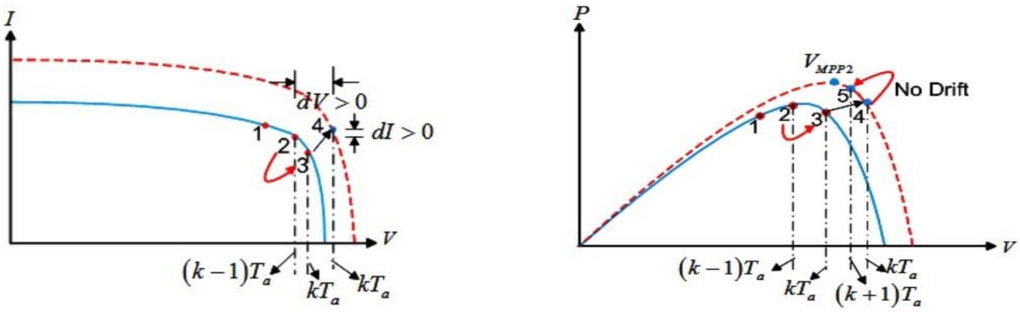


Figure 7. Resulting drift curves for sunlight fluctuations [17]

From the characteristics I(V), we can observe that the two parameters dV and dI can never have the same sign for a single irradiation. These parameters (dV and dI) will only be positive for an increase in insolation, as shown in Figure 8. As shown in Figure 8(a), assuming that there is an increase in sunlight during operation at point 3, the operating point will stabilize at a new point 4 in the new sunlight curve. Now the algorithm at point 3, as shown in Figure 8(a) must make the decision. An increase in solar irradiance can be detected using the additional parameter dI, and therefore, increasing the duty cycle (decreasing the operating voltage), where both dV and dI are positive, can eliminate the drift problem by moving the operating point closer to the MPP as shown in Figure 8(b). The flow chart associated with this "P&OM" technique without drift is presented in Figure 9 [18].



(a) (b)

Figure 8. Drift-free analysis with the MPPT "POM" (a) current variation with PV module output voltage and (b) brief increase in solar irradiance

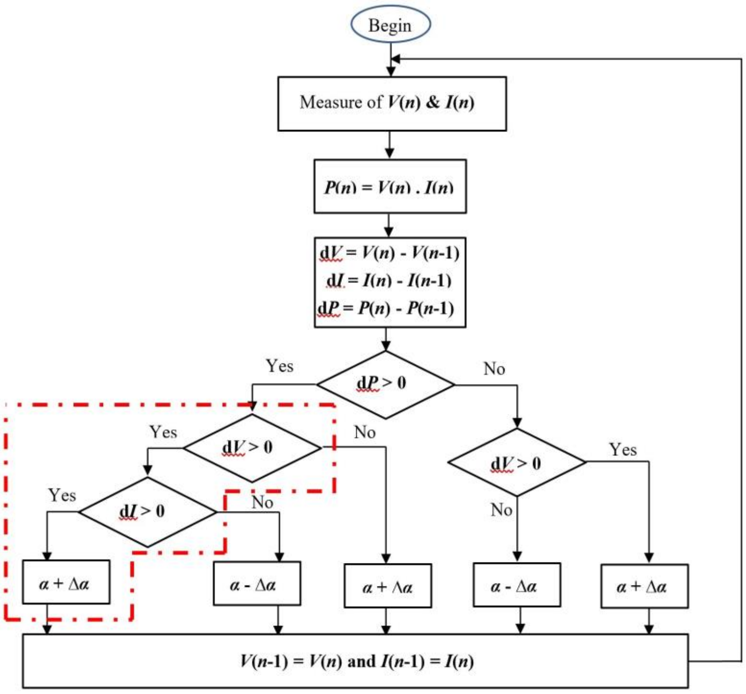


Figure 9. Flowchart of the "P&OM" algorithm without derivative (dotted box) [18]

The simulation results presented in Figure 10 ("P& OM") show that the "P& OM" technique allows to reduce relatively the oscillations during the fast variations of the solar irradiation. And more weakly during the brutal switching from 100 W/m^2 to 1000 W/m^2 (Zoom 1). Nevertheless, the "P& OM" algorithm still causes slight oscillations around the optimal values (Zoom 2).

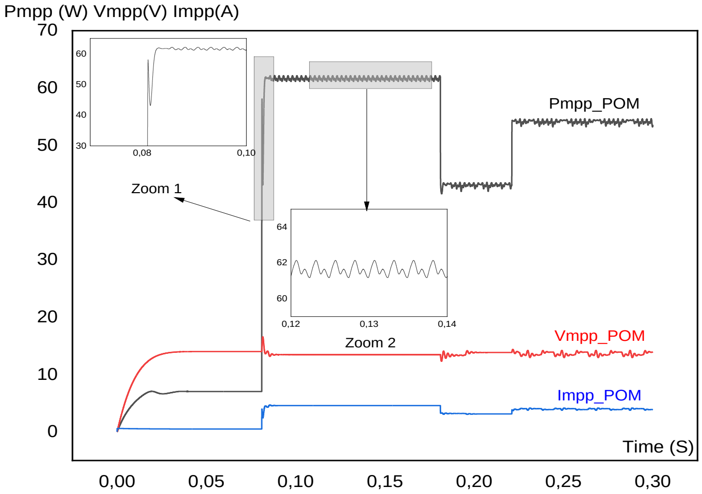


Figure 10. Power response of the PV module with the "P& OM" algorithm

3.2. Control with the IncM method noted here "MPPT- IncM"

For this technique, we use a variable called which is used to indicate that the MPP is reached when it is 1. So initially this variable is set to zero. When the condition in (2) is met, the system operates in MPP. Therefore, the algorithm sets to 1, then switches to the improved adaptive algorithm "IncM".

$$\left|\frac{I}{V}+\frac{dI}{dV}\right| < 0.06 \tag{2}$$

In the modified algorithm "IncM", it continues to check the state of (2). If the solar radiation and the load remain unchanged, the duty cycle α will not change. When the solar radiation changes, the algorithm resets the variable β to 0 and then evaluates the changes in the output voltage and current of the PV module. If the algorithm finds that the current and voltage increase, the duty cycle α also increases [19]. The Figure 11 represents the Flowchart of the "IncM" algorithm, which the response in terms of PV module power in the case of this algorithm is given in the Figure 12.

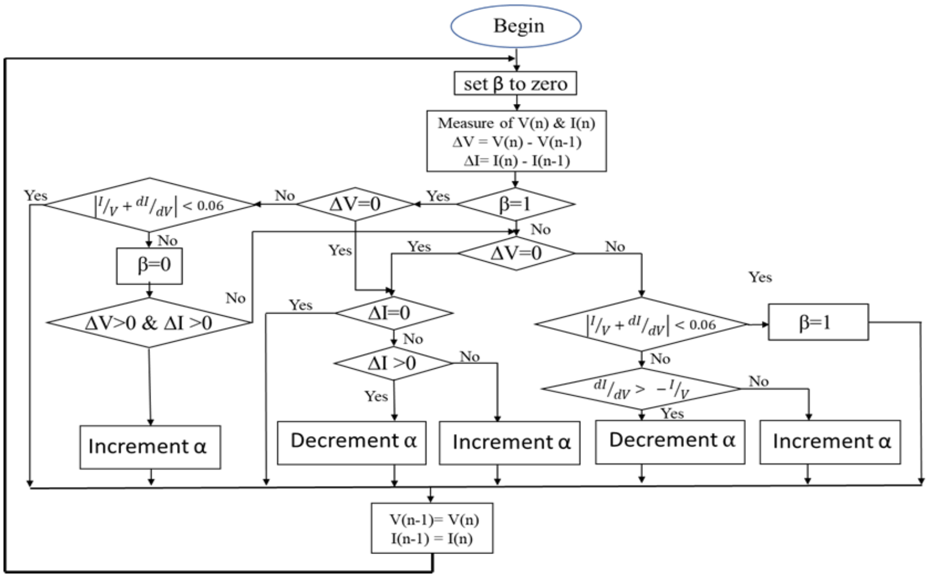


Figure 11. Flowchart of the "IncM" algorithm [20]

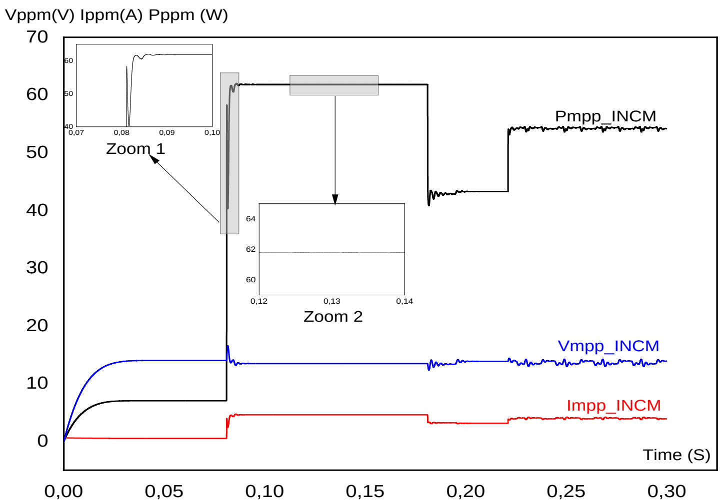


Figure 12. Response in terms of PV module power in the case of the "IncM" algorithm

The results obtained summarized in Figure 12, show that for a fast variation of the solar irradiation level (Zoom 1) the variation of Pmpp-IncM is done in a fluid way around 0.075 s. Corresponding to the passage of the irradiation from 100 W/m^2 to 1000 W/m^2, as well as the satisfactory follow up of the MPP under different illumination conditions. When the MPP is reached the steady state oscillations do not occur anymore.

3.3. Control with a PI and P&OC controller noted here as "MPPT-PI-P&OC

Unlike the MPPT control using the PI corrector, with the one named "MPPT-PI-P&OC", the referential voltage is obtained from the P&OC algorithm. This leads to a system that becomes autonomous

[21], [22]. The diagram corresponding to this "MPPT-PI-P&OC" method is presented in Figure 13. The simulation results of this "MPPT-PI-P&OC" technique under MATLAB/Simulink using the conditions quoted at the beginning of this paper, are presented in Figure 14. The latter is composed of three simulation graphs spread over a duration of 0.3 s. These graphs correspond respectively to the evolutions of the output quantities of the PV panel, namely; the voltage, the current and the electric power.

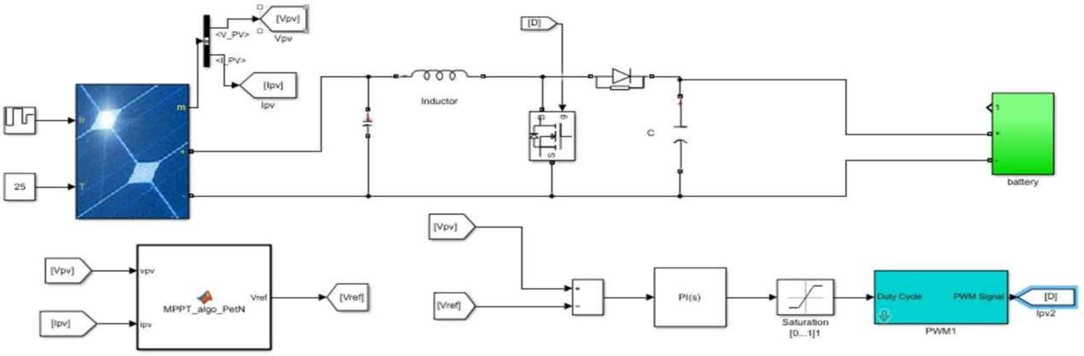


Figure 13. Simulink block diagram used for the "MPPT-PI-P&OC" method

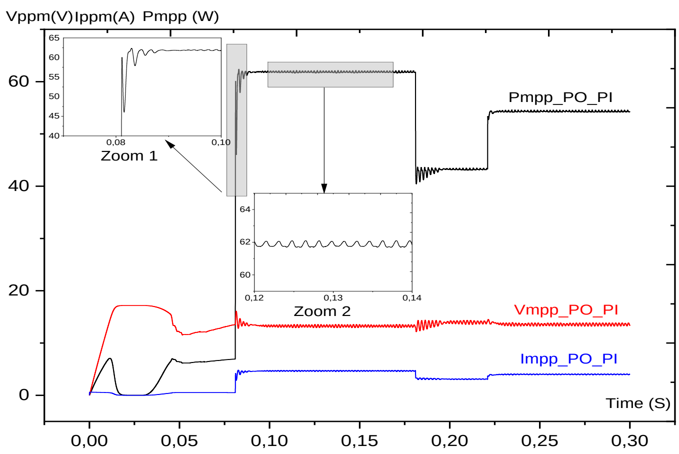


Figure 14. PV system response using the "MPPT-PI-P&OC" algorithm

These simulation results (Figure 14) show that the "MPPT-PI-P&OC" method has the same advantages as the MPPT-PI method over conventional algorithms. However, with this "MPPT-PI-P&OC" method, the system is autonomous because in this case, the reference voltage is automatically evaluated by the P&OC algorithm.

3.4. MPPT control by a fractional order PI and P&OC noted here "MPPT-FOPIP&OC"

In the case of the fractional order PI corrector, the transfer function C(s) is given by the following expression [23], [24].

$$C(s) = \frac{U(s)}{E(s)} = K_p + K_i \frac{1}{s^m} \qquad \text{With } m \geq 0 \tag{3}$$

Where U(s) is the control signal, E(s) is the error signal, Kp is the proportional constant gain, Ki is the integration constant gain and finally m is the integration order.

The synthesis of the fractional corrector we will use is based on the optimization of the parameters Kp, Ki and m using an evolutionary algorithm (PSO) [25]. The proposed scheme for this MPPT control using fractional order PI with P&OC (MPPT-FOPI-P&OC) on MATLAB/Simulink is presented on Figure 15. The simulation results of this algorithm, under the conditions mentioned at the beginning of this work is presented in Figure 16. This Figure 16 shows us that the PV system converges to the optimal values with less oscillations compared to the previous methods.

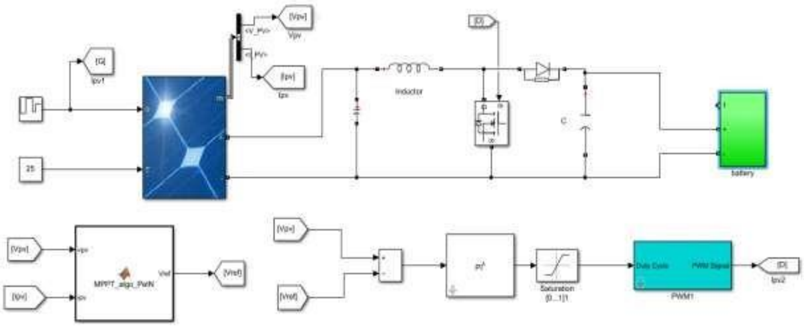


Figure 15. Simulink block diagram adopted for this "MPPT-FOPI-P&OC" technique

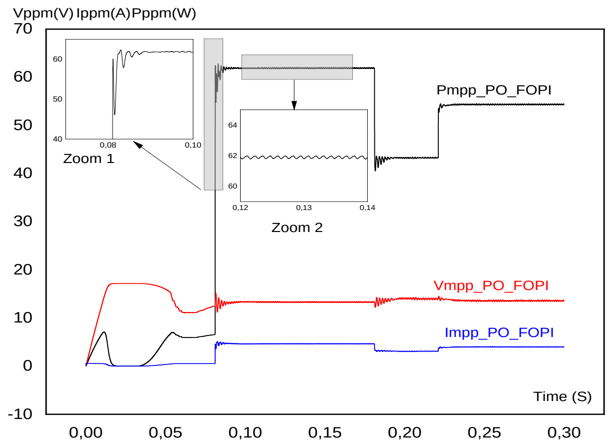


Figure 16. PV system response with the "MPPT-FOPI-P&OC" algorithm

4. COMPARISON OF THE DIFFERENT TECHNIQUES TREATED

A comparison between the different control techniques described above is presented in Figure 17. In order to ensure a proper comparative study between the treated MPPT algorithms, we evaluated some performance parameters; namely the convergence timec and the oscillation deviationo for a tilting irradiation from 600 to 1000 W/m² for each of the four algorithms. The results of the calculations are summarized in Table 4. The results reported in Table 4 show that the best of the four techniques processed is the "MPPT-IncM". It has almost zero oscillations and a static deviation0 less than 0.02 at steady state. By the comparison of results of the various techniques presented in the Table 3. We can conclude that for an irradiance of 1000 W/m2, the IncM method performs the best one. Due to its very low convergence timec and a lowest oscillation deviation of 0.02 s.

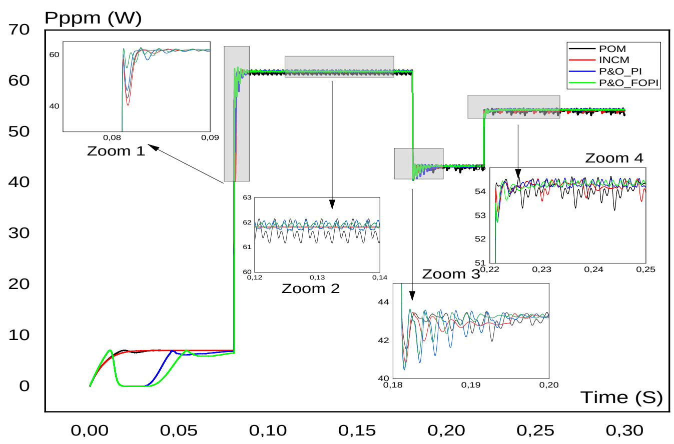


Figure 17. Comparative results between MPPT algorithms

Table 4. Battery specifications

-	Convergence time c (in ms)	Oscillation gap o (in W)
1: P&OM	0.0841	0.19
2: IncM	0.0846	0.02
3: MPPT-PI-P&OC	0.0846	0.32
4: MPPT- FOPI -P&OC	0.0842	0.22

5. CONCLUSION

In our present study we have presented the comparison of four MPPT techniques to optimize the maximum power produced by PV systems. The performance of the proposed techniques, namely: "MPPT-P&OM", "MPPT-IncM", "MPPT-PI-P&OC" and "MPPT-FOPIP&OC" controls have been studied in this work. The simulation results of a PV array and the maximum power were obtained by MATLAB/Simulink development tool. Based on the comparison of the simulation results of the various techniques, we came to the following conclusions: For an irradiance of 1000 W/m^2, the IncM method performs best due to its very low convergence timec and a lowest oscillation deviation of 0.02 s.

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