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Photovoltaic System Equipped with a DC/DC Buck Converter and a MPPT Command Ensuring an Optimal Functioning Independently of System Perturbations

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Authors' contributions

This work was carried out in collaboration between all authors. Author EB designed the study, carried out the field work along with authors MM and MFY, and wrote the first draft of the manuscript. Author KK supervised the work and managed the analyses of the study. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

In this paper, we analyze the conception, the realization, and the characterization of a photovoltaic system (PV) equipped by a DC/DC buck converter and an analogical MPPT controller provided with detection circuit of dysfunction and convergence of the system (CDCS). We demonstrate that The CDCS circuit ensures an optimal functioning of the PV panels independently of variations of the weather conditions (illumination, temperature,…) and the load. From the modeling of the optimal functioning of PV panels and the complete system in the Pspice simulator, we showed the good functioning of the PV system conceived and realized in this work. During whole days of functioning, we showed that the efficiency of the converter is very satisfactory (about 80 %) and the electric power losses of the PV panel are lower than 8 %.

Keywords: Panels and photovoltaic system; MPPT command; the detection circuit of dysfunction and convergence (CDCS); Buck DC-DC converter; optimal functioning; energy losses.

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1. INTRODUCTION

Currently, the PV energy is produced by panels and PV systems [1-7]. These last ones suffer from a lack of optimization and the divergence after sudden variations of the illumination and the load [2,3]. In the literature, MPPT commands (Maximum Power Point Tracking) provided with a detection circuit of divergence (dysfunction) were proposed [1], but the inconvenience is that they restart the PV system during the detection of a possible dysfunction. Besides, we find very few results concerning the PV systems which use converters DC/DC of Buck type.

In this frame, we have studied in previous work [2,3], the conception, the realization and the optimization of a PV system provided with a DC/DC Boost converter and an analogical MPPT command followed with a detection circuit of dysfunction and convergence of the system (CDCS). We obtained a good functioning of the PV system when applications required a higher voltage than optimal PV panels. However, in case of plants that feed solar battery with lower voltage than optimal, the system can no longer be used. In this case, a development of new system equipped with the DC-DC Buck converter is required. For this type of installation we can found in the literature very few results.

In this paper, we present the results of the adaptation of the PV panels to the load using a DC/DC Buck converter [2-8] and MPPT command [9-18] .This latter is followed by a circuit capable to detect dysfunction and convergence of the system (CDCS) towards its new maximal power point (MPP), independently of the variation of the illumination or the load. These works bring in within the framework of the Program of Nations United in our region and concern the optimization and the reliability of an installation in progress by our team. We analyze in particular the command circuit of the converter Buck (CCB) and the global functioning of the PV system, in the presence of CDCS circuit, during days in function of the variation of the illumination or the load.

2. STRUCTURE AND FUNCTIONING OF THE PHOTOVOLTAIC SYSTEM

The Fig. 1 represents the synoptic the overview of a photovoltaic system (PV) which is constituted by:

- PV panels, in monocrystalline silicon, formed by 36 cells in series (Fig. 2) [2-3,19-20]. As shown in the Fig. 2, a PV cell is formed by the generator of current ICC (short-circuit current), the diode (D), the shunt resistance (R_{Sh}), and series resistance (R_S). The current of the diode depends on the technological parameters and of the temperature (T) according to the expression:

$$I_D = I_S(T) \bullet \exp(-\frac{q \bullet V_D}{K_B \bullet T} \qquad (1)$$

Where:

V_D : voltage at diode terminals, I_S (T) : saturation current,
q : charge of the free electron, K_B : Boltzmann constant.

From the comparison of the results of simulations to those provided by the manufacturer, we have deduced the various parameters from the diode and PV cell (R_S and R_{Sh}), and dependence of the short-circuit current (I_{CC}) with solar radiation (Le (W/m^2)) [19].

- A quadripole of adaptation which is a DC-DC Buck converter [2-8] (Fig. 3A), dimensioned to works in continuous regime with a frequency of 10 kHz and a variable duty cycle α (PWM Signal) [2,3].

In our work, we analyzed the functioning of the DC-DC converter from the relations between the voltages and the currents, at the exit (V_S, I_S) and the entrance (V_{PV}, I_{PV}), according to the duty cycle α:

$$Vs = \alpha \bullet Vpv \tag{2}$$

$$Is = \frac{Ipv}{\alpha} \tag{3}$$

- An analogical MPPT command [2,3] (Fig. 3B) allowing pursuing the maximal power point of the PV panel independently of the weather conditions and the load. In [2,3], the feasibility of the functioning of this MPPT command was showed in the case of a DC/DC converter of Boost type [2,3]. The functioning of this command is:

  - A shunt resistor (R) of very low value that can withstand a current of 10 A. This shunt resistance allows to have the Ipv current of PV panel,
  - A resistor bridge (R_1 and R_2) for taking a fraction of the voltage of PV generator,
  - A multiplier which provides at its output the image of the instantaneous power delivered by the PV generator.
  - Two integrators: one is fast with time ζ_R constant, and one slow with time ζ_L constant. The fast integration delivers at its output a homogeneous voltage to the power provided by PV panel, and the slow integrator provides at its output a delayed power Pl (t+dt). The comparison between these two powers (Pr and Pl) allows deducing the direction of system evolution: an increase or decrease the power of the PV panel. At a given instant t, if the Pr power is higher (lower) than Pl power then there is an increase (decrease) in power output of PV generator.
  - A comparator (1) whose role is to make the comparison between the Pr power and the delayed Pl, and provide a rectangular signal at its output.
  - A Flip-Flop whose Q output changes state on each rising edge of the clock signal which is the output of the comparator (1). When the system evolves towards a decrease in power, the Q output changes state in order to reverse the direction of system evolution.
  - Integrator (Ro, Co) with the capacitor charges and discharges slowly. It delivers at its output a voltage constituting the reference Vref voltage.
  - A comparator (2) which generates a rectangular signal (PWM signal of variable duty cycle α), resulting from the comparison between the Vref voltage and the saw tooth issued by an oscillator frequency of 10 kHz. The variation of α duty cycle depends on the Vref voltage: when Vref voltage increases (decreases), the duty cycle α increases (decreases).

In the case of a DC/DC converter of Buck type, the switch command of the converter requires the use of a circuit which improves the amplitude of the PWM signal (CCB circuit). This CCB circuit (Fig. 4) ensures turning On and OFF the power switch of the Buck converter. In the case of DC/DC Boost converters [2,3], a signal which its voltage amplitude is around 6 V is sufficient to command the power switch. However an important amplitude superior to the optimal voltage of PV panels is required. To do it, and reduce the cost of the PV system commands realization, we propose the simple circuit of the Fig. 4, alimented by the solar batteries (12 V), and charged by the same installation. This is circuit contains: an oscillator, a pumping circuit of load, a reverser with bipolar transistor and a driver. Its functioning is as follows: The oscillator generates a square signal to the input of the Pumping of load (Vs) (Fig. 4). When its output is zero, the first capacitor C2 is charged and the voltage VA is equal to Vcc = 12 V (unless the voltage drop across the diode D1) (Vcc is fixed by the solar batteries of the installation). Similarly, the capacitor C3 is charged and the voltage VC3 is equal to Vcc (minus the voltage drop across the two diodes D1 and D2). When the output of the oscillator switches to Vcc, the voltage VA increases and reaches the value of 2xVcc (less the voltage drop in the diode D1). Consequently, following the charging of the capacitor C3, the rated voltage of the capacitor C3 reaches the value of 2xVcc (less voltage drop in diodes D1 and D2). The latter voltage polarizes a bipolar transistor functioning in switching mode. To obtain a PWM signal with a voltage amplitude of 2xVcc, an inverter with a bipolar transistor (Fig. 4) was used. So, the signal provided by the MPPT command (Fig. 3B) is injected in the base of the bipolar transistor and the collector signal is injected into the MOSFET of the converter through a driver. The given signal, with an amplitude of 2x Vcc, is largely enough for the opening and the closing of the MOSFET in our application.

- A load which can be either a resistance with value less than the optimum one of the module resistance [2,3], or a battery with voltage less than the optimum tension of the module.
- A detection Circuit and Convergence of the system (CDCS) detects the dysfunction of the system after sudden variations of the illumination or the load, and converges the PV system to its new maximal power point (MPP) without restarting it. The structure of this circuit is represented in Fig. 5. It contains:

  - ❖ Two monostables which detect the divergence of the PV system. The inputs of these monostables are connected to the Q and Qb outputs of flip-flop of the MPPT command. If the system diverges, the two Q and Qb outputs do not change their state: one output of a monostable system detects the divergence to the closed circuit conditions and the other output to the open circuit conditions. The duration of the detection of divergence is determined by the period of the monostable (T_1 and T_2) :

$$T_1=1.1*R_1*C_3 \qquad T_2=1.1*R_3*C_5 \tag{4}$$

  - ❖ The two outputs of the two monostables are connected to a logical door of OU-Exclusif (XOR) type. If the system loses its point of optimal functioning, the output of the X-OR door changes its state.
  - ❖ The state corresponding to the X-OR output is then inverted by a logical inverter. This pulse is applied to the clock of another 'Flip Flop' and consequently the change state of its output Q. This change of state, changes the position of the blade of a relay which connects the input of the integrator RoCo to the two Q and Qb outputs of the flip-flop of the MPPT command. If the RoCo integrator is connected to the Q (Qb) output, then the detection of a dysfunction reconnects the RoCo integrator to the Qb (Q) output of the control of the Flip Flop MPPT. This change of position of the blade of the relay, induces change of the direction of variation of the cyclic report of signal PWM generated by MPPT command, and thus changing the direction of displacement of the point of functioning of the PV generator. This movement allows the PV system to evolve to the new PPM.

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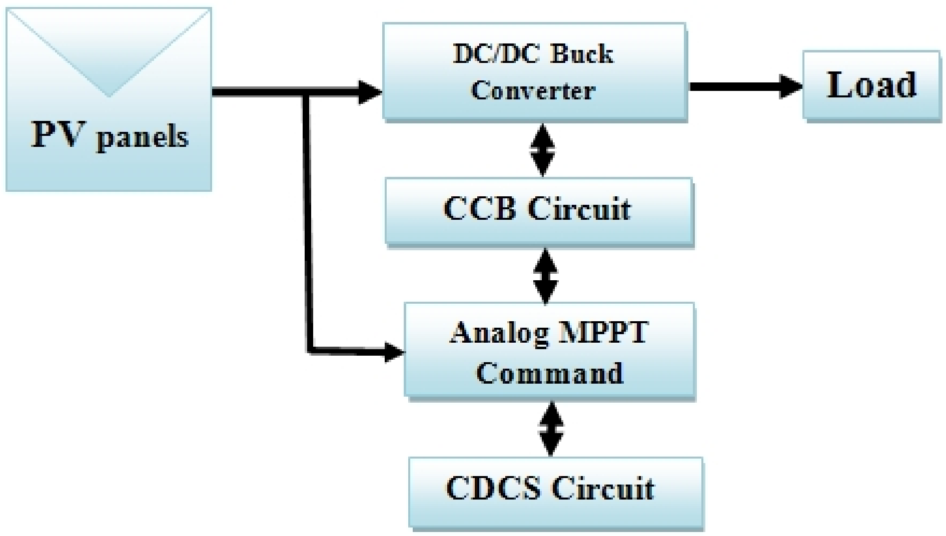


Fig. 1. Synoptic diagram of the PV system equipped with a MPPT command and a CDCS circuit

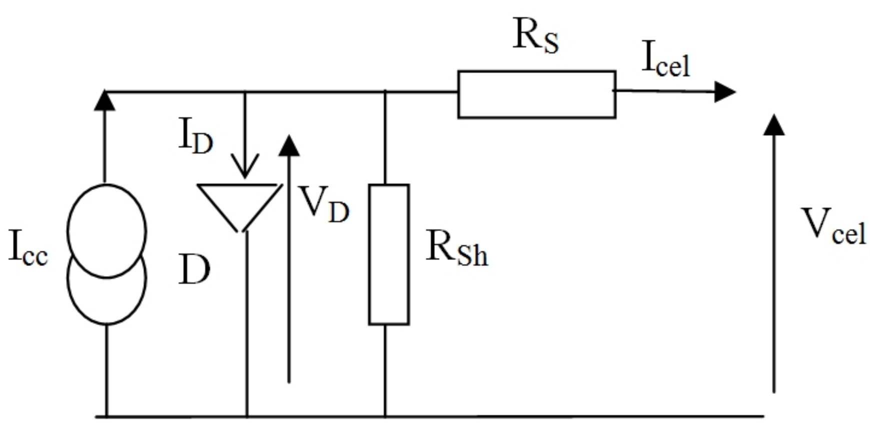


Fig . 2. Electric diagram of a photovoltaic cell

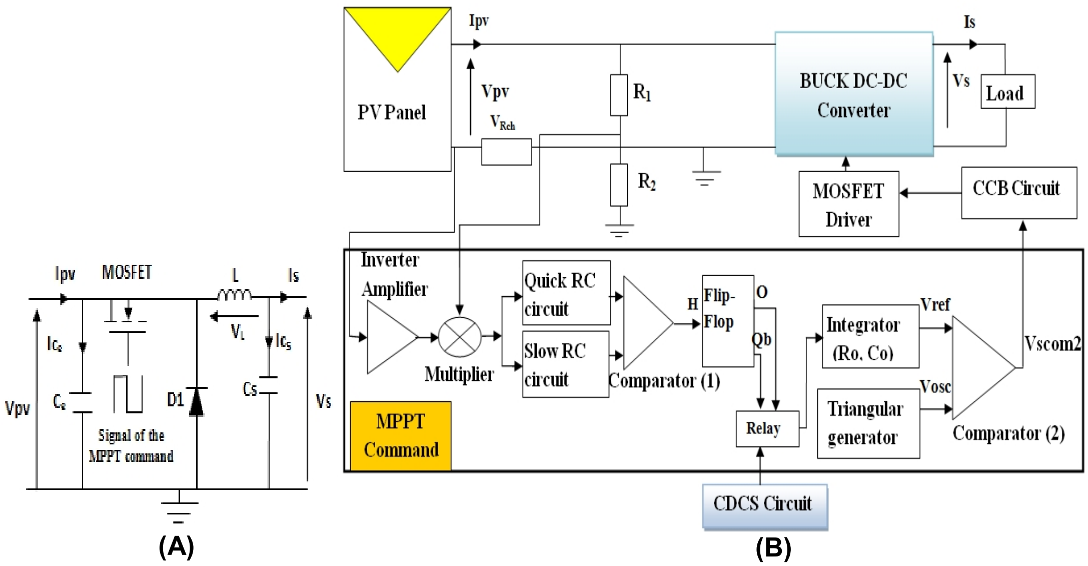


Fig. 3. Structures of the DC/DC Buck converter (A) and the MPPT command (B)

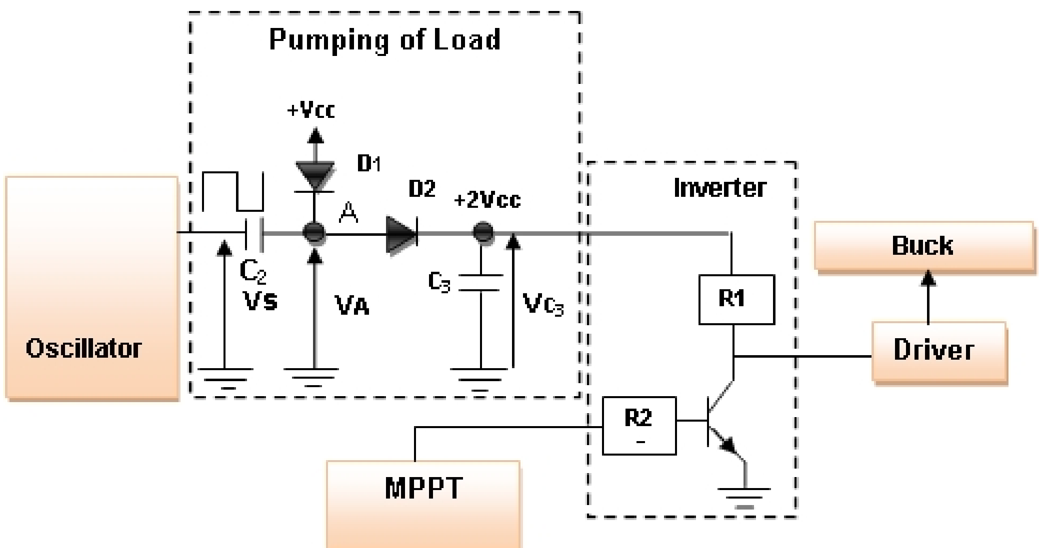


Fig. 4. Structure of the CCB circuit

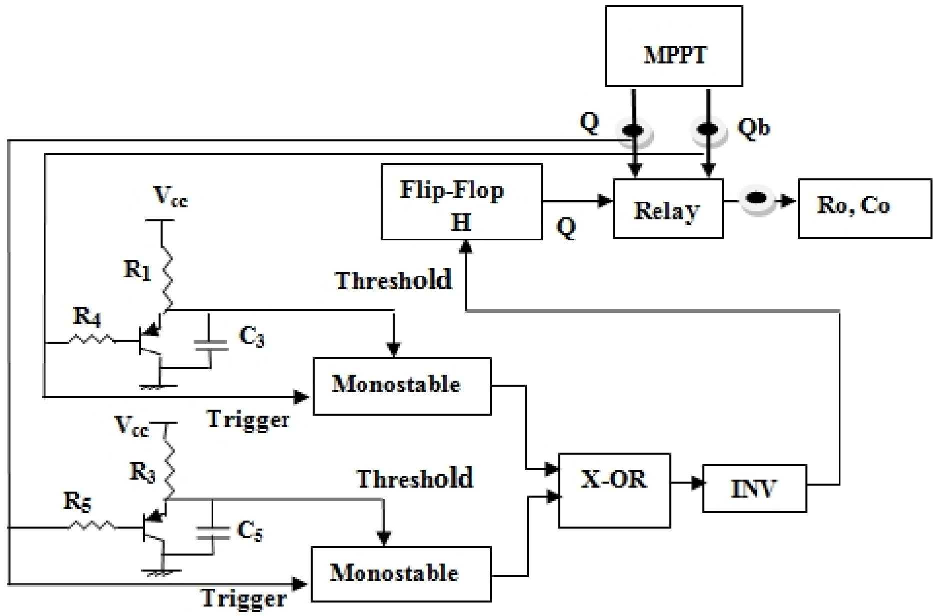


Fig. 5. Synoptic diagram of the CDCS circuit

3. SIMULATION RESULTS OF THE PV SYSTEM IN PSPICE

We have implemented and simulated the functioning of electric PV system in Fig. 1, the circuit with CDCS, in Orcad-Pspice simulator for an illumination of 909 W / m², a temperature of 25ºC and a resistive load of 1.5 Ω. We have measured the different electrical quantities and the MPPT command signals when the RoCo integrator is connected either to the Q or Qb output of the flip-flop (Fig. 3B). We have concluded that the different MPPT command signals are identical to those obtained in the case of the DC/DC converter of Boost type [1,2].

3.1 CCB Circuit

The typical signals of the CCB (Fig. 4) circuit and MPPT command shows (Fig. 6): The oscillator (Fig. 6A) and the diode D1 and D2 (Fig. 6B) double the potential in the borders of the condenser C3 (Fig. 6C). So, a signal with a frequency of 10 kHz and an amplitude in order of 20 V (Fig. 6D) are generated by the MPPT command and the CCB circuit. In the case of our PV system, since the optimal voltage of PV panel is lower than 15 V, we can deduce that this signal commands correctly the MOSFET transistor of the DC-DC converter Buck (On and off) (Fig .3A).

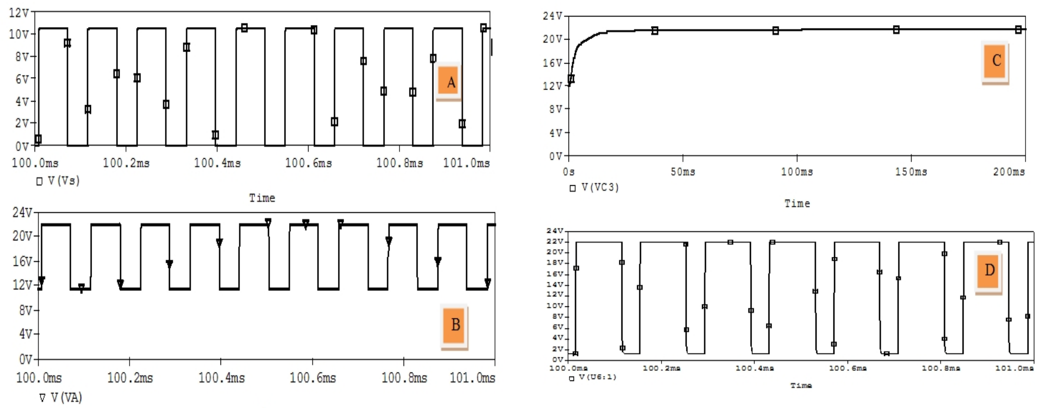


Fig. 6. Typical signals of the CCB circuit (Fig. 3) obtained in Pspice: (A) voltage at the output of the oscillator; (B) Voltage at the point A (VA) ;(C) Voltage in the border of condenser C3; (D) voltage at the output of the driver

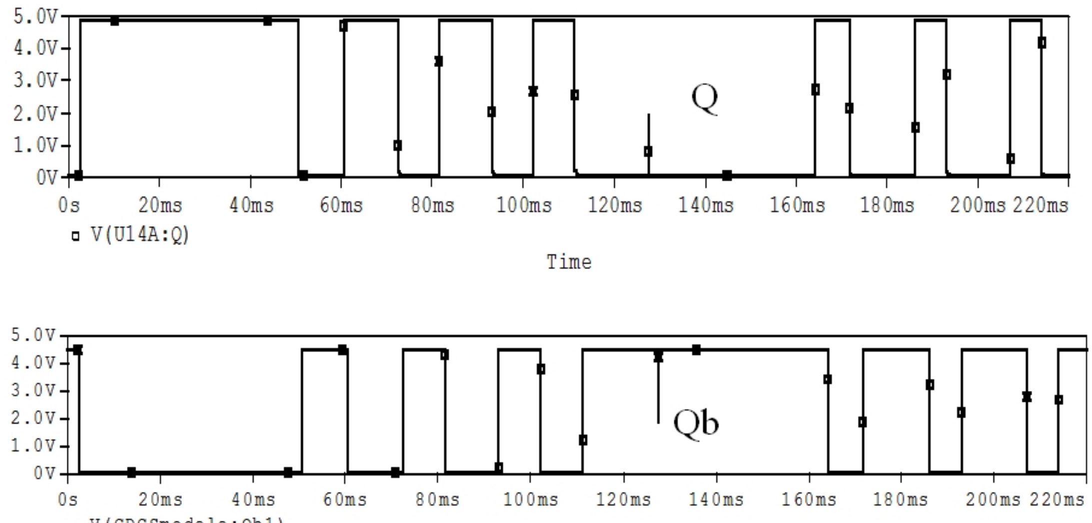
3.2 Global System

The PV system in the presence of the MPPT command diverges during a sudden variation of the load or the illumination towards the opened or the closed circuit [2,3]. Consequently, the conception and the realization of detection circuit of the divergence and reconvergence instantly to the optimal conditions is indispensable.

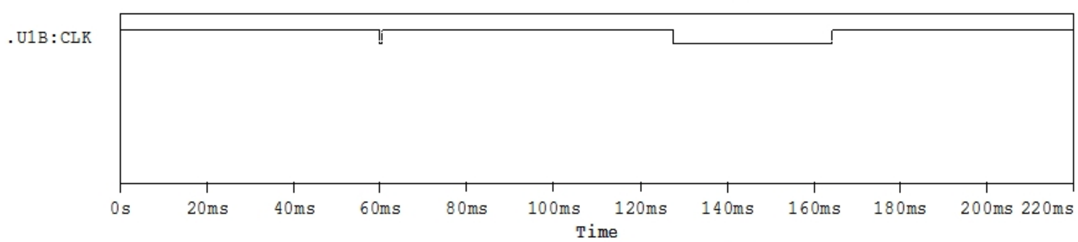
The functioning of the PV system equipped with analogical MPPT command (Fig. 1) and the detection circuit of the dysfunction and convergence the system (CDCS) (Fig. 5) were analyzed in Pspice. The various blocks of the PV system were studied in case of sudden load changes. Similar resultants are obtained in the case of the fast variation of the illumination. Typical results obtained are represented in Figs. 7 and 8. It appears that, during the normal functioning of the system before the dysfunction (t < 110 ms), the output Q of the MPPT command is in the low state (Fig. 7A), the voltage Vref decreases (Fig. 7D)) and the duty cycle of the PWM signal decreases **(**Fig. 7E). When the load changes (at t = 110 ms), the PV system diverges and the Q output of flip-flop of the MPPT command locks in the low state (Fig. 7A). As in the case of the DC / DC Boost, for a time of about 20 ms set by the monostable (Fig 4), the CDCS circuit generates a signal (clock signal of Flip Flop) that activates the flip-flop of the CDCS circuit (Fig. 7B). The change of state of the Qb output switches to the Up state (Fig. 7C). Therefore the relay is activated and the RoCo integrator of the MPPT command is again connected to the output Qb of flip-flop of the MPPT command. During the detection of the dysfunction, the RoCo integrator is connected to the Qb output which is in the up state (Flip-Flop of the MPPT command), the Vref voltage (Fig. 7D) and the duty cycle of the PWM signal (Fig. 7E) increase. Then, the operating point of the panel change direction by moving to the closed circuit conditions. So, the PV panel voltages decreases and reconverge to optimal voltage (Fig. 8).Once the operating point reaches the optimum conditions (time of about 20 ms), corresponding to the load of 3 Ω, pulses appear at the outputs Q and Qb of flip-flop of the MPPT command. The clock signal of the flip-flop switches, so in the high state and the PV system oscillates around the optimal electrical quantities. The RoCo integrator is connected to the output Qb of the flip-flop of the MPPT command until the next divergence.

Note that the oscillations of the electric quantities (voltage, current and power) of the DC/DC converter's output (Fig. 8) are important compared to those in input. This is due to the low value of the condenser CS (Fig. 3A), fixed to reduce the time of simulation.

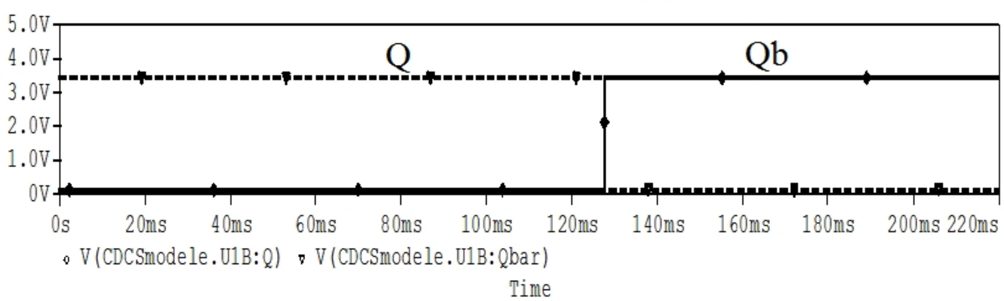
All of these results show that the MPPT command, the CCB circuit and the CDCS circuit played correctly their roles. Despite the perturbation of the PV system, the functioning of the complete PV system is optimal.



(A)



(B)



(C)

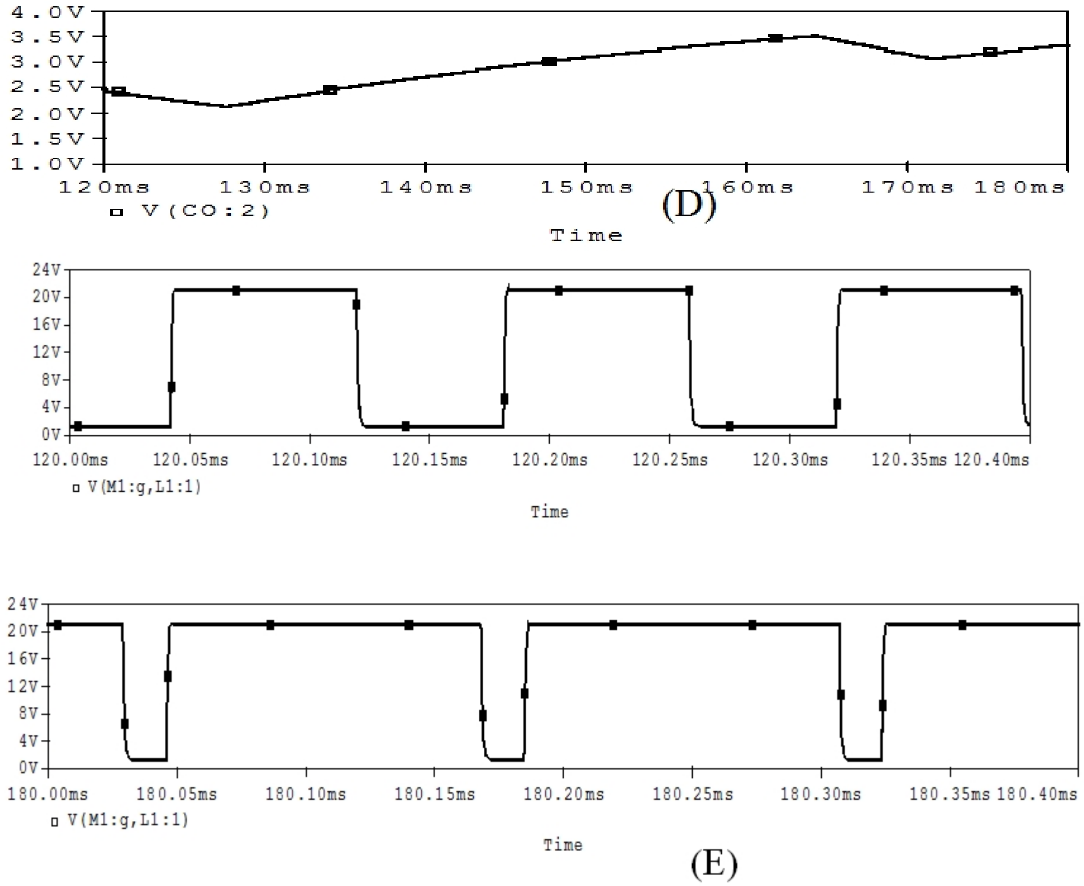
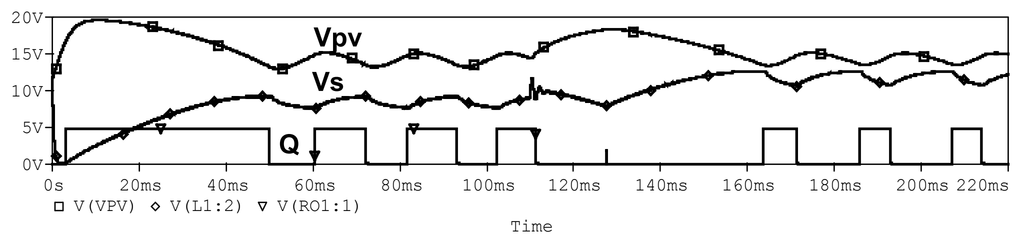


Fig. 7. Typical Simulations in Pspice of the functioning of blocks of the MPPT, CDCS and CCB circuits due to variation in load of 1.5 Ω to 3 Ω :(A) MPPT command outputs Q and Qb; (B) Clock signal input of CDCS Flip-Flop;(C) Flip-flop outputs of the CDCS circuit (Q, Qb); (D) Vref voltage of the MPPT command; (E) PWM signal generated by the CCB circuit



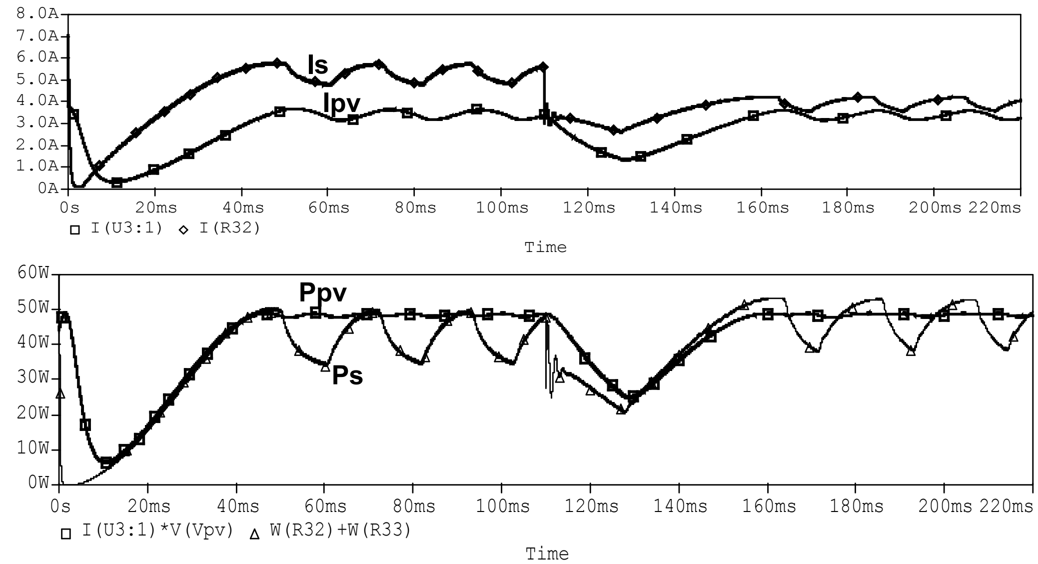


Fig. 8. Simulation in Pspice of the electrical quantities (voltages, current, power) to the input and output of the Buck converter, signal Q of the Flip Flop due to variation of the load of 1.5 Ω to 3Ω. Illumination: 803 W / m², T: 25ºC

4. EXPERIMENTAL RESULTS

4.1 Experimental Procedures

The PV panels of 300 W powers and completely automated measurement bench (Keithley model 2700 multimeter, connected to the PC) used in our work are shown in Fig. 9. The Keithley multimeter performs measurements on 20 lines during the day. The different results are discussed and analyzed from the Pspice simulator.

The DC-DC Buck converter, the analogical MPPT command equipped by the CCB circuit and the CDCS circuit dimensioned, designed and realized in the course of this work are shown in Fig. 10.

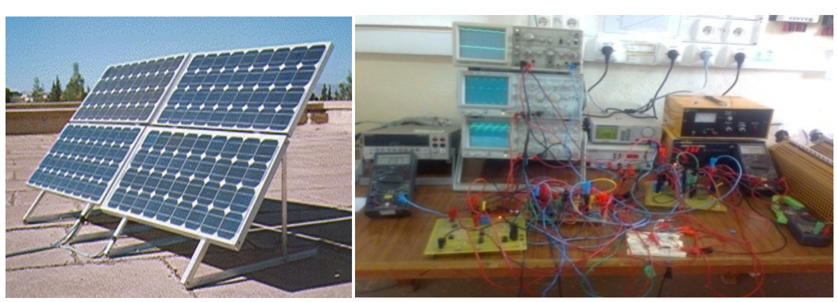
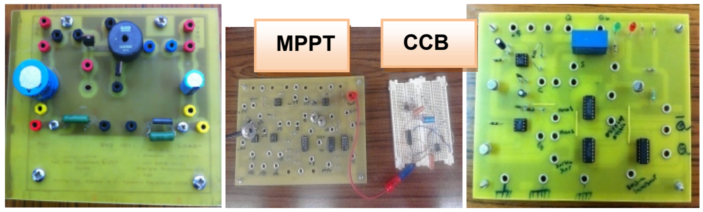


Fig. 9. Photovoltaic panel (300 W) installed in the laboratory and Bench of measure set up to characterize panels and photovoltaic systems



(A) (B) (C)

Fig. 10. Photos of Cards realized in the laboratory: (A) DC-DC Buck converter; (B) analogical MPPT command equipped by the CCB circuit; (C) CDCS Circuit

4.2 Functioning of Complete PV System

4.2.1 Functioning of the buck DC/DC converter

To ensure the good functioning of the DC/DC Buck converter, the system shown in Fig. 1 was realized and the functioning of each block of the converter was tested in the oscilloscope (Voltage according to time) (Fig. 11). It appears that the signal generated by the Buck command circuit CCB (Vgs) has a frequency in order of 10 kHz, a duty cycle (α) of 0.53 and an amplitude in the order of 20V (Fig. 11A). The functioning of the DC/DC converter depends on the time (t). During a cycle of hashing we deduce that (Fig. 11B): switch is closed when 0 <t <αT, and open when If αT <t <T.

For a load of 3 Ω and an illumination of 750 W/m², the PV panel generates at its output a voltage (Vpv) in the order of 13.4 V and the voltage across the load (Vs) about 7 V (Fig. 11C). From these values and those of the input current Ipv = 2.8 A (Behavior similar to Vpv/R_{opt}, R_{opt}= optimal resistance of PV panel [2,3], Fig. 11C) and output Is = 5.2 A (Behavior similar to Vs/R_S, R_S=3 Ω, Fig. 11C), we have found a very satisfactory efficiency (> 85%) and validation of equations 2 and 3 [1]:

All the signals and results obtained show the good functioning of the Buck DC / DC converter.

4.2.2 Functioning of the CDCS circuit

The functioning of the CDCS circuit was experimented by measuring signals with a digital oscilloscope at a divergence of the system after a sudden load change. We have concluded that the outputs Q and Qb of the flip-flop of the MPPT command sticks either in 1 or 0 state. The transistor which receives a signal 1 is blocked and the capacitor in the output of this transistor is charging until the terminal voltage reaches about 2.5 V (≈ 2Vcc / 3 [2,3]) (Fig 12A). In our case, since a charging time was fixed at 10 ms, the clock signal of the flip-flop switches to state '0 '(Fig. 12B), showing the detection of system dysfunction, and the output of this flip-flop changes state. This change of state switches the connection of the RoCo integrator of the MPPT command from Q to Qb or Qb to Q output of the flip-flop (MPPT command). The functioning point of the PV generator changes its direction of displacement to reconverge to the new MPP. Once the system oscillates around MPP, the output Q (Qb) of Flip-Flop of the MPPT command switches between states '1 '(0) and '0' (1), and the Clock signal of the CDCS Flip-Flop circuit to the state `1' (Fig. 12B).

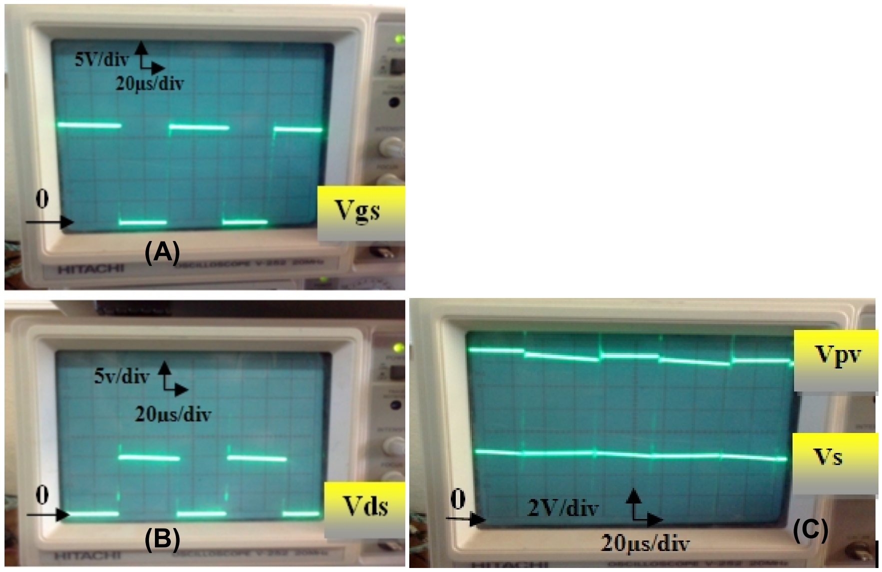


Fig. 11. Typical voltages of the DC-DC Buck converter (Voltage according to time): (A) Vgs: voltage gate-source of the MOSFET; (B) Vds: drain-source voltage of the MOSFET;(C) Vpv and Vs: Voltage to input and output of the Buck DC/DC converter

Note that the detection of the dysfunction and the convergence depends on the condensers values of the MPPT command, the CDCS circuit and the DC/DC converter. Because the time of the simulations depends on these values, we took different condensers values than those used in the experiment of the PV system (Figs. 13 and 14) to reduce the time of the simulation. In the case of the detection of the dysfunction, the values of the condensers of the circuit CDCS used are relatively weaker than those used in the simulations.

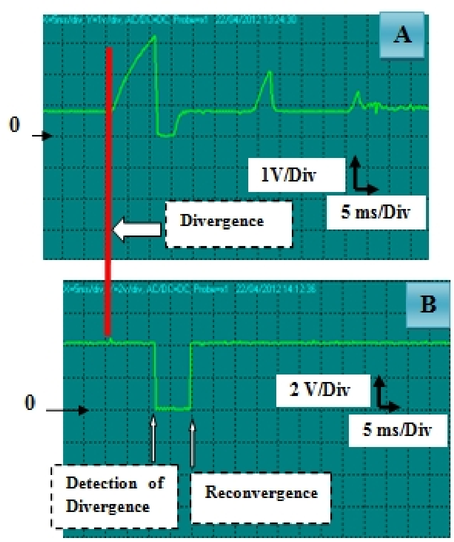
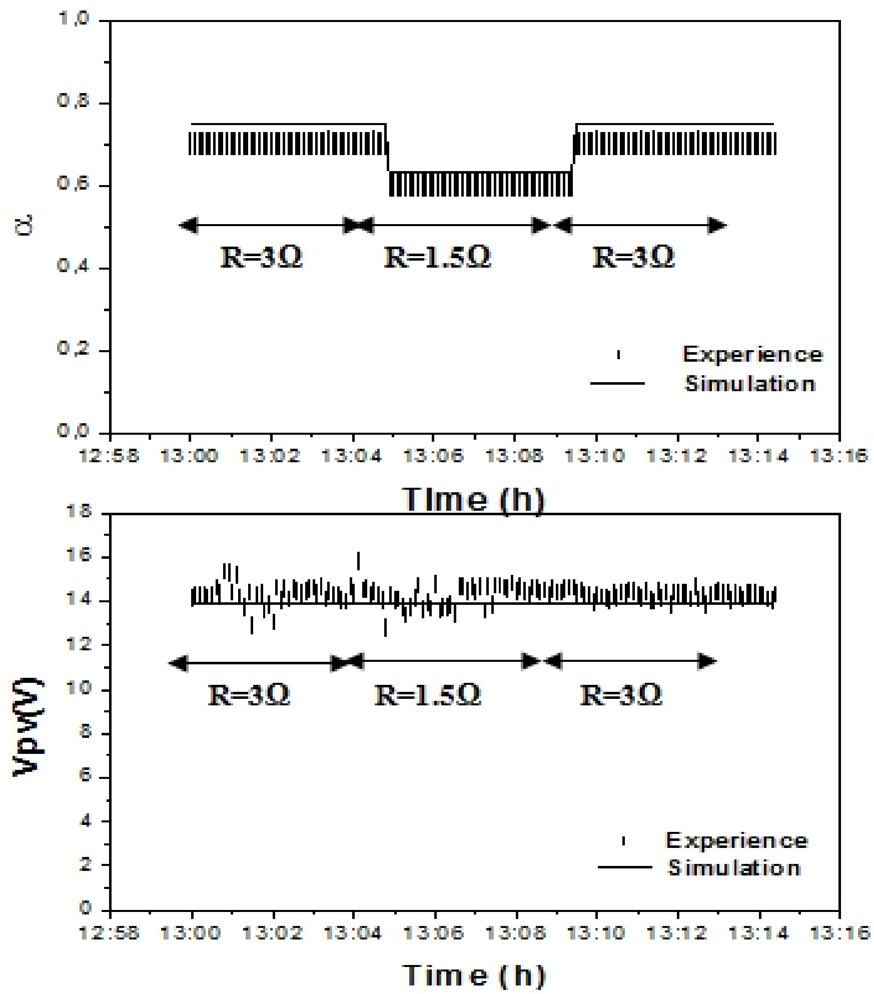


Fig. 12. Typical shape of the signals of the CDCS circuit (Fig. 5):(A) across the capacitor C; (B) Clock of the Flip-Flop

4.2.3 Functioning of complete PV system

The Fig. 13 represents the operation of the complete system equipped with the MPPT command and CDCS circuit in the case a sudden variation of the load. We can conclude that:

- The system does not lose its maximum power point (MPP): the duty cycle of PWM signal, the electrical values (voltage, current and power) to the input of the DC / DC converter oscillate around the optimal electrical quantities (MPP).
- The CDCS circuit detects the dysfunction and switches the connection of the RoCo integrator an output of the flip-flop of the MPPT command to another. Therefore the PV panel functions all day at its optimum power.



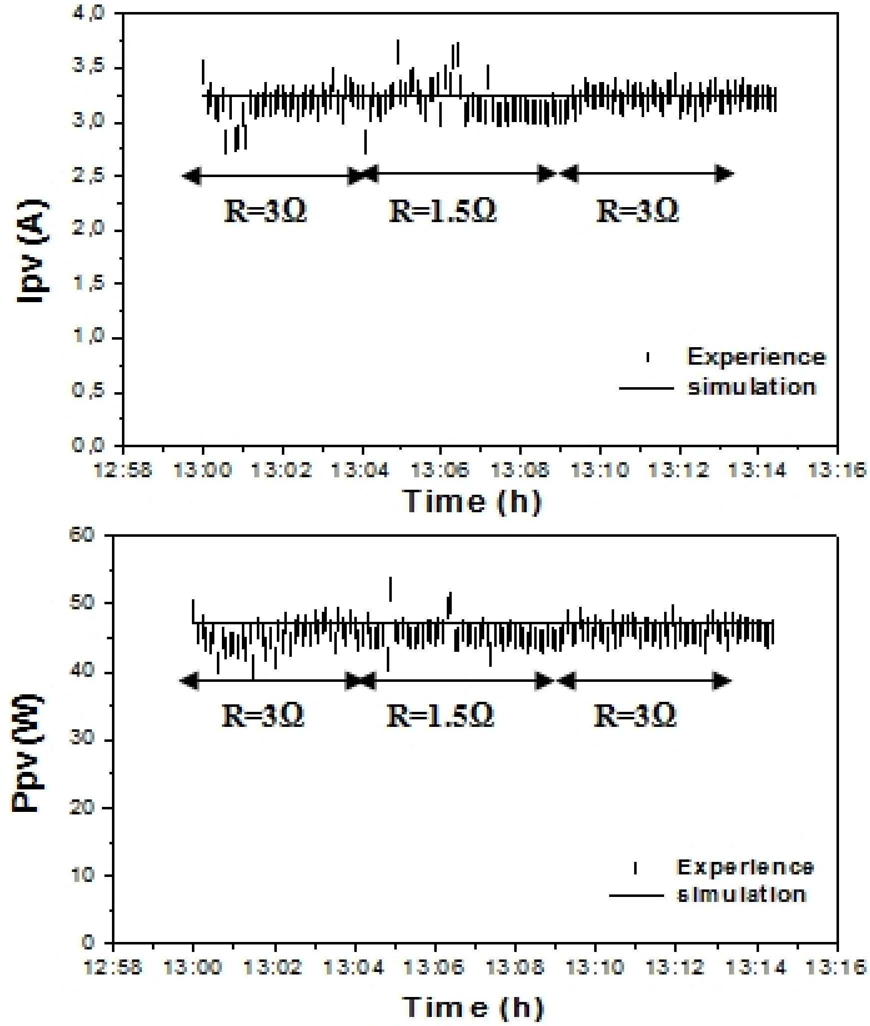


Fig. 13. Experimental and simulated in Pspice (Optimum) of Duty cycle, electrical quantities to the input of the converter, for a PV system, perturbed by sudden changes of the load (R) 3 Ω to 1.5 Ω, and 1.5 Ω to 3 Ω. Illumination: 803 W / m² and T = 18ºC

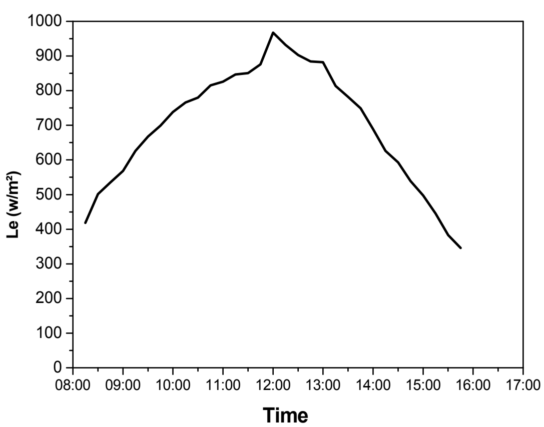
4.2.4 Functioning of complete PV system for an entire day

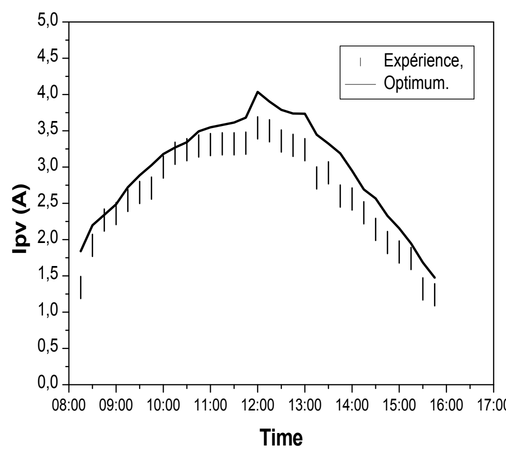
During an entire day of November when the ambient temperature was in the order of 22ºC in the morning and 32ºC in the afternoon, we have followed the functioning of the PV system (PV panel, Buck DC/DC converter, MPPT commands, CDCS circuit and resistive load) of the Fig. 1. On the Fig. 14, the experimental results and simulated were represented in Pspice (optimum): variation of the illumination, the duty cycle (α) of the PWM signal, the electrical quantities (voltage, current and power) in the input of the DC/DC converter, the efficiency of the DC/DC Buck converter and the losses of energies of the PV panel. All these obtained results show that:

- During this day of measure, the illumination varies from 418 W/m² to 967 W/m²,
- A very good agreement between the experience and the simulation (Optimum).
- After every perturbation of the system (Variations of the illumination), the CDCS circuit detects the dysfunction and reconverges the point of functioning of the PV panel to the PPM,
- Low losses of energy produced by the PV generator, in particular, for the strong illuminations. During this day, the produced energy is about 291 Wh, corresponding to losses lower than 8%.
- This evaluation is deduced from the model based from the experimental parameters values (closed circuit, diodes) [2,3].
- The experimental efficiency of the converter is satisfactory; it varies during the day between 65 % and 85 %.

To validate the performances of the photovoltaic systems of the Fig. 1, we followed its functioning during a whole day system presenting sudden change of irradiance levels. The variation of the illumination were represented On Fig. 15, we represented the experimental results and the optimal simulated results of the power of the PV panel. These obtained results show that during the entire day, the PV system works in the optimum conditions. No divergence was observed, despite fast variations of the lighting levels, the PV system works always around its PPM.

All the obtained results, shows the good functioning of the PV panel designed and realized on this work. Within the framework of projects which we committed in isolated sites (lighting and pumping of water), this prototype will be used to minimize the PV panels power and to satisfy people needs in electricity and in pumping water).





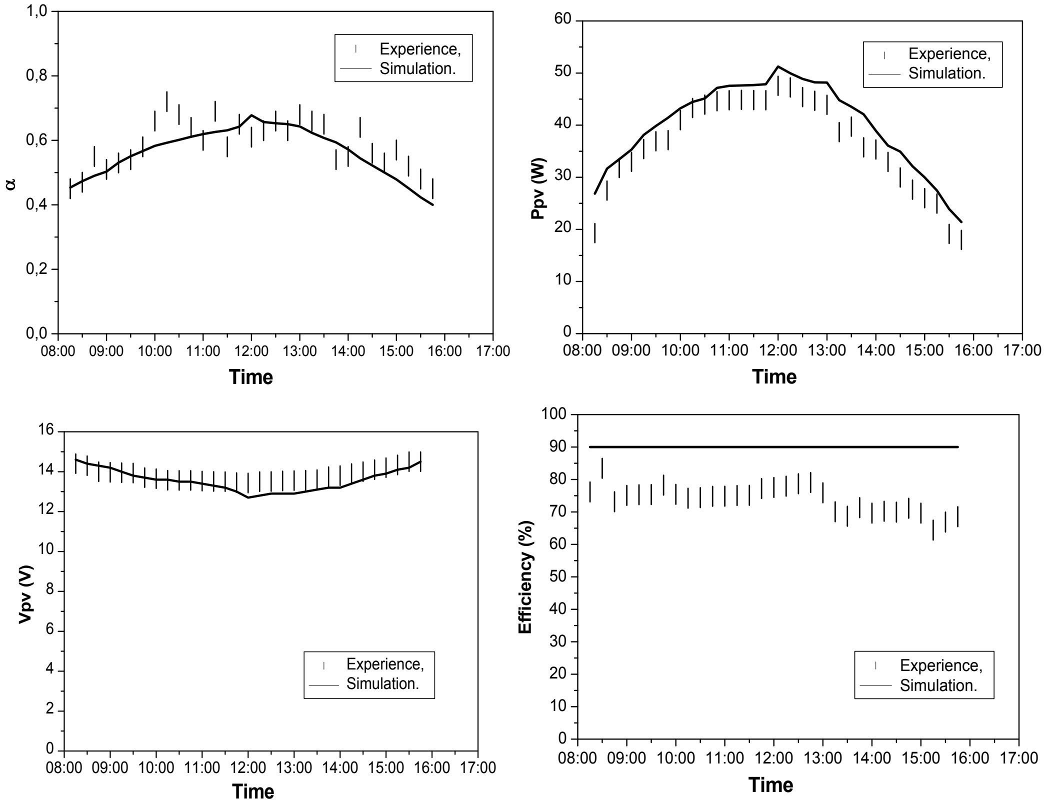


Fig. 14. Illumination experimental, experimental and simulated (Optimum): duty cycle α, electrical quantities (voltages and Powers) at the input of the DC/DC converter, DC/DC converter efficiency

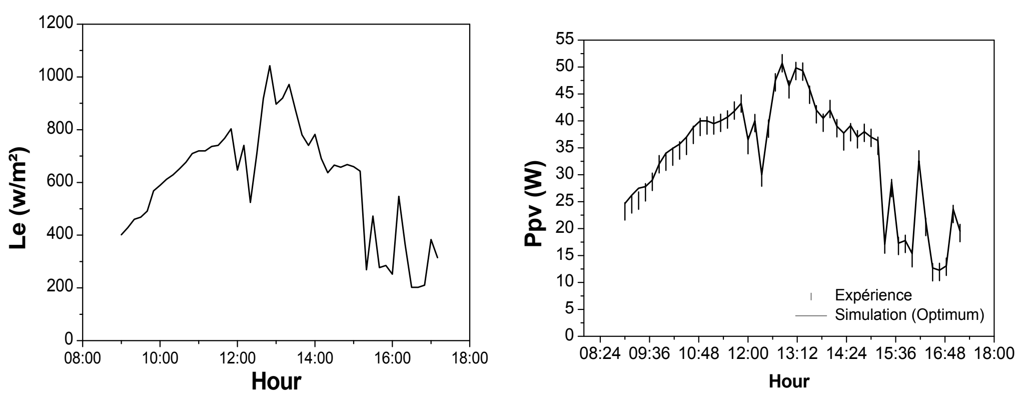


Fig. 15. Irradiance and the input power of the PV panel (Experimental and the optimal simulated with Pspice) during the entire day

5. CONCLUSION

In this work, we have analyzed in the Pspice simulator and experimentally the conception and the functioning of a PV system, using DC-DC Buck converter, an analogical MPPT command and a detection circuit of the dysfunction and reconvergence the system (CDCS). We have analyzed the functioning of every block and the electric quantities (voltage, current and power) in the input and in the output of the DC/DC converter during a sudden variation of the load (or the illumination). The obtained results show that: all the experimental electric quantities are in very good agreement with those (optimal) simulated in Pspice, the CDCS circuit detects the dysfunction of the system and reconverges it to a new maximal power point (MPP) without restarting the PV system.

During a day when the illumination reaches 1000 W/m² in the middle of the day, the PV system oscillates around the maximum power point. At every divergence, the CDCS circuit ensures an optimal functioning. The good efficiency of the DC/DC converter (about 80 %) and the low losses of the PV panel energies (lower then 8 %), show the good functioning of the complete prototype conceived and realized in this work.

In perspective, the PV system conceived and realized in this work will be used to improve the functioning of a PV station (lightings, pumping of the water) installed in an isolated site (a rural District of Oujda-Angad Prefecture) within the framework of the Nation Unis ArtGold Maroc Program. This site is not connected to the electrical network and does not have access to drinking water.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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