Design and implementation of MPPT technique on reconfigurable technology

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Abstract. *The photovoltaic energy produces electrical energy. Photovoltaic panels have nonlinear characteristics that depend of irradiation and temperature. This variation makes the delivered power not necessary maximum. Therefore, an algorithm called "maximum power point tracker" (MPPT) is used to extract the maximum energy. In this context, this work is to design and implement a control system for the continuous search of MPPT ensuring a perfect adaptation between the generator and its load. We targeted an innovative and advanced technology, compared to conventional control processors, called "field-programmable gate array" (FPGA) to prototype two algorithms one classic and the other more evolved based on fuzzy logic. The fuzzy algorithm consumes more energy and uses more CLB than the classical algorithm. Therefore, the fuzzy technique is complex and accurat .*

Résumé. *L'énergie photovoltaïque est une source d'énergie électrique. L'énergie récupérée n'est pas forcement optimale car le panneau possède des caractéristiques non-linéaires qui dépendent de l'éclairement et de la température. Pour extraire le maximum de puissance on fait appel à un algorithme nommé MPPT. Dans ce cadre, ce travail consiste à concevoir et à réaliser un système de commande pour la recherche permanente du MPP en assurant à tout instant une adaptation parfaite entre le générateur et sa charge. Nous avons développé deux techniques de commande: classique et floue. Afin d'implémenter ces deux techniques, les circuits FPGA ont été adopté. On constate que la technique floue consomme plus d'énergie et utilise un nombre important de CLB. En effet, elle est plus complexe et précise que le classique.*

Keywords. *Photovoltaic panel, DC-DC converter, MPPT Algorithm, FPGA*

Mots clés. *Algorithme MPPT, FPGA, panneau photovoltaïque, convertisseur statique DC-DC*.

1. Introduction

In the recent years, global warming and energy policy have become a hot topic on the international level. A denouement to our energy production problems is present in the use of renewable energy resources such as photovoltaic energy. The principle of the photovoltaic energy is based on the conversion of solar radiation into electricity. It is a promising solution in terms of security of supply and environmental protection.

However, the production of energy is not linear and there is only one operating point where the solar panels produce the maximum energy. In addition, the position of this point is not static but changes according to the irradiation and temperature. This requires a mechanism called "Maximum Power Point Tracking". The MPPT ensures a continuous producing of maximum power. Therefore, different and effective techniques of MPPT have been developed and proposed in the literature. Those most commonly used are: the method perturb and observe (P & O), Hill Climbing method, increment conductance, neural network method and fuzzy logic method etc...

First, these methods were implemented by using analog solutions and second by using numerical solutions. The first numeric achievements of control implementation were performed by microcontrollers and digital signal processors (DSP). These tools allowed solving problems of analog solutions. The DSP can grant reasonable performance and it is characterized by its flexibility, but it can't provide the benefits that hardware solutions can potentially give to the MPPT control. In addition, the programmable logic circuits (FPGA) or ASICs afford to the designer the management of the architectural part. This new degree of freedom was beneficial because it contributes to develop specific architectures of algorithmic requirements. In this paper we are interested to the implementation of the MPPT algorithms on the FPGA. In the second section we recall the electrical model of the photovoltaic panel. In the third section we begin by presenting the PV system then the MPPT algorithms. In the fourth section we present the implementation of the MPPT algorithm in the FPGA then we enclosed by simulations results.

2. Model of photovoltaic panel

A photovoltaic cell presents a PN junction which is sensitive to light. This cell has the particularity to operate as a generator of energy.

The electrical scheme of photovoltaic cell is given by the following figure [1]:

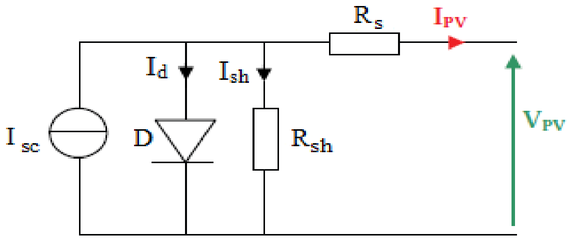

Figure 1. *Equivalent circuit for PV cell*

The PV cell can be described by the following equations [1]:

$$I_{sh}=\frac{V_{PV}+R_S I_{PV}}{R_{sh}} \quad (1)$$

$$I_{PV}=I_{sc}-I_d-I_{sh} \quad (2)$$

$$I_{PV}=I_{sc}-I_s\left[\exp\left(\frac{V_{PV}+R_S I_{PV}}{nV_T}\right)-1\right]-\frac{V_{PV}+R_S I_{PV}}{R_{sh}} \quad (3)$$

$$I_{sc}=(I_{sc,n}+K_I\Delta T)\frac{E}{E_n} \quad (4)$$

$$V=n\frac{kT}{q}\mathrm{Log}\left(\frac{Isc+Is-Ipv}{I_s}\right) \quad (5)$$

Where:
$V_T = kT_c / q$: thermodynamic potential
n: non-ideality factor of the junction
I_{sc}: Short Circuit dependent on irradiation and temperature
I_s : current saturation
I_{PV}: current supplied by the cell
V_{PV}: voltage across the cell
D: diode representing the PN junction
R_{sh}: shunt resistance characterizing the leakage of current junction
R_s: serial resistance representing the resistance of contacts and connections.
K: Boltzmann constant $1{,}38.10^{-23}$J/K
q : electron charge ($1{,}6.10^{-19}$ C)
T_c : junction temperature (K).

2.1 Temperature and irradiation influence on the PV characteristics

The values of current and voltage depend on the climatic parameters such as, irradiation and temperature. The figures 2,3,4 and 5 show the characteristics evolution of current-voltage and power-voltage in terms of irradiation and temperature.

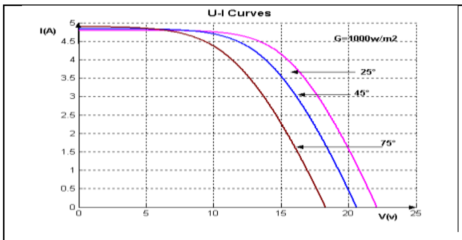

Figure 2. *Voltage current characteristic in terms of temperature*

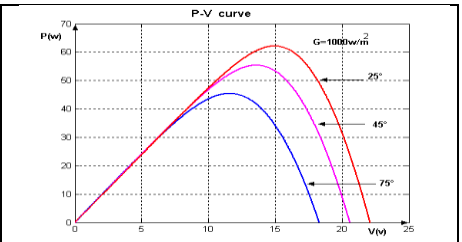

Figure 3. *The voltage power characteristic in terms of temperature*

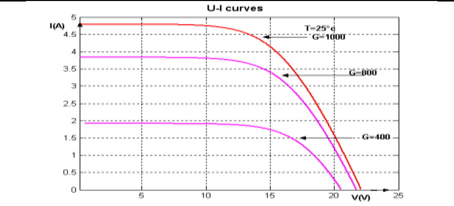

Figure 4. *the voltage current characteristic as a function of irradiation*

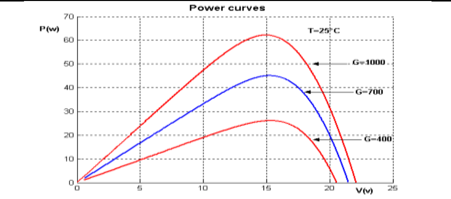

Figure 5. *the voltage power characteristic as a function of irradiation*

The figure 2 shows the increase of the temperature at a constant irradiation leads to a slight increase in I_{sc} and a remarkable decrease in V_{oc}.

The figure 3 shows the variation of the voltage and current at constant temperature causes a displacement of the maximum power point. We note that an increase of the temperature at a fixed irradiation results in a shift of the maximum power point of the solar panel to the lower powers.

The figure 4 shows a decrease in irradiation at constant temperature causes a slight lowering of the voltage V_{oc} and a huge decrease in current I_{sc}.

The figure 5 shows the variation of the voltage and power according to the irradiation that causes a displacement of the maximum power point. We note that a decrease in irradiation at fixed temperature results in a shift of the maximum power point of the solar panel to the lower powers.

In conclusion, the PV array panel is non linear system. There is only one operating point MPP where the PV array panels produce the maximum energy. In addition, the position of this point is not static but it changes according to the irradiation and temperature. This requires a specific algorithm to track the MPP [2].

2.2. Photovoltaic system

The general structure of the control system of photovoltaic panels consists of three main parts as shown in Figure 6.

The first part is the power part. Its components are the GPV photovoltaic generator, the static converter DC-DC and load.

The second part is the control part. It is based on FPGA circuit. This circuit generates the PWM signal for controlling the switch of converter. The third part is the interface which adapts the signals between the power and control part.

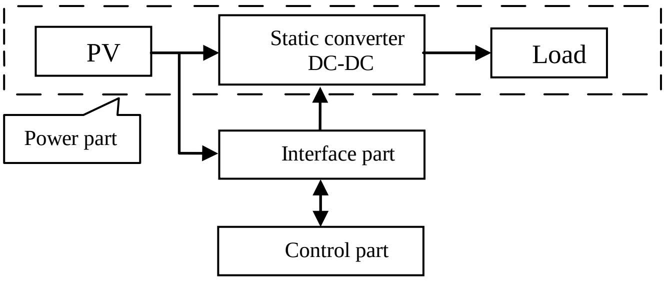

Figure 6. *Photovoltaic system*

2.3 Boost converter

The classical conventional DC-DC converter used in photovoltaic system to track the MPP is the Boost converter which is presented by the following figure 7.

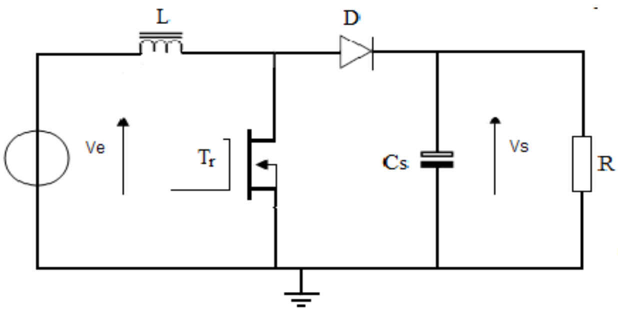

Figure 7. B*oost converter*

The MPPT algorithm provides the optimum duty cycle α ($0 < \alpha < 1$) that is the target input to the switch of boost converter.

The output equation of boost converter is [3]:

$$V_s = \frac{V_e}{1-\alpha} \tag{6}$$

The Resistance to the terminals of PV is $R_{pv} = \frac{Ve}{Ie}$ and the system load resistance is $R_L = \frac{V_s}{I_s}$:

We replace R_{pv} and R_L expression in equation (6) and we admit that the yield is equal to 1 we have so $I_s = (1-\alpha)I_e$, therefore we obtain:

$$Rpv = \frac{Vs}{Is(1-\alpha)^2} \tag{7}$$

Then $$\alpha = 1 - \sqrt{\frac{R_{PV}}{R_L}} \tag{8}$$

By adjusting the duty ratio α, the value of R_{PV} can be adjusted to R_{opt}.

R_{opt} is the load of the PV array panel which permits to extract the maximum of power. It is described as:

$$R_{opt} = \frac{V_{MPP}}{I_{MPP}}$$

Consequently $$\alpha = 1 - \sqrt{\frac{R_{opt}}{R_L}} = 1 - \sqrt{\frac{V_{MPP}}{R_L I_{MPP}}} \tag{9}$$

3. Techniques of MPPT control

Several types of MPPT techniques are presented in literature [6]. In this paper, we will focus on a few techniques one classic named Perturb and Observe (P&O) MPPT and the other advanced based on Fuzzy logic.
We have to develop these techniques then we conclude on their performances.

3.1. P&O MPPT technique

This technique is based on comparing the power produced by the panel at two different instants. This algorithm has as inputs the current and voltage of the PV and as output the PWM signal as shown in Figure 8.

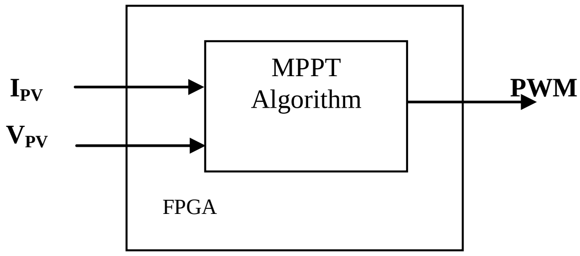

Figure 8. G*lobal schema of P&O MPPT control*

In fact, the operation of the P&O algorithm [8] is illustrated by Figure 9.

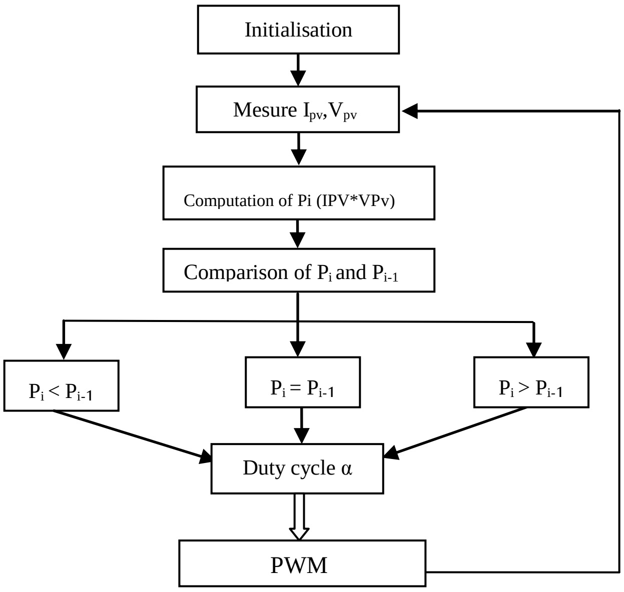

Figure 9. *Algorithm of P&O MPPT*

3.2. Fuzzy MPPT technique

For the MPPT algorithm based on fuzzy logic we use the Takagi-Sugeno model [7]. This model has the values of temperature and irradiance as inputs and duty cycle as an output. The membership functions of the premises variables (G and T) are given by Figure 10.

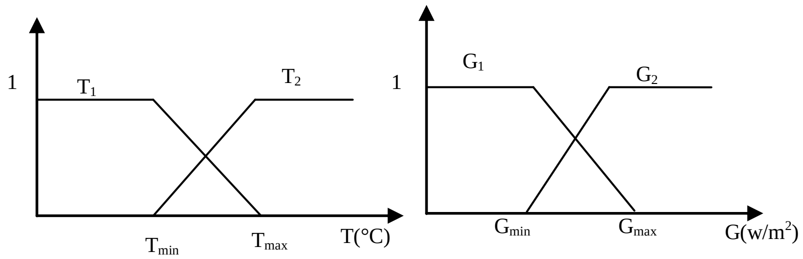

Figure 10. *Membership function of the temperature and irradiation*

$$U_{T1} = \frac{Tmax - Ti}{Tmax - Tmin} \quad , \quad U_{T2} = \frac{Ti - Tmin}{Tmax - Tmin}$$

$$U_{G1} = \frac{Gmax - Gi}{Gmax - Gmin} \quad , \quad U_{G2} = \frac{Gi - Gmin}{Gmax - Gmin}$$

The TS fuzzy model of the system consists of four sets that are defined by the following four rules:

Rule 1: If T_i is U_{T1} and G_i is U_{G1} then $V_{MPP}=V_{MPP1}$ and $I_{MPP}=I_{MPP1}$.
Rule 2: If T_i is U_{T1} and G_i is U_{G2} then $V_{MPP}=V_{MPP2}$ and $I_{MPP}=I_{MPP2}$.
Rule 3: If T_i is U_{T2} and G_i is U_{G1} then $V_{MPP}=V_{MPP3}$ and $I_{MPP}=I_{MPP3}$.
Rule 4: If T_i is U_{T2} and G_i is U_{G2} then $V_{MPP}=V_{MPP4}$ and $I_{MPP}=I_{MPP4}$.

Finally, the rational values of the PV are obtained by the following inference mechanism:

$$V_{MPP} = \frac{\sum_{i=1}^{4} W_i V_{MPPi}}{\sum_{i=1}^{4} W_i} \quad (10)$$

$$I_{MPP} = \frac{\sum_{i=1}^{4} W_i I_{MPPi}}{\sum_{i=1}^{4} W_i} \quad (11)$$

By replacing V_{MPP} and I_{MPP} in equation (9) we obtain the value of the duty cycle:

$$\alpha = 1 - \sqrt{\frac{V_{MPP}}{R_S I_{MPP}}} \quad (12)$$

4. Target technology

The structure of the control system is independent from the algorithm to implement, but it is heavily related to the techniques used. There is many types of MPPT techniques in literature such as analog MPPT, numeric MPPT used PIC or DSP and currently we use FPGA (Field Programmable Gate Array) or ASIC (Application Specific Integrated Circuit).

The FPGA circuit allows new contributions thanks to its wired architecture. Indeed, the FPGAs are characterized by their simultaneous operation (continuous execution of all the control procedures), which allows high performance and new control methods. In fact, the control algorithm is developed with a hardware description language that provides a great flexibility and an independence of technology. Finally, the control system can be designed trough a simple way with keeping a good accuracy and a dynamic response [4].

To perform a fast and efficient implementation on FPGA we must follow a 'design flow' shown in figure 11.

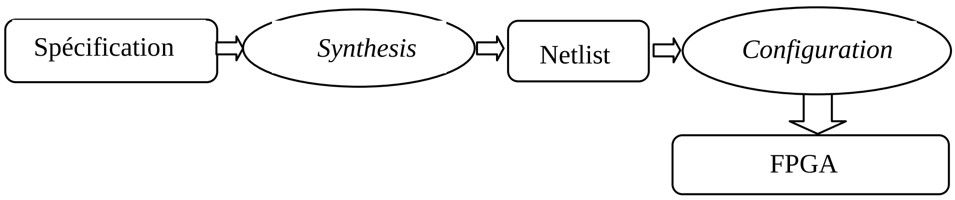

Figure 11. Typical *design flow*

In fact, the design of FPGA circuit is done thanks to specified design tools. These tools generate a configuration file of the FPGA circuit called "bit-stream" from a high-level description [5]. The main steps are: the specification that models the system at very high level, the synthesis that allows the transition from a higher abstraction level to lower level, and the configuration that permit a bit-stream from Netlist. A simulation step is presented in each passage to test the functionality of each step.

5. Design and results

In this section, we will simulate the VHDL source code of classic and fuzzy technique. In fact, we used AGLN250 Actel Igloo nano to implement these two techniques. Its environment Libero includes the simulator Modelsim.

5.1. P&O algorithm

To measure current and voltage, we propose to use respectively LEM-LA25NP, and AD636.
The figure 13 shows the simulation of P&O algorithm. It is clear that when P1>P2, alpha_sens = 11 so α🡐 α+step and PWM signal periodically load the value of α, when P1<P2, alpha_sens = 00 so α🡐 α-step and PWM signal periodically load the value of α and finally when P1=P2 alpha_sens = 10 and PWM signal periodically load the same value of α,

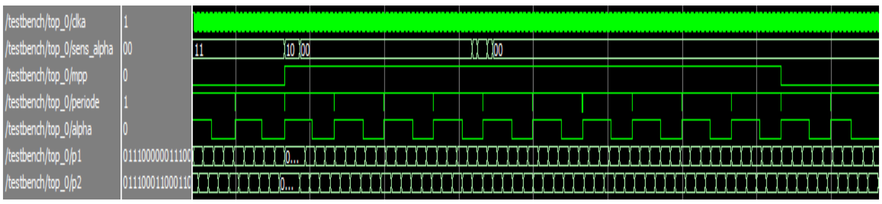

Figure 12. *simulation of P&O algorithm*

5.2. Algorithm based on T-S Fuzzy system

To measure the irradiation and the temperature, we propose to use respectively LDR, and LM35.
We choose the value of variables as:

T_{min}=5°C , T_{max} =75°C
G_{min}=200 w/m^2 , G_{max} =1000 w/m^2
V_{MPP1} =16.527 , V_{MPP2}=16.348
V_{MPP3} =10.838 , V_{MPP4} =11.576
I_{MPP1}=0.866 , I_{MPP2}=4.234

I_{MPP3}=0.8181 , I_{MPP4}=3.925.

To test and verify the operation of this program with Modelsim, we have used as inputs these following four pairs (Irradiation, Temperature):

(G1 = 800, T1 = 35 °), (G2 = 700, T2 = 35 °),
(G3 = 900, T3 = 45 °) and (G4 = 700, T4 = 45 °).

Each pair has only one rational operating point. This point can be determined from the power-voltage characteristic of PV. Indeed the values (V_{MPP}, I_{MPP}) below correspond respectively to the operating point of the previous pairs (G, T).

(14445, 3343), (14.5195, 2904), (13.6563, 3.7052) and (13794, 2917).

Thus the values (V_{MPP}, I_{MPP}) given by simulation are respectively:

(14249, 3287), (14.222, 2880), (13578, 3655), (13491, 2850).

The figure 13 shows the simulation of the program:

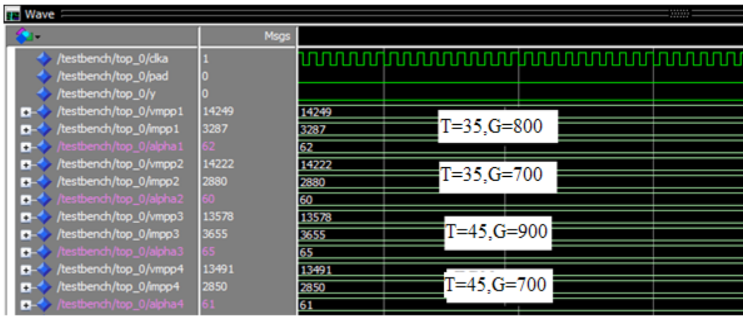

Figure13. *Simulation of fuzzy method*

The table 1 is a summary table that shows the results given by simulation are almost the same to the theoretical values.

Table 1. *Comparison of simulation results of the MPPT fuzzy program and theoretical results*

		VHDL program results (*1000)	theoretical results
(800,35)	Vmpp	14 .249	14.445
	Impp	3.287	3.343
	α	0.62	0.62048
(700,35)	Vmpp	14 .222	14.5195
	Impp	2.880	2.904
	α	0.60	0.59
(900,45)	Vmpp	13.578	13.6563
	Impp	3.655	3.7052
	α	0.65	0.649
(700,45)	Vmpp	13 .491	13.794
	Impp	2.880	2.917
	A	0.61	0.60

The table 2 summarizes the results in terms of complexity (number of I /O and CLBs), consumption of energy and execution time.

Table 2. *Comparison of the MPPT fuzzy program and the P&O MPPT*

	P&O MPPT method	Fuzzy MPPT method
I/O used	11	11
Logic block used	1236	5811
Rams block	2	0
energy consumed	1.268mw	1.618mw
Execution time	≈50 µs	12,4 µs

It is difficult to determine the exact execution time T_{ex} of MPPT classic control because it is heavily dependent on climatic conditions and initial values of the duty cycle. This time is about 50 ms. In contrast, it is relatively easy for fuzzy MPPT control to determine the execution time which is about 12.4 µs.

We note so that the fuzzy method is faster than the classic method. However, it is more complex, it consumes more energy and uses a large number of CLB almost five times greater than the number of CLBs used by the P&O method.

6. Conclusion

In this paper, we have designed a control system of photovoltaic panels for permanent research of MPP. We have described the PV system by an equivalent model, as well we have study the whole system and take out the functional equations. Then we elaborated two algorithms classic and fuzzy. Finally, we have used the FPGA circuit as a powerful and efficient in terms of computing power and parallelism treatment to implement these algorithms.

The results of simulation of these two algorithms prove that the fuzzy algorithm is fast and accurate. However, it is very complex and leads to a higher energy consumption compared with the classical algorithm.

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