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Modeling and simulation of a photovoltaic conversion system

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Abstract—this paper presents the implementation of a generalized photovoltaic model using MATLAB / SIMULINK. This mathematical model is based on equations that refer to an equivalent circuit. It allows the prediction of the behavior of PV cells, taking into account the impact of solar radiation and temperature variation. The objective of the designed system is to guarantee a maximum power operation. The adaptation between the PV generator and the load was carried out by means of a booster and inverter converter controlled by a pulse width modulation (PWM).

The different simulation results of our conversion system under the MATLAB/SIMULINK environment, improve the system performances, the high stability, the high efficiency and robustness of the proposed control with good performances.

***Index Terms*—Photovoltaic (PV), irradiation, temperature, MPPT, booster, Inverter, PV cells, PV module,PI Controller, PWM, Perturb and observe (P&O).**

I. INTRODUCTION

With the expansion of social welfare devices and the automation of production in different economic fields, the global energy consumption continues to increase as never before. Most of the energy comes from fossil fuels (oil, natural gas, ... etc.), whose extensive use can lead to the depletion of these reserves and actually threatens the environment mainly through pollution and global warming of the earth by greenhouse gases. In this context, the awareness of the importance of a sustainable economic development is deemed necessary. Face to these problems, and to limit the use of extinguishable fuel source, some countries have opted for renewable energy sources (wind, solar, hydro, hydrogen, ...) which have the potential to produce clean electricity and especially in less dependence to resources provided that they accept their natural and sometimes random fluctuations. In this study, we focus on the exploitation of the solar potential i.e. the development of photovoltaic energy in an isolated site.

Photovoltaic energy (PV) is the direct conversion of light into electricity using solar cells is an interesting alternative that fits specific needs. Despite its easy implementation, its low environmental impact and low maintenance that it requires, the performance of a PV system depends highly on weather conditions, such as solar radiation and temperature.

The main objective of this paper is to provide power to a load in an isolated site with recourse to PV energy. The first of this paper presents an analytical model of the PV module based on mathematical equations. The second part describes the control algorithm that guarantees the extraction of the maximum power based on a conventional PI control while ensuring the control of a booster and inverterconverter installed at the output of the PV panel. The effects of solar variation and the influence of temperature on the photovoltaic panel are presented in the third part. The final parts describe the validation of our photovoltaic model by using an experimental banc. The conclusion and future works are presented in the last section.

II. PHOTOVOLTAIC MODEL

The photovoltaic effect principle lies in a collision of incident photons (light output) with free electrons and valence electrons by sharing energy h_{υ}. If this energy is greater than or equal to the gap energy of the semiconductor (E_g=E_c-E_v), the electron moves from the valence band to the conduction band leaving a void, thus the onset of electrons-void pairs at different parts of the junction.Solar radiation is anelectromagnetic radiation composed of light particles called photons. The energy of each photon is directly related to the wave length. 98% of energy is between $\lambda = 0.25\mu m$ and$\lambda = 4\mu m$; the remainder is 1% above and 1% below this interval.

A. PV cell modelling

The solar cell is a means for the conversion of light into electrical energy by a process called the photovoltaic effect.

The solar cells technologies are divided into two main categories:

- The crystal cell:

This technology is whether mono or poly crystalline. It is characterized by its robustness (life expectancy: 30 years), the yield is about 13%. These cells are suitable for powers of a few hundred watts to a few tens of kilowatts. They represent the majority of the world production.

- The amorphous cell:

Manufacturing costs of amorphous cell are significantly better than those of the crystalline silicon. Amorphous cells are used wherever an economical alternative is sought, or when very little electricity is needed (for example, power watches, calculators, emergency lights). They are also often used where strong heating of the modules is expected. However, the yield is more than two times lower than that of crystalline silicon and therefore requires more surface area for the same installed power. The amorphous silicon cells are today less used in global production.

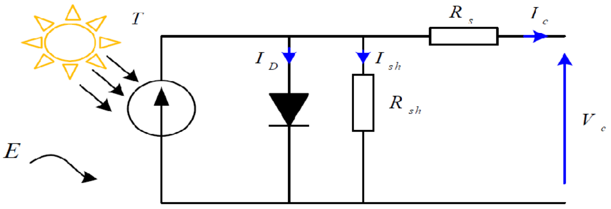

Fig.1. PV cells equivalent circuit.

$$I_{pv} = I_0 - I_D - I_p \qquad (1)$$

$$I_p = \frac{(V_{pv} + R_sI_{pv})}{R_p} \qquad (2)$$

Where:

I_{pv}: Photocurrent

I_s: Reverse saturation current of diode (A),

q: Electron charge (1.602×10 -19 C),

V: Voltage across the diode (V),

K:Boltzmann's constant (1.381×10 -23 J/K),

T: Junction temperature in *Kelvin (K).*

R_s: Series resistance of diode,

R_{sh}: Shunt resistance of diode,

I_D: diode current, it is the same order of magnitude as$I_{RP}$for low voltages and becomes very large in the vicinity of the V_{co}, it is expressed as follows:

$$I_D = I_0\left(e^{\frac{qV_D}{AKT}} - 1\right)(3)$$

Where:

$$V_D = V_{pv} + R_sI_{pv} \qquad (4)$$

A: the ideality factor dependent on recombination mechanisms in the space load area for cells currently marketed in silicon: A = 1

$$I_{pv} = I_0 - \mathrm{I}\left(e^{\frac{qV_D}{AKT}} - 1\right) - \frac{(V_{pv} + R_sI_{pv})}{R_p} \qquad (5)$$

1) I_{sc} short-circuit current

This is achieved when the module terminals are connected to an ideal conductor called (I_{sc}), through which a current flows. In this situation, the voltage between the terminals of the module is equal to zero.For a zero output voltage, we obtain:

In the case of an ideal cell $R_s = 0$ and $R_p -> \infty$

$$I_{sc} = I_0 \qquad (6)$$

Taking into account the effect of resistors RS and RP; the short-circuit current varies according to the two resistors and is proportional to the flow incident.

$$I_{sc} = I_0 - \mathrm{I}\left(e^{\frac{qR_sI_{sc}}{KT}} - 1\right) - \frac{R_sI_{sc}}{R_p} \qquad (7)$$

2) Open circuit voltage V_{co}:

This point is obtained when the terminals of the module are disconnected. This module presents a voltage V_{co} analytically expressed with the equation

In the case of an ideal cell $R_s = 0$ and $R_p -> \infty$

$$I_{sc} = I_0 \qquad (8)$$

V_{co} increases as I_0decreases, it depends only on the nature of the crystal and junction

$$V_{co} = \frac{KT}{q}Log(1 + \frac{I_{sc}}{I}) \qquad (9)$$

B. PV module modelling

The power delivered by cells is not enough to power a load. Indeed, it must connect multiple cells in series and in parallel to form a PV module and obtain the desired power, defining the concept of photovoltaic generator (GPV). For each module, the manufacturer gives the short-circuit current (I_{sc}) and open circuit voltage (V_{co}) at standard conditions (T = 25 ° C andE_s = 1000W / m2). We consider Ns the number of modules connected in series in a branch and $N_p$the number of branches connected in parallel.

III. CONTROL STRATEGY OF PHOTOVOLTAIC CONVERSION SYSTEM CONNECTED TO AC LOAD

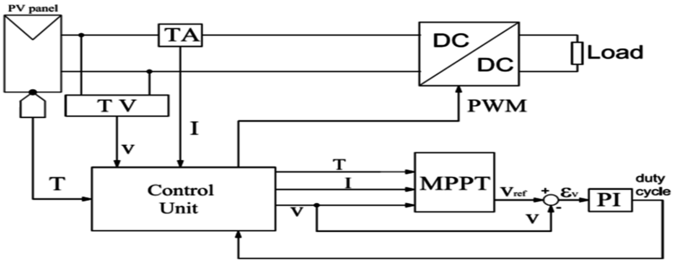

Fig.2.Control strategy of a photovoltaic system

A. Maximum Power Point Tracking (MPPT)

The step-up choppers are frequently used in photovoltaic applications. Modelling a booster chopper is obtained by applying the fundamental laws governing the operation of the system. A boost converter is a power converter with a DC voltage output larger than its DC input voltage. The basic components of the power supply switch mode are two static semiconductor switches (diode D and K transistor IGBT), a real capacitor at the input to transform the GPV into a voltage source.The inputs of the MPPT controller are the voltage and current of the PV array, and its output is the reference voltage used for the PI control of the DC-DC. When atmospheric conditions changes, the MPPT controller increments or decrements the reference voltage by a predefined iteration step in order to reach the new MPPT.The MPPT controller delivers the appropriate control action to follow the maximum power pointin every moment. The latter acts directly on the duty cycle of the chopper inverter.

MPPT is essentially a real time process to search for the operating point, which gives the maximum available powerthat can be extracted from the PV under given operating conditions. Three MPPT control algorithms are here presented:

- First Order Differential (FOD)
- Perturb & Observe (P&O)
- Incremental Conductance (IC)

The figure below shows the classical algorithm associated with MPPT control type P&O, where the power evolution isanalysed after each voltage disturbance. For this type of control, two sensors (measuring the current and voltage of PV panels) are needed to determine the power of the PV every moment.

$$\frac{\partial P}{\partial V_{pv}} = \frac{\partial (V_{pv}) I_{pv}}{\partial V_{pv}} \tag{10}$$

$$\frac{\partial P}{\partial V_{pv}} = I_{pv} + V \frac{\partial I_{pv}}{\partial V_{pv}} \tag{11}$$

$$\frac{\partial P}{\partial V_{pv}} = 0 \tag{12}$$

$$\frac{\partial P}{\partial V_{pv}} = \frac{\Delta I}{\Delta V_{pv}} = \frac{-1}{V} \tag{13}$$

$\frac{\Delta \mathrm{I}}{\Delta \mathrm{V}_{\mathrm{pv}}}$: Presents the incremental conductance

$\frac{1}{\mathrm{V}}$: Presents the instantaneous conductance

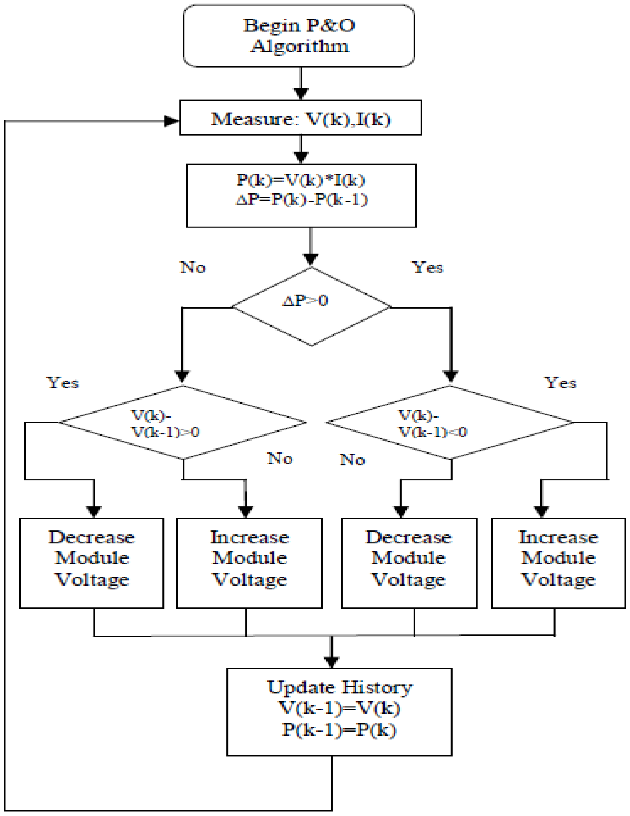

Fig.3.Flow chart of the P&Oalgorithm

The MPPT can be tracked by comparing $\frac{1}{V}$to $\frac{\Delta I}{\Delta V_{pv}}$as follows

$\frac{\Delta I}{\Delta V_{pv}} = -\frac{1}{V}$, at MPPT

$\frac{\Delta I}{\Delta V_{pv}} > -\frac{1}{V}$, left of MPPT

$\frac{\Delta I}{\Delta V_{pv}} < -\frac{1}{V}$, right of MPPT

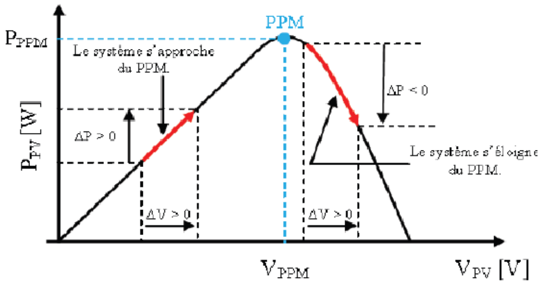

Fig.4. $P_{pv}(V_{pv})$ characteristics of a module photovoltaic

B. *Boosterconvertercontrol strategy*

Theboostconverter is DC-DC converters whom are used to transfer power of solar panel to load side ensuring that maximum power has been transferred [12]. The regulation is normally achieved by pulse within modulation (PWM) and the switching device is normally MOSFET or IGBT. Boost dc-dc converter's function is to step up dc voltage. Fig. 10 shows configuration of dc-dc boost converter with PV as input. Maximum power is reached when the MPPT algorithm changes and adjusts the duty cycle of the boost dc-dc converter.

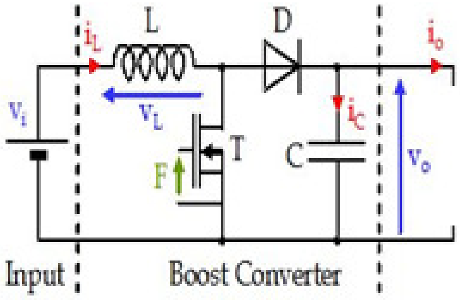

Fig.4.Boost converter Circuit

The boost converter operates in two modes:Discontinuous mode and continuous mode.

We interest to present the continuous mode, when the current through the inductor (I_L) never falls to zero.

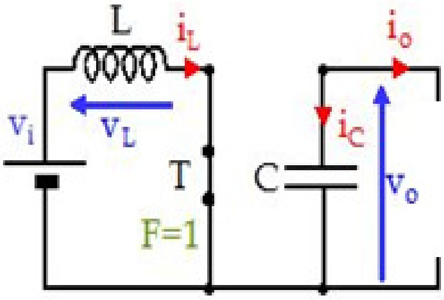

Fig.5.Boost converter Circuit on t= Ton

During the On-state, the switch S is closed, which makes the input voltage (V_i) appear across the inductor, which causes a change in current (I_L) flowing through the inductor during a time period (t) by the formula:

$$\frac{\Delta I_L}{\Delta t} = \frac{V_i}{L} \qquad (14)$$

At the end of the On-state, the increase of I_L is therefore:

$$\Delta I_{L_{on}} = \frac{1}{L}\int_0^{\alpha T} V_i \, dt = \frac{\alpha T}{L} V_i \qquad (15)$$

A α is the duty cycle. It represents the fraction of the commutation period T during which the switch is on. Therefore α ranges between 0 (S is never on) and 1 (S is always on).

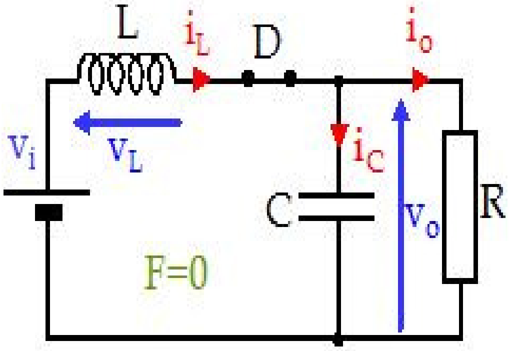

Fig.6.Boost converter Circuit on the t= Toff

During the Off-state, the switch S is open, so the inductor current flows through the load. If we consider zero voltage drops in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of I_L is:

$$V_i - V_{out} = L\frac{dI_L}{dt} \qquad (16)$$

Therefore, the variation of I_L during the Off-period is:

$$\Delta I_{L_{off}} = \frac{1}{L}\int_0^{\alpha T} (V_i - V_{out}) = \frac{(V_i - V_{out})(1-\alpha)T}{L} \qquad (17)$$

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. In particular, the energy stored in the inductor is given by:

$$E = \frac{1}{2} L I_L^{\,2} \qquad (18)$$

So, the inductor current has to be the same at the start and end of the commutation cycle. This means the overall change in the current (the sum of the changes) is zero:

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = 0 \qquad (19)$$

Substituting $\Delta I_{L_{on}}$ *and* $\Delta I_{L_{off}}$ by their expressions yields:

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = \frac{V_i \alpha T}{L} + \frac{(V_i - V_o)(1-\alpha)}{L} = 0 \qquad (20)$$

This can be written as:

$$\frac{V_0}{V_i} = \frac{1}{1-\alpha} \qquad (21)$$

The above equation shows that the output voltage is always higher than the input voltage (as the duty cycle goes from 0 to 1), and that it increases with α, theoretically to infinity as α approach 1. This is why this converter is sometimes referred to as a step-*up* converter.

Rearranging the equation reveals the duty cycle to be:

$$\alpha = 1 - \frac{V_i}{V_o} \qquad (22)$$

IV. SIMULATION RESULTS

The following figures show the current-voltage and power-voltage characteristic of a solar PV cell depending on the illumination at a constant temperature and the temperature at a constant illumination.Simulation results under Matlab/ Simulink environment showed that it is possible to properly adjust the MPPT adaptation.

We start with a constant Temperature at T=25°C with illumination between 200W/m2 and 1000W/m2.

This model includes two subsystems: one that calculates the PV cell photocurrent which depends on the radiation and the temperature according to equation:

$$I_{ph} = I_{sc} + K_i(T - 298)\frac{\beta}{1000} \qquad (23)$$

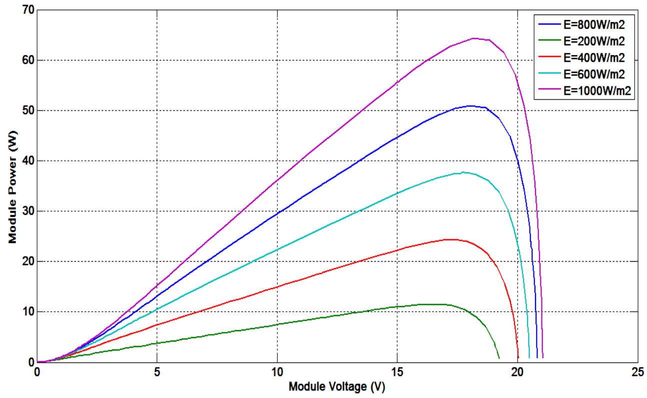

Fig.7. P-V characteristics with varying irradiance & constant temperature

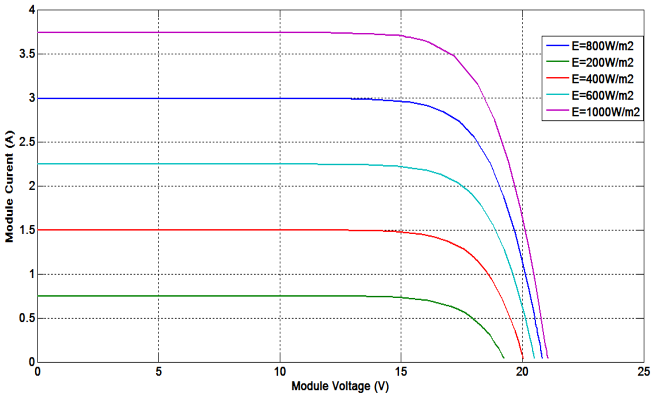

Fig.8. I-V characteristics with varying irradiance and constant temperature

The characteristic I = f (V) indicates that there are two regions in the curve: one is the current source region and the other is the voltage source. At the voltage source region (on the right of the curve), the internal impedance is low and in the current source region (on the left of the curve), the impedance is high. We notice that the short-circuit current I_{sc} is directly proportional to the incident light intensity. On the other hand, the increase of solar radiation causes a slight increase in the open circuit voltage V_{co}.

Temperature is an important parameter in the behaviour of solar cells since they are exposed to solar radiation. The curves I = f (V) and P = f (V) for various temperatures with a sunlight set at 1000W / m2 are presented in the figure 9 and 10. This figure shows the influence of temperature on the characteristic of the solar cell.

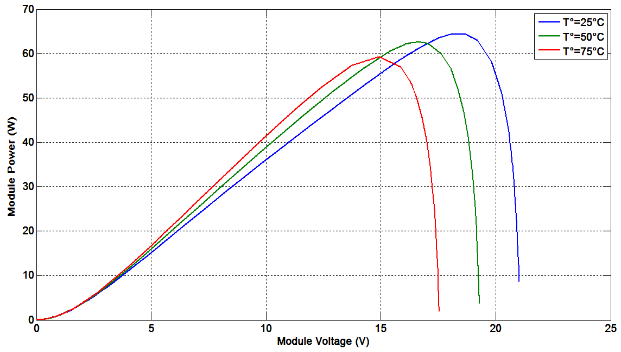

Fig.9.P-V Characteristics with varying temperature and constant irradiation

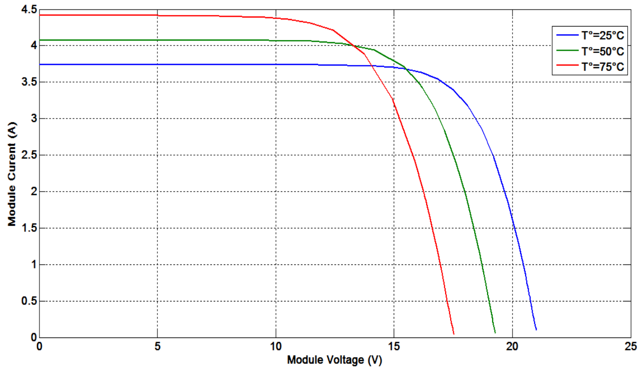

Fig.10. I-V Characteristics with varying temperature and constant irradiation

The diode reverse saturation current varies as a cubic function of the temperature and it can be expressed as:

$$I_s(T) = I_s\left(\frac{T}{T_{nom}}\right)^3 \exp\left[\left(\frac{T}{T_{nom}} - 1\right)\frac{E_g}{NV_t}\right] \qquad (24)$$

If the temperature of the cell increases, the I_{ph} photocurrent increases as well mainly due to the reduction of the width of the forbidden band of the material.The direct current of the junction also increases but much faster resulting in a decrease in the open circuit voltage per cell.We notice that the increase in temperature causes an increase in short-circuit current (I_{sc}). We obtain at the same time a marked decrease in the open circuit voltage (V_{co}) and then a relative decline of maximum power (P_m). The electrical characteristic P - V and I - V of the used GPV type turns close to that of the PV cell with close proportionality reports. These reports depend on the number of cells connected in series and the number of cell branches associated in parallel. This characteristic is not linear, it has a maximum power point (MPP), characterized by a current (I_{max}) and a voltage (V_{max}).

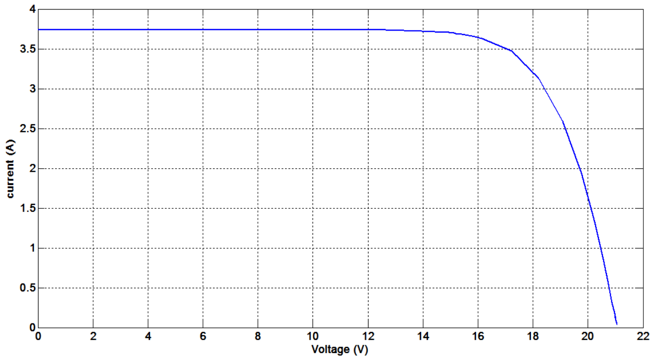

Fig.11.I-V curves of the PV cell model

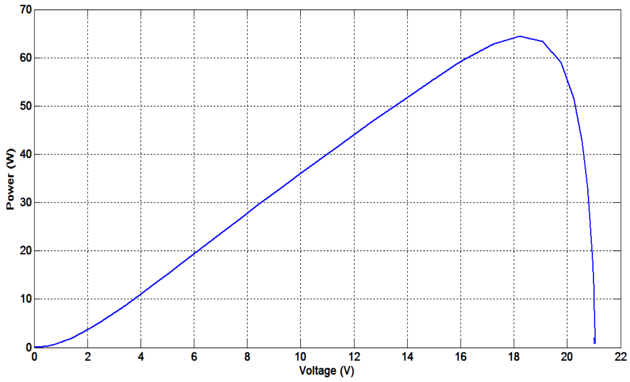

Fig.12. P-V curves of the PV cell model

Our objective is to present the comportment of the photovoltaic systems during the radiation variation with temperature T = 398K presented by the fig.14. The radiation level varies between 1000 Wh / m2 / days and 600 Wh / m2 / days. In this context, Figure 15 and Figure 16 respectively show the power generated by the photovoltaic system and the current drawn by the load. Indeed, we observed in our case the effect of control by P & O. It is also clear that these gaits show no oscillations on the first hand and they quickly reach their maximum values set out in the conditions considered on the second hand.

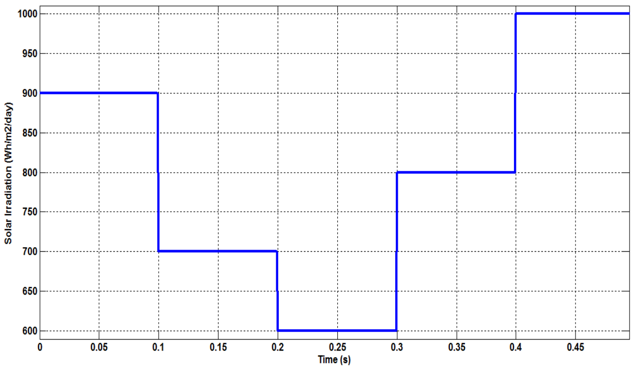

Fig.14.Radiation variation

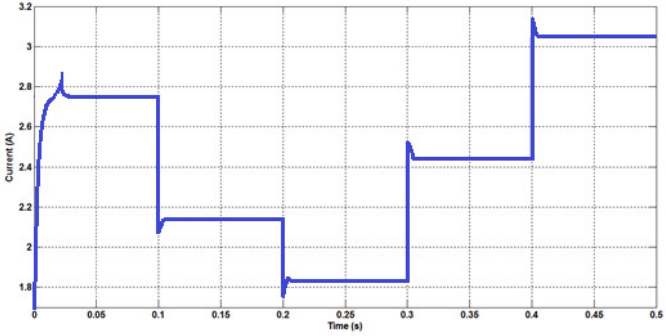

Fig.15.active power generated by the PV system based on the P & O algorithm

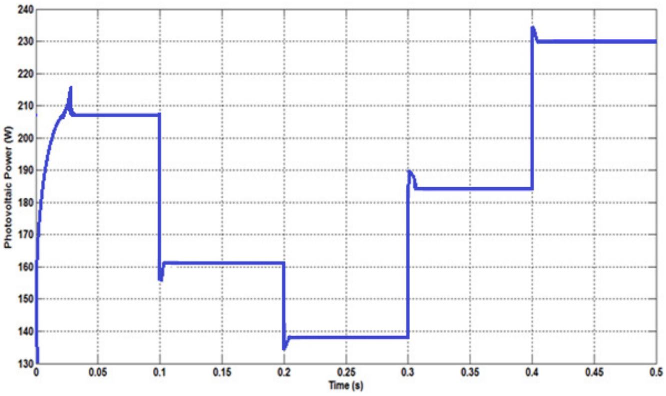

Fig.16.Current generated by the PV system based on the MPPT control

The evolution of PV voltage is presented by figure 17:

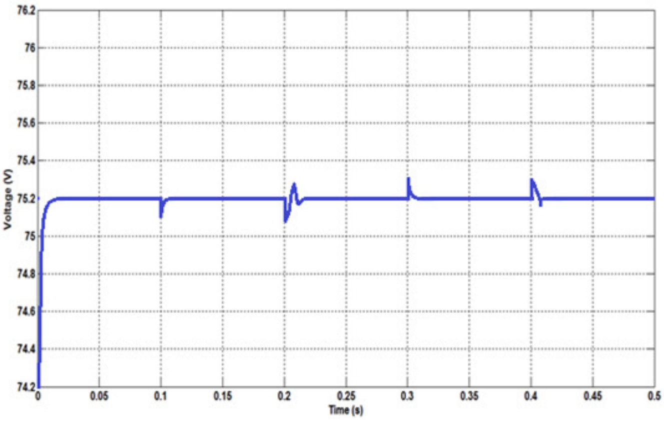

Fig.17. PV voltage response based on MPPT control

CONCLUSION

To obtain the best power transfer between the photovoltaic generator GPV and the load, we modelled an entire conversion chain with 'MATLAB/SIMULINK' and the search algorithm of maximum power point tracking (MPPT). It forces the GPV generator to work its Maximum Power Point Tracking (MPPT) by using the Perturb and observe algorithm, leading to an overall improvement in the performance of an electric conversion system. An improvement of the algorithm may be necessary in the case of sudden changes in temperature and solar radiation.

A control strategy by the classic PI leads to minimizing the fluctuation of the continuous bus despite the variation of the sunlight and temperature. Therefore, temperature and radiation have an important role in the prediction of the characteristic I-V and the effects of these two factors must be considered when designing the PV system.

A simulation results valid our photovoltaic system model and improve the system performances, the high stability, the high efficiency and robustness of the proposed control with good performances.

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