



International Journal of Emerging Technologies in Computational and Applied Sciences (IJETCAS) www.iasir.net

Protection of the photovoltaic (PV) systems by a dysfunction detection circuit of the PV system (DDCS)

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Abstract: In this paper, we analyze the design and the realization of a photovoltaic system (PV system) provided with a digital MPPT regulator and a dysfunction detection circuit of the PV system (DDCS). The role of the MPPT regulator is to control the solar Battery charging status when PV panel works around the maximal power point (MPP). The DDCS Circuit detect the dysfunction of the PV system following the failure of the MPPT regulator control and connect the PV panels directly to the load (battery, network, ...). The experimental and the simulated (Optimum) results show firstly, the smooth functioning of each block of the PV system and secondly, the detection of any dysfunction of the MPPT regulator and the connection of panels to the load. The load is directly supplied by the energy provided by the PV panels during the failure of the MPPT regulator.

Keywords: Photovoltaic system, Maximum power point tracking (MPPT), Digital MPPT regulator, dysfunction detection circuit of the PV system (DDCS), Batteries, Simulator Pspice.

I. Introduction

The rising energy demand and concerns about renewable energy production arouses an increasing interest on the part of government, energy distributors and consumers [1]. Currently, the photovoltaic (PV) energy is produced by PV systems [1-9], which suffer from a lack of optimization as well as any problems of dysfunction (failure) [2-3]. The classic PV systems use analog [2-3] or digital [4] MPPT controls, and regulators charge/discharge when using solar batteries [4]. Not practically all of these blocs (MPPT and regulators) have protection circuits, which detect any dysfunction and ensure the operation of the load (load of solar batteries, electricity power grid ...). The failure of the MPPT control causes a complete stop of the PV system. In addition, the MPPT control requires the use of DC-DC converters (boost, buck,...) where its components, especially the power switches can be damaged when the regulator is failing [5]. This is due to the charge/discharge of the inductor of the converters which can suffer of a sudden change in current and therefore a high potential difference [6]. So the failure of MPPT or MPPT regulator control induces the power loss generated by the PV panels and the complete stop of PV systems [2-3].

In this context, we studied the design and realization of a regulator MPPT [4] to control the charge/discharge of the solar batteries. The MPPT devices are intended to provide power to the load when the PV panels work at their maximum power point (PPM) [2-4]. As result of any unforeseen, sudden variation of illumination or failure of the MPPT control, the duty cycle of the PWM signal generated by the MPPT control can be locked at a value of 0, 1 or another value. This may block the installation and the functioning of the load (batteries...).

To ensure the functioning of the load by connecting it directly to PV panels, we studied the design and the feasibility of a dysfunction detection circuit of the PV system (DDCS). This circuit has for role, during the failure of the MPPT regulator control, to detect the dysfunction of the PV system and to connect the PV panel directly to the load (batteries, electricity power grid,...). During charging of batteries, the DDCS circuit has a digital regulator to control the functioning of the batteries [4].

In this paper, we present the results concerning the design and the experimental functioning of the dysfunction detection circuit and the MPPT regulator controls (DDCS). We study the cases of PV system equipped by the 12V solar batteries provided by the DC/DC Buck converter. L'ensemble des résultats obtenus sont comparés par rapport à ceux optimum déterminés par le simulateur Pspice. All the obtained results are compared with regard to the optimum determined by the Pspice simulator.

II. Photovoltaic systems provided with the dysfunction detection circuit of the PV system (DDCS)

In our study, we analyzed both cases of photovoltaic systems (PV) used in the current installations: pumping of water in the course of the sun [7] and the electrification with storage in the solar batteries [8] (Figure 1). The PV system allows storing the electrical energy in the batteries of 12 V by using the Buck DC/DC converter. In the both PV installations, the failure of the control causes the complete stop of the production of the electrical energy by PV panels.

The synoptic diagrams of two PV systems constituted by:

- Photovoltaic panels in monocrystalline silicon. Every panel is constituted by 36 photovoltaic cells and can deliver in the standard conditions of test (CST) a power of 55 W, a current of 4.2 and a voltage of 13V (Figure 2) [2,4].
- A charge which can be either a battery (110Ah, 12V), or a resistor 10 Ω of value.
- A DC-DC Buck converter [2] (Figure 2). These converters functioning in continuous regime with a hashing frequency of 10 kHz and dimensioned for a power of the order of 200 W [2,4].
- A digital MPPT control coupled with a regulator (MPPT Regulator) [4]. Its role is to follow the maximum power point (MPP) of PV panels independently of the weather conditions (Illumination, Temperature) and of the load, and to control the charge/discharge of batteries. The regulation of power supplied by the PV panels is carried out by the algorithm in Figure 3 (Hill Climbing Algorithm) whose principle is to calculate the derivative of the power and modify the duty cycle as a function of several parameters (Derivative of power, at the end of the temporization and the variable state used in our program) [4]. Contrary to other algorithms [9], our algorithm treats the problem of divergence of the PV system consequences in the sudden variations of the illumination and the load [4]. This detection of dysfunction remains insufficient if the MPPT control undergoes a failure at the level of the microcontroller or their components. In these conditions, the MPPT control generates a PWM signal whose duty cycle is blocked in a fixed status (In our case we took the high state '1').
- A regulator whose role is to follow the state of charge/discharge following three phases [4]:
 - Boost stage: where the battery is charged with the maximum current supplied by PV panels.
 - Absorption stage: when the battery reaches a maximum threshold voltage (gassing). This phase allows to battery to charge by the application of the variable current impulses in frequency following the state of the battery charge in order to avoid the surcharge and sulfation.
 - Floating stage: keep the battery completely charged and avoid the deep discharge. The regulator applies to the battery a floating voltage. To do it, a charge current, pulsed in frequency and in duration, is maintained to keep the voltage of battery around the voltage of maintenance.
- A dysfunction detection circuit of the PV system (DDCS) which has for objective to intervene soon as it detects a failure of the MPPT control and to connect the PV system directly to the load for not losing the totality of the energy produced by PV panels (Figure 4). In our study, we improved the structure and the functioning of a circuit used to restart the PV systems in case of dysfunction [2-3]. The functioning of the DDCS circuit designed during our work (Figure 4) is:
 - During a normal functioning (switching of the MPPT control output between the states 1 and 0), the MPPT control output and the inverted signal of this output, by an inverter, are connected to the inputs of two monostables (Trigger) and bipolar transistors (PNP). The outputs of both bipolar transistors switch between 0 and a voltage lower than the voltage Threshold of the monostable (charging of the capacitor). The both monostables are in the unstable state 'state 1'. The output of the XOR gate is thus in the '0' state. In this case, the relay assures the normal connection of the PV system: panels, DC/DC converter, MPPT regulator control, classic regulator, resistive load, batteries, electricity network,...
 - During a dysfunction of the PV system, the output of the MPPT command is blocked in a (low, high, or other) state. The blocked transistor provokes the charge of the condenser at its output (C1 or C2) until the voltage in borders reaches the 2 / 3Vcc threshold. The duration of the charge is fixed by the user and estimated from the relations [2]:

$$T1=1.1 \cdot R_2 \cdot C_1 \quad \text{and} \quad T_2=1.1 \cdot R_4 \cdot C_2 \quad -1-$$

In our case, these durations represent the dysfunction of the PV system. We fixed a duration of 50 ms to detect the dysfunction of the PV system. After these durations, one of the two monostables change state and as a consequence the output of the XOR logical gate toggle from the low state to the high state. This results in the activation of the relay and the connection of PV panels directly to the load (resistor, batteries, electricity network).

Figure 1 Synoptic diagram of a PV system equipped with the MPPT regulator control, DDCS circuit, a solar battery and a load (electrical network).

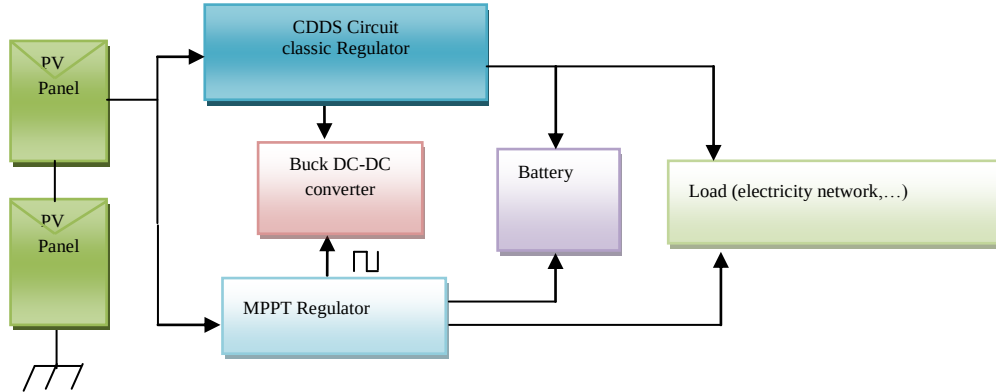


Figure 2 Experimental Characteristics Current -Voltage and Power-Voltage (■, △, ▲) and simulated in Pspice (—) of SP75 panel. T: 22-25 °C.

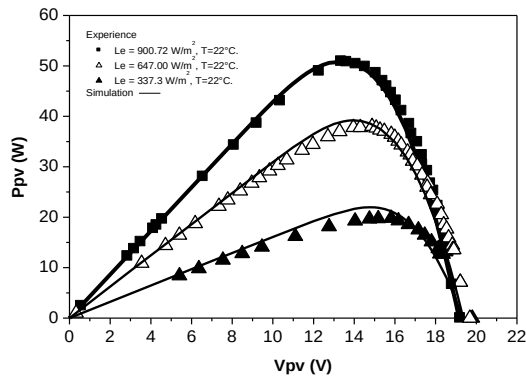


Figure 3 MPPT control Algorithm

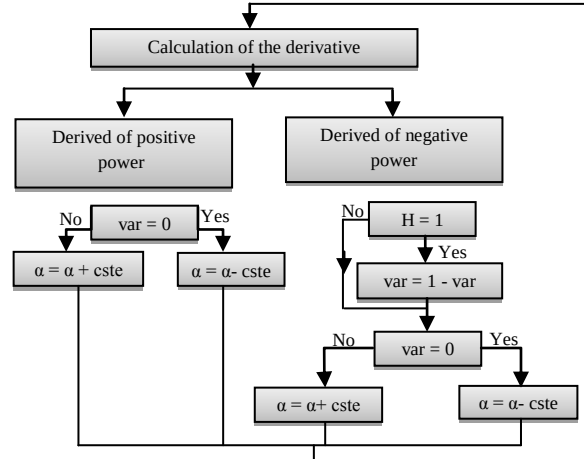
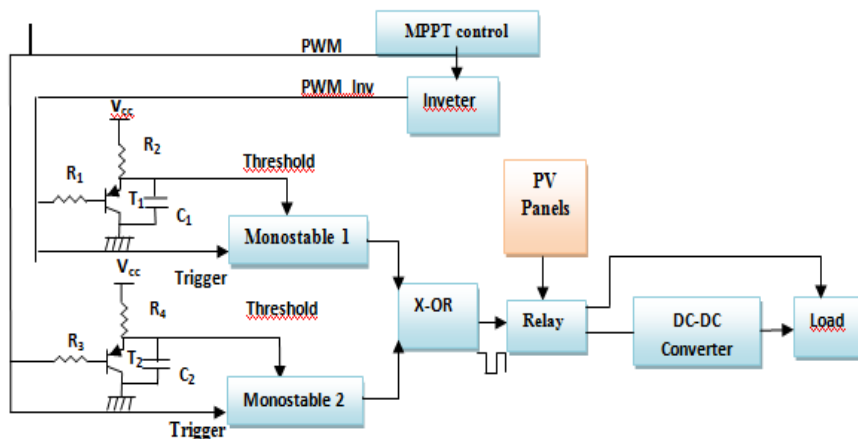


Figure 4 Synoptic diagram of a dysfunction detection circuit of the PV system (DDCS)



III. Experimental results

A. Experimental procedures

The bench of measure used in our laboratory to characterize the PV panels and the PV systems are shown in Fig 5. The fully automated bench is constituted of: PV modules providing 300 W of electrical power, A meteorological station (pyranometer and temperature sensor) to accurately track the values of irradiance and temperature, A multimeter (Keithley 2700) and oscilloscopes connected to a computer for data acquisition and real time trace of various electrical quantities of the PV system. The DC/DC Buck converter, the MPPT

regulator control and the CDDC circuit dimensioned, designed and realized in the course of this work are shown in Figure 6.

Figure 5 The bench of measure used in LETAS laboratory:

A) PV Panels, B) Pyranometre, C) Equipements (multimeters, Rheostat, Oscilloscopes, Supplies, Batteries), digital D) Oscilloscope.

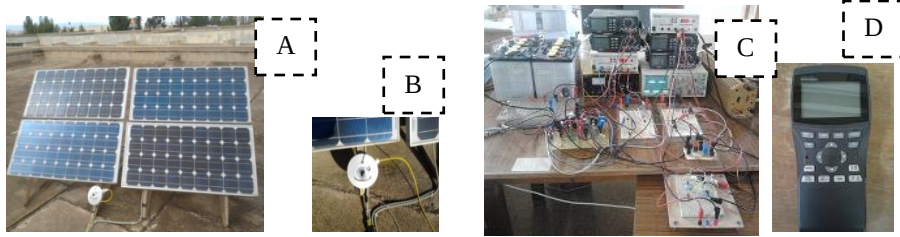
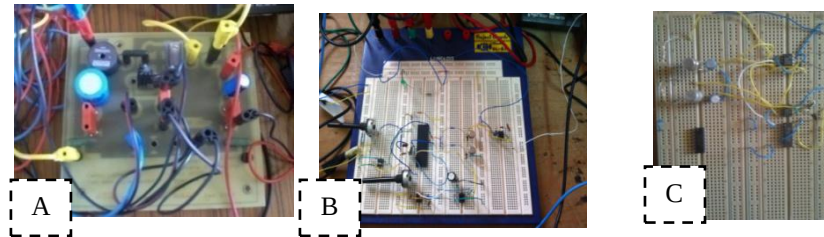


Figure 6 Cards realized in the laboratory.

A) DC-DC (Boost / Buck) converter, (B) MPPT control and digital MPPT regulator, (C) DDCS Circuit.



B. Typical functioning of DDCS Circuit

To validate the functioning of the DDCS circuit, we experimented it (Figure 6) and noted the electrical quantities of each block of this circuit using a digital oscilloscope. The obtained results in the Figure 7 show that:

- During the normal functioning of the PV system around the maximal power point (MPP), the PWM signal of the digital MPPT control switches between the high state '1' and the low one '0' (Fig 7 A1). The PWM signal is injected on the monostable 1 of the DDCS circuit whereas the monostable 2 receives the PWM signal inverted using an inverter circuit (Fig 7 A2). Because the time fixed to load the condensers is of the order of 50 ms (relation 1), the PNP transistor of the DDCS circuit closes and opens and C1, C2 condenser charge and discharge slowly (Fig 7 A2, B2). Thus, the outputs of both monostable are in the state 1 (Fig 7 A3, B3), and the XOR output is in the low state (Fig 7 B4). As a result, the relay is in a position to connect the PV panel to the DC/DC converter (relay deactivated). As shown in Fig 7. A4 and A5, during the deactivation of the relay, the PV panels voltage and the DC/DC converter voltage A4 (the load A5) are of the order of 0 V (- 11 V).

- At the given moment t , the PWM signal of the MPPT control is blocked in the state 0 (figure 7 A1). The PNP transistor (T2), which receives a signal at the low state '0', leads and the condenser at its output, is short-circuited. The monostable 2 associated with this condenser does not change its state (1) (Fig 7. A3).). On the other hand the PNP transistor (T1), which receives a signal at the high state '1', (figure 7 B1) is blocked

Figure 7 electrical quantities of DDCS circuit during brusque dysfunctions:

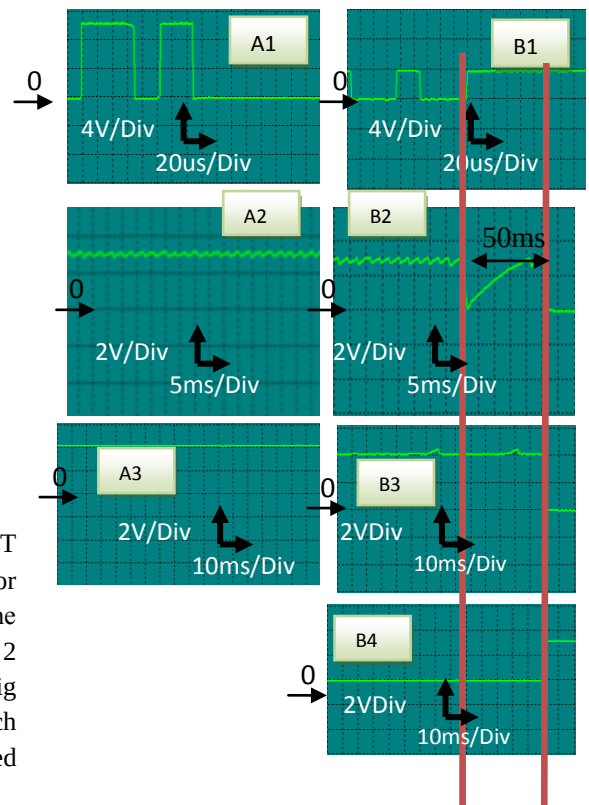
A1 and B1: PWM and PWM_IN signals

A2 and B2: Outputs signals of the transistors T2 et T1

A3 and B3: Outputs signals of the monostable 2 et the monostable 1,

B4: Output signal of the Gate Xor,

A4 and A5: relay's potential difference when it is connected to the DC/DC converter and the load



and the condenser at its output charges until reach the threshold $2/3V_{cc}$ (Fig 7 B2).

This voltage is reached at the end of 50ms (relations 1). Then, the monostable 1, switches from the high state '1' to the low state '0' (Fig 7 B3). Then, the XOR logical gate; which receives the output of the monostable 1 that is in the low state '0' and the output of the monostable 2 that is in the high state '1'; switches its output from the low state '0' to the high one '1' (Figure 7 B4). This switching shows the detection of the dysfunction of the PV system. As a consequence, the relay is activated (change the position of the blade) and connects directly the PV panel to the load (Figure 1). As shows him the figure 7. A4 and A5, during the activation, the voltage between the PV panels and DC / DC converter (A4) (the load A5) is 19 V (0 V).

C. Functioning of PV systems in the presence of the DDCS circuit

To validate the conception of the PV systems and the functioning of the obtained results, we realized and characterized two PV systems, by generating a dysfunction on the MPPT control, as follows: the DC/DC converter used is of type Buck, which supplies power to a battery of 24 V-120 Ah, using the PWM control blocked at the low state '0'. The PV system is exposed to the illumination of the order of 710 W/m^2 and a temperature of 32°C

On the Figure 8, we represented the PWM signal, the duty cycle (experimental and simulated (optimum)), the experimental electrical quantities and simulated (optimum) of the PV panel (V_{pv} , I_{pv} , P_{pv}) and the efficiencies of the PV system (PV panels and DC/DC converter). The obtained results show:

- At the Normal functioning: the PV system oscillates around the maximal functioning point (MPP). During this functioning, the efficiencies of the PV panel are 9.5%, of the DC/DC Buck converter is 75 % and the PV system efficiency is of the order of 6.5 %.
- Dysfunction: in every failure of MPPT control (its output is blocked at the low 'state 0'), the DDCS circuit detects the dysfunction at the end of a time of 50 ms and connects the PV panel directly to the load. It seems clear from the characteristics on the figure 8 that the DDCS circuit prevents the absence of the electrical energy to the load during the failure of the MPPT control.
- Connection of the PV panels directly to the load: upon the detection of the dysfunction, the PV panel is directly connected to the load. In this case, the functioning point of the PV panels depends on the load [2]. In our case, the load continues to receive the energy from PV panels with the efficiencies of the order of 87.38 % compared to efficiencies of the PV system using the MPPT control.

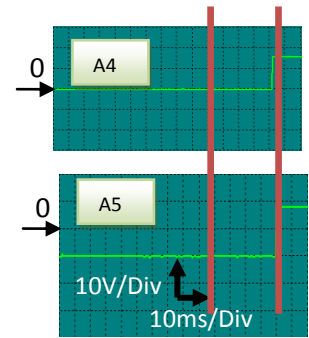
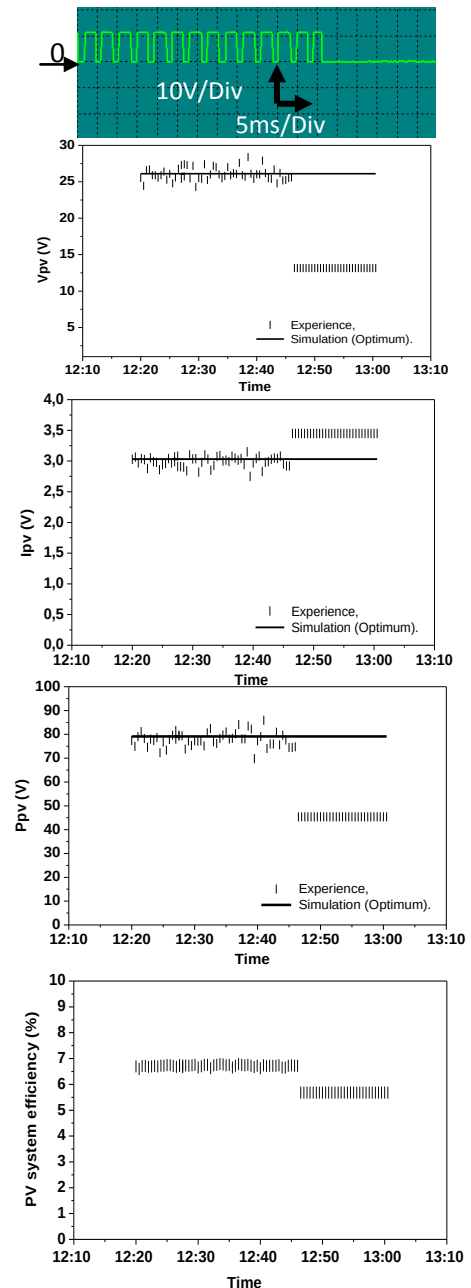


Figure 8: Experimental and simulated in Pspice (optimum) of electrical quantities (Duty cycle, panel (V_{pv} , I_{pv} and P_{pv})), experimental efficiency of the PV system. Le: 710 W/m^2 , $T=32^\circ\text{C}$.



All the obtained results show that when the MPPT control crashes, the DDCS circuit detects the dysfunction and re-connects the PV panels directly to the load. In spite of the dysfunction of the DC/DC converter and the MPPT control, the DDCS circuit allows to supply the load by the PV panel's energy. In our case, the load continues to receive an energy, which could reach 88 % of the energy received in the presence of the MPPT control and the DC/DC converter.

IV. Conclusion

In this paper, we analyzed, in the Pspice simulator and experimentally, the conception and the functioning of a DDCS circuit, which allows detecting the dysfunction of the PV system and connecting the PV panels directly to the load. This operation allows insuring the load functioning by connecting the PV panels to the load. The obtained results show:

- In a normal functioning, the MPPT control and the DC/DC Buck converters insure correctly their roles. The PV panels produce the energy in the optimal conditions, practically transferred to the load. In our case, the PV whole system efficiency is of the order of 6.5 %.
- In absence of the DDCS circuit, upon a dysfunction of the MPPT control, the load receives no energy of the PV panels. The efficiency of the system is 0 %.
- By using the DDCS circuit, upon a dysfunction of the MPPT control, the DDCS circuit detects the dysfunction and connects directly the PV panel to the load. In these situations, the PV panels supply the energy, which could reach 88 % of the energy supplied in the presence of the MPPT control.

All the obtained results show the smooth functioning and the reliability of PV systems using the DDCS circuit. Thus, it shows clearly the necessity of using this circuit in the current installations (isolated sites, network connection) to insure the production of the energy by the PV panels and load supply independently of the failures of the PV installation equipment (DC/DC converters, MPPT control).

Thanks:

This work is supported by:

- Belgian Development Agency CTB (ProjectMIP/012/010).
- PNUD Art Gold Morocco Program, 2008 2 ENV OO.
- Cooperation Morocco-Belgian "Institutional University Commission " CUD-Oujda 2008-2012 (Water and Environment Activity/Sub-Activity Renewable Energy).
- Moroccan-Tunisian Cooperation SCIENTIFIC RESEARCH AND TECHNOLOGY project (11/MT/38).

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