Experimental Test Bench of Photovoltaic Systems Using Backstepping MPPT Algorithm

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Abstract— The varying time weather conditions, and the nonlinearity of the characteristics of the PV influence its performance, and cause also the difficult maximum point power tracking (MPPT) process. In this paper, a system equipped with PV panel, control and power card has been analyzed and designed. The Power card is formed with voltage and current sensors, boost converter, and a driver which ensures the control of the Mosfet. The control card contains a Backstepping algorithm which needed for solving the nonlinear relation and draws the MPP from the PV panel. The simulation results show a great performance and improve a high efficiency with good accuracy. The developed system is designed in Isis Proteus, simulated in Matlab/Simulink, implemented and tested successfully on an Arduino board with a graphical LabVIEW interface which allows us to visualize and interpret PV parameters in real time.

Keywords— Backstepping, Matlab/simulink, MPPT, Boost converter, Arduino Board.

1. Introduction

Solar energy is available all over the planet in varying degrees and is fully renewable. Its contribution varies, depending on the days and the seasons, but it is relatively predictable. Although it is relatively diluted, its annual energy intake could meet energy consumption in most countries. [1]. However Solar panels, although they are increasingly efficient, they conversion still quite low (around 20%) with a poor transfer of the maximum power. Therefore, In the literature, there are several MPPT methods, ranging from the simplest one that uses a manual adaptation to the more complex ones that call for complicated algorithms [1,2]. Fuzzy logic and neural network methods gives a satisfactory results but difficult algorithm and expensive implementation [5,10]. For this work a control card with a backstepping MPPT algorithm has been used. Comparing with another digital or analog system design [11] .The nonlinear command aims to maximize the power by ensuring a remarkable robustness, and guarantees also satisfactory performance and good efficiency even with climate change [3]. There are a few topologies can be used with PV system for load connectivity, among them boost converter has been used as an adaptation stage here due to its available use in standalone and grid connected PV system and simultaneous step up capability [4.5]. This paper results show that the proposed backstepping MPPT method can track maximum power point (MPP) under different atmospheric conditions on the basis of voltage and current of PV panel, which has excellent output characteristic of high accuracy and good robustness. A driver which ensures a very high PWM frequency was added in order to control the gate of the Power Mosfet.

This work presents the results of simulation in Matlab/ Simulink, and experimental concerning the design of power card containing boost converter, current and voltage sensors, and a driver developed at the laboratory, which implemented in an Arduino card with a graphical user interface [6].

The paper is decomposed into seven sections: In section 2, complete working procedure of the system has been illustrated. Section 3 covers the design of boost converter, followed by the design of current, voltage sensors and the driver. The nonlinear MPPT backstepping command is detailed in section 4. Simulation results and experimental works are discussed in Section 5 and 6 respectively. Lastly, in section 7, a conclusion has been added.

The energy captured by the PV panel using cells, is converted after to electricity, it will be supplied to the load or batteries through the power card, and the converter will be controlled by a MPPT algorithm implemented in the control card, provided with a driver. The whole complete system is shown in Fig. 1.

2. Complete System Overview

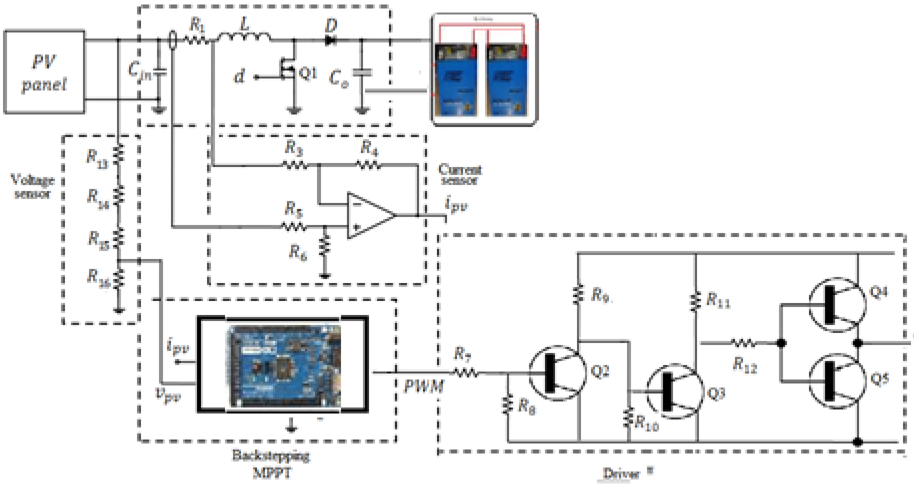


Fig.1 The main system design

2.1 Caracteristic of solar panels

Solar panel parameters are shown in Table I. PV module is made by Shell solar company and product name is LDK-020P.

TABLE I. PARAMETRS OF LDK-020P

Parameters	Values
Open Circuit Voltage(Voc)	21.7Volt
Short Circuit Current(Isc)	1.26Amp
Voltage at Pmax(Vmpp)	17.3Volt
Current at Pmax(Impp)	1.17Amp
Maximum Power (Pmpp)	20Watt

3. Boost Converter

Boost converters are used to control electrical power of solar panel to load side with high flexibility and efficiency[3]. The converter consists of capacitors, inductors and switches. In the ideal case, all these devices do not consume any active power, that is why we have good performance.

Fig. 2 shows configuration of dc-dc boost converter with PV as input and batteries as output.

Maximum power is reached by an action on the duty cycle of the boost dc-dc converter, when the MPPT algorithm operates.

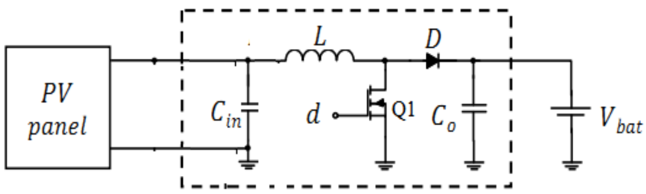


Fig. 2 Boost converter with PV as input

3.1 Duty cycle

If the converter is in continuous conduction mode, a factor of efficiency η (about 80%) is included between input and output voltage [12], which contribute to calculate a more reasonable duty cycle d :

$$V_{out}=\frac{\eta}{1-d}V_{in} \quad (1)$$

3.2 Inductor choice

The needed parameters to calculate the power stage (inductance and capacitance) were input voltage V_{pv}= 17V, desired output voltage V_{bat}= 25V (slightly higher than the rated voltage of the two batteries series which is 24V).

In order to calculate the inductance L of converter, we need to calculate first the estimated current ripple ΔI_L :

$$\Delta I_L= (0.2 \text{ to } 0.4) \times I_{out} \times \frac{V_{bat}}{Vpv} \quad (2)$$

We take I_{out}= 1A, then 0.294A< ΔI_L<0.588A

The magnetic hysteresis losses in the inductor are reduced with a smaller ripple value.

The inductor value L , according to varied parameters, is given below:

$$\frac{V_{pv}}{f.\Delta I_{Lmin}}.d_{min} < L < \frac{V_{pv}}{f.\Delta I_{Lmax}}.d_{max} \quad (3)$$

Which duty cycle is between 10%< d <90% and the switching frequency is f==62.5Khz.

Then 92.51 μH < L< 416.32 μH

We take L= 200 μH.

3.3 Input capacitor choice

The equation of the input capacitor is given as :

$$\frac{V_{pv}}{L.f^2.\Delta V_{pv}}.d_{min} < C_{in} < \frac{V_{pv}}{L.f^2.\Delta V_{pv}}.d_{max} \quad (4)$$

We take C_{in} = 100 μF

With ΔV_{pv}an input voltage ripple ΔV_{pv}<100mV.
A high input ripple will require a large value of capacitance, which increase the losses.

3.4 Output capacitor choice

The output capacitor is:

$$\frac{I_{Out}}{f.\Delta V_{out}}.d_{min} < C_{out} < \frac{I_{Out}}{f.\Delta V_{out}}.d_{max} \quad (5)$$

We take C_{out}= 800 μF

Where ΔV_{out}<10mV is the output ripple voltage, a large value can cause fluctuations which exceeds the limits.

4. The Proposed Backstepping MPPT

We can classify the MPPT commands in general according to the type of electronic implementation: analogue, digital or mixed. However, it is best to classify them according to the type of search they perform and the input parameters of the MPPT command [5].

At present, The PO method is now widely used because of its ease of implementation, but it presents some problems related to the oscillations around the PPM and to time of tracking speed[4,5].

For this, this paper introduced a MPPT method based on backstepping algorithm [7]. This nonlinear algorithm is implemented in an Arduino board to achieve the MPP even with variations of irradiation and PV array temperature. The control input are the duty cycle d of the boost converter.

3.5 MPPT algorithm

As can be seen in Figure 1, the boost converter consists of the transistor Mosfet Q1 controlled by a PWM signal d ∈ [0,1]. The Kirchhoff's laws were applied in order to develop our switched system. Thus, we obtain :

$$\begin{cases} \frac{dv_{pv}}{dt} = \frac{1}{C_{in}}(i_{pv}-i_L) \\ \frac{di_L}{dt} = \frac{v_{pv}}{L} - \frac{R}{L}i_L - \frac{V_{bat}}{L}(1-d) \end{cases} \quad (6)$$

The key goal of the nonlinear MPPT algorithm is to control an appropriate duty cycle signal d used to regulate the controlled output $z_1 = \frac{\partial P}{\partial v_{pv}}$ of photovoltaic panel to its reference $z_{1ref} = \frac{\partial P}{\partial v_{pv}}\Big|_{MPP} = 0$ in order to drive boost converter to achieve the MPP.

Design step 1

We introduce the tracking error :
$e_1 = z_1 - z_{1ref}$ where

$$z_{1ref} = \frac{\partial P}{\partial v_{pv}}\Big|_{MPP} = \frac{\partial(v_{pv}i_{pv})}{\partial v_{pv}}=I_{pv} + v_{pv}\frac{\partial i_{pv}}{\partial v_{pv}} = 0 \quad (7)$$

Using 6 and 7, time derivation of e_1, is the dynamic error:

$$\dot{e}_1=\left[i_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}v_{pv}\right]\ddot{v}_{pv}\frac{\delta t}{\delta v_{pv}}+\left[\frac{\delta i_{pv}}{\delta v_{pv}} + \frac{\partial^2 i_{pv}}{\partial^2 v_{pv}}v_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}\right]\left[\frac{1}{C_{in}}(i_{pv}-i_L)\right] \quad (8)$$

Taking the boost inductor current i_L as a virtual control input, with respect to candidate Lyapunov function $V_1 = \frac{1}{2}e^2{}_1$

indeed, its time derivate is :

$$\dot{V}_1 = e_1\left[i_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}} v_{pv}\right] \ddot{v}_{pv}\frac{\delta t}{\delta v_{pv}} + \left[\frac{\delta i_{pv}}{\delta v_{pv}} + \frac{\partial^2 i_{pv}}{\partial^2 v_{pv}} v_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}\right]\left[\frac{1}{C_{in}}(i_{pv} - i_L)\right] \quad (9)$$

Choosing $X_1 = (i_L)_d$ as a desired virtual control, the stabilizing function of e_1 is given by:

$$-C_1 e_1 = \left[i_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}} v_{pv}\right] \ddot{v}_{pv}\frac{\delta t}{\delta v_{pv}} + \left[\frac{\delta i_{pv}}{\delta v_{pv}} + \frac{\partial^2 i_{pv}}{\partial^2 v_{pv}} v_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}\right]\left[\frac{1}{C_{in}}(i_{pv} - X_1)\right] \quad (10)$$

with $C_1 > 0$ is a design parameter.
The stabilization function X_1 is :

$$X_1 = i_{pv} + \left(C_{in}\frac{1}{\left[\frac{\delta i_{pv}}{\delta v_{pv}} + \frac{\partial^2 i_{pv}}{\partial^2 v_{pv}} v_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}\right]}\right)\left(C_1 e_1 + \left(\left[i_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}} v_{pv}\right] \ddot{v}_{pv}\frac{\delta t}{\delta v_{pv}}\right)\right) \quad (11)$$

Design step 2

As i_L is not the actual control input, a new error variable $e_2 = i_L - X_1$, between the virtual control and its desired value X_1 should be vanish, then from 7 and 9:

$$\dot{e}_2 = \frac{v_{pv}}{L} - \frac{R}{L} i_L - \frac{V_{bat}}{L}(1-d) - X_1 \quad (12)$$

$$\dot{e}_1 = \left[i_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}} v_{pv}\right] \ddot{v}_{pv}\frac{\delta t}{\delta v_{pv}} + \left[\frac{\delta i_{pv}}{\delta v_{pv}} + \frac{\partial^2 i_{pv}}{\partial^2 v_{pv}} v_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}\right]\left[\frac{1}{C_{in}}(i_{pv} - (e_2 + X_1))\right] \quad (13)$$

Adding (10), we define $\dot{e}_1$ and $\dot{V}_1$:

$$\dot{e}_1 = -\frac{1}{C_{in}}\left[\frac{\delta i_{pv}}{\delta v_{pv}} + \frac{\partial^2 i_{pv}}{\partial^2 v_{pv}} v_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}\right] - C_1 e_1 \quad (14)$$

$$\dot{V}_1 = -\frac{1}{C_{in}}\left[\frac{\delta i_{pv}}{\delta v_{pv}} + \frac{\partial^2 i_{pv}}{\partial^2 v_{pv}} v_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}\right] e_1 - C_1 {e^2}_1 \quad (15)$$

The time derivate of stabilizing function $\dot{X}_1$ is :

$$\dot{X}_1 = \left[\frac{\partial i_{pv}}{\partial t}\left(\frac{(C_1\dot{e}_1 + e_1)}{\left(\frac{\delta i_{pv}}{\delta v_{pv}} + \frac{\partial^2 i_{pv}}{\partial^2 v_{pv}} v_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}\right)} - \frac{(C_1 e_1)}{\left(\frac{\delta i_{pv}}{\delta v_{pv}} + \frac{\partial^2 i_{pv}}{\partial^2 v_{pv}} v_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}\right)^2}\left(2\frac{\delta^2 i_{pv}}{\delta v^2_{pv}} + \frac{\partial^3 i_{pv}}{\partial v^3_{pv}} v_{pv} + \frac{\delta^2 i_{pv}}{\delta v^2_{pv}}\right)\frac{\partial v_{pv}}{\partial t}\right)\right] \quad (16)$$

Consider the augmented candidate Lyapunov function:

$$V_2 = V_1 + \frac{1}{2}{e^2}_2 \quad (17)$$

Time derivative of V_2 is given by :

$$\dot{V}_2 = e_2\left[-\frac{1}{C_{in}}\left(\frac{\delta i_{pv}}{\delta v_{pv}} + \frac{\partial^2 i_{pv}}{\partial^2 v_{pv}} v_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}\right) e_1 + \frac{1}{L}\left(R - v_{pv} - v_{bat}\right) + \frac{v_{bat}}{L} d - \dot{X}_1\right] - C_1 {e^2}_1 \quad (18)$$

Then the control law d which guarantees the global stability is :

$$d = \frac{L}{v_{bat}}\left[-\frac{1}{C_{in}}\left(\frac{\delta i_{pv}}{\delta v_{pv}} + \frac{\partial^2 i_{pv}}{\partial^2 v_{pv}} v_{pv} + \frac{\delta i_{pv}}{\delta v_{pv}}\right) e_1 - \frac{1}{L}\left(R - v_{pv} - v_{bat}\right) + \dot{X}_1 - C_2 e_2\right] \quad (19)$$

Where $C_2 > 0$ being a design parameter, the dynamics of Lyapunov function is reduced to :

$$\dot{V}_2 = -C_1 {e^2}_1 - C_2 {e^2}_2 < 0 \quad (20)$$

This vector error (e_1, e_2) ensures that the error $e_1 = z_1 - z_{1ref}$ converges to the origin. Therefore, the MPPT is reached.

3.6 Current and voltage sensors

The MPPT algorithm needs the output current and voltage of the PV panel to calculate the output power. Hence, figure 3 depicts the current and voltage sensors designed to sense respectively the PV array's current and voltage i_{pv} and v_{pv}.

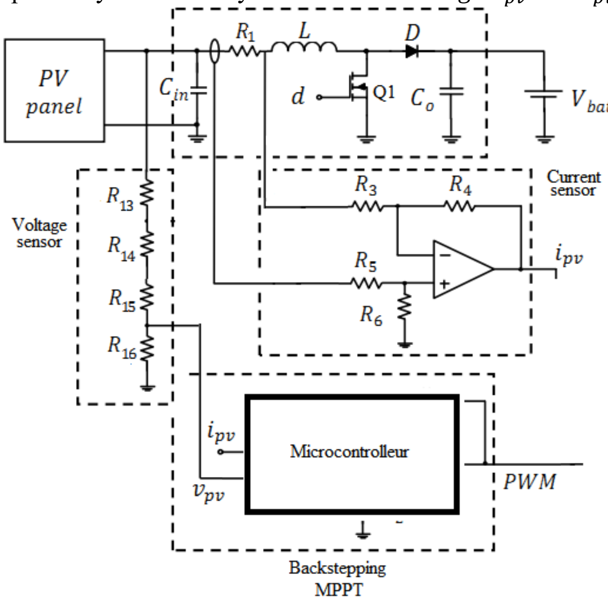


Fig. 3 Current and voltage sensors

A current detection module named ACS712 can be used [8]. In this work, we designed our appropriate sensor. The method consists in measuring the voltage across a shunt resistor R_1 set in series with the system. This voltage is measured by a differential amplifier LM324, which deliver a proportional current based on Ohm's law, readable by the Arduino board.

A voltage divider which converts the voltage of PV panel in range that is 0-5V, so that the Arduino Board can interpret the voltage level. The combination of resistor in voltage divider is high 10KΩ in order to minimize the power losses.

Figure 4 shows the driver designed to transmit the control signal to MOSFET transistor of the boost converter. It has capability of operating at high PWM frequency 62.5 KHz that the boost converter gets, with a specific duty cycle for its MOSFET, from the Arduino Board.

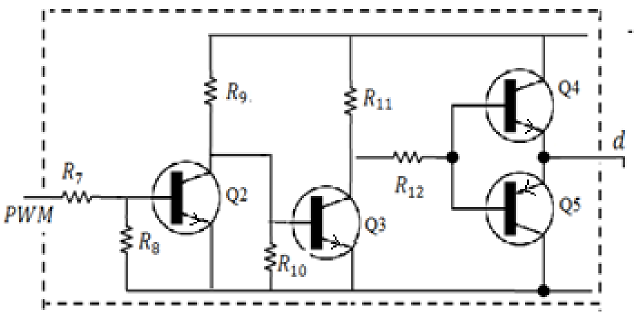


Fig. 4 Design of the driver

There is a level-shifting circuit using a push-pull amplifier as an output stage between Arduino board and converter. It increases the level of PWM from Arduino Board according to the gate to source voltage of MOSFET (from 5V to 12V).

4 Simulation and Results

We have implemented the circuit of fig 3 in Matlab/Simulink environment in order to verify the performance of our system using Backstepping algorithm. Firstly, a variation step of solar radiation from 600w/m² to 1000w/m² is imposed while the temperature is kept constant at 298K. Secondly, we imposed a variation of temperature from 273K to 298K while the radiation is kept constant at 1000w/m². The different value of parameters used in simulation was aforementioned in section 3, the Backstepping parameters was $C_1 = 50, C_2 = 1000$.

In figures 5 and 9, the output power curve by using backstepping MPPT algorithm deliver a adjustable duty cycle used to reach without oscillations and very quickly the MPP. Figures 6 and 10 show that the input voltage was boosted to output voltage v_{bat}= 25v with a good efficiency. The input and inductor current of the converter with variation of radiation and temperature was presented in figures 7 and 11. They show that the electric values oscillate around the optimal values which present a concordance between theory and simulation.

Finally, Figures 8 and 12 presented the control signal d, it shows that the signals are between 0 and 1

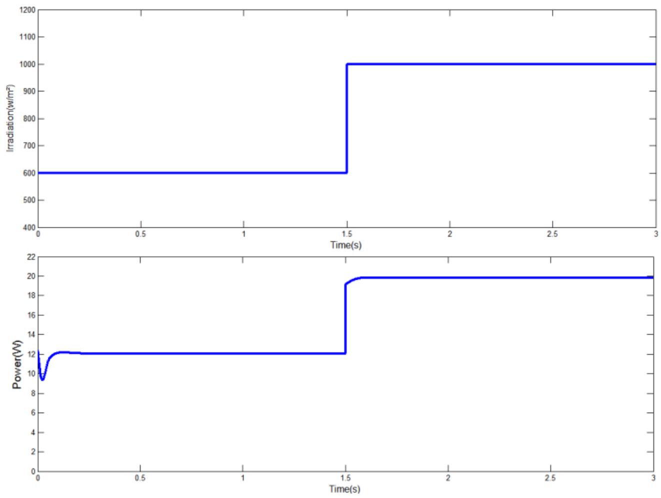


Fig. 5 Output Power with variation irradiation

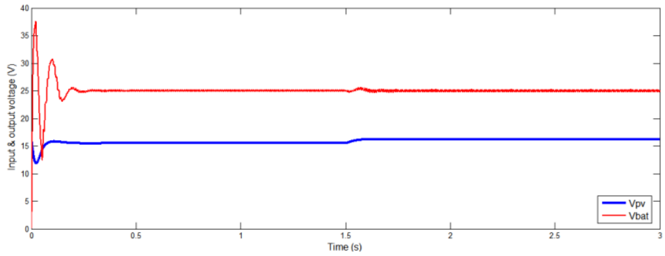


Fig. 6 Input and Output voltage of the converter

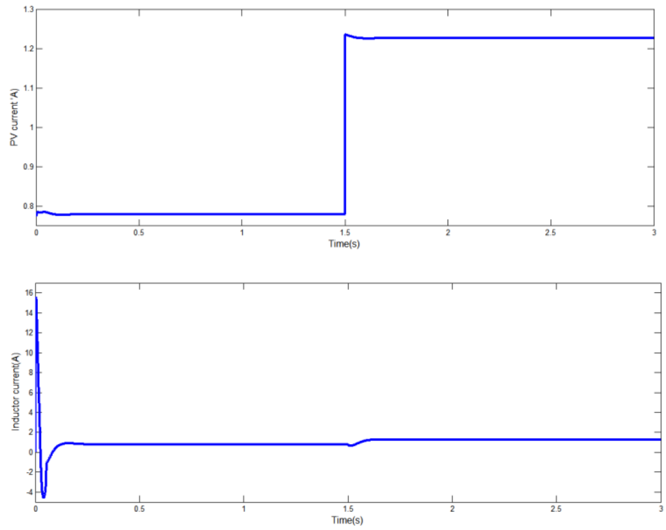


Fig. 7 Input and inductor current of the converter

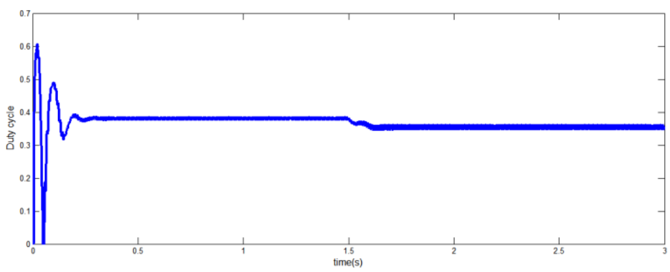


Fig.8 Control signal of the converter

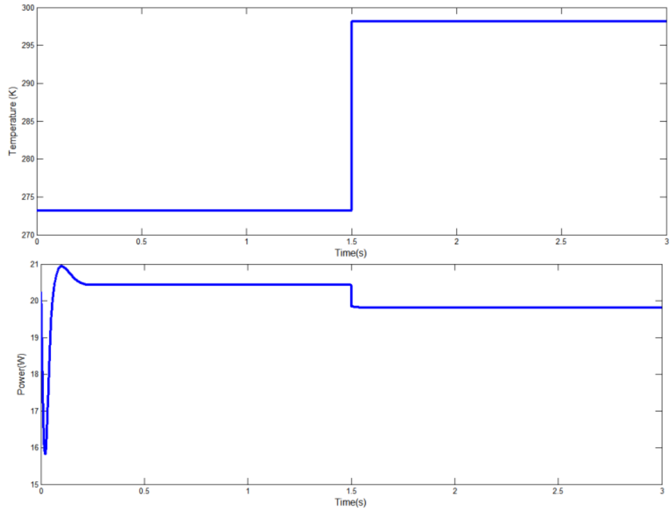


Fig.9 Output Power with variation temperature

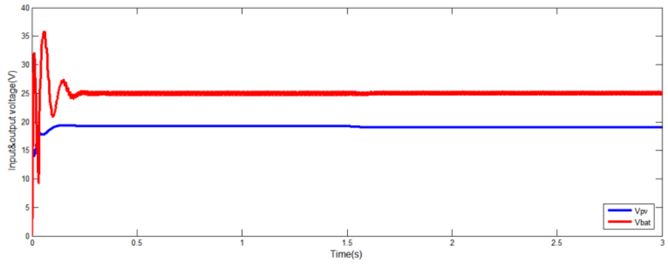


Fig. 10 Input and Output voltage of the converter

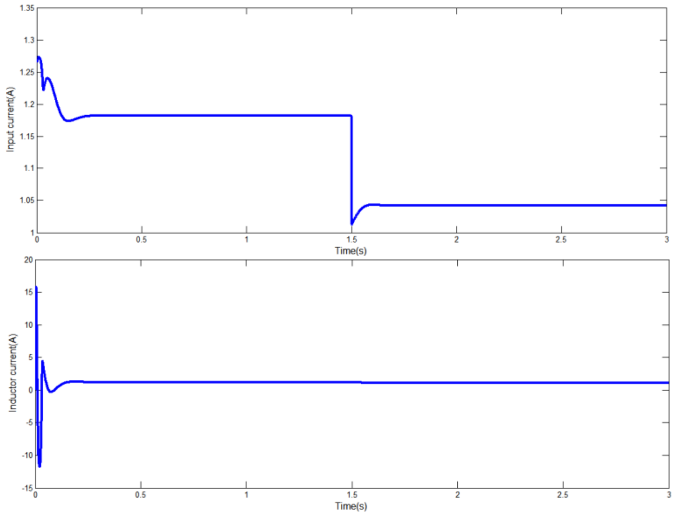


Fig.11 Input and inductor current of the converter

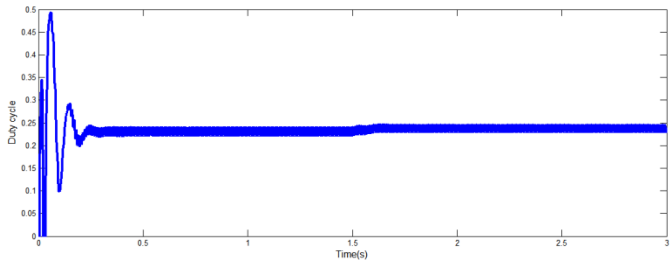


Fig.12 Control signal of the converter

5 Experimental Results

The PV system which is the object of our study is formed by:

- A support equipped with PV panel and light source imitating solar energy (fig 13).
- Two batteries (12V, 5Ah) in series.
- A power circuit which is Boost converter dimensioned at frequency of switching 62.5 KHz. In this converter; we used a SCHOOTKY DIODE and a MOSFET (IRFP250) which presents an interesting performance for our system. A voltage and current sensors are needed. The first one to detect voltage of the PV panel which must be < 5V because the analog input in Arduino is limited to 5 V. The second one to measure the output PV current and they transmitted to the analog pin A1.(Fig 14, Fig 15)
- The driver is formed by a combination of amplifier which contains a push-pull stage in order to generate a control signal to ensure the opening and closing of the Mosfet Transistor. The amplitude of the signal generated by the MPPT algorithm from the Arduino board is 5V and the voltage drain-source generated by the driver is 12V which is largely sufficient to control the Mosfet.(Fig 18).

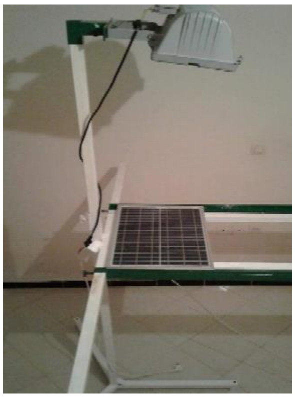


Fig 13 Support for PV panel

At first time, the feasibility of the developed system containing boost converter, sensors, driver and Arduino board was tested and guaranteed by 100 MS/s oscilloscope option (NI ELVIS II+) used with an incandescent lamp (24V, 5W) as charge (Fig 14).

In order to create an embedded system, a location is designed for the input/output of the Arduino board to mount it under our electronic card.(Fig 16)

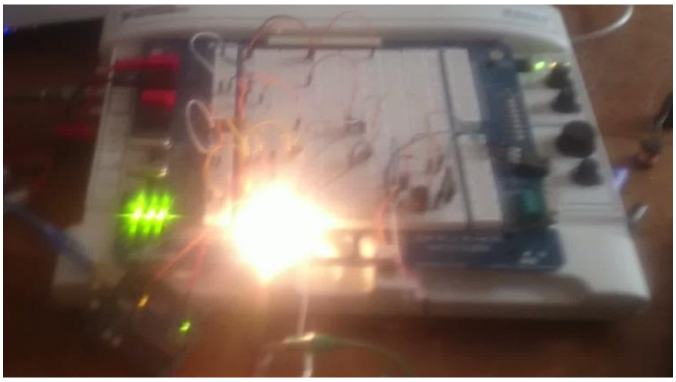


Fig 14 Converter and MPPT implementation test

Fig 15 Designed MPPT controller

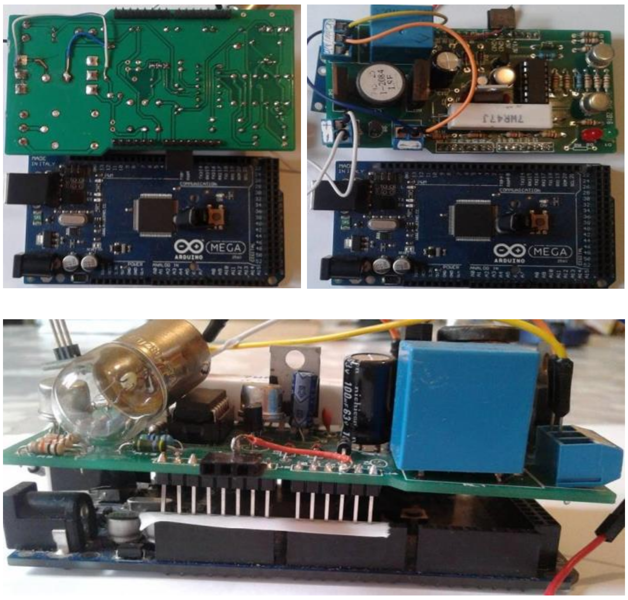


Fig. 16 Location of the Arduino board

The MPPT's implementation with batteries is shown in figure 17.

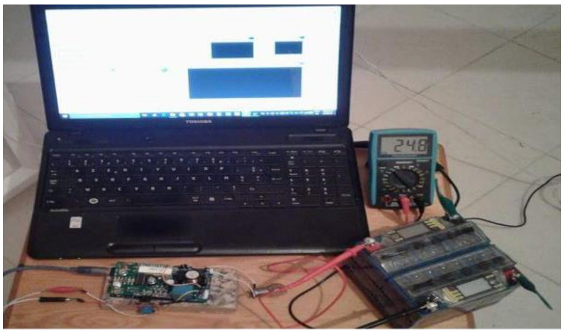
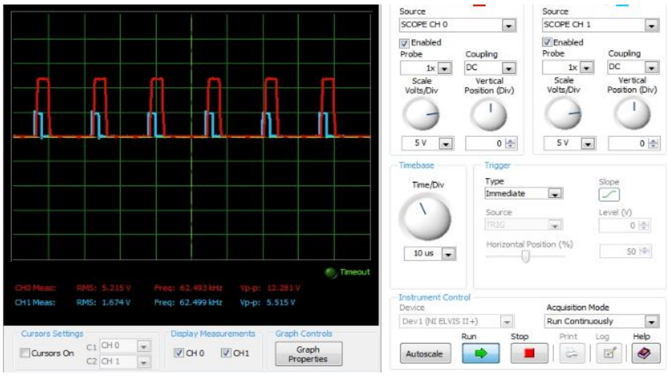


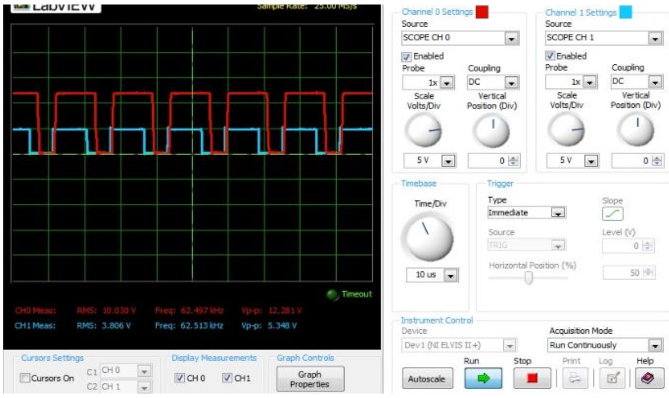
Fig 17 Designed test bench

Fig 18 shows also that the signals of the input and output of the driver with 25 and 50% of the duty cycle

Fig 19 shows experimental delay (On-Off delay) between the input and the output driver signals due to propagation delay of the duty cycle signal.



a. 25% of duty cycle



b. 50% of duty cycle

Fig 18. Input & output of the driver

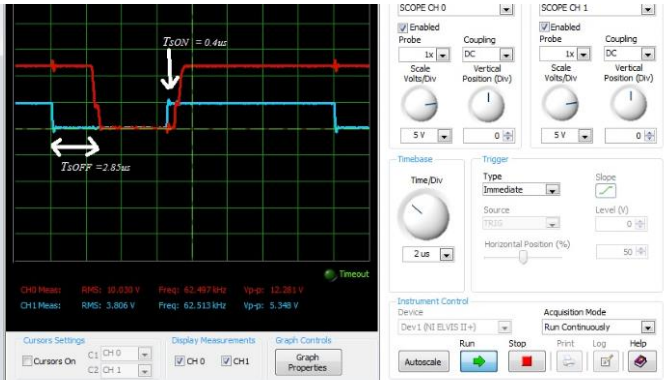


Fig 19. Input/output driver delay

Figure 20 shows that the V_{pv}=17V and the value of V_{bat}=24.8V which needed to charge the batteries.

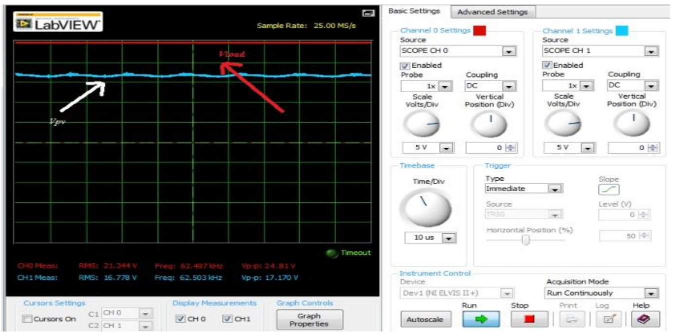


Fig 20 Input & output voltage converter

In order to control and visualize the performance and the evolution of our system in real-time, a serial communication with a computer containing a graphical user interface is developed by exploiting LabVIEW software.

Fig 21 shows that the MPPT controller converging the system towards the PPM, even with variation of atmospheric conditions.

Fig 21 Graphical user interface

6 Conclusion

In this paper, a modular system which contains a control and power card is designed. A proposed Backstepping MPPT algorithm is implemented in the Arduino board to control the power adaptation stage. The output characteristic of PV system by using Backstepping MPPT method present a high performance, and the simulation shows that the proposed method gives very satisfactory results with a good efficiency and high accuracy. A test bench has been developed with graphical user interface built in LabVIEW which present more abilities to control and supervise the system in real time. The author strongly believes that this system will be helpful for students and researchers in the field of solar systems

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