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Modeling and simulation of a photovoltaic generator based non-linear Backstepping control for maximum power point Tracking

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Abstract

In this paper, we propose a no-linear backstepping method of control to look for a maximum power point of the MPPT techniques used in the implementation of photovoltaic power systems. It will discuss between Perturb & Observe and Backstpping techniques used in tracking maximum power in photovoltaic arrays. Lyapunov's method is used to archive the stabilization objectives. The proposed model is realized using power system block set under Matlab/SIMULINK.

Keywords: PV solar, DC buck converter, backstepping control, P&O Algorithm, Lyapunov method

1. Introduction

Solar energy is considered to be one of the most promising alternative energy sources, but it has the problem of low efficiency due to varying environmental conditions.

In this context, photovoltaic (PV) systems offer a very competitive solution. To overcome the efficiency problem of solar panels and obtain maximum efficiency, it is necessary to optimize the design of all parts of the PV system. In addition, it is necessary to optimize the converters DC / DC used as interface between the PV generator and the load in order to extract the maximum power and thus operate the PV generator at its maximum power point (MPP) using a controller MPPT (maximum power point tracking), therefore, obtain a maximum electric current under the variation of the load and atmospheric conditions (brightness and temperature). [1]

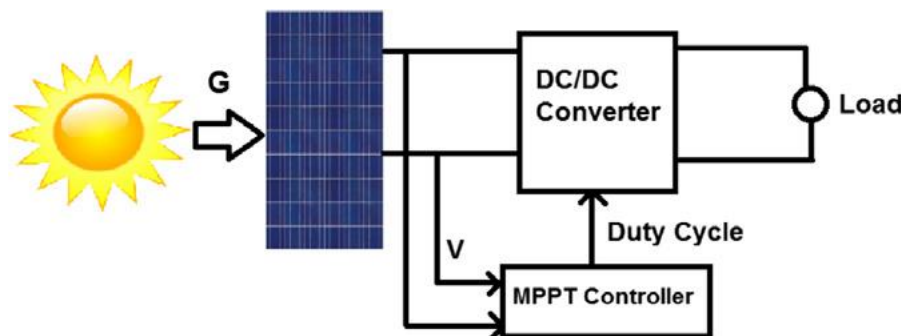


Fig.1 Basic modeling process for a PV cell

A large number of MPPT control techniques have been developed since the 1970, starting with simple techniques such as MPPT controllers based on voltage and current feedback, to more efficient controllers using algorithms for calculate MPP of GPV, among the most used technique is P&O. [2]

In recent years more robust control techniques have been done for MPPT such as O&P to increase the efficiency of solar panels. In this perspective, we will present the comparison Backstepping and O&P technique of a PV system, for extracting the maximum power from the solar photovoltaic generator a based on a Buck converter driven by a Backstepping method, the modeling and simulation of the system (photovoltaic generator, buck converter DC, and Backstepping control) is then made with Matlab / Simulink software.

2. Model Solar PV for One diode

A solar cell basically is a p-n semiconductor junction. When exposed to light, a current proportional to solar irradiance is generated. The circuit model of PV cell is illustrated in Fig. 2. [3]

It is the mathematical model the more used, The photovoltaic cell is also represented by the standard model with one diode, establishes by Shokly for only one PV cell as the shows the fig.2. [4]

This model is realized by the connection in parallel of one diode of saturation's current I_0 , a source of current producing the current of short circuit of the cell that depends on the solar irradiance, the series resistance R_s , and the resistance shunt R_{sh} as shown Fig.2.

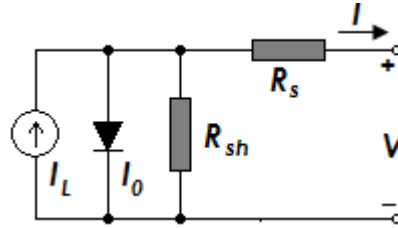


Fig.2 Electric model equivalent to one diode of the photovoltaic cell

The equations that describe I-V characteristics of the solar cell based on simple equivalent circuit shown in Fig. 2, are given below. [3]

$$I = I_L - I_0 \left(e^{\frac{q(V+I.R_s)}{AKT}} - 1 \right) - \frac{V + I.R_s}{R_{sh}} \quad (1)$$

where:

I_L : light current (A)/ or I_{ph}: photocurrent

I_0 : saturation current (A) of diod1,

K : Boltzmann constant, ($K=1.381 \times 10^{-23}$ J/K)

A : Factor of quality of the diode, normally included between 1 and 2. [4]

T : (K), the temperature of p-n junction .

q : electron charge, ($q=1.602 \times 10^{-19}$ C),

I : (A), The current supplied by the cell, (load current)

V : (V), output voltage (V),

R_{sh} : (Ω), the shunt resistance characterizing the leakage currents of the junction,

R_s : (Ω), series resistance.

3. Simulink Modeling for PV Module

To perform the required simulations the MATLAB Simulink software has been used. The simulations result for appropriate Models is presented in this part. Temperature and solar irradiation are used as input parameter and current-voltage and power-voltage characteristics are output.

A block diagram of the stage by stage model based upon the equations of PV model is represented in Simulink environment as given in Fig. 3. [5]

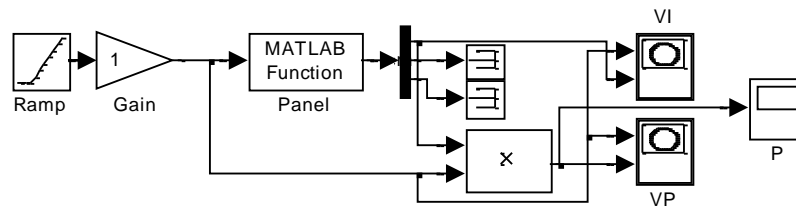


Fig.3 Matlab Similink model of PV module

Fig 4 and 5 showed the effect of these different parameters corresponding to temperature and solar irradiation respectively. The temperature is changed from 25°C to 100°C and the sun irradiation from 400w/m² to 1000 w/m². [6]

With increase the working temperature, the short-circuit current of cell is increased and open-circuit voltage is decreases. Sun irradiation is the variable and the effect of that on appropriate model is presented in Fig. 4 & Fig. 5.

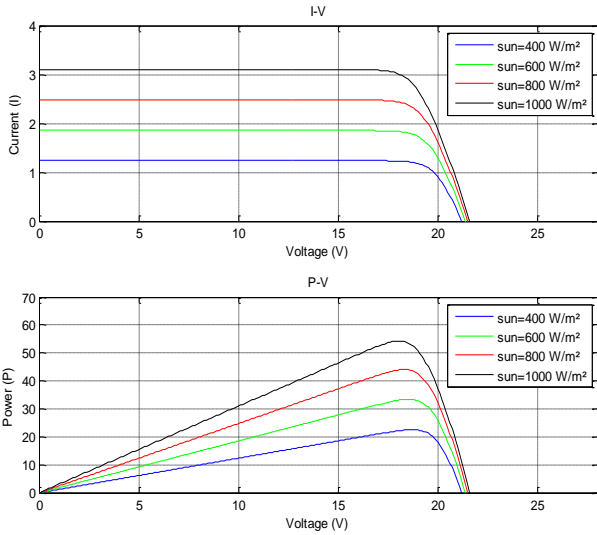


Fig.4 characteristics I-V and P-V at different irradiation

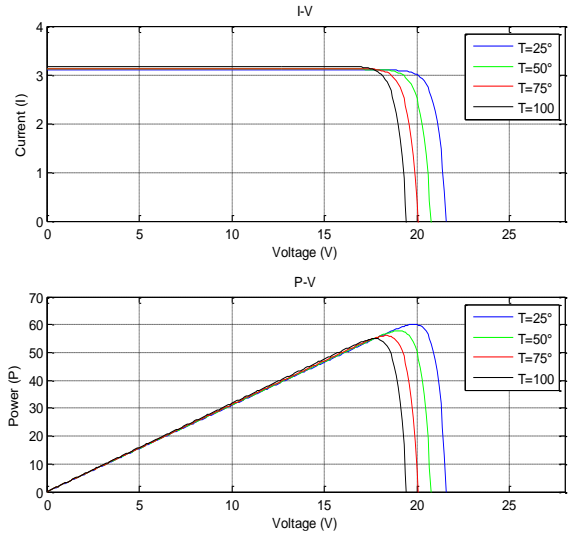


Fig.5 characteristics I-V and P-V at different temperature

4. Buck (DC/DC) Converter Modeling

The mathematical model of the Buck converter is obtained by the application of the laws of Kirchhoff on the diagram of basis of the converter, represented in Fig.6, and in relation to the regime of working and the condition of the S. switch

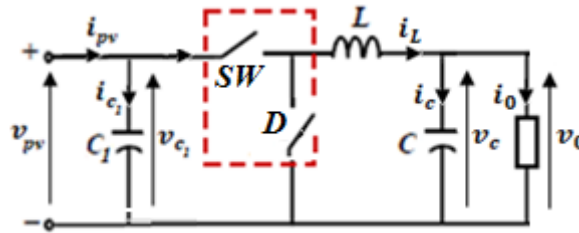


Fig.6 diagram of Buck converter

The switching DC-DC converters are hybrid dynamical systems characterized by both continuous and discrete dynamic behavior. In the following, we present only a general modeling approach of DC-DC converters by application of the state space averaging technique of the Buck converters for the case of a continuous conduction mode. [7]

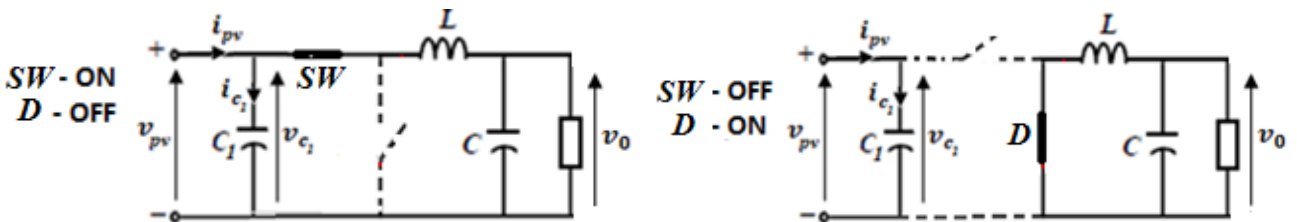


Fig.7 Buck converter with cycle of commutation

Let us consider a switching converter which has two working topologies during a period T. When the switches are closed, the converter model is linear. The state-space equations of the circuit can be written and noted as follows:

$$\begin{cases} i_L = i_c + i_R \\ v_{pv} = V_L + v_c \\ i_{pv} = i_{c1} + i_L \end{cases} \Rightarrow \begin{cases} i_L = C \frac{dv_c}{dt} + \frac{1}{R} v_c \\ v_{pv} = L \frac{di_L}{dt} + v_c \\ i_{pv} = C_1 \frac{dv_{pv}}{dt} + i_L \end{cases} \quad (2)$$

When the switches are opened, the converter can be modeled by another linear state-space representation written and noted as follows:

$$\begin{cases} i_L = i_c + i_R \\ 0 = V_L + v_c \\ i_{pv} = i_{C_1} \end{cases} \Rightarrow \begin{cases} i_L = C \frac{dv_c}{dt} + \frac{1}{R} v_c \\ 0 = L \frac{di_L}{dt} + v_c \\ i_{pv} = C_1 \frac{dv_{pv}}{dt} \end{cases} \quad (3)$$

From the equation (2) & (3) we can determine the average model given by equation (3) for an entire switching cycle T.

$$\begin{cases} i_L = C \frac{dv_c}{dt} + \frac{1}{R} v_c \\ d. v_{pv} = L \frac{di_L}{dt} + v_c \\ i_{pv} = C_1 \frac{dv_{pv}}{dt} + d. i_L \end{cases} \quad (4)$$

4.2. Presentation of the Buck converter model under Simulink®

The stat equation (4) become :

$$\begin{cases} \frac{dv_c}{dt} = \frac{1}{C} i_L - \frac{1}{RC} v_c \\ \frac{di_L}{dt} = \frac{d}{L} v_{pv} - \frac{1}{L} v_c \\ \frac{dv_{pv}}{dt} = \frac{1}{C_1} i_{pv} - \frac{d}{C_1} i_L \end{cases} \quad (5)$$

The Fig8 presents the model of simulation in Matlab Simulink®

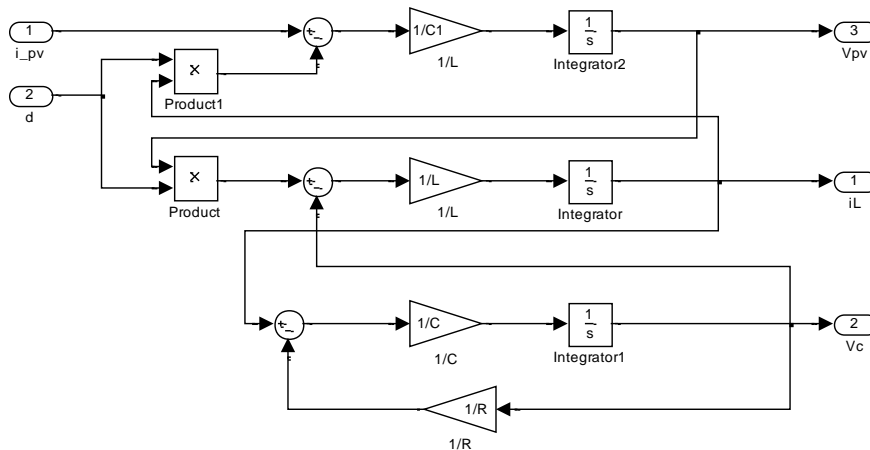


Fig8. Model of simulation for Buck under Simulink® Matlab

5. Perturb & Observe algorithm

The P&O algorithms are widely used in control of MPPT thanks to their simple structure and reduced number of necessary measured parameters [4].

The principle of this command is to generate disturbances by reducing or increasing the duty cycle D and to observe the effect on the power delivered by the GPV. The Stateflow® chart implementation of P&O method is given in Fig.9. [8]

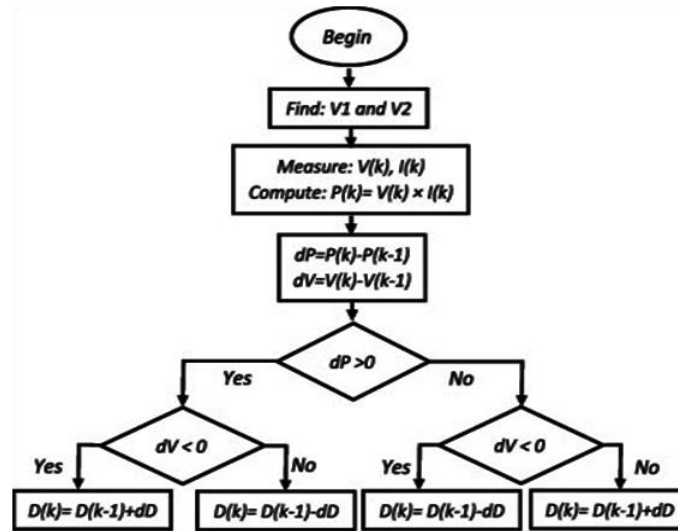


Fig.9. Flowchart of Perturb and Observe Algorithm

When $dP/dV > 0$ and the operating voltage of PV array is perturbed in a specific direction, it is known that perturbation moves the operating point of PV array to the MPP. P&O method will then continue to perturb the PV voltage in the same direction. When $dP/dV < 0$, the perturbation moves the operating point of PV array away from the MPP and the P&O method reverses the direction of the perturbation [8].

In simulated the P&O algorithms using the step variation of irradiance at temperature of 25°C and different values of step change of time (0.5 ms, 1 ms, until 5 ms) of implemented MPPT algorithms, and the simulation result are presented in Fig. 10. The Power of PV panel is represented by red line and the output of buck converter is represented by blue line.

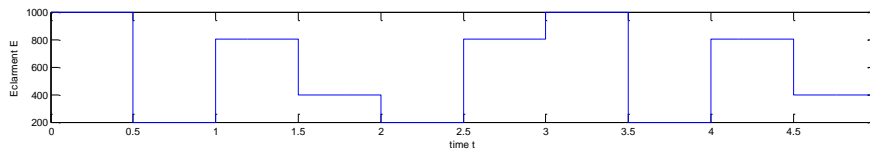


Fig.10 Step variation of irradiance.

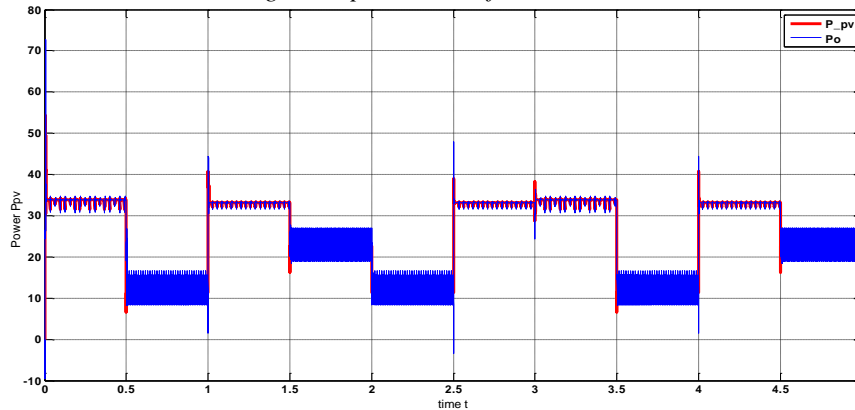


Fig.11 Simulation result of P&O for step irradiance

6. Stabilization and Control of Buck Converter using Backstepping Controller

6.1. Integrator Backstepping

The technique of backstepping is one of the most known techniques and used of control of the non linear systems. It is about an order technique for the non-linear systems, backstepping is a recursive Lyapunov-based scheme proposed in the beginning of 1990s. The technique was comprehensively addressed by Krstic, Kanellakopoulos and Kokotovic. The idea of backstepping is to design a controller recursively by considering some of the state variables as “virtual controls” and designing for them intermediate control laws. Backstepping achieves the goals of stabilization and tracking. The proof of these properties is a direct consequence of the recursive procedure, because a Lyapunov function is constructed for the entire system including the parameter estimates. [9]

$$\begin{bmatrix} \dot{v}_c \\ \dot{i}_L \\ \dot{v}_{pv} \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} & \frac{1}{C} & 0 \\ -\frac{1}{L} & 0 & \frac{d}{L} \\ 0 & -\frac{d}{C_1} & 0 \end{bmatrix} \begin{bmatrix} v_c \\ i_L \\ v_{pv} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{C_1} \end{bmatrix} i_{pv} \quad (6)$$

The idea consists in calculating a law of control, and to guarantee that the derivative of certain function Lyapunov is defined positive and that its derivative is always negative the method consists to break up the system in a set of subsystems overlapped of decreasing order. The calculation of the function of Lyapunov takes place recursive, while leaving from the inside of the loop.

6.2. The stability of Lyapunov :

The method of Lyapunov is in particular the second method (direct method) based on the concept of energy in a system, it consists in found a positive definite function (energy) noted $V(x)$ associated to the system. [10]

The idea of this method is to analyze the stability of the system, without having to solve the non linear differential equations. If the function of Lyapunov is strictly decreasing, that is to say that:

$$\dot{V}(x) < 0, \quad \forall x \neq 0$$

Then for guarantee the asymptotic stability

The function of Lyapunov. $V(x)$ is continuous as:

$$\begin{cases} V(x) > 0, & \forall x \neq 0 \\ \dot{V}(x) < 0, & \forall x \neq 0 \end{cases} \quad (7)$$

The dynamic equations of the converter DC/DC are presented under variables of state, the current of the inductance i_L , the tension of the capacitor v_c and the tension of the panel v_{pv}

$$[x_1 \quad x_2 \quad x_3] = [v_c \quad i_L \quad v_{pv}] \quad \& \quad u = i_{pv} \quad (8)$$

The stat equation (5) becomes:

$$\begin{cases} \dot{x}_1 = \frac{1}{C}x_2 - \frac{1}{RC}x_1 \\ \dot{x}_2 = \frac{d}{L}x_3 - \frac{1}{L}x_1 \\ \dot{x}_3 = \frac{1}{C_1}i_{pv} - \frac{d}{C_1}x_2 \end{cases} \quad (9)$$

Where x_1 , x_2 and x_3 are system sates and u is control input. The control objective is to design a state feedback control to asymptotically stabilize the origin.

The primary control objective is to track the value of output voltage converter v_o to reference voltage $v_{o,ref}$ generated under varying environmental conditions, first we define the error signal, and we make $y = v_o = v_c = x_1$

Step 1: $\alpha_0 = x_1$

$$z_1 = y - y_r \quad \Rightarrow \quad z_1 = x_1 - \alpha_0 \quad (10)$$

$$\dot{z}_1 = \dot{x}_1 - \dot{\alpha}_0 \quad (11)$$

Using Eq. \dot{x}_1 from (9), we get

$$\dot{z}_1 = \frac{1}{C}x_2 - \frac{1}{RC}x_1 - \dot{\alpha}_0 \quad (12)$$

In Eq. (12), taking x_2 as a virtual control input and define V_1 as Lyapunov candidate function to check the convergence of the error e_1 to equilibrium point. [11]

$$V_1 = \frac{1}{2}z_1^2 \quad (13)$$

In order to assure the asymptotic stability, the Lyapunov function must be positive definite and radially unbounded and its derivative with respect to time must be negative definite. Taking time derivative of Eq. (13), we get

$$\dot{V}_1 = z_1\dot{z}_1 \quad (14)$$

Putting (12) in (14), we get

$$\dot{V}_1 = z_1\dot{z}_1 = z_1 \left(\frac{1}{C}x_2 - \frac{1}{RC}x_1 - \dot{\alpha}_0 \right) \quad (15)$$

The stability of Lyapunov verified the condition

$$\dot{V}_1 = -k_1z_1^2 < 0 \quad (k_1 > 0) \quad (16)$$

(15) & (16), we got

$$\dot{V}_1 = -k_1z_1^2 + z_1 \left(k_1z_1 + \frac{1}{C}x_2 - \frac{1}{RC}x_1 - \dot{\alpha}_0 \right) \quad (17)$$

For V_1 to be negative and, k_1 must be positive, we define the virtual reference value from Eq. (17) must be satisfied. Is α_1 the stabilization function, acts as reference current for x_2 .

$$\alpha_1 = C \left(\frac{1}{RC} x_1 - k_1 z_1 + \dot{\alpha}_0 \right) \quad (18)$$

The diagram Fig.12, present the reference current

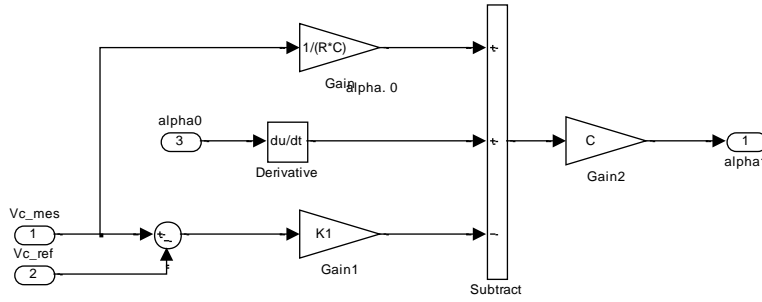


Fig.12 The reference current bloc α_1

Step 2: $\alpha_1 = x_2$

$$z_2 = x_2 - \alpha_1 \quad (19)$$

$$x_2 = z_2 + \alpha_1 \quad (20)$$

$$x_2 = z_2 + \alpha_1 \quad (20)$$

(12) & (18) in (20), we obtain

$$\dot{z}_1 = \frac{1}{C} z_2 - k_1 z_1 \quad (21)$$

We've

$$z_2 = \dot{x}_2 - \dot{\alpha}_1 \quad (22)$$

Using Eq. \dot{x}_2 from (9), we get

$$\begin{cases} \dot{z}_2 = \frac{d}{L} x_3 - \frac{1}{L} x_1 - \dot{\alpha}_1 \\ \dot{\alpha}_1 = C \left(\frac{1}{RC} \dot{x}_1 + \ddot{\alpha}_0 - k_1 \dot{z}_1 \right) \end{cases} \quad (23)$$

Lyapov equation for V_2 :

$$V_2 = \frac{1}{2} z_1^2 + \frac{1}{2} z_2^2 \quad (24)$$

$$\dot{V}_2 = z_1 \dot{z}_1 + z_2 \dot{z}_2 = z_1 \left(-k_1 z_1 + \frac{1}{C} z_2 \right) + z_2 \dot{z}_2 \quad (25)$$

$$\dot{V}_2 = -k_1 z_1^2 + \frac{1}{C} z_2 z_1 + z_2 \dot{z}_2 = -k_1 z_1^2 + \left(\frac{1}{C} z_1 + \dot{z}_2 \right) z_2 \quad (26)$$

The stability of Lyapunov verified the condition $V_2 < 0, k_2 > 0$

$$\dot{V}_2 = -k_1 z_1^2 - k_2 z_2^2 \quad (k_2 > 0) \quad (27)$$

We obtain

$$\alpha_2 = \frac{L}{d} \left(\frac{1}{L} x_1 - \frac{1}{C} z_1 + \dot{\alpha}_1 - k_2 z_2 \right) \quad (28)$$

The diagram Fig.13, present the reference tension of panel

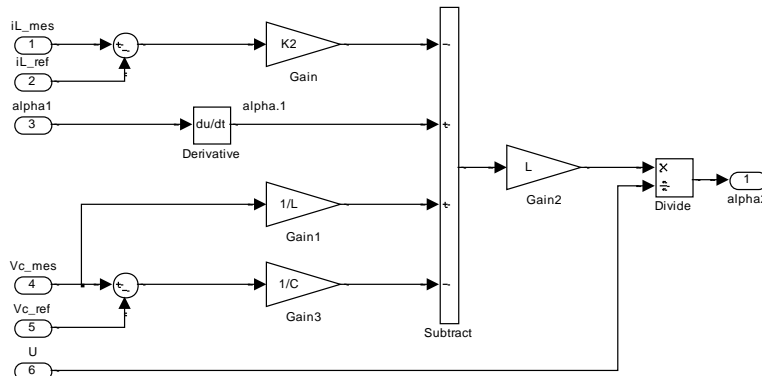


Fig.13 The reference tension reference PV bloc α_2

Step 3: $\alpha_2 = x_3$

$$z_3 = x_3 - \alpha_2 \quad (29)$$

$$x_3 = z_3 + \alpha_2 \quad (30)$$

(23) & (28) in (30), we obtain

$$\dot{z}_2 = \frac{d}{L}z_3 - \frac{1}{C}z_1 - k_2z_2 \quad (31)$$

$$\dot{z}_3 = \dot{x}_3 - \dot{\alpha}_2 \quad (32)$$

Lyapunve control equation for V_c :

$$V_c = \frac{1}{2}z_1^2 + \frac{1}{2}z_2^2 + \frac{1}{2}z_3^2 \quad (33)$$

$$\dot{V}_c = z_1\dot{z}_1 + z_2\dot{z}_2 + z_3\dot{z}_3 \quad (34)$$

(21) & (23) in (34)

$$\dot{V}_c = z_1\left(\frac{1}{C}z_2 - k_1z_1\right) + z_2\left(\frac{d}{L}z_3 - k_2z_2 - \frac{1}{C}z_1\right) + z_3\dot{z}_3 \quad (35)$$

We obtain

$$\dot{V}_c = -k_1z_1^2 - k_2z_2^2 + \left(\frac{d}{L}z_2 + \dot{z}_3\right)z_3 \quad (36)$$

The stability of Lyapunov verified the condition $V_3 < 0, k_3 > 0$

$$\dot{V}_c = -k_1z_1^2 - k_2z_2^2 - k_3z_3^2 \quad (k_3 > 0) \quad (37)$$

Therefore

$$\frac{d}{L}z_2 + z_3 = -k_3z_3 \quad (38)$$

We combine (31), (28), (23), (38) and (9), we get

$$\frac{d}{L}z_2 + \frac{1}{C}i_{pv} - \frac{d}{C_1}x_2 - \frac{L}{d}\left[-k_2\dot{z}_2 + \ddot{\alpha}_1 + \frac{1}{L}\dot{x}_1 - \frac{1}{C}\dot{z}_1\right] - \frac{\alpha_2\dot{d}}{L} = -k_3z_3 \quad (39)$$

The control law can be written:

$$\dot{d} = \frac{L}{\alpha_2}\left[\frac{d}{L}z_2 + k_3z_3 + \frac{1}{C_1}i_{pv} - \frac{d}{C_1}x_2 - \frac{L}{d}\left(-k_2\dot{z}_2 + \ddot{\alpha}_1 + \frac{1}{L}\dot{x}_1 - \frac{1}{C}\dot{z}_1\right)\right] \quad (40)$$

Table 1. Parameters of controller and converter

| Parameter | Value |
|--------------------|--------|
| Output capacitor C | 470e-7 |
| Input capacitor C1 | 470e-6 |
| Inductance L | 5e-3 |
| Resistor R | 12 |
| Constant K1 | 0.5 |
| Constant K2 | 200 |
| Constant K3 | 600 |

The figure Fig.14 below presents the global diagram of (PV generator, Buck Converter and integrator Backstepping), derived in law control (40).

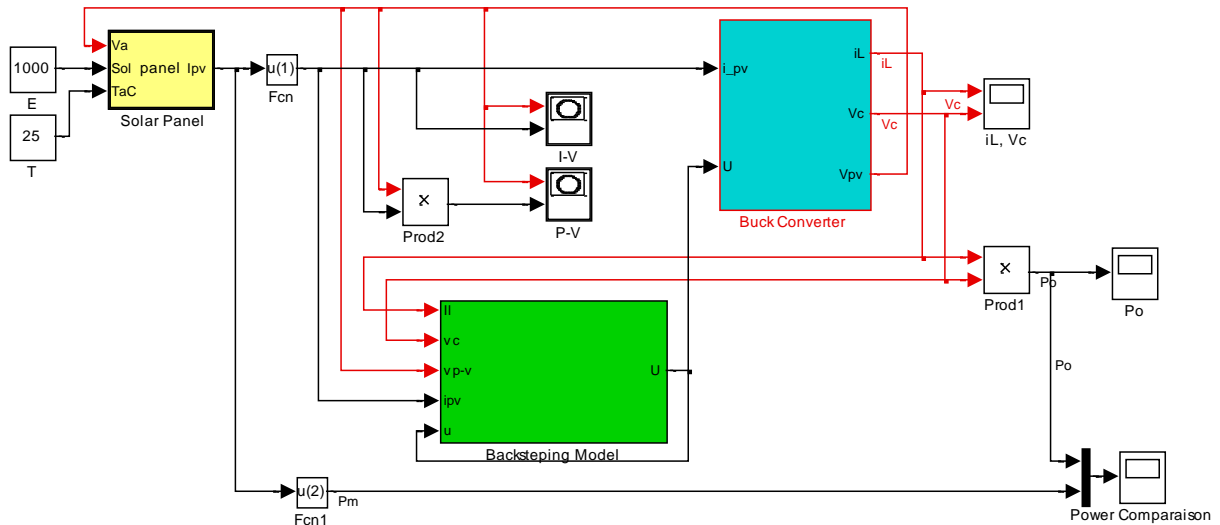


Fig.14 Integrator Backstepping with converter Buck and GPV Model

7. Results and discussion

We evaluate the Backstepping control using the step variation of irradiance at temperature of 25°C and different values of step change of the time (0.5 ms, 1 ms, until 5 ms), the simulation result are presented in Fig. 15. The Power of PV panel is represented by red line and the output of buck converter is represented by blue line. The output power signal track the reference signal (the maximum power) as shown in Fig15.

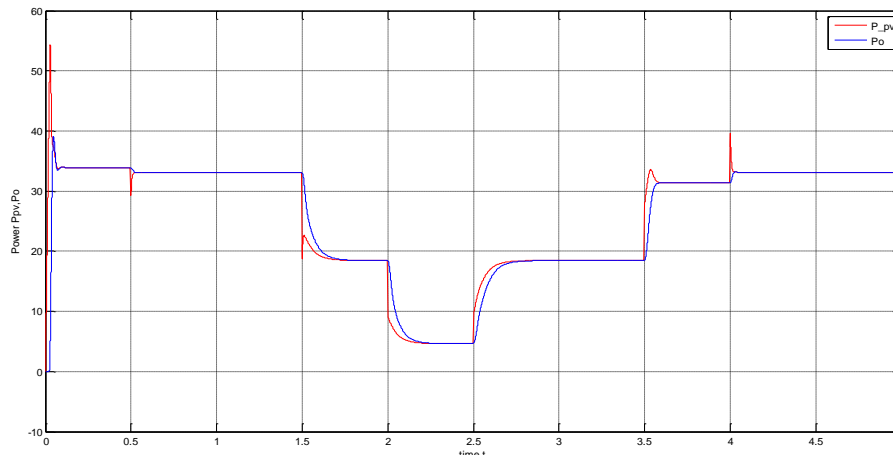


Fig.15 Simulation result of Integrator Backstepping for step irradiance

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8. Conclusion

This paper presents a comparative study between the Backstepping control and P&O to MPPT technique under Matlab / Simulink. We consider a GPV as a system used for simulation of the varying irradiance subsystem. The PV system model used for simulation consists of the PV panel, the variant subsystem of irradiance, the buck converter and the variant subsystem of MPPT controller. This comparative analysis aims to establish which of these two algorithms is indicated for MPPT in case of analysis depending on solar radiation and temperature considering the modification of change of duty cycle of MPPT controller.

Have been simulated the PV system with both Backstepping P&O algorithms at different solar radiation, and finally are presented some simulations result. Considering the optimal rapport between time of simulation, step change response of buck converter and the maximum power obtained, the best result for both Backstepping, and result of P&O algorithm contained oscillation when we applied the perturbation of MPPT controller.

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