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Simulation of Photovoltaic Generators and Comparison of two common Maximum Power Point trackers.

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Abstract: Maximum power point tracker algorithms play an important role in the optimization of the power and the efficiency of a photovoltaic generator 'PVG'. We made the comparison between two algorithms currently implemented for the power optimization of PVG. These algorithms are based on the Perturb & Observe and the Conductance-Increment methods allowing the Maximum Power Point Tracking, 'MPPT', principle. The study leads us to conclude that these algorithms are not well adapted for PVG exposures in very unfavorable but realistic external conditions.

Key words:MPPT, PVG (Photovoltaic Generator), Boost (Chopper), microcontroller, solar energy.

I. Introduction

The solar photovoltaic found its utility in applications for small scale, autonomic and isolated or unconnected systems but also for high power PV installations or stations. Photovoltaic energy is a source of interesting energy: it is renewable, inexhaustible and nonpolluting, so that, it is more and more intensively used as energy sources in various applications. Nevertheless, to satisfy industrial, commercial and exploiting constraints link to the cost, the system should present a good exploitation of all the photovoltaic modules and a high general efficiency.

For that, it is necessary to extract the maximum of power from the photovoltaic generator, PVG, i.e. the maximum of the power delivered by the ' PVG', not directly droved by the load. A good profitability of the ' PVG' can be carried out if it works to the maximum of the available solar power all the time. However, the maximum power point 'MPP' varies according to several parameters like the solar irradiation E_s, the temperature T, the nature of the load, the technology of the PV cells and the shadowing of the panels from various sources (falling leaves, dust...). In a current solar photovoltaic system, we can consider the random existence of these parameters. Nevertheless, associated with a voltage converter, e.g. a DC-DC one as in this study, the PVG requires a permanent maximum power production.

Thus, whatever the weather conditions (temperature and irradiation) and whatever the load, the control system of the converter must place the system at the optimal power point (I_{PVopt},V_{PVopt}). Nevertheless, the functioning point of the generator on the I-V curve is dynamically modified; the MPPT must get the MPP (maximum power point) at any moment and must maintain PVG power in the neighborhoods of this point and to produce power with the higher efficiency.

Within this framework, we made a comparison between two algorithms of optimization of the power of the PVG under the Matlab/Simulink environment and test a new algorithm under the software PROTEUS and CCs. The results obtained in these last simulations seem to offer the possibility of an improvement of the PVG efficiency.

II. The Photovoltaic generator

II.1. The photovoltaic cell

In the literature [1], a photovoltaic cell is often presented as in Fig. 1. This model includes also a serial resistance R_s, which represents the ohmic contacts between metal and the semiconductor as well as the intrinsic resistance of silicon and a shunt one R_{sh} linked to the surface quality along the cell periphery.

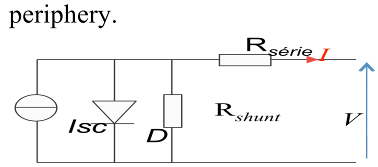


Fig. 1. Equivalent circuit of a photovoltaïc cell

The cell can be described by the relation linking the photo-current of cell, I to the reverse saturation current of the diode I_0 and to the short circuit current I_{sc}(currents expressed in A)as a function of the photovoltaic cell voltage, V (V), the solar radiation, ψ (Wc/m²) and the temperature of the junction, T (K). The characterisitc equation describing the photovoltaic cell is. :

$$I = I_{sc}\left(\frac{\psi}{1000}\right) - I_0\left[\exp\left(\frac{q(V+R_s I)}{nKT}\right)-1\right]-\left(\frac{V+R_s I}{R_{sh}}\right) \qquad (1)$$

with q, the electron charge (1,6 10^{-19} c), k, the Boltzmann constant (1, 38 10^{-23} J/°K) and n the factor of ideality of the photovoltaic cell, (ranging between 1 and 5 in practice.

The simulated I-V and P-V characteristics of such a system deduced from Eq. 1 with Rs =1m,Rsh =15mk are represented in Fig. 2. We notice on these curves the MPP of the PV cell.

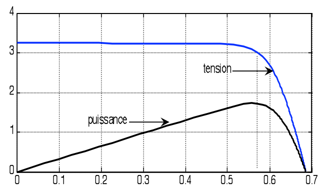
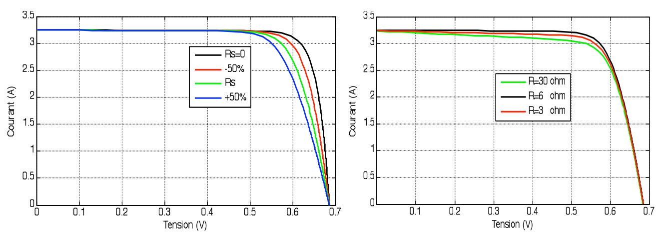


Fig. 2: I-V and P-V cell Characteristics.

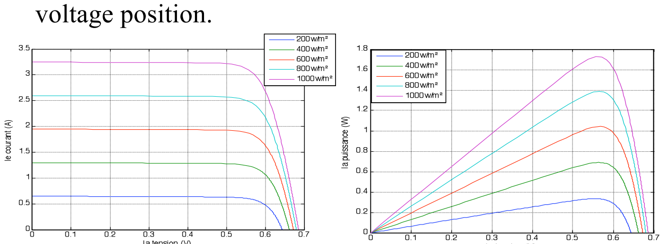
To highlight the influence of the passive components of the cell on its behavior, we have plotted the I-V characteristic at temperature constant, in Figs. 3 (a) and (b), as a function of the resistance $R_s$and R_{sh}, respectively. As predicted by this model, we note a huge displacement of the MPP with $R_s$see Fig. 3, mainly due to a change of the intensity and a small decrease of the voltage with the increase of R_{sh}, see Fig.4.



(a) (b)

Fig.3: Influence of: (a) R_s and (b) R_{sh} on I-V characteristic.

At fixed values for R_s =1 m and R_{sh} = 15k, we report in Fig 5 the influence of the irradiation at constant temperature, T=25°C. We note that the cell can be considered as a current generator and, as a consequence that the MPP move with the irradiation on a constant voltage position.



(a) (b)

Fig. 5: Irradiation influence on PV cell characteristics at constant temperature T=25°C. (a) I-V curves, (b) P-V curves.

For the same values of the resistances, we also report in Fig. 6, and the influence of the temperature at constant irradiation, E=1000 w/m².

As well known, this figure point out the large decrease of the efficiency of a photovoltaic cell with the temperature.

This behavior is mainly due to the influence of the temperature on the delivered voltage by the cell.(1)

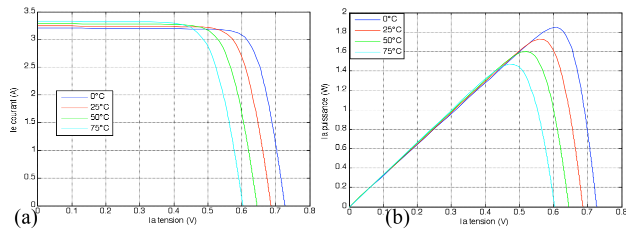
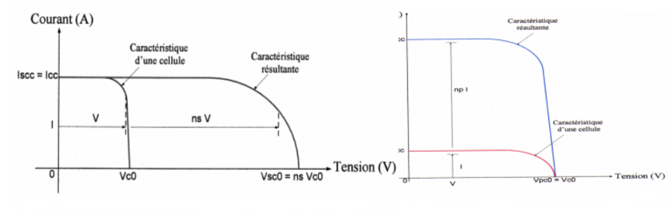


Fig.6: Temperature dependence of the P-V characteristics at constant irradiation E=1000 w/m². (a) I-V curves, (b) P-V curves.

II.2. The photovoltaic array

Practically, a photovoltaic array results of the association of Ns photovoltaic cells in series and Np cells in shunt. The judicious choice of Ns and Np makes the possibility to have the desired output power for a given voltage. In Fig. 7, we show the I-V characteristics for a serial association of cells, Fig. 7.a., i.e. the influence of Ns, for a parallel association of cells, Fig.7.b., i.e. the influence of Np.

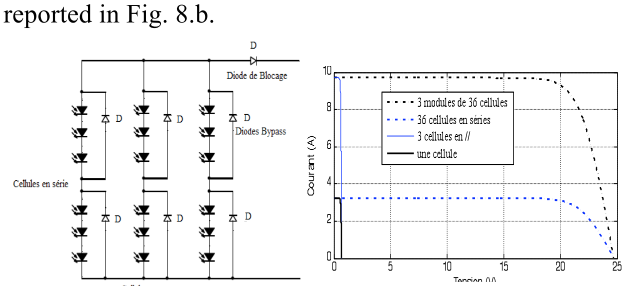


(a) (b)

Fig. 7: I-V characteristic of a photovoltaic module with cells in(a) series associating and in (b) Shunt associating.

II.3. The photovoltaic generator

To consider a real installation comprising a set of module as in Ref.[1], we report in Fig. 8, a practical case which is composedof three panels with thirty-six cells (not all represented), shown in Fig.8.a and its I-V characteristic, reported in Fig. 8.b.



(a) (b)

Fig. 8: (a) Scheme of a photovoltaic generator and (b) its I-V curve compared with I-V curves for modules and cells.

This characteristic is compared with the I-V response for a string of thirty-six cells, a shunt of three cells and an alone cell.

Finally, the complete photovoltaic installation is represented in Fig. 9. It is based on a photovoltaic generator supplying a dc load, i.e. a battery through an adaptation stage constituted by a boost converter headed by a MPPT controller for a maximum efficiency.

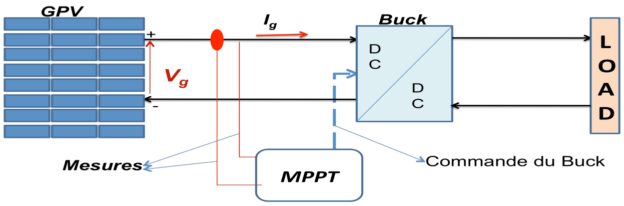


Fig. 9: The complete photovoltaic installation: PVG-Boost-Load and MPPT controller.

Controllers MPPT are usually integrated in the PVG to ensure that it operates on its maximum power point (MPP). These controllers are intended to minimize the error between the available power at PPM and the maximum power of variable reference according to the climatic and external conditions. This MPP value is easily calculated from the product tension-current available at the output of the PVG. Nevertheless, the determination of the maximum reference power is more delicate thanks to the fact that is a function of the climatic conditions, i.e. the illumination and the temperature. This reference, being not constant is characterized by a nonlinear function, returns the high difficulties for the PVG to operate at the maximum power.

In order to overcome these difficulties, several methods are often adopted such as the analogical methods and the numerical methods using of data-processing tools.

III. Evaluation of the two MPPT algorithms

III.1. Perturb-and-observe MPPT algorithm (P&O)

This method has a structure of a simple regulation, and few parameters of measurement [4]. It operates by disturbing the voltage of the panel periodically, and by comparing the energy previously delivered with those after disturbance. This quite simple structure of the process and the few measured parameters required make that these algorithms are widely used in commercial systems.

With the help of an P-V characteristic, as plotted in Fig.10, the principle can be described as follow: If the disturbance as the addition of a positive contribution ΔV to the voltage implies an increase in the delivered power, then the functioning point, i.g. X_i is in the ascending phase of the characteristic and therefore the output voltage will have to be increased up to a new point X_{i+1} and conversely. Treatments have to be in opposite direction when the additive contribution is negative. Under these conditions, the tracker seeks the maximum of power permanently.Nevertheless, the change in power is only considered as a perturbation of the output voltage and the algorithm does not compare this voltage with the present MPP voltage.

At a specified insulation level I_{ph}, the desired PVG current is the solution of the following nonlinear equation:

$$\frac{dP_g}{dI_g} = \frac{d(V_g I_g)}{dI_g} = 0 \qquad (2)$$

with Vg and Ig the voltage and the current at the output of the generator.

As a consequence of the principle of the P&O algorithms, when the MPP is reached, the tracker will oscillate around it, resulting in a loss of PV available power, especially in perturb atmospheric conditions with constant or slowly varying changes. By else, in case of rapid changes of atmospheric conditions, i.e. occurrence of clouds, it is noted that due to the change of the solar radiation, the P&O algorithm deviates from the MPP until a slow solar radiation change occurs or settles down.

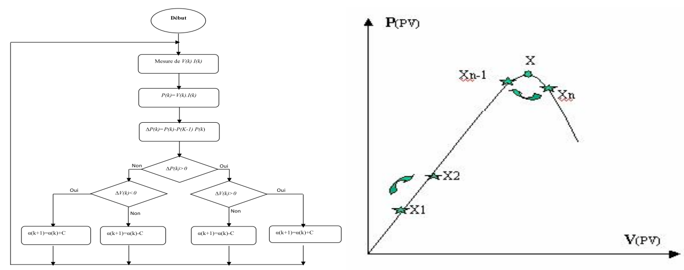


Fig. 10: Flow chart algorithm of perturb-and-observe (P&O) MPPT and principle show in a P-V characteristic.

III.2. Incremental conductance MPPT algorithm(IncCond)

To solve the previous problem, the track of the MPP was performed with an other technique giving rise to the Incremental Conductance algorithm [4]. On the contrary to the P&O algorithms and to avoid their drawbacks, the output voltage of the generator is continuously adjusted according to its value relative to the MPP voltage. Then, the basic principle of this algorithm, represented in Fig.11 calculates the derivative of the power extracted of the installation. The main operation done by this algorithm is to compare the dI/dV to I/V ratios and according to the result of this comparison, the reference signal will be adjusted in order to move the output voltage towards the MPP voltage. This derivative equal zero at the maximum power point and positive on its left and negative on its right.

As well as the PVG power is described by P=VI, the derivative as function of the voltage is then defined by

$$\frac{dP}{dV} = I - V\frac{dI}{dV}, \quad \begin{cases} \frac{dP}{dV} > 0 \text{ if } \frac{dI}{dV} > -\frac{I}{V} \\ \frac{dP}{dV} = 0 \text{ if } \frac{dI}{dV} = -\frac{I}{V} \\ \frac{dP}{dV} < 0 \text{ if } \frac{dI}{dV} < -\frac{I}{V} \end{cases} \qquad (3)$$

Two other controls are included in this algorithm to take into account of a change of the atmospheric conditions when the tracker is located at the MPP. Thus, when dv=0, the determination of the sign of dI indicates the direction of changes.

This algorithm lies a primary advantage over the P&O algorithm by the fact that he can continuously calculate the direction to reach the MPP after a perturbation of the array's operating point and he can determine when the MPP is attained.

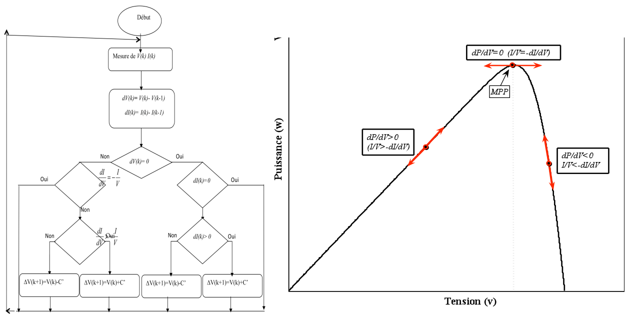


Figure 11: Flow chart algorithm of IncCond MPPT and principle show in a P-V characterisitic.

IV. Experimental procedure and results

To compare the performance of the two common algorithms presented above, we have developed a series of tests based on a change of one functioning parameters of the photovoltaic generator. For that, the algorithms were implemented in a microcontroller under Matlab/Simulink environments. To have an absolute overview of the MPPT, we have also compared the responses of a photovoltaic system without and with a tracker. The general flow chart of the developed simulation tool is represented in Fig.12.

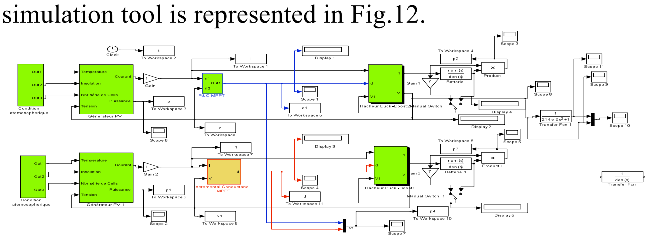


Fig. 12: The Matlab/Simulink Model developed for the series of tests performed on the MPPT algorithms.

IV.1. PVG response to an illumination step

To analyze and compare the performances of the algorithms of the P&O MPPT and the IncCond MPPT methods, we carried out a test in which the photovoltaic generator is exposed at the same standard environmental conditions based on the appearance of a step of illumination. In Fig.13, we report the dynamic response of the PV system dived by the two algorithms.

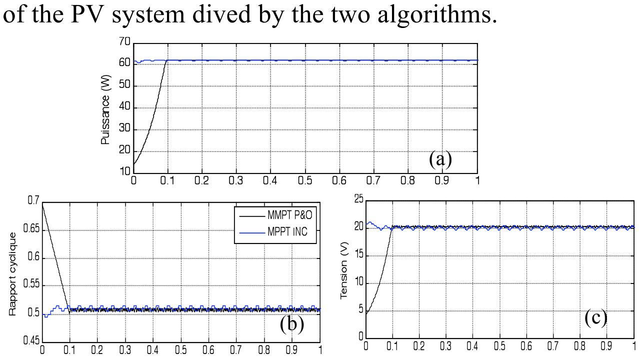


Fig.13: Variation of (a) the power, (b) the voltage of the module and (c) the duty cycle of two controllers P&O MPPT (grey line) and IncCond MPPT (blue line) for T = 25°C and G =1000W/m².

As we can observe in the responses reported in Fig. 12, the two algorithms present response times different to an illumination step. So, these characteristics curves, especially the power and voltage ones show the faster response offered by the IncCond MPPT compared to the P&O.

IV.2. PVG response as function of the charges

To studythe robustness and the performances of the two algorithms we carried out tests without and with the MPPT for the two following cases:

- A dynamic resistor load.
- A battery load.

For the first series of test, a resistor is placed as charge and is continuously set at various values as shown in Fig. 14.

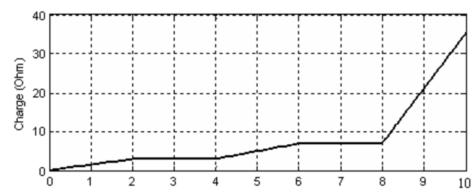
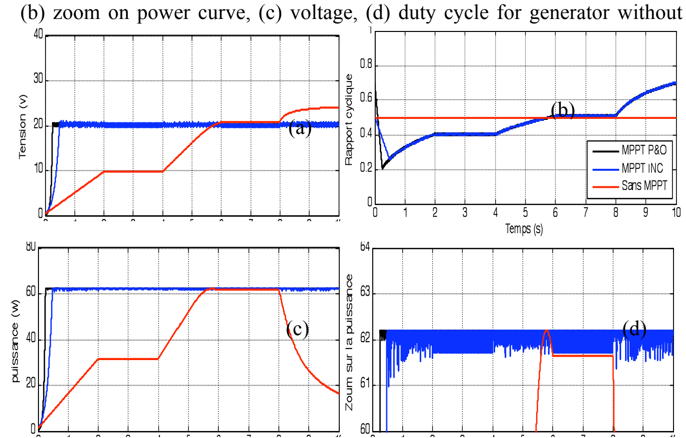


Fig. 14: Dynamic resistor load. The variation of the resistor is shown according to time.

The results of the variation of the resistive charge values on the power and the voltage of the generator and on the duty cycle of the system with and without MPPT are reported in Fig.15 where, in these figures, the blue, grey and red lines are related to the responses with the P&O, Inc-Cond algorithms and without, respectively.

Fig. 15: Influence of the resistor load value according to time on: (a) power, (b) zoom on power curve, (c) voltage, (d) duty cycle for generator without



(red line), with P&O (grey line) and IncCond MPPT (blue line) controllers.

The PVG without MPPTcontroller never work at the maximum power except when the load equals the optimum value of the load impedance. On the other hand, with the both MPPT algorithms the functioning point always follows the maximum power and does not depend on the load variation. We also notice that the PV voltage is stable in the system droved with these MPPT algorithms and, on the contrary, it is variable according to the load without them.

For the second series of tests we simulated the load with three batteries. The results of the response variations of the batteries on the power and on the voltage of the generator with and without MPPT are reported in Fig.16 where, in these figures, the blue, grey and red lines are related to the responses with the P&O, IncCond algorithms and without, respectively.

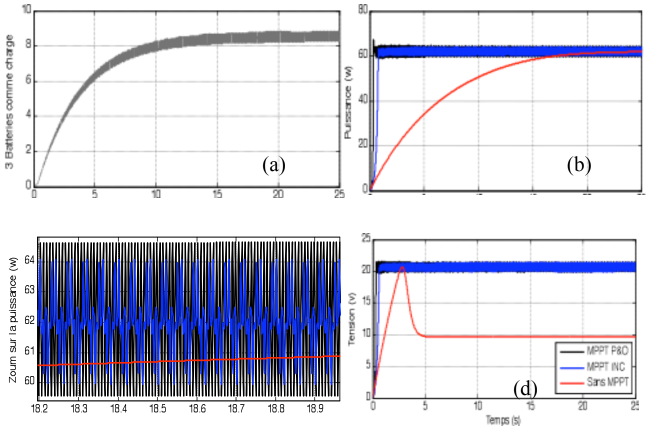


Fig. 16: Influence of the load (a) of three batteries according to time on: (b) power, (c) zoom on power curve, (d) voltage, without (red line), with P&O (grey line) and IncCond MPPT (blue line) controllers.

The maximum power point is achieved by the use of a MPPT stage and for a direct connection. The response closely approaches the optimum efficiency with both MPPT. Nevertheless, the IncCondMPPT presents smaller oscillations around the MPP. The voltage is weaker without the MPPT algorithms and the losses without regulation hugely increase.

IV.3. PVG response to a temperature step

We have also analyzed the influence of the temperature on the response of the MPPT algorithms. For that, we have considered a variation of the temperature from 25°C to 50°C at a fixed irradiation equal to 1000W/m² and we have reported the response of the MPPT in Fig.17.

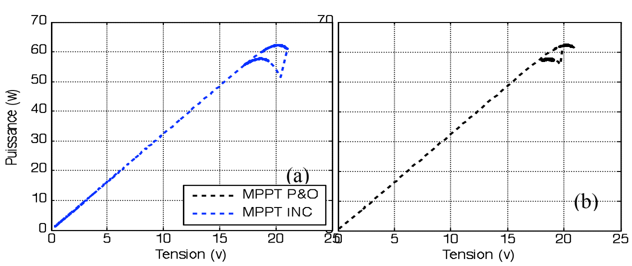


Fig. 17: Characteristic curve P(V) of (a) P&O and (b) IncCondMPPT controllers for a change in the temperature from 25°C to 50°C at a fixed irradiation equal to1000W/m².

These curves show that the P&O MPPT algorithm carries out variations before reaching the new MPP whereas the IncCond MPPT one tends directly towards this MPP. Thus, with this simulation tool, we have highlight the fact that the advantages of the IncCond to the P&O algorithms by a faster achievement of the MPP which is carried out immediately in the good direction without additional oscillations when the MPP is reached.

IV.4. Robustness of the two algorithms

Finally, to study the robustness of the two algorithms with respect to various and randomly environmental conditions, we have defined an original set of tests and are carried out by simulations. Currently, basic tests in literature present change of parameters following a high amplitude step or a rapid change of one of the external parameter of the system. In real conditions of exploitation of the photovoltaic energy production, i.e.when arrays and PVG are exposed to real climatic conditions, for small or unconnected installations or for installations inserted in an energy network, the changes are no so abrupt and not with a so huge amplitude as theoretically simulated. Even when shadows appears on a panel or an array or specially when temperature increase or decrease, the dynamic of the change is in order of the second which is at a minimum of two order of magnitude of the controller response.

Thus, to perform test closer to the reality, we consider the system under various environmental conditions:

- Initially the temperature is maintained constant *(T=25°C)* and the solar radiation increases or decreases (Fig. 18).
- Then the illumination is maintained with a fixed value *(1000 W/m²)* and we varies the value of the temperature in the two directions of variation (Fig. 19).
- And finally, we subjected two algorithms *MPPT* to a random change of temperature (Figure 20).

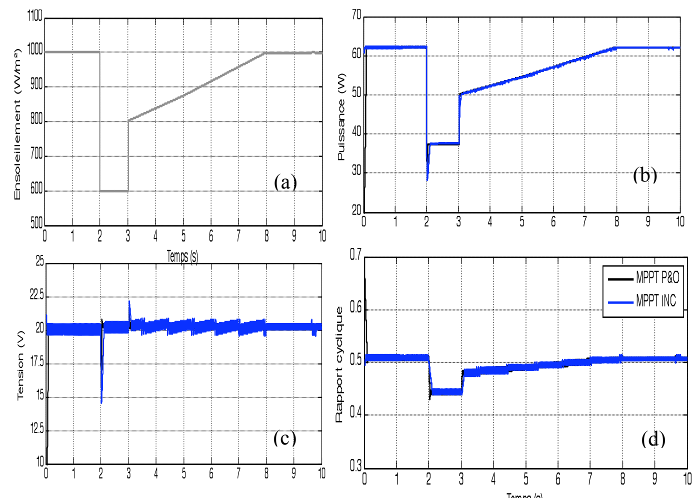


Fig. 18: P&O MPPT and IncCond MPPT algorithm responses for a variation of illumination and a constant temperature of 25°C: (a) variation of the irradiation, (b) PVG power, (c) PVG voltage, (d) duty cycle.

In a first approach and at the contrary to the P&O algorithm, we can predict that the IncCond algorithm doesn't track in the wrong direction after a rapid change of the functioning conditions and doesn't oscillate about the MPP when it reaches it.

We can noticed that IncCond MPPT offers a better continuation to discontinuous changes of the atmospheric conditions, but the differences in both algorithms is not drastic in case of continuous changes of the irradiations. We can also confirm with these tests that the temperature is a well-known factor that decreases the efficiency of the installation.

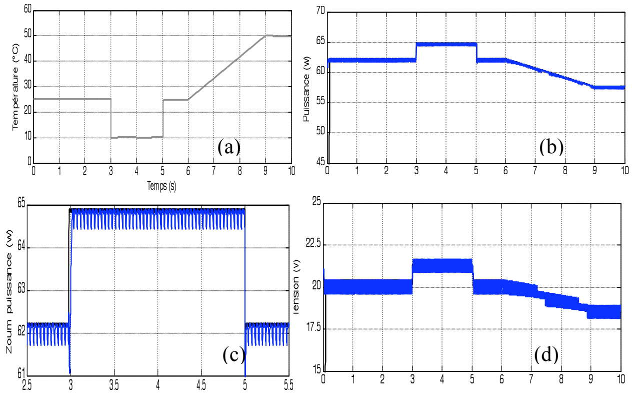


Fig. 19: P&O MPPT and IncCond MPPT algorithm responses for a variation of temperature and a constant illumination of 1000W/m^2: (a) variation of the temperature, (b) PVG power, (c) Zoom in PVG power, (d) PVG voltage.

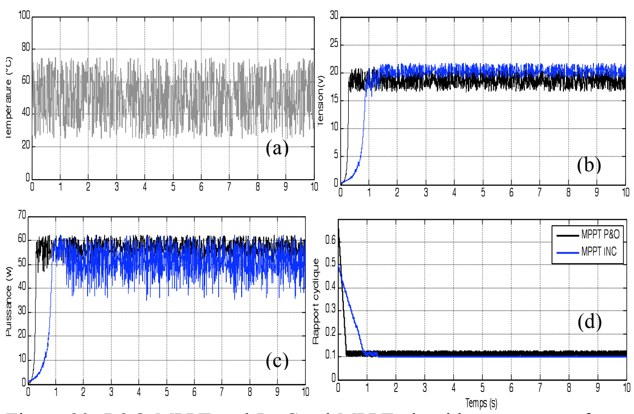


Figure 20: P&O MPPT and IncCond MPPT algorithm responses for a random variation of temperature: (a) variation of the temperature, (b) PVG power, (c) PVG voltage, (d) duty cycle.

Finally, even if the overall better intrinsic performances of the IncCond algorithm can be shown by this study, we have to consider the simplicity of the P&O MPPT one, which makes it largely used according to the facility to implement in practical applications.

V. Conclusion

In this study, we investigated the optimal utilization of the solar energy by analyzing and comparing the two most common algorithms used for maximum power point tracking. The optimization has been targeted towards the implementation of the maximum power point tracker algorithms in Matlab/Simulink environment. The role of the maximum power point tracker was to match the load power required with a maximum of the available power that can be generated from a photovoltaic generator (PVG), i.e. with the higher efficiency. The maximum power point will be reached by any irradiation levels and for any temperatures or variations of them. The simulation results prove positively that the P&O and the IncCondMPPTs reach the intended maximum power point tracker. Nevertheless, the approach and the stability of the MPP are not achieved within the same manner. The IncCond MPPT presents better efficiency for rapid changes and a better stability when the MPP is achieved. However, the P&O MPPT are widely used in practice due to their simplicity.

The originality and the specificity of the presented resultsobtain during this research reside in the fact that external parameters as irradiation and temperature were introduced, at first as linear functions and, at second as random ones describing more closely the real applicative conditions. In cases of random functions for the simulation of external parameters, the defects and any other unfavorable conditions, which can affect the PVG are taken into considerations. We have shown that the two simulated MPPT algorithms responded with a non optimal efficiency to these functions in order to reach the MPP.

This work is the first part of a global research on MPP trackers. A novel algorithm, which was developed, recently tested and implemented in a microcontroller for the driving of DC-DC Boost generator, will be presented soon. This new algorithm avoids the drawbacks of the P&O and IncCond algorithms presented in this communication.`

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