

Modeling and simulation of a photovoltaic system:

An advanced synthetic study*

Dhaker ABBES, Gérard CHAMPENOIS, André MARTINEZ, Benoit ROBYNS

Abstract— This paper focuses on modeling and simulation of a buck converter based on a PV standalone system. This advanced synthetic study includes PV generator modeling with parameters identification, an improved P&O (Perturb and Observe) algorithm with adaptive increment step and a detailed approach of DC-DC converter modeling. A thorough method is used to determine parameters for PI current controller. The set was used to simulate a whole photovoltaic conversion chain under Matlab/Simulink environment. A special focus has been dedicated to the influence of solar irradiation variations on converter dynamic and behavior as a range of PV current 0-8 A was considered. Simulation results confirm stability, accuracy and speed response of synthesized regulator and MPPT algorithm employed. Dynamic analyses show that the more restricting control concerns low values of current I_{pv} (low irradiation). This work will be useful for PhD students and researchers who need an effective and straightforward way to model and simulate photovoltaic systems.

I. INTRODUCTION

A photovoltaic (PV) system directly converts sunlight into electricity. Basic device of a PV system is the PV cell. Cells are grouped to form panels or arrays. The voltage and current available at output PV device may directly feed small loads such as lighting systems and DC motors. More sophisticated applications require electronic converters to process electricity from PV device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid-connected systems, and mainly to track the maximum power point (MPP) of the device [1]. This paper focus on modeling and simulation of a buck converter based on a PV standalone system.

In order to study such a system, we need to know how to model the PV device associated to the converter. PV devices present a

nonlinear (I, V) characteristic with several parameters that need to be adjusted from experimental data of practical devices. The mathematical model of the PV device may be useful for investigation of dynamic analysis of converters and MPP tracking (MPPT) algorithms, and mainly to simulate the PV system and its components using circuit simulators. Then, it is important to model converter and to design adequate proportional and integral compensators to control inputs (voltage or current or both) of the converter. All these aspects are treated in this paper and a particular emphasis is focused on the modeling and control of DC-DC converter.

Control of the input voltage of DC-DC converters is frequently required in photovoltaic (PV) applications. In this special situation, unlike conventional converters, the output voltage is constant and the input voltage is variable. Converters with constant output voltage are well known. Buck, boost and other topologies have been employed in PV applications where input is controlled instead of output. In most of works and investigations, power tracking methods and other subjects regarding the PV system control are studied, but a little attention is given to the converter [2]. References [3-5] are showing systems where a PV array and a battery are interfaced with a buck converter (output voltage of converter is essentially constant) and study power tracking algorithms to adjust the condition of the PV array in order to match desired operating point.

Few authors have investigated the input control of converters with a mathematical approach. In [6], the authors present the analysis of open-loop power-stage dynamics relevant to current-mode control for a boost pulse width-modulated (PWM) DC-DC converter operating in Continuous-Conduction Mode (CCM). In [7], boost converter with input control for PV systems is analyzed. In [8], there is a study of the buck converter with controlled input used in a PV system.

Finally, Kislovski [9] makes considerations about the dynamic analysis of the buck converter employed in a battery charging system.

Although many papers bring information and even experimental results with buck-based systems, many questions still remain unanswered. These questions consider dynamic behavior of the buck converter (especially for irradiation) with constant output voltage and the design of proportional and integral compensators to control the input current of the converter.

So, in this paper, detailed approaches for modeling DC-DC converter as well as a method for determining parameters of PI controller are discussed. Detailed and specific calculations are applied and a study of the influence of solar irradiation variations on converter dynamic and behavior is conducted. A range of PV current 0-8 A was considered.

The paper is organized as follows:

Section II concerns PV generator modeling. Model is described and photovoltaic panel parameters are identified using a lever iterative algorithm. Then, in section III, an improved P&O (Perturb and Observe) algorithm with adaptive increment step is detailed.

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Finally, in the remaining sections, we are interested in the simulation of the complete system under Matlab / Simulink and in the synthesis of DC-DC converter PI current regulator parameters. An analysis of converter behavior and influence of solar irradiation variations on its dynamics is presented then simulation results are shown.

II. PV GENERATOR MODELING

A. Model Description

In the literature, a photovoltaic cell is often depicted as a current generator with a behavior equivalent to a current source shunted by a diode. To take into account real phenomena, model is completed by two resistors in parallel and series R_s and R_p as shown in figure 1 [1].

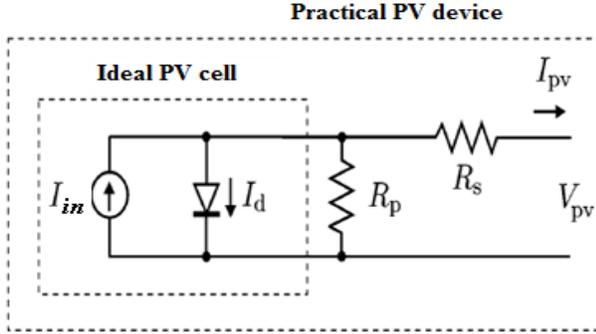


Figure 1. PV generator model with a single diode and two resistors

Current I_{pv} generated by the panel is expressed as a function of R_s and R_p resistors, voltage V_{pv} and currents I_{in} and I_0 , as follows:

$$I_{pv} = I_{in} + I_0 \left[\exp\left(\frac{V_{pv} + R_s I_{pv}}{V_t a}\right) - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_p} \quad (1)$$

With:

I_{in} : photovoltaic current due to irradiation. If the panel is composed of N_p cells connected in parallel, then $I_{in} = I_{in\ cell} \times N_p$ where $I_{in\ cell}$ is the saturation current for a single cell,

I_0 : saturation current of the PV panel. $I_0 = I_{0\ cell} \times N_p$ where $I_{0\ cell}$ is the current of a single cell and N_p the number of cells in parallel,

V_t : thermal potential of the panel. $V_t = \frac{N_s \times K \times T}{q}$, N_s is number of cells in series, K : Boltzmann constant [$1.3806503 \times 10^{-23}$ J/K], q charge of an electron [$1.60217646 \times 10^{-19}$ C] and T temperature of the p-n junction in Kelvin degree [°K]. T is assumed equal to the ambient temperature.

a : ideal constant of the diode, assumed equal to 1 in our case.

V_{pv} : voltage across the panel.

The photovoltaic current I_{in} is linearly dependent on the irradiance (G) and is also influenced by the temperature T according to the following equation:

$$I_{in} = (I_{in,n} + K_I \Delta T) \frac{G}{G_n} \quad (2)$$

$I_{in,n}$ is the photovoltaic current generated at nominal conditions ($T_n = 298.15$ K and $G_n = 1000$ W/m²), $\Delta T = T - T_n$ and K_I coefficient of variation of current as a function of temperature.

$$I_{in,n} = \frac{R_p + R_s}{R_p} \times I_{sc,n} \quad (3)$$

$I_{sc,n}$ is the rated short-circuit current under nominal conditions of temperature and irradiation (under T_n and G_n).

The saturation current I_0 also depends on the temperature according to the following expression:

$$I_0 = I_{0,n} \left(\frac{T_n}{T}\right)^3 \exp\left[\frac{q E_g}{ak} \left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \quad (4)$$

with: E_g is energy bandgap of the semiconductor, $E_g \approx 1.12$ eV for polycrystalline silicon panels [1] [10].

$I_{0,n}$ is the nominal saturation current given by:

$$I_{0,n} = \frac{I_{sc,n} + K_I \Delta T}{\exp\left(\frac{V_{oc,n} + K_V \Delta T}{a V_t}\right) - 1} \quad (5)$$

where: $V_{oc,n}$ corresponds to nominal voltage vacuum and K_V of coefficient of variation of the voltage as a function of temperature.

B. Photovoltaic panel parameters identification

In our case, simulated panels are "Sharp ND-240QCJ Poly" with a peak power of 240Wp. Properties of solar panel, according to the technical specification sheet, are shown table I.

TABLE I. ELECTRICAL CHARACTERISTICS OF SHARP ND-240QCJ POLY (240WC), SOLAR PANEL

Electrical characteristics of the ND-240 Poly	
P_{max}	240 W _c
I_{sc}	8.75 A
V_{oc}	37.5 V
I_{mp}	8.19 A
V_{mp}	29.3 V
K_I	53×10^{-5} A/K
K_V	-36×10^{-3} V/K

Unfortunately, not all the parameters are given in the data sheet. The values for R_s and R_p are missing and have to be found in another way. When taking a look at the formula for the maximum power output, we see that these parameters are easily extractable.

$$P_{max,m} = V_{mp} \left\{ I_{in} + I_0 \left[\exp\left(\frac{q}{kT} \frac{V_{mp} + R_s I_{mp}}{a N_s}\right) - 1 \right] - \frac{V_{mp} + R_s I_{mp}}{R_p} \right\} = P_{max,e} \quad (6)$$

$$R_p = \frac{V_{mp}(V_{mp} + R_s I_{mp})}{\left\{ V_{mp} I_{in} - V_{mp} I_0 \exp\left[\frac{(V_{mp} + R_s I_{mp}) q}{a N_s k T a}\right] + V_{mp} I_0 - P_{max,e} \right\}} \quad (7)$$

I_{mp} and V_{mp} are respectively current and voltage of photovoltaic panel at maximum power point. $P_{max,m}$ is maximum power deduced via model identification procedure and $P_{max,e}$ is the experimental maximum power indicated by the panel manufacturer under nominal conditions.

To find R_p value, we have to find a value of R_s so that $P_{max,m}$ is equal to $P_{max,e}$ ($\epsilon_{P_{max}} = P_{max,m} - P_{max,e} \cong 0 < tol = 0.01$). This is possible with an iterative algorithm. For this purpose, we can use the procedure described by MG Villalva and al. [1] and represented by the flowchart in Figure 2.

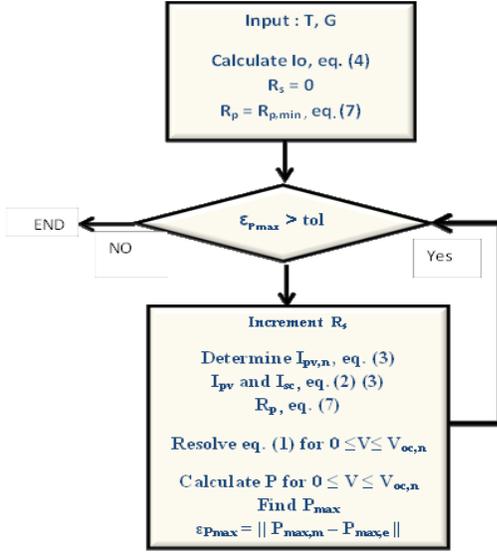


Figure 2. Iterative algorithm to find the R_s and R_p parameters

To compute this algorithm, initial values for R_s and R_p are needed. The value for $R_{s,ini}$ is fixed to zero and $R_{p,ini}$ is found by substituting R_s by zero in the equation (7):

$$R_{p,ini} = R_{p,min} = \frac{V_{mp}}{I_{sc,n} - I_{mp}} - \frac{V_{oc,n} - V_{mp}}{I_{mp}} \quad (8)$$

Using the procedure, we obtain the following values for R_s and R_p :

$$\begin{cases} R_s = 0,409 \Omega \\ R_p = 158,774 \Omega \end{cases}$$

With these parameters we can represent the electrical characteristics (Figure 3) of the photovoltaic panel "Sharp ND-240QCJ Poly (240Wp)" and present the evolution of its maximum power as a function of ambient temperature (T_a [° C]) and the irradiance (G [W/m²]) (Figure 4).

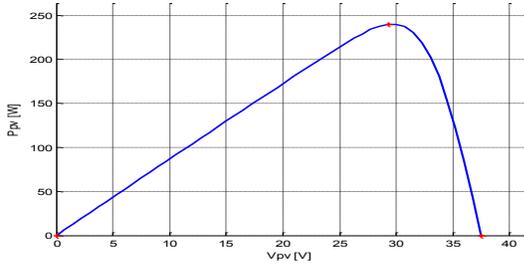


Figure 3.a Evolution panel power as a function of the voltage across

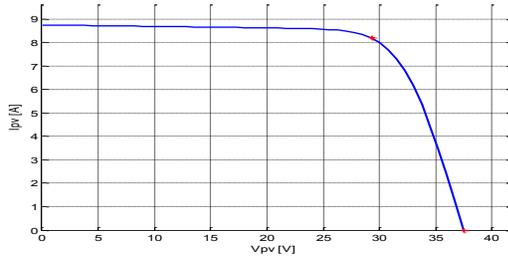


Figure 3.b Evolution of the current generated by the photovoltaic panel as a function of the voltage across

Figure 3. Characteristic curves of the "Sharp ND-240QCJ Poly (240Wp)" ($G = 1000 \text{ W/m}^2$, $T_a = 25 \text{ }^\circ \text{C}$)

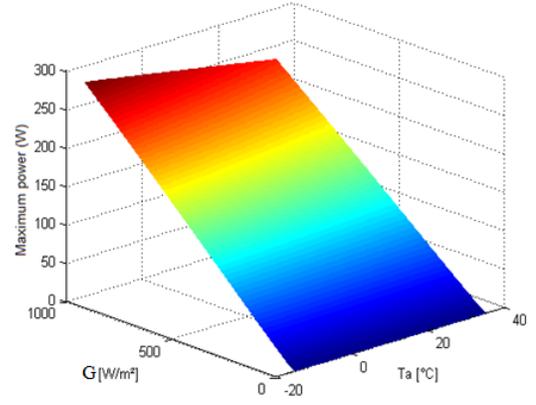


Figure 4. Evolution of the maximum power of the photovoltaic panel "Sharp ND-240QCJ Poly (240Wp)" depending on the ambient temperature (T_a) and irradiance (G)

It is interesting to note that after calculation of the different values of the maximum power P_{max} depending on the ambient temperature T_a [°C] and irradiance G [W/m²], it is possible with a "fitting" under Matlab to have a polynomial model of the panel as follows:

$$P_{max} = -8.286 \cdot 10^{-6} \times G^2 + 1.919 \cdot 10^{-5} \times T_a^2 - 0.0004092 \times T_a \times G + 0.2653 \times G + 0.004106 \times T_a - 6.051 \quad (9)$$

In this paper, we are focusing on parameters to consider for the simulation. More generally, this model could be useful to estimate photovoltaic production or could be employed for the design of a simple method of Maximum Power Point Tracking.

III. DESCRIPTION OF MAXIMUM POWER POINT TRACKING (MPPT) ALGORITHM

In the literature, there are different types of MPPT algorithms for photovoltaic systems [11]. In our case, an improved P&O algorithm is chosen with adaptive increment step [12]. Fundamental principle of this method is increment step variation to converge faster towards optimal point (MPP) while reducing oscillations around. Indeed, in order to quickly converge, increment step C is reduced or adapted from a region to another: $C = 0.01$ in "S" region and 0.001 in "r" region (Figure 5). MPPT algorithm is shown Figure 6.

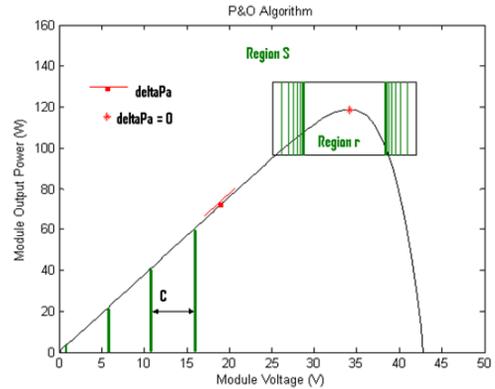


Figure 5. Principle of the P&O algorithm with an adaptive step increment [12]

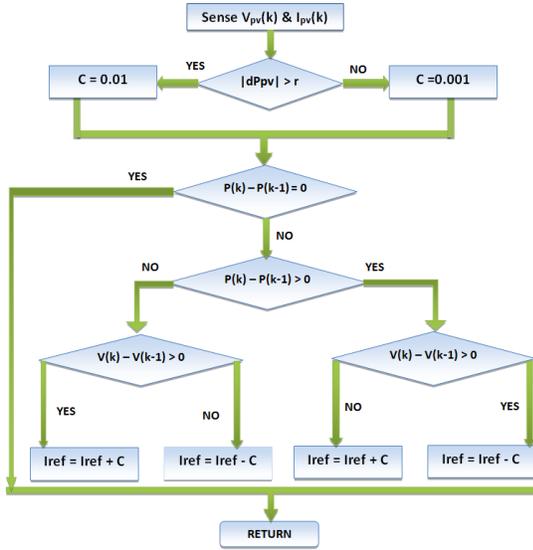


Figure 6. Flowchart of the improved P&O MPPT algorithm

IV. DEVELOPMENT AND SIMULATION OF A PHOTOVOLTAIC SYSTEM

A. System description

The simulated photovoltaic system consists of four main components:

- photovoltaic generator composed of two panels "Sharp ND-240QCJ Poly (240Wp)",
- energy storage device (battery or accumulator)
- control system (controller): here it is a step down chopper current controlled by an MPPT unit and via a PI compensator
- load (assumed to be continuous in this work).

The set is simulated with Matlab / Simulink / Simpower as shown in Figure 7. The parameters used are summarized in Table II.

TABLE II. PARAMETERS USED FOR SIMULATION IN MATLAB / SIMULINK / SIMPOWER

Parameter	Value
L	3 mH
C	1,1 mF
Rab	0,001 Ω
Vbat	48V
Charge	4,8 Ω
Pas de simulation	10 ⁻⁶ s
Fréquence PWM	20Khz

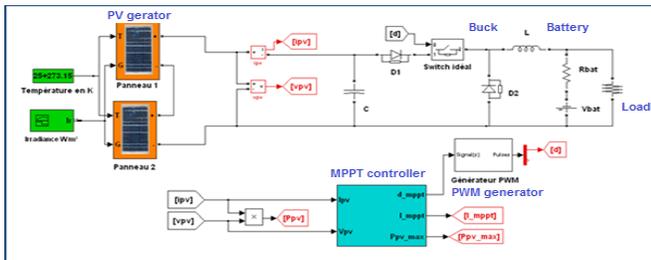


Figure 7. Schematic of the photovoltaic conversion chain developed in Matlab / Simulink / Simpower

The control unit consists of the MPPT algorithm and the PI regulator for the current loop as shown in Figure 8.

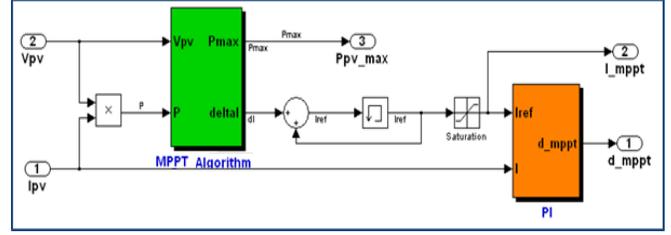


Figure 8. Block Diagram of the MPPT control developed in Matlab / Simulink

The parameters of the PI compensator for current loop are calculated as follows:

B. Procedure for determining the parameters of the PI corrector

To calculate the PI parameters for the current input I_{pv} control, we use the average model of the next chopper [6]:

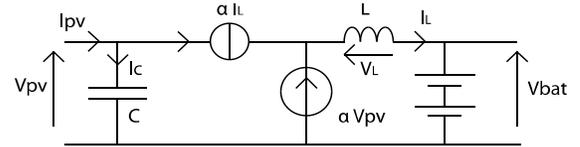


Figure 9. Average model of the chopper in interface between the photovoltaic panels and the battery

According to this model, there are two state variables: voltage V_{pv} and current I_L with the following expressions in the formalism of Laplace (s):

$$\begin{cases} C \times s \times V_{pv} = (I_{pv} - \alpha \times I_L) \\ L \times s \times I_L = (\alpha \times V_{pv} - V_{bat}) \end{cases} \quad (10)$$

Our objective is to control the current I_{pv} acting on the duty cycle α . However, we note from the two equations above that the transfer function between I_{pv} and α is nonlinear. For this reason, we propose to express a transfer function linearized around an operating average point, considering: $C \times S \times V_{pv0} = 0$ and $L \times S \times I_{pv0} = 0$

$$\begin{cases} I_{pv0} = +\alpha_0 \times I_{L0} \\ \alpha_0 \times V_{pv0} = V_{bat} \end{cases} \quad (11)$$

Thus, variables are defined as follows:

$$\begin{cases} I_{pv} = I_{pv0} + \tilde{I}_{pv} & ; & I_L = I_{L0} + \tilde{I}_L \\ V_{pv} = V_{pv0} + \tilde{V}_{pv} & ; & \alpha = \alpha_0 + \tilde{\alpha} \end{cases} \quad (12)$$

From (10) and (11), we obtain:

$$\begin{cases} C \times s \times \tilde{V}_{pv} = (\tilde{I}_{pv} - \alpha_0 \times \tilde{I}_L - \tilde{\alpha} \times I_{L0} - \tilde{\alpha} \times \tilde{I}_L) \\ L \times s \times \tilde{I}_L = (\alpha_0 \times \tilde{V}_{pv} + \tilde{\alpha} \times V_{pv0} + \tilde{\alpha} \times \tilde{V}_{pv}) \end{cases} \quad (13)$$

Considering $\tilde{\alpha} \times \tilde{I}_L$ and $\tilde{\alpha} \times \tilde{V}_{pv}$ negligible compared to the other terms, we obtain the following system:

$$\begin{cases} C \times s \times \tilde{V}_{pv} = (\tilde{I}_{pv} - \alpha_0 \times \tilde{I}_L - \tilde{\alpha} \times I_{L0}) \\ L \times s \times \tilde{I}_L = (\alpha_0 \times \tilde{V}_{pv} + \tilde{\alpha} \times V_{pv0}) \end{cases} \quad (14)$$

Due to the presence of solar panels (PV) at the entrance of the chopper, there is a link between \widetilde{V}_{pv} and \widetilde{I}_{pv} we must express. The optimum operating point of PV generator is normally situated on the hyperbole (zone) of equal power, that is to say $V_{pv} \times I_{pv} = V_{pvo} \times I_{pvo}$.

So, according to equation (12), we can write:

$$V_{pvo} \times \widetilde{I}_{pv} + \widetilde{V}_{pv} \times I_{pvo} + \widetilde{V}_{pv} \times \widetilde{I}_{pv} = 0 \quad (15)$$

Neglecting $\widetilde{V}_{pv} \times \widetilde{I}_{pv}$ to the other terms, we have:

$$\frac{\widetilde{V}_{pv}}{\widetilde{I}_{pv}} = -\frac{V_{pvo}}{I_{pvo}} \quad (16)$$

Substituting \widetilde{V}_{pv} by $-\frac{V_{pvo}}{I_{pvo}} \times \widetilde{I}_{pv}$ into (13), eliminating I_L and replacing I_{Lo} by $\frac{I_{pvo}}{\alpha_0}$ into (11), we can express the transfer function between \widetilde{I}_{pv} and $\widetilde{\alpha}$. Considering $\alpha = \alpha_0 \times V_{pvo}$, we obtain :

$$\frac{\widetilde{I}_{pv}}{\widetilde{\alpha}} = + \frac{\alpha_0 \times V_{pvo} + \frac{I_{pvo}}{\alpha_0} \times L \times s}{L \times C \times \frac{V_{pvo}}{I_{pvo}} \times s^2 + L \times s + \alpha_0^2 \times \frac{V_{pvo}}{I_{pvo}}} \quad (17)$$

$$\text{Then: } \frac{\widetilde{I}_{pv}}{\widetilde{\alpha}} = G \times \frac{1 + \frac{s}{\omega_n}}{1 + \frac{2 \times \zeta \times s}{\omega_D} + \frac{s^2}{\omega_D^2}} \quad (18)$$

With: $G = +\frac{I_{pvo}}{\alpha_0}$; $\omega_n = \frac{\alpha_0 \times V_{bat}}{L \times I_{pvo}}$; $\omega_D = \frac{\alpha_0}{\sqrt{L \times C}}$ and

$$\zeta = \frac{I_{pvo}}{2 \times V_{bat}} \times \sqrt{\frac{L}{C}}$$

So the transfer function between \widetilde{I}_{pv} and $\widetilde{\alpha}$ is a system with a zero inversely proportional to I_{pvo} (irradiation), two complex conjugate poles almost constant because α_0 little depends from irradiation, a damping factor and a gain proportional to I_{pvo} .

With the numerical application: $L = 3$ mH, $C = 1100\mu\text{F}$, $V_{bat} = 48$ V, $V_{pvo} = 60$ V, means $\alpha_0 = 0,8$, we obtain:

$$G = 1,25 \times I_{pvo}; \quad \omega_n = \frac{12800 \text{ rad/s}}{I_{pvo}}; \quad \omega_D = 440 \text{ rad/s};$$

$$\zeta = 0,035 \times I_{pvo}.$$

When varying I_{pvo} from 0 to 8A, we have always $\omega_n > \omega_D$, a gain varying approximately between 0 and 20 and a damping coefficient that still small. Thus, the more restricting control concerns low values of current I_{pvo} (low irradiation).

Example: For $I_{pvo} = 0,2$ A (with a peak of $I_{pvo} = 8$ A), we obtain a transfer function with poles at 440 rad/s and a damping coefficient of $0,0035 \times 0,2 = 0,0007$, which gives a resonance gain of $\frac{1}{2 \times \zeta \times \sqrt{1 - \zeta^2}} = 71,4$ (37 dB). So to avoid resonance in closed loop, it is necessary to reduce the bandwidth. We choose a bandwidth of 1 rad/s. At this frequency, the transfer function can be reduced to the gain:

$$G = 1,25 \times I_{pvo} = 0,25 \text{ then the transfer function } T_{I_{pv}}$$

with a PI regulator : $PI = \frac{K_p \times (s + K_i)}{s}$ becomes :

$$T_{I_{pvBO}} = \frac{G \times K_p \times (s + K_i)}{s} \quad (19)$$

$$\begin{aligned} T_{I_{pvBF}} &= \frac{1}{1 + \frac{s}{G \times K_p \times (s + K_i)}} = \frac{G \times K_p \times (s + K_i)}{G \times K_p \times (s + K_i) + s} = \frac{G \times K_p \times (s + K_i)}{G \times K_p \times K_i + (1 + G \times K_p) \times s} \\ &= \frac{(1 + \frac{s}{K_i})}{(1 + \frac{1 + G \times K_p}{G \times K_p \times K_i} \times s)} \end{aligned} \quad (20)$$

K_i is chosen equal to the pole (compensation pole/zero) $K_i = 440$, and with a bandwidth of 1 rad/s ; which gives :

$$\frac{G \times K_p \times K_i}{1 + G \times K_p} = 1 \quad (21)$$

Then $K_p = 0,01$.

Figure 10 shows the plot of the Bode diagram for the transfer functions of open and closed loops ($T_{I_{pvBO}}$ and $T_{I_{pvBF}}$) for $I_{pvo} = 0,2$ A and $I_{pvo} = 8$ A.

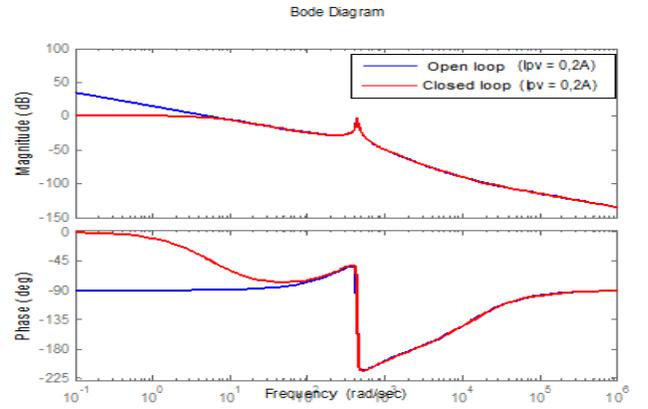


Figure 10.a Bode diagram of open and closed loops (Case $I_{pvo} = 0,2$ A)

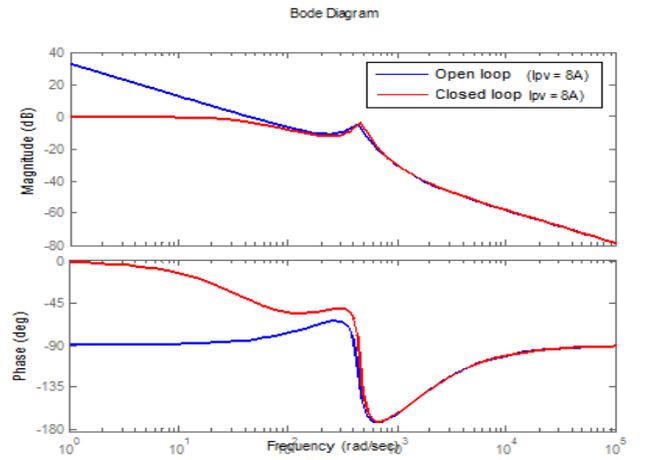


Figure 10.b Bode diagram of open and closed loops (Case $I_{pvo} = 8$ A)

Figure 10. The Bode plot of the transfer functions for the open and closed loop and closed loops ($T_{I_{pvBO}}$ and $T_{I_{pvBF}}$) for $I_{pvo} = 0,2$ A and $I_{pvo} = 8$ A.

V. SIMULATION AND CONTROL RESULTS

Simulation results of the photovoltaic conversion chain developed in Matlab / Simulink / Simpower (figure 7) are shown below. They confirm the stability, accuracy and speed response of the synthesized regulator and used MPPT algorithm.

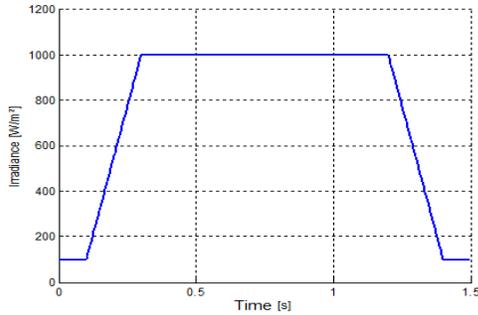


Figure 11.a irradiance profile versus time used for the simulation

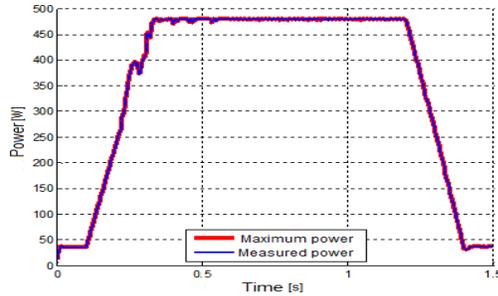


Figure 11.b Maximum power tracking over the time

Figure 11. Simulation results of the photovoltaic system conversion chain under Matlab / Simulink

VI. CONCLUSION

In this paper, an advanced synthetic study of a standalone buck-based PV system is presented. It includes: PV generator modeling and its parameters identification, an improved P&O (Perturb and Observe) algorithm with adaptive increment step, a detailed approach to the modeling of DC-DC converter and a thorough method for determining the parameters of the PI controller used for converter current control.

This study has yielded some benefit results:

- The model presented in section II was integrated in a programmable power source to emulate two solar panels in a PV system.
- By calculating different values of the maximum power P_{max} for various ambient temperatures T_a [°C] and irradiances G [W/m²], we have established an accurate polynomial model of the PV panel used ("Sharp ND-240QCJ Poly (240Wp)").
- Section IV has presented the development of converter average model and transfer functions for the input current control of the buck converter operating with duty-cycle control (current mode) and with inductor peak current control (current-programmed mode). The transfer functions reveal important dynamic characteristics of the input-controlled buck converter when it is fed by a PV array. They show that the more restricting control concerns low values of current I_{pv} (low irradiation).

With these transfer functions it is possible to design compensators and feedback controllers for the control of the input current of the buck converter.

- Simulation results confirm the stability, accuracy and speed response of the synthesized regulator and used MPPT algorithm. However, these results should be experimentally validated using a PV system test bed.

Finally, this paper with its quantity of information, its references and its synthetic aspect will be useful for PhD students and researchers who need an effective and straightforward way to model and simulate photovoltaic systems.

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