

# Design, Simulation and Voltage Control of Standalone Photovoltaic System Based MPPT: Application to a Pumping system

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**Abstract-** In this paper a circuit-based simulation model is defined for a PV cell in order to allow estimating the electrical behaviour of the cell with respect changes on environmental parameter of temperature and irradiance. Maximum power point trackers (MPPT) play an important role in photovoltaic (PV) power systems because they maximize the power output from a PV system for a given set of conditions, and therefore maximize the array efficiency. DC-DC converters together with MPPT systems are used to avoid the energy losses. Different algorithms have been proposed for maximum power point tracking, the Perturb & Observe (P&O) and Incremental Conductance (incCond) methods are illustrated in this work. In this paper the implementation of a photovoltaic model using Matlab/Simulink are presented, which can be representative of PV cell module, for easy use on simulation platform. Taking the effect of sunlight irradiance and cell temperature into consideration, the output current and power characteristics of PV model are simulated and optimized using the proposed model. Next, a voltage control of a photovoltaic system is studied in order to have a constant voltage at the output, always keeping the system to operate at maximum power. Indeed, in most industrial applications, the load must be supplied by a constant voltage. The simulation results are carried out using Matlab/Simulink.

**Keywords:** Photovoltaic generators, Maximum power point tracking (MPPT), DC-DC converters, PWM generator, Voltage control.

## 1. Introduction

A PVG consists of a number of solar cells connected as series and parallel units depending on the required power, voltage and current ratings. Although their prices are decreasing, PVG systems still require expensive investments. Therefore, it is very important to extract as much energy as possible from a PVG system. A PVG can only be used efficiently when it operates at its optimum operating point. In fact, that is ensured by using MPPT technique which allows to the PV system to track its maximum power. Since the operating point of a PVG-load system depends on the load, irradiance and temperature [1], it is almost impossible to utilize the total available solar energy in varying load and

atmospheric conditions with an uncontrolled system. It is crucial to force PVG systems to operate at their optimum operating points. Therefore, various solutions are presented in the literature.

The perturbation and observation method is an algorithm which is used in maximum power tracking. It is based on periodically changing the operating point and observing the resultant change in power. Although it is well established algorithm, some confusions and instabilities may occur when the irradiation and (or) load changes rapidly and randomly. Another algorithm (Incremental Conductance) is based on the searching of operating point which makes  $dP/dV = 0$ . Since the sign of  $dP/dV$  gives the direction of the search, it is

possible to determine the maximum power operation by continuously detecting the PVG power and voltage [2].

The nonlinear characteristics of the photovoltaic module and its sensitivity to external conditions, such as light and temperature, induce energy losses. As an adequate solution to this problem, we can opt for the MPPT technique. Indeed, this technique is based on the use of an adaptation interface. This interface is constituted by a DC-DC converter which is mounted between the PV module and the load, maximizing therefore at any time the energy [3].

In this paper, we are interested especially to the design, the simulation and the voltage control of a standalone Photovoltaic (PV) system based on MPPT technique with an application to a pumping system.

We present a photovoltaic module with a stage adaptation of DC-DC between the PV cell and the output load. This structure allows most often feed a load or using a battery of stock of energy. This stage adaptation has a command MPPT, which allows it to track the MPP that can provides a photovoltaic solar panel. The MPPT search algorithm may be more or less complex depending on the type of implementation chosen and the performances. In Our study we used the (P & O) method [4].

In our study, a PV system including the MPPT technique with a constant resistive load is designed and simulated. The curves of input and output voltages and currents for variation of temperature and irradiance are shown. Then, we cause sudden climatic variations (such as irradiance and temperature) in order to study the behaviour of the PV system.

Finally, we present a system for regulating the output voltage of the photovoltaic system. We test this system for a resistive load and for a centrifugal pump driven by a permanent magnetic DC (PMDC) [5].

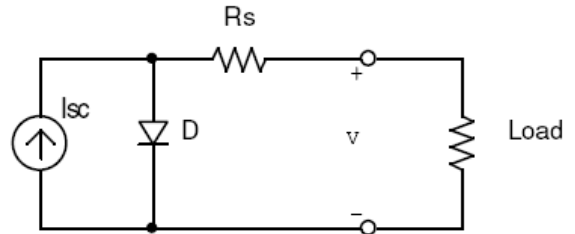
**2. Photovoltaic modules**

Solar cells consist of a p-n junction fabricated in a thin wafer or layer of semiconductor. In the dark, the I-V output characteristic of a solar cell has an exponential characteristic similar to that of a diode. When exposed to light, photons with energy greater than the bandgap energy of the semiconductor are absorbed and create an electron-hole pair. These carriers are swept apart under the influence of the internal electric fields of the p-n junction and create a current proportional to the incident radiation.

*2.1. Modelling the Solar Cell*

The model consists of a current source (**I<sub>sc</sub>**), a diode (**D**), and a series resistance (**R<sub>s</sub>**), shown in Figure 1.

The effect of shunt resistance (**R<sub>sh</sub>**) is very small in a single module, thus the model does not include it. To make a better model, it also includes temperature effects on the short-circuit current (**I<sub>sc</sub>**) and the reverse saturation current of diode (**I<sub>0</sub>**). It uses a single diode with the diode idealist factor (**n**) set to achieve the best I-V curve match [6, 4].



**Fig. 1:** Equivalent circuit used in the MATLAB simulations

The equation that describes the current-voltage relationship of the PV cell is [4]:

$$I = I_{sc} - I_0 \left[ e^{q \left( \frac{V + I R_s}{nkT} \right)} - 1 \right] \tag{1}$$

Where:

- I** is the cell current,
- V** is the cell voltage,
- T** is the cell temperature in Kelvin (**K**),
- I<sub>0</sub>** is the reverse saturation current of diode (**A**),
- q** is the electron charge (**1.602×10<sup>-19</sup> C**),
- k** is the Boltzmann’s constant (**1.381×10<sup>-23</sup> J/K**).

First, calculate the short-circuit current (**I<sub>sc</sub>**) at a given cell temperature (**T**):

$$I_{sc(T)} = I_{sc(Tref)} \cdot [1 + a(T - Tref)] \tag{2}$$

Where:

- I<sub>sc</sub>** at **Tref** is given in the datasheet (measured under irradiance of **1000W/m<sup>2</sup>**),
- Tref** is the reference temperature of PV cell in Kelvin (**K**), usually **298°K (25°C)**,
- a** is the temperature coefficient of **I<sub>sc</sub>** in percent change per degree temperature, it is also given in the datasheet.

The short-circuit current (**I<sub>sc</sub>**) is proportional to the intensity of irradiance, thus **I<sub>sc</sub>** at a given irradiance (**G**) is:

$$I_{sc(G)} = \left( \frac{G}{G_0} \right) I_{sc(G_0)} \tag{3}$$

Where:  $G_0$  is the nominal value of irradiance, which is normally  $1000W/m^2$ .

The reverse saturation current of diode ( $I_0$ ) at the reference temperature ( $T_{ref}$ ) is given by:

$$I_0 = \frac{I_{sc}}{\left( e^{\frac{qV_{oc}}{nkT}} - 1 \right)} \tag{4}$$

The reverse saturation current ( $I_0$ ) at a given temperature ( $T$ ) is calculated by the following equation:

$$I_{0(T)} = I_{0(T_{ref})} \cdot \left( \frac{T}{T_{ref}} \right)^{\frac{3}{n}} \cdot e^{\frac{-qE_g}{nk} \left( \frac{1}{T} - \frac{1}{T_{ref}} \right)} \tag{5}$$

The equation for  $R_s$  at the open circuit voltage is:

$$R_s = - \frac{dV}{dI_{(Voc)}} - \frac{nkT/q}{I_0 \cdot e^{\frac{qV_{oc}}{nkT}}} \tag{6}$$

2.2. Design and simulation of the PV model (BP SX 150S)

In this subsection, we will be interesting to the design and the simulation of BP SX 150S module (manufactured by BP solar).

In order to modelling a PV module (which is constituted by a set of serie-parallel cells), it is important to build firstly a model suitable for a PV cell. Indeed, illuminated with radiation of sunlight, a PV cell converts, with some losses, the photovoltaic energy to an electrical energy.

We build a PV model using Matlab/Simulink to illustrate its nonlinear I-V and P-V output characteristics [9, 10, and 11]. The proposed model is implemented and shown in Figure 2.

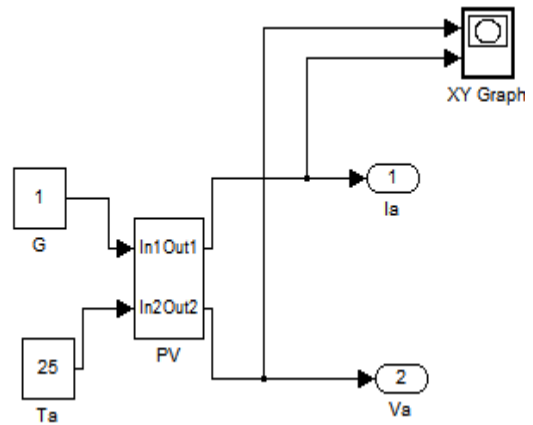


Fig. 2: Photovoltaic model.

BP Solar BP SX 150S PV module is chosen for a MATLAB simulation model. The module is made of 72 multi-crystalline silicon solar cells in series and provides 150W of nominal maximum power [7]. Table1 shows its electrical specification.

Table 1: Electrical characteristics data of PV module taken from the datasheet.

Electrical Characteristics	
Maximum Power (Pmax)	<b>150W</b>
Voltage at Pmax (Vmp)	<b>34.5V</b>
Current at Pmax (Imp)	<b>4.35A</b>
Open-circuit voltage (Voc)	<b>43.5V</b>
Short-circuit current (Isc)	<b>4.75A</b>
Temperature coefficient of Isc	<b>0.065 ± 0.015 %/ °C</b>
Temperature coefficient of Voc	<b>-160 ± 20 mV/ °C</b>
Temperature coefficient of power	<b>-0.5 ± 0.05 %/ °C</b>
NOCT	<b>47 ± 2°C</b>

The output of the Matlab function is shown first for various irradiation levels (Fig. 3), and then for various temperatures (Fig. 4).

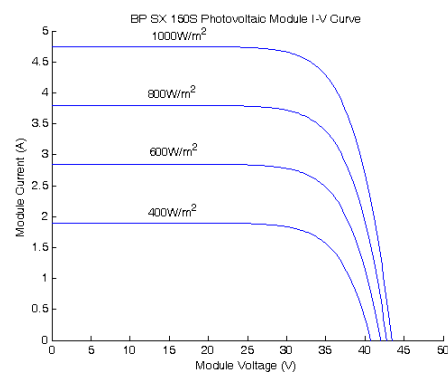


Fig. 3: The Matlab model I-V curves for various irradiation levels.

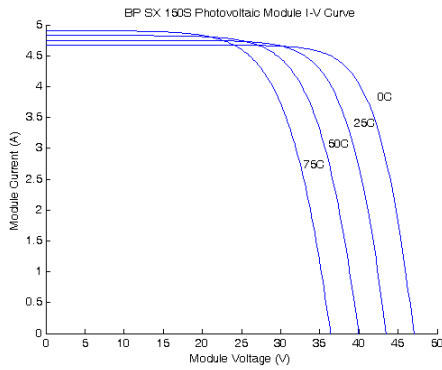


Fig. 4: The Matlab model I-V curves for various temperatures levels.

3. Maximum Power Point Tracker

The MPPT technique uses a DC-DC converter in order to allow the PV module to operate at its maximum power. This is achieved by an intelligent algorithm to solve the problems related to the variation of temperature, the insolation and module load. Many tracking algorithms have been proven and used with variety of kind of DC-DC converters [4, 6, 8]. Among these algorithms, the Perturb & Observe (P&O) and Incremental Conductance (incCond) methods are studied here.

It is to notice that the choice of the DC-DC converter in a photovoltaic system is important when a highest efficiency of the MPPT is desired. In [2] the author demonstrates that only the buck–boost DC-DC converter is able to manage the facility to follow the photovoltaic panel maximum power point at all times, regardless of cell temperature, solar global irradiation and connected load.

The following voltage transfer function is:

$$\frac{V_o}{V_s} = \frac{D}{1-D} \tag{7}$$

Its relationship to the duty cycle (D) is:

- \* If  $0 < D < 0.5$ , the output is smaller than the input.
- \* If  $D = 0.5$ , the output is the same as the input.
- \* If  $0.5 < D < 1$ , the output is larger than the input.

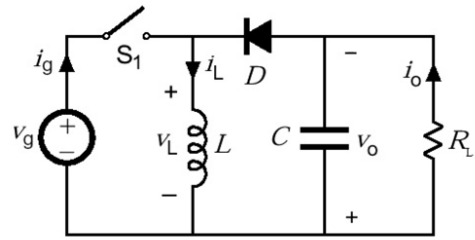


Fig. 5: buck– boost DC-DC converter

3.1. Perturb & Observe Algorithm

The perturb & observe (P&O) algorithm, also known as the “hill climbing” method, is very popular and the most commonly used in practice because of its simplicity in algorithm and the ease of implementation. Figure 5 shows the P-V curve, at the constant irradiance and the constant module temperature, assuming the PV module is operating at a point which is away from the MPP. In this algorithm the operating voltage of the PV module is perturbed by a small increment, and the resulting change of power,  $\Delta P$ , is observed. If the  $\Delta P$  is positive, then it is supposed that it has moved the operating point closer to the MPP. Thus, further voltage perturbations in the same direction should move the operating point toward the MPP. If the  $\Delta P$  is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP. Figure 7 shows the flowchart of this algorithm [4].

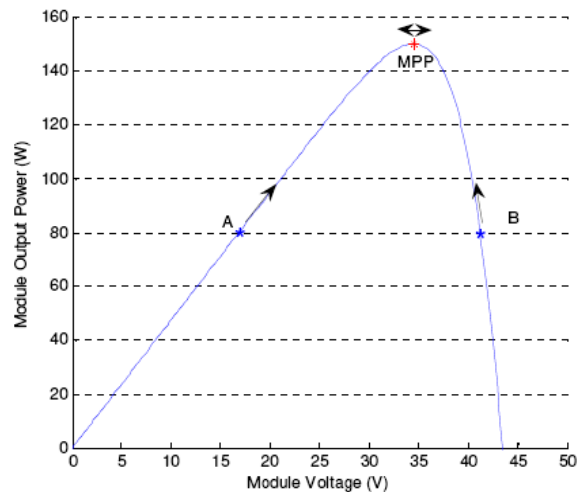


Fig. 6: P-V curve (1000W/m<sup>2</sup>, 25°C)

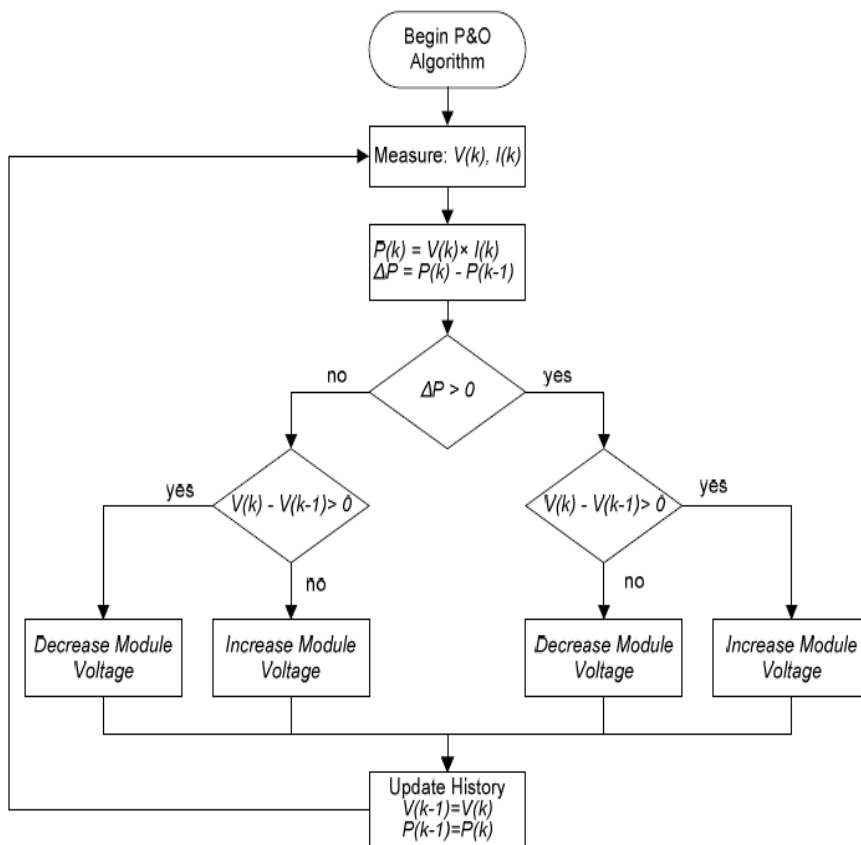


Fig. 7: Flowchart of the P&O algorithm.

Figure 8 shows the P-V curve, at different irradiance and the constant module temperature, and figure 9 shows the P-V curve, at the constant irradiance and different module temperature.

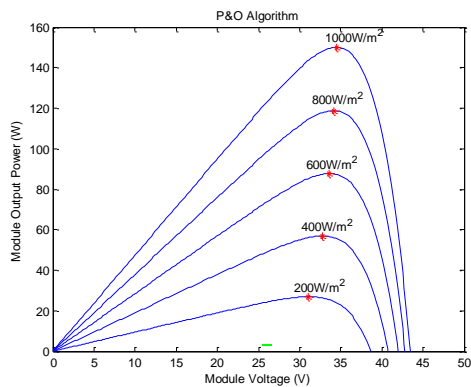


Fig. 8: P-V curve (25°C)

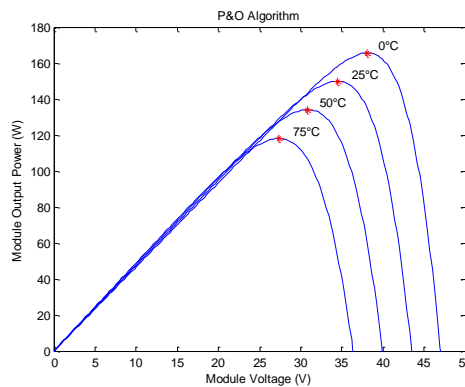


Fig. 9: P-V curve (1000W/m<sup>2</sup>)

### 3.2. Incremental Conductance Algorithm

The basic idea is that the slope of P-V curve becomes zero at the MPP, as shown in Figure 5. It is also possible to find a relative location of the operating point to the MPP by looking at the slopes. The slope is the derivative of the PV module's power with respect to its voltage and has the following relationships with the MPP [4].

$$\frac{dP}{dV} = 0 \quad \text{at MPP} \quad (8)$$

$$\frac{dP}{dV} = \frac{d(V.I)}{dV} = I \cdot \frac{dV}{dV} + V \cdot \frac{dI}{dV} = I + V \frac{dI}{dV} \quad (9)$$

$$\text{At MPP: } I + V \frac{dI}{dV} = 0 \Rightarrow \frac{dI}{dV} = -\frac{I}{V} \quad (10)$$

If the operating point is at the left side of the MPP, the equation (8) becomes:

$$I + V \frac{dI}{dV} > 0 \Rightarrow \frac{dI}{dV} > -\frac{I}{V} \quad (11)$$

If the operating point is at the right side of the MPP, the equation (8) becomes:

$$I + V \frac{dI}{dV} < 0 \Rightarrow \frac{dI}{dV} < -\frac{I}{V} \quad (12)$$

Figure 10 shows the P-V curve, at different irradiance and constant module temperature. The flowchart shown, Figure 11, explains the operation of the MPPT algorithm.

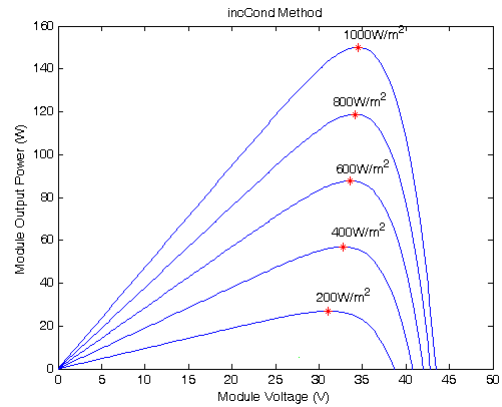


Fig. 10: P-V curve (25°C)

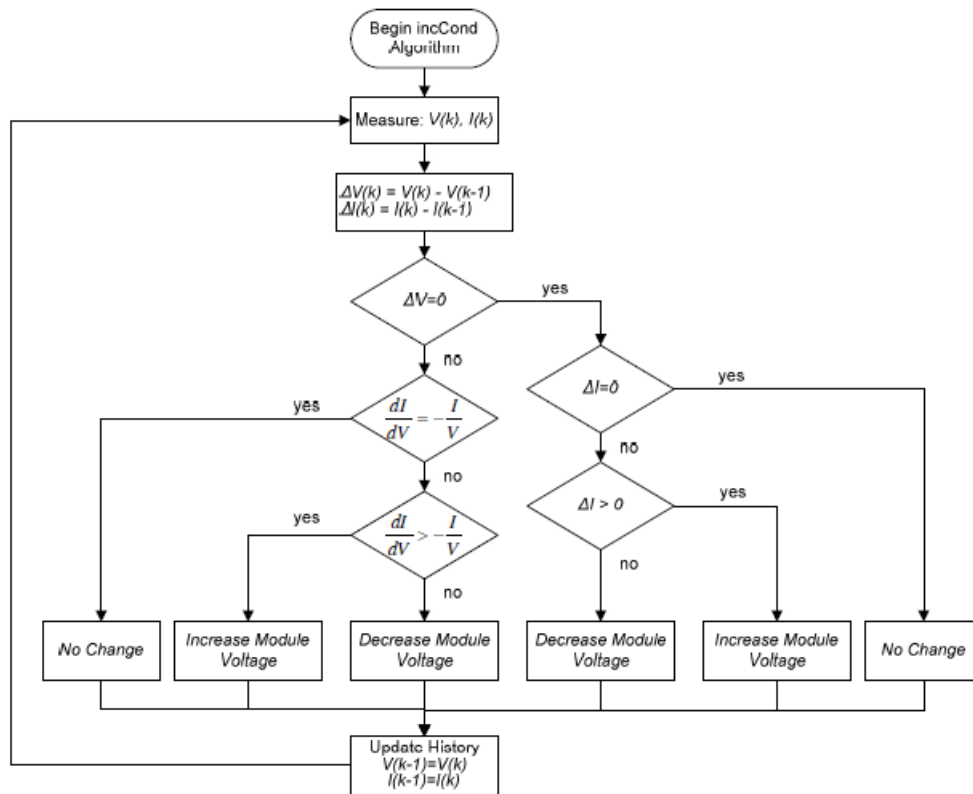


Fig. 11: Flowchart of the incCond algorithm

4. MPPT Simulations with Resistive Load

As shown in Figure 12, the impedance seen by PV is the input impedance of the converter (Rin). By changing the duty cycle (D), the value of Rin can be matched and the input impedance of the converter is:

$$R_{in} = \frac{V_s}{I_s} = \frac{(1-D)^2}{D^2} \cdot \frac{V_o}{I_o} = \frac{(1-D)^2}{D^2} \cdot R_{load} \quad (13)$$

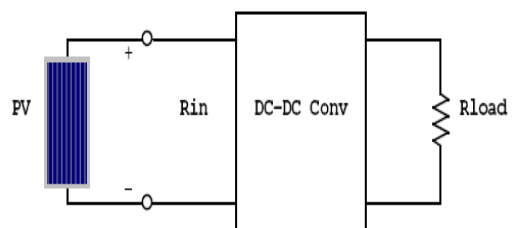


Fig. 12: Panel-converter connection.

The simulated system consists of the **BP SX 150S** PV model, the ideal converter, the MPPT control, and the resistive load. The function, **bp\_sx150s**, calculates the module current for the given module voltage, irradiance, and module temperature.

The simulation is performed under the linearly increasing irradiance varying from  $100\text{W/m}^2$  to  $1000\text{W/m}^2$  with a moderate rate of  $0.3\text{W/m}^2$  per sample. Figures 13 a and 13 b show that the trace of operating point is staying close to the MPPs during the simulation.

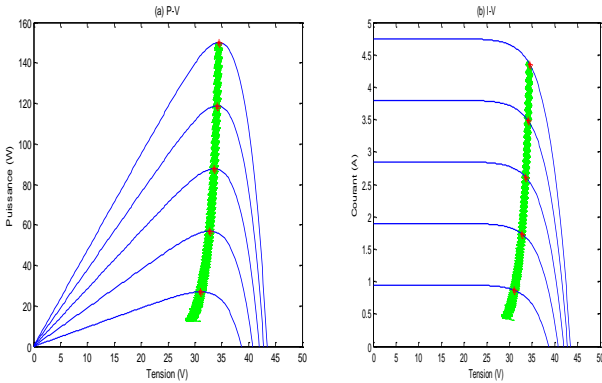


Fig. 13a: P-V curve

Fig. 13b: I-V curve

**5. Simulation of the PV system for variation of temperature or irradiance**

The photovoltaic system studied is composed of the PV panel, the MPPT control based on P & O algorithm, a DC-DC boost converter, a PWM generator (to control the duty cycle of the converter) and a resistive load as shown in Figure 14.

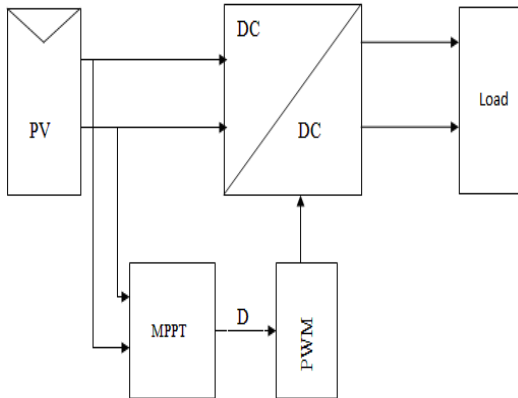


Fig. 14: photovoltaic system.

For a given temperature and irradiance, the photovoltaic panel delivers a voltage  $V_a$  and a current  $I_a$  dependent on the load. The MPPT control will search the values of  $V_a$  and  $I_a$ , which correspond to the value of the maximum power. Then it gives the value of duty cycle that should be applied to the

DC-DC converter in order to control the adaptation interface allowing the operating at maximum power.

*5.1. Simulation results for a constant irradiance and different values of temperature*

We simulate, in Matlab-simulink, the curves of the input and output voltages and the input and output currents for a constant irradiance of  $100\text{W/m}^2$  and two values of temperatures:  $25^\circ\text{C}$  and  $50^\circ\text{C}$ . The figures 15 (a, b, c and d) show the simulation results concerning the input and the output voltages and currents for different values of temperature with constant value of irradiance as precised previously. It is to notice that these curves are carried out for a resistive load. The simulation results with the use of the MPPT allow us to conclude that there is a little change of voltages (input and output voltages), a little change in the output currents but the input currents remain approximately constant.

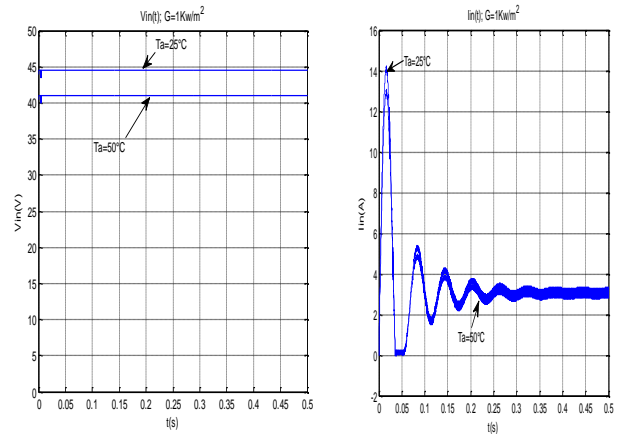


Fig. 15 a. Vin

Fig. 15 b. Iin

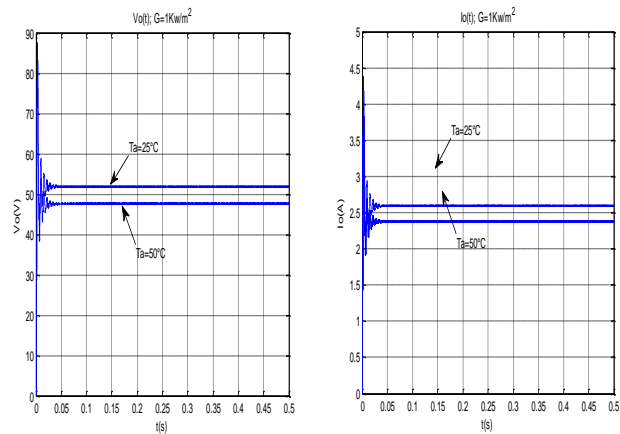


Fig. 15 c. Vo

Fig. 15 d. Io

5.2. Simulation results for a constant temperature and different values of irradiance

We repeat the same simulation for a constant temperature of 25°C and two values of irradiance: 500W/m<sup>2</sup> and 1000W/m<sup>2</sup>. The figures 16 (a, b, c and d) illustrate the simulation results concerning the input and the output voltages and currents for different values of irradiance with constant value of temperature.

As stated by the simulation results using MPPT, it is to notice here that the change in the voltages is little clear with the variation of the irradiance. Concerning the currents, we remark the same conclusion that is given in the precedent subsection (but here for a constant temperature and variable irradiance).

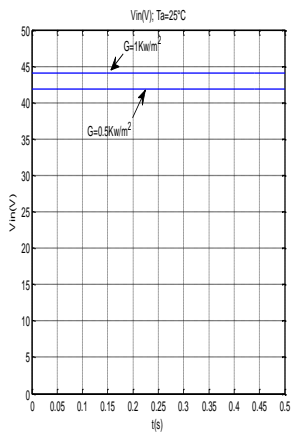


Fig. 16 a. Vin

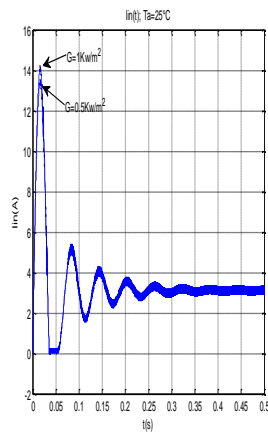


Fig. 16 b. Iin

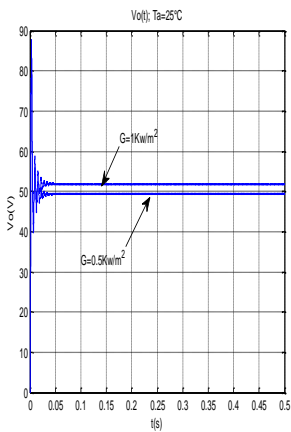


Fig. 16 c. Vo

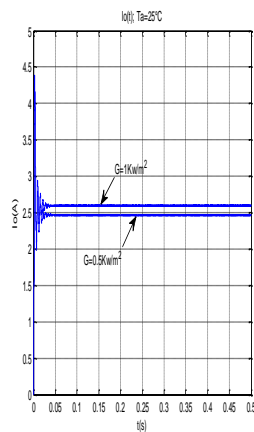


Fig. 16 d. Iout

The figures represented above show the variation in voltage and current input and output of the converter for different values of temperature or irradiance. In effect the system meets the climatic variations and the results are satisfactory.

6. Simulation results for sudden changes in temperature or irradiance

To demonstrate the effectiveness of the proposed system, simulations were performed with Matlab Simulink. The simulation study was conducted to illustrate the response of the proposed method to sudden change in temperature or irradiance with a resistive load of value  $R=20\Omega$ . For this, we initially take the value of the irradiance  $G=700W/m^2$ ; at  $t=0.2s$ , we apply a sudden change in irradiance that passes from  $G=700W/m^2$  to  $G=1000W/m^2$  while keeping the temperature constant at 25°C. The following figures (17a and 17b) show the simulation results.

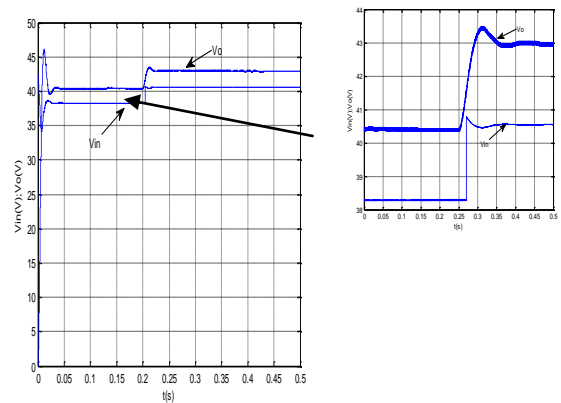


Fig. 17 a. Vin(t) & Vo(t)

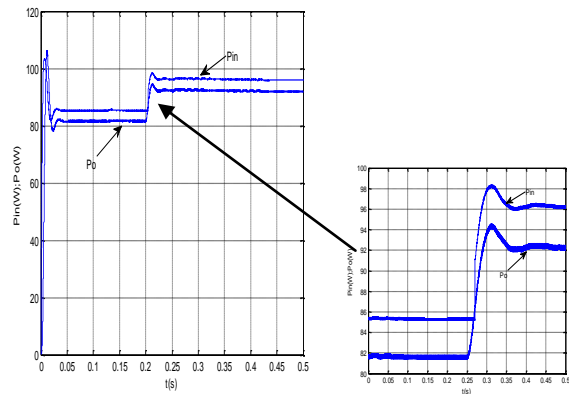


Fig. 17 b. Pin(t) & Po(t)

Then we keep the value of irradiance constant at 1000W/m<sup>2</sup>, and we caused a sudden change of temperature from 25°C to 50°C. The simulation results are given by the following figures (18a and 18b).



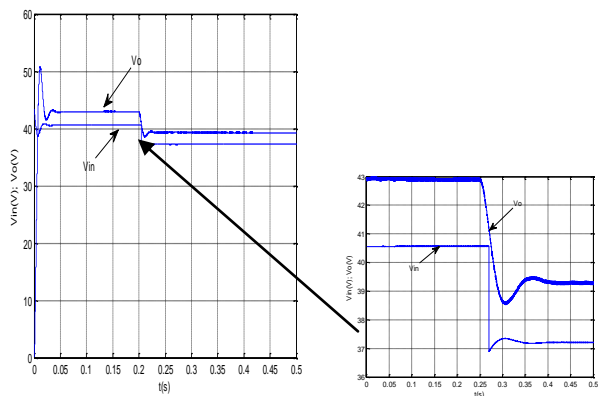


Fig. 18 a. Vin(t) & Vo(t)

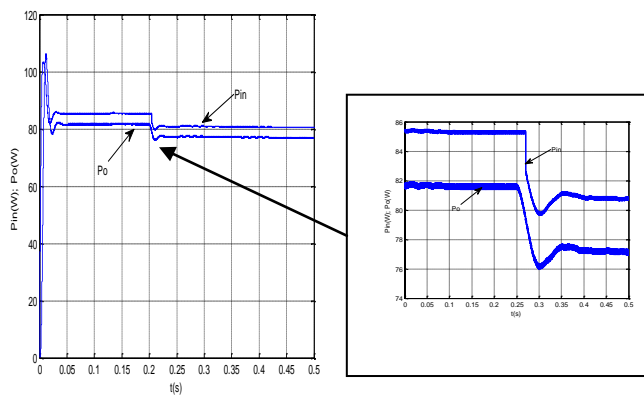


Fig. 19 b. Pin(t) & Po(t)

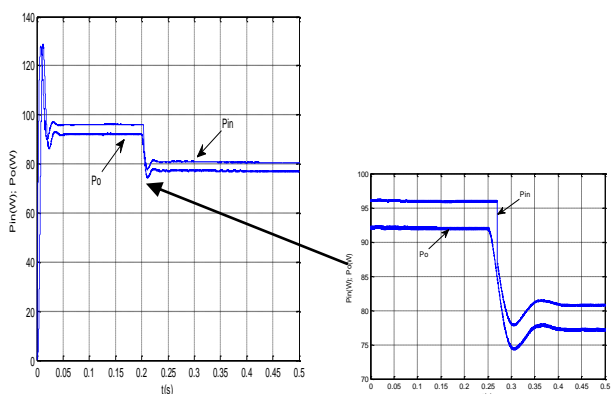


Fig. 18 b. Pin(t) & Po(t)

We study, then, the behaviour of the system to the sudden change of temperature and irradiance at the same time. So, we cause a sudden change of temperature and irradiance at the same time  $t=0.2s$ . The simulation results are given by the following figures (19a and 19b).

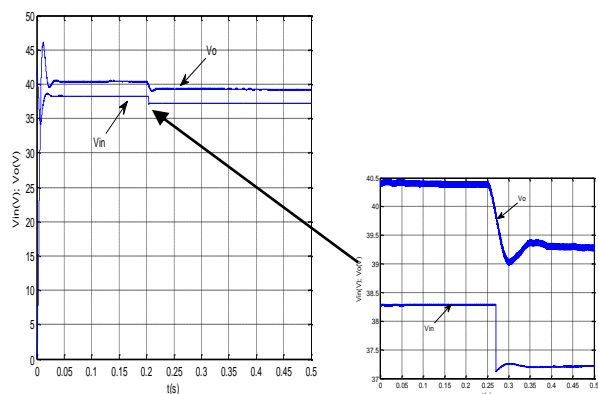


Fig. 19 a. Vin(t) & Vo(t)

Simulation results show that the system is stable for sudden changes in temperature and, or irradiance, and the system response reaches immediately the steady state. Figure 17-b shows that the power increases with only a sudden change of irradiance. It is to notice that this result is predictable; because from the I-V curves of the panel it appears that the voltage decreases slightly while the increase of the current is important. At contrary, Figure 18-b demonstrates that the power decreases with only a sudden increase of temperature; this is due to the decrease in voltage while the current remains approximately constant. For the increase of the temperature and the irradiance at the same time the power and voltage vary slightly.

### 7. Simulation results for different values of the load

In this section, we carry out the simulation results for the both variation in temperature and irradiance, for two values of the resistive load.

In order to study the influence of the variation of the load, we take two cases: a load of value  $R = 15\Omega$ , and then a load of value  $R = 30\Omega$  for a sudden change of both temperature and irradiance at time  $t = 0.2s$ . The simulation results are given by the following figures (Figures 20-a-b-c-d).

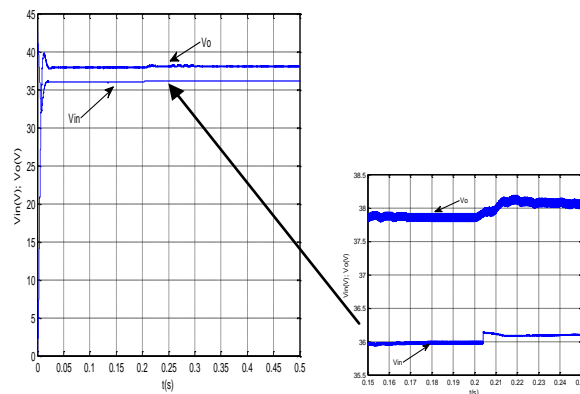


Fig. 20 a. Vin(t) & Vo(t) – R=15Ω

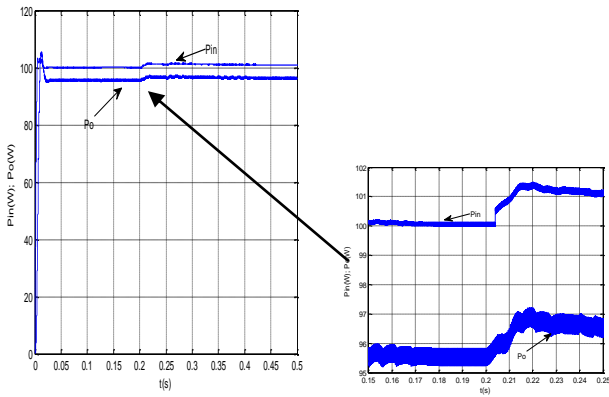


Fig. 20 b. Pin(t) & Po(t) - R=15Ω

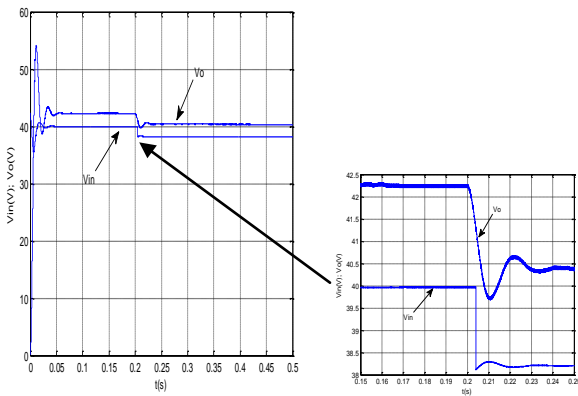


Fig. 20c. Vin(t) & Vo(t) – R=30Ω

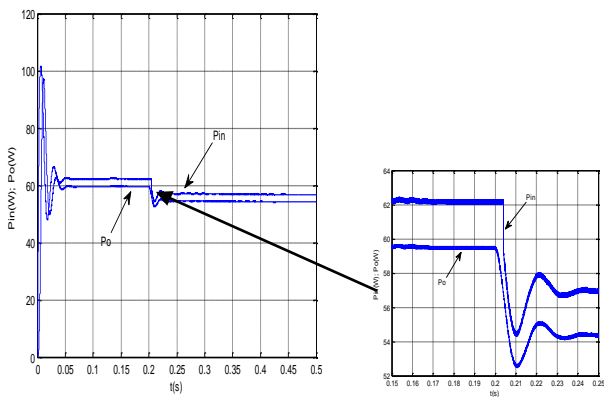


Fig. 20 d. Pin(t) & Po(t) - R=30Ω

It is to remark that when the value of the load increases, the input and output voltages increase slightly but the decrease of power is important. This is due to the linear variation of the current with the load.

### 8. Regulation of the output voltage of the PV system

In this section, we study the regulation of the output voltage in the PV system for a resistive load and a pumping

system. This study seems interesting for many industrial applications where it is required that the voltage delivered by the photovoltaic system should be constant.

#### 8.1. Description of the regulation system

The designed system includes a PV panel, a buck-boost converter with the MPPT control, a storage battery, a boost converter equipped with a control system based on a PID controller, used to regulate the output voltage, and a load. The synoptic diagram of the system is shown in Figure 21.

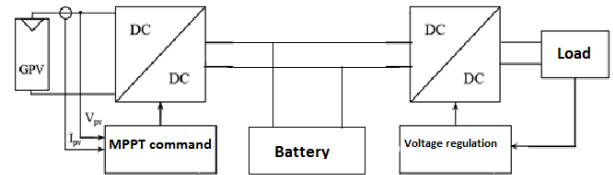


Fig. 21 . Block diagram of the photovoltaic system

#### 8.2. Voltage regulation with a resistive load

The figure 22 shows the simulation results of output voltage ( $V_o$ ) with a resistive load ( $R=100\Omega$ ) for an initial battery charge to 80% (Initial State of Charge – ISC such as  $ISC = 80\%$ ) and a voltage reference of  $V_{ref}=50V$ .

We remark that the regulated voltage output tracks well the value of the voltage reference.

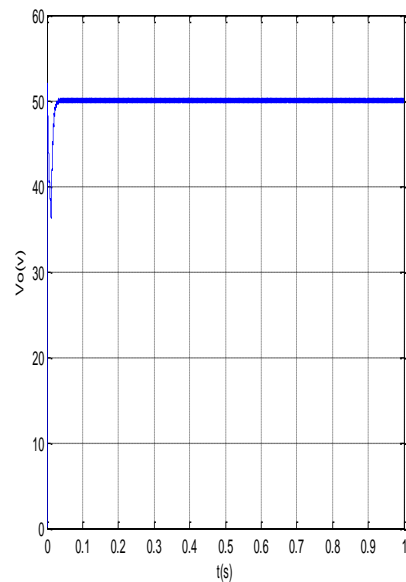


Fig. 22. Output voltage  $V_o$

#### 8.3. Voltage regulation for a pumping system

In recent years, there has been rapid growth in the use of permanent magnet DC motor as a rotary machine for photovoltaic pump systems. Indeed, this type of motors has

good performance and requires no maintenance. As well, the centrifugal system has many advantages over other types of pumping: it guarantees a volume of reduced size, a relatively quiet service and easy implementation with all types of electric motors on the market. The pumping unit studied in our system will be composed of a permanent magnet DC motor and a centrifugal pump.

In this section, our goal is to replace the resistive load by a pump unit which consists of a permanent magnet DC motor (PMDC motor) and a centrifugal pump. This type of engine is not in the library of Simpower system of Matlab; for this we will proceed with the modelling and simulation of the motor-pump.

- Modeling of the pump unit

The modelling of PMDC motor is performed with the basic equations of the DC current machine [5, 12]. Its electrical equivalent scheme is illustrated at Figure 23.

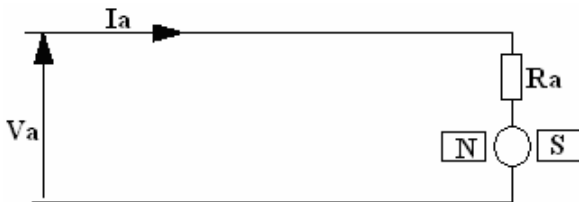


Fig. 23. Permanent magnet DC motor

$$V_a = R_a \cdot I_a + L_a \cdot \frac{dI_a}{dt} + K_e \cdot \omega \tag{14}$$

$$T_e = K_t \cdot I_a \tag{15}$$

$$T_e - T_l = J \frac{d\omega}{dt} \tag{16}$$

where: **Ke**: constant voltage, **Kt**: constant of motor torque, **Ia**: the motor armature current, **Ra**: resistance of armature circuit of the motor, **Te**: the electromagnetic torque of the engine, **Tl**: the load torque, **ω**: the angular speed of motor shaft and **J**: the inertia moment.

Our goal is to build a model of a PMDC motor with two inputs (the load torque and the inertia moment), and three outputs (the electromagnetic torque, the speed and the current) as shown in the following figure.

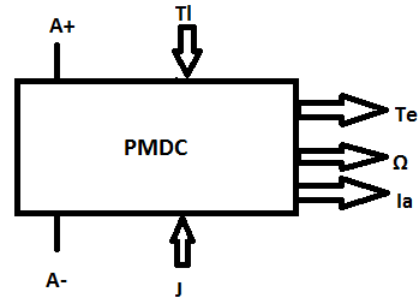


Fig. 24. Model of the PMDC motor

Centrifugal pumps are widely used for applications with photovoltaic power because the engine can provide a fast speed approximately constant.

The load torque of the centrifugal pump is expressed by:

$$T_l = K_r \cdot \omega^2 + T_s \tag{17}$$

Where: **Kr** is the coefficient of proportionality, **Ts** is the static torque which is very small.

- Simulation results for the voltage regulation

In the following, we simulate the photovoltaic system by replacing the resistive load by the pump unit which is studied previously. The figure 25 illustrates the simulation results concerning the regulated voltage with a voltage reference (**Vref=50V**).

The simulated curve lets us conclude that the regulated voltage output tracks well the value of the voltage reference.

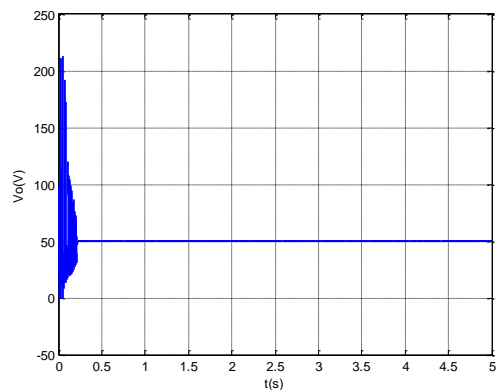


Fig. 25. Output voltage Vo

### 9. Conclusion

In this work, we have proposed the design, the simulation and the voltage control of standalone Photovoltaic system based MPPT with an application to a pumping system. In this study, we first described the Photovoltaic PV module: in a first step, the modelling of the solar cell is

presented, and then the design and simulation of the I-V curves of the PV model are done. The non linear behaviour of the PV and its sensitivity to external conditions such as light and temperature induce energy losses. In the goal to reduce these losses, it is required to operate at the maximum power: this is the role of the MPPT technique. In the literature there are many kinds of algorithms to achieve the tracking of the MPP. In this paper we have presented P&O and IncCond algorithms. A study, in simulation in Matlab-simulink environment of the MPPT with resistive load has been made to illustrate the tracking of the MPP.

In a second step we have designed a PV system including the MPPT technique with a constant resistive load and simulate the input and output voltages as well as the input and output currents for variation of temperature and irradiance in order to illustrate its efficiency in regard with sudden climatic variations. Indeed, the simulation results have shown that the system operates at its maximum power of a satisfactory manner.

In the third step, a similar work has been done for different values of the resistive load.

In the last part of this work, we are interested to the regulation of the output voltage of the PV system for a resistive load, then for a pumping system as a load. It has been demonstrated, in these two cases, that the regulated voltage tracks well the reference voltage.

In the future, we hope testing in experiment the developed works in this paper.

#### Acknowledgements

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