Integral Backstepping Control for Maximum Power Point Tracking and Unity Power Factor of a Three Phase Grid Connected Photovoltaic System

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ABSTRACT

This paper presents a robust control strategy for a grid connected photovoltaic system with a boost converter by using an integral Backstepping method based on a nonlinear state model, which guarantees the Lyapunov stability of the global system. The system has tracked precisely the maximum power point, with a very fast response and the unit power factor has been observed under different atmospheric conditions. Moreover, the best advantage of the controller is that it's a good corrector of the grid perturbation and system parameter disturbance. The simulation result has demonstrated the performance of this strategy.

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1. INTRODUCTION

Due to much concerned about fossil fuel exhaustion and the environmental problems caused by the conventional power generation [1], nowadays, renewable energy sources, such as solar energy and wind-generators, are widely used.

Tropical countries are based on the exploitation of solar energy because they contain a wide surface and the amount of the intensity of the sunlight can reach up to 1000W / m² [2]. Moreover, solar photovoltaic systems are rapidly growing in electricity markets due to the declining cost of PV modules, increasing efficiency of PV cells, manufacturing-technology enhancements and economics of scale [3], [4]. In this context, the installations connected to the grid are the most used for their advantages compared to autonomous systems [5], [6]. So, this installation doesn't need batteries which increase the cost of the system, needs monitoring and limits the exploitation of total energy produced by photovoltaic generator PVG.

Therefore, the three phase grid connected photovoltaic system with a boost converter and three phase voltage source inverter has been selected to be studied in this paper. The use of boost converter will increase the degree of freedom of the system that will not require a large number of panels in series to give the minimal input voltage of the inverter and to be able to operate correctly with selected grid voltage.

The goals of this work are: In the first time, to control the boost converter to track very fast the maximum power generated by the photovoltaic generator PVG under climatic changes, then to deliver this power to the grid with a reactive power converging to zero via a control of the inverter. In the second time, to elaborate control laws in order to be able to correct all the perturbations of the system, like grid harmonic distortion and parameter's disturbance. In this context, many researches have been realized about the controllers of this system [7], but the performance of these controllers is not sufficient and the intrusiveness of the perturbations hasn't been considered in these works.

For that, this paper describes a nonlinear control strategy by applying the Backstepping method to achieve precisely the maximum power point tracking with a very good response time under environmental factors changes, then inject in to grid a three phase current in phase with the grid voltage (UPF Achievement). In other hand, the present controller with added integral action represents a good robustness in front of grid harmonic pollution and system's parameters disturbance that is the best contribution of this controller compared to others strategies.

The rest of the paper is organized as follow: in the first time, a system description and dynamic model are shown in Section 2. In the Section 3, the integral Backstepping controller design of a three phase grid connected PV system and its analysis will be shown in Section 4. Section 5 is focused on the simulation results with different analysis. Finally, we finish with a conclusion.

2. SYSTEM DESCRIPTION AND DYNAMIC MODEL

The system that has been considered is presented in Figure 1. So, firstly the boost converter is commanded to realize the MPPT function. Secondly the inverter is controlled by a PWM switching signals to inject a three phase current into the grid in phase with grid voltages. Finally, the inductor filter is used to filter out the harmonic distortion. i_p, v_p are respectly the PVG current and voltage. C_p is input capacitor of the boost converter taken as $4700 * 10^{-6}F$, L=$1 * 10^{-3}$ is boost converter inductor, i_L is boost converter inductor current, C_{dc} is DC link capacitor taken as $470 * 10^{-6}F$, v_{dc} is DC link voltage, i_a, i_b, i_c are injected currents, e_a, e_b, e_c are three phase grid voltages ($V_{max} = 380V$), ($L_f = 3 * 10^{-3}H, r = 0.02\Omega$) is a low pass filter.

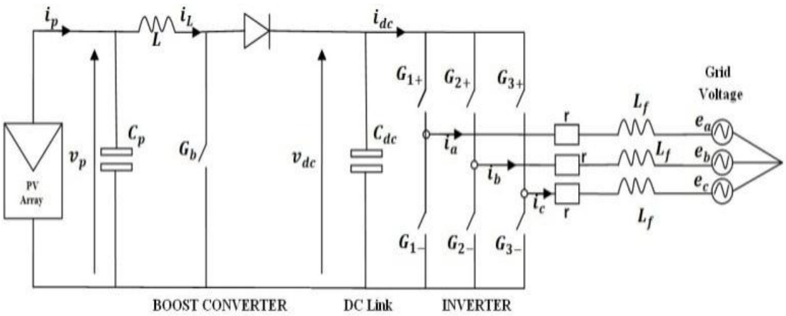

Figure 1. Configuration of three phase grid connected Photovoltaic system with a boost converter

The PV array used in this work has a peak value of 20 KW at standard atmospheric conditions.

Based on the research carried out recently [8], the system will operate in the maximum power point where the derivative of PV module power with respect to the PV voltage equals zero.

The backstepping method used in this paper has been implemented by using the following state-space model in d-q axis of the global system shown in Figure 1. This model is given as follows:

$$\begin{cases} \frac{dv_p}{dt} = \frac{1}{C_p} i_p - \frac{1}{C_p} i_L \\ \frac{di_L}{dt} = \frac{1}{L} v_p - \frac{1}{L}(1-\alpha) v_{dc} \\ \frac{dv_{dc}}{dt} = \frac{1}{C_{dc}}(1-\alpha) i_L - \frac{3}{2C_{dc}} C_d i_d - \frac{3}{2C_{dc}} C_q i_q \\ \frac{di_d}{dt} = w i_q - \frac{r}{L_f} i_d - \frac{1}{L_f} E_d + \frac{v_{dc}}{L_f} C_d \\ \frac{di_q}{dt} = -w i_d - \frac{r}{L_f} i_q - \frac{1}{L_f} E_q + \frac{v_{dc}}{L_f} C_q \end{cases} \quad (1)$$

Where: $(E_d\ E_q\ E_0)^T = D_{abc}^{dq0}(e_a\ e_b\ e_c)^T$, $(i_d\ i_q\ i_0)^T = D_{abc}^{dq0}(i_1\ i_2\ i_3)$, $(C_d\ C_q\ C_0)^T = D_{abc}^{dq0}(c_1\ c_2\ c_3)^T$. The transformation matrix D_{abc}^{dq0} using the phase angle θ is given by [9]:

$$D_{abc}^{dq0}=\frac{2}{3}\begin{pmatrix}\sin(\theta) & \sin(\theta-\frac{2\pi}{3}) & \sin(\theta-\frac{4\pi}{3})\\ \cos(\theta) & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta-\frac{4\pi}{3})\\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2}\end{pmatrix} \quad (2)$$

With E_d, E_q grid voltages components in the d-q axis, i_d,i_q injected currents components in the d-q axis, C_d, C_q PWM inputs components in the d-q axis of the inverter.

P is the photovoltaic output power defined by $P=i_p v_p$, $(v_p i_L v_{dc} i_d i_q)^T$ is the state vector, $(\alpha\ c_d\ c_q)^T$ is the control vector.

α is duty cycle used to switch the boost converter by generating the PWM output g_b , and c_1,c_2,c_3 are the signals used by PWM to generate switching signals of the inverter g_1, g_2, g_3.

Where: $g_b=\begin{cases}1\rightarrow G_b\text{:on}\\ 0\rightarrow G_b\text{:off}\end{cases}$, $g_{i=1..3}=\begin{cases}1\rightarrow G_{i+}\text{:on}; G_{i-}\text{:off}\\ 0\rightarrow G_{i+}\text{:off}; G_{i-}\text{:on}\end{cases}$ And: $c_{i=1..3}\in[-0.5\ ;\ 0.5]$.

The outputs $y_1=\frac{dp}{dv_p}=i_p+vp\frac{di_p}{dv_p}$, $y_2=i_q$, $y_3=i_d$ are selected to optimize the operation of the studied system. Indeed, $\frac{dp}{dv_p}$ must converge to zero in order that the system operates in the maximum power point. Moreover, the instantaneous reactive power Q is describes in the dq-axis by:

$$Q=-\frac{3}{2}E_d i_q \quad (3)$$

With E_d positive and constant. Therefore, the phase shift between the grid voltages and the inverter currents can be controlled to be neglected by converging i_q to zero. In other hand, the active power injected to the grid varies according to the d-component of the inverter current as follows:

$$P=\frac{3}{2}E_d i_d \quad (4)$$

Where E_d is positive and constant. Therefore, P can be maximized by controlling i_d to get a maximum value.

The next step presents a backstepping control with integral action of the current system. This nonlinear controller will stabilize the whole system in Lyapunov sense.

3. CONTROLLER DESIGN AND ANALYSIS

In this section, a backstepping approach with integral action has been applied to realize all the objectives. This method has been used by [10], [11] to control others system. The inverter output currents will be synchronized with the phase and frequency grid variation by using the phase lock loop technique which generates the phase angle θ of the grid [12].

3.1. Block Diagram of the Closed Loop Control

The scheme of the system controlled by integral backstepping method and the PLL technique, which will be described in details later in this paper, is presented in Figure 2.

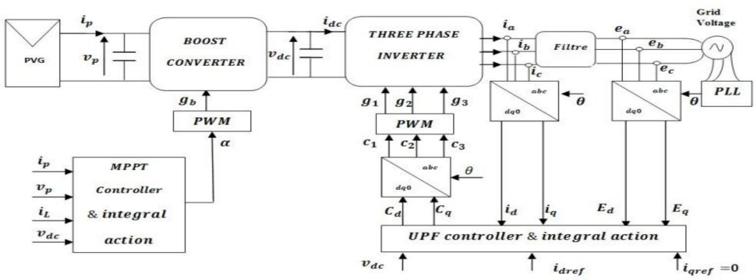

Figure 2. Block diagram of the closed loop control of a three phase grid connected PV system with boost converter.

3.2. Parameters Values of the Inductive Filter

The inductive filter is a simple low filter that is used to filter out the harmonic distortion. Knowing that the hight harmonic distortion frequency is higher than PWM frequency, to eliminate the harmonic distortion of the inverter currents we must choose a cut-off frequency of the low passe filter strictly less than PWM frequency. Moreover, the relationship between the phase 1 of the inverter's line voltage v_a and inverter's current i_a is given by:

$$v_a = ri_a + L_f \frac{di_a}{dt} + e_a \quad (5)$$

Hence, the transfer function of the inductive filter is as follows:

$$G_f = \frac{1/r}{1 + jw/(\frac{r}{L_f})} \quad (6)$$

And the cut-off frequency are given by:

$$f_c = \frac{r}{2\pi L_f} \quad (7)$$

So, to filter out the harmonic distortion, f_c must realize the following inequality:

$$50Hz < f_c < f_{PWM} \quad (8)$$

Therefore, the values of L_f and r must realize the aforementioned inequality.

3.3. The Maximum Power Point Tracking Control

The boost converter input signal α is used to stabilize the controlled output y_1 : to its reference:

$$y_{1ref} = \frac{\partial p_{mpp}}{\partial v_{pmpp}} = 0 \quad (9)$$

The Backstepping control of the MPPT is developed below:
In the first step, let's define the following tracking error:

$$\varepsilon_{p1} = y_1 - y_{1ref} = i_p + v_p \frac{\partial i_p}{\partial v_p} \quad (10)$$

The derivative of ε_{p1} is calculated as follows:

$$\dot{\varepsilon}_{p1} = \frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p} + v_p \frac{\partial^2 i_p}{\partial {v_p}^2}\right) (i_p - i_L) \quad (11)$$

The first Lyapunov function, including the integral action is defined in (12)

$$\delta_p = \int_0^t y_1(z) - y_{1ref}(z) dz = \int_0^t i_p + v_p \frac{\partial i_p}{\partial v_p} dz \quad (12)$$

To enhance the robustness of the controller in the following form:

$$V_{p1}(\varepsilon_{p1}, \delta_p) = \frac{1}{2}{\varepsilon_{p1}}^2 + \frac{1}{2}{\delta_p}^2 \quad (13)$$

Then, the expression of its derivative can be written as follows:

$$\dot{V}_{p1}(\varepsilon_{p1}, \delta_p) = \varepsilon_{p1}\left[\delta_p + \frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p} + v_p \frac{\partial^2 i_p}{\partial {v_p}^2}\right) (i_p - i_L)\right] \quad (14)$$

To stabilize the tracking error ε_{p1} and the integral action δ_p to zero a virtual control μ should be introduced. Where μ is the desired value of the boost inductor's current, it's defined by $\mu=(i_L)_d$. So to force the derivative of the candidate lyapunov function to be negative, the virtual control law must realize the relation below:

$$\delta_p + \frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p} + v_p\frac{\partial^2 i_p}{\partial {v_p}^2}\right)(i_p - \mu) = c_{1p}\varepsilon_{p1} \quad (15)$$

With : $c_{1p} > 0$, that is an adjustment parameter taken as 10000. Hence:

$$\mu=i_p+\frac{C_p}{2\frac{\partial i_p}{\partial v_p}+v_p\frac{\partial^2 i_p}{\partial {v_p}^2}}(c_{1p}\varepsilon_{p1}+\delta_p) \quad (16)$$

This choice of the virtual controller makes the derivative of the Lyapunov function V_{p1}negative:

$$\dot{V}_{p1}=-c_{1p}{\varepsilon_{p1}}^2<0 \quad (17)$$

The second step: in the reality, the virtual controller considered in the first step is not equal to the inductor's current. Indeed, there is an error between them. So, a tracking error is considered. To correct this error, it is defined by:

$$\varepsilon_{p2}=i_L-\mu \quad (18)$$

So, the inductor's current form can be written as follows:

$$i_L=\varepsilon_{p2}+\mu \quad (19)$$

Including the last form of the $i_L$into the equation (14), $\dot{\varepsilon}_{p1}$ becomes:

$$\dot{\varepsilon}_{p1}=\frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p}+v_p\frac{\partial^2 i_p}{\partial {v_p}^2}\right)(i_p-\varepsilon_{p2}-\mu) \quad (20)$$

From the equations (15) and (20), we obtain the following expression:

$$\delta_p+\dot{\varepsilon}_{p1}=-c_{1p}\varepsilon_{p1}-\frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p}+v_p\frac{\partial^2 i_p}{\partial {v_p}^2}\right)\varepsilon_{p2} \quad (21)$$

The lyapunov function V_{p1} lost the negativity of its dynamics as follows:

$$\dot{V}_{p1}=-c_{1p}{\varepsilon_{p1}}^2-\frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p}+v_p\frac{\partial^2 i_p}{\partial {v_p}^2}\right)\varepsilon_{p1}\varepsilon_{p2} \quad (22)$$

Therefore, the derivative of V_{p1} is not necessarily negative.
To solve this problem a second lyapunov candidate function is considered:

$$V_{p2}(\delta_p,\varepsilon_{p1},\varepsilon_{p2})=V_{p1}+\frac{1}{2}{\varepsilon_{p2}}^2 \quad (23)$$

And its derivative can be defined by:

$$\dot{V}_{p2}(\delta_p,\varepsilon_{p1},\varepsilon_{p2})=\dot{V}_{p1}+\varepsilon_{p2}\dot{\varepsilon}_{p2} \quad (24)$$

The final expression of $\dot{V}_{p2}$, presented in (25), can be obtained by substituting (22) into (24):

$$\dot{V}_{p2}(\delta_p,\varepsilon_{p1},\varepsilon_{p2})=-c_{1p}{\varepsilon_{p1}}^2+\varepsilon_{p2}\left[\dot{\varepsilon}_{p2}-\frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p}+v_p\frac{\partial^2 i_p}{\partial {v_p}^2}\right)\varepsilon_{p1}\right] \quad (25)$$

Where the time derivative of the tracking error ε_{p2} is:

$$\dot{\varepsilon}_{p2}=\frac{di_L}{dt}-\dot{\mu}=\frac{1}{L}v_p-\frac{1}{L}(1-\alpha)v_{dc}-\dot{\mu} \quad (26)$$

And the derivative of the virtual controller is given by:

$$\dot{\mu}=\frac{\partial i_p}{\partial v_p}\frac{\partial v_p}{\partial t}+C_p\frac{\left(c_1\dot{\varepsilon}_{p1}+\varepsilon_{p1}\right)}{\left(2\frac{\partial i_p}{\partial v_p}+v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)}-C_p\frac{\left(c_1\varepsilon_{p1}+\delta_p\right)}{\left(2\frac{\partial i_p}{\partial v_p}+v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)^2}*\left(3\frac{\partial^2 i_p}{\partial v_p^2}+v_p\frac{\partial^3 i_p}{\partial v_p^3}\right)\frac{\partial v_p}{\partial t} \quad (27)$$

By substituting the expression of $\dot{\varepsilon}_{p2}$ from (26) into (27) we obtain:

$$\dot{V}_{p2}(\delta_p,\varepsilon_{p1},\varepsilon_{p2})=-c_{1p}\varepsilon_{p1}^2+\varepsilon_{p2}\begin{bmatrix}\frac{1}{L}v_p-\frac{1}{L}(1-\alpha)v_{dc}-\dot{\mu}- \\ \frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p}+v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)\varepsilon_{p1}\end{bmatrix} \quad (28)$$

The real control input α which guarantees that the derivative of the augmented lyapunov function $\dot{V}_{p2}$ be negative is given by:

$$\alpha=\frac{L}{v_{dc}}\left[-c_{2p}\varepsilon_{p2}+\frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p}+v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)\varepsilon_{p1}-\frac{1}{L}(v_p-v_{dc})+\dot{\mu}\right] \quad (29)$$

With c_{2p} is a positive constant taken as 10000. Hence, the derivative of V_{p2} is negative and can be written as follows:

$$\dot{V}_{p2}=-c_{1p}\varepsilon_{p1}^2-c_{2p}\varepsilon_{p2}^2<0 \quad (30)$$

Which forces the state vector error $(\varepsilon_{p1},\varepsilon_{p2})$ to converge asymptotically to the origin. Consequently, $\frac{\partial p}{\partial v_p}$ will converge to zero and the maximum power point tracking will be achieved. Moreover, the established control law α forces the integral error δ_p to converge to the origin, which ensures disturbance rejection. Hence, the subsystem formed by the Photovoltaic generator, the input capacitor and the boost converter is globally asymptotically stable.

3.4. The Unity Power Factor Control

As seeing before, the control of the reactive power Q can be realized by regulating i_q at its desired value $i_{qref}=0$. In other hand, applying the control of the MPPT, the power transferred by the boost converter to the inverter is maximal, it's named P_{max}. Moreover, supposing that there is no dissipation of energy at the level of the inverter (the inverter is perfect), the maximum active power which can be delivered to the grid is P_{max}. Furthermore, the active power P must track P_{max} . So, it can be realized by controlling the d-component i_d of the injected currents to converge to its reference i_{dref}, which can be defined by using (4) as follows:

$$i_{dref}=\frac{2}{3}\frac{P_{max}}{E_d} \quad (31)$$

The backstepping procedure to control the reactive power and the maximum active power tracking can be formulated asfollows:

First, to control the Reactive Power, let's create the following error:

$$\varepsilon_{iq}=i_q-i_{qref} \quad (32)$$

And introduce the integral action below:

$$\delta_{iq}=\int_0^t i_q(z)-i_{qref}(z)\ dz \quad (33)$$

Then define the lyapunov function corresponding to δ_{iq} and ε_{iq} as follows:

$$V_{iq}(\varepsilon_{iq},\delta_{iq})=\frac{1}{2}\varepsilon_{iq}^2+\frac{1}{2}\delta_{iq}^2 \quad (34)$$

Where, its time derivative is given by:

$$\dot{V}_{iq}(\varepsilon_{iq},\delta_{iq})=\varepsilon_{iq}\left[\delta_{iq}-wi_d-\frac{r}{L_f}i_q-\frac{1}{L_f}E_q+\frac{v_{dc}}{L_f}C_q\right] \quad (35)$$

The control law C_q can be chosen as:

$$C_q=\frac{L_f}{v_{dc}}\left(-c_{iq}\varepsilon_{iq}-\delta_{iq}+wi_d+\frac{r}{L_f}i_q+\frac{1}{L_f}E_q\right) \quad (36)$$

With $c_{iq} > 0$ is a setting parameter taken as 50000.
So, the derivative of the lyapunov function V_{iq} will be negative as follows:

$$\dot{V}_{iq}(\varepsilon_{iq},\delta_{iq})=-c_{iq}\varepsilon_{iq}^2 \quad (37)$$

Which stabilize the component q of the inverter currents to zero, then the UPF is achieved.
The next aim is to inject a maximum active power produced by the Photovoltaic generator to the grid. To this end, a new tracking error is introduced as follows:

$$\varepsilon_{id}=i_d-i_{dref} \quad (38)$$

And its integral action is defined as:

$$\delta_{id}=\int_0^t i_d(z)-i_{dref}(z)\ dz \quad (39)$$

The expression of the stabilization function with the considered integral action is as follows:

$$V_{id}(\varepsilon_{id},\delta_{id})=\frac{1}{2}\varepsilon_{id}^2+\frac{1}{2}\delta_{id}^2 \quad (40)$$

To find the control law C_d , let's observe the derivative of the lyapunov function V_{id} that is given by:

$$\dot{V}_{id}(\varepsilon_{id},\delta_{id})=\varepsilon_{id}\left[\delta_{id}+wi_q-\frac{r}{L_f}i_d-\frac{1}{L_f}E_d+\frac{v_{dc}}{L_f}C_d-\frac{di_{dref}}{dt}\right] \quad (41)$$

Furthermore, to guarantee the negativity of the lyapunov candidate function the control law C_d should be selected as:

$$C_d=\frac{L_f}{v_{dc}}\left(-c_{id}\varepsilon_{id}-\delta_{id}-wi_q+\frac{r}{L_f}i_d+\frac{1}{L_f}E_d+\frac{di_{dref}}{dt}\right) \quad (42)$$

With $c_{id} > 0$ is a setting parameter taken as 50000.
Moreover, this choice makes the derivative of the lyapunov function at the form:

$$\dot{V}_{id}(\varepsilon_{id},\delta_{id})=-c_{id}\varepsilon_{id}^2 \quad (43)$$

Therefore, $\dot{V}_{id}$ is negative and the last control aim is realized.
By Applying this control strategy, the inverter delivers a maximum active power with a reactive power converges to zero even in the presence of system perturbation. Finally, the proposed backstepping control achieves all the defined goals and the whole system is globally asymptotically stable. Moreover, to observe all the performances of this method applied on the three phase grid connected photovoltaic system, a simulation with MATLAB/SIMULINK platform will be presented in the next section.

4. SIMULATION RESULTS AND ANALYSIS

In this section, simulation results are presented for the studied system. This system is simulated under Matlab/Simulink environment and it is controlled by the proposed integral backstepping control.

In this simulation, the considered scenario combines various environmental conditions, grid perturbation and parameters disturbance as shown in Figure 3. So, the dc link capacitor suffered a perturbation of 5% of its original value at 1.5 s. At 2 s the grid perturbation has been introduced by polluting the grid voltage with the fifth harmonic, which represents 12% of the fundamental grid voltage.

The MPP tracking under environmental conditions changes and system's perturbations as demonstrated by the same Figure 4. Thus, it's clear that the maximum power point is tracked with a very fast response and very good precision. The Figure 5 shows the injected current and the grid voltage of phase 1. In the beginning, the inverter output voltage is less than the grid voltage. Hence, the utility grid is disconnected from the inverter by using an automatically controlled switch. At 0.05s the inverter output voltage becomes more than the grid voltage. So, the PV system begins injecting current into the grid. Moreover, this figure demonstrates that the injected current is in phase with the grid voltage after a very reduced time about 0.01s.

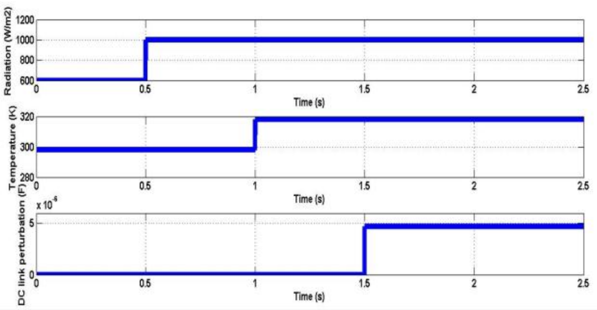

Figure 3. Radiation and temperature changes

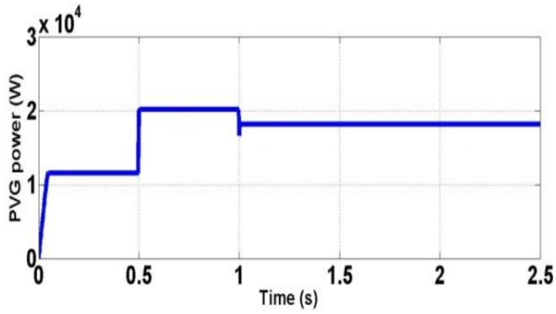

Figure 4. MPPT climatical changes, grid perturbation and parameters disturbance)

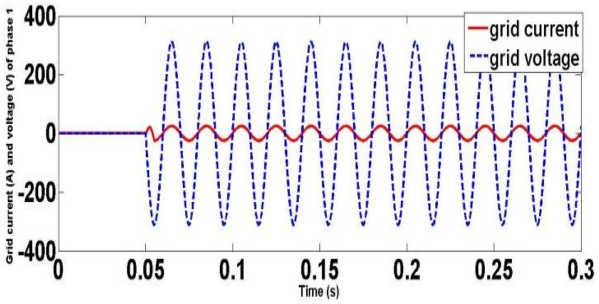

Figure 5. Zoomed injected current i_1 and grid voltage e_1 of the phase 1 (UPF achievement)

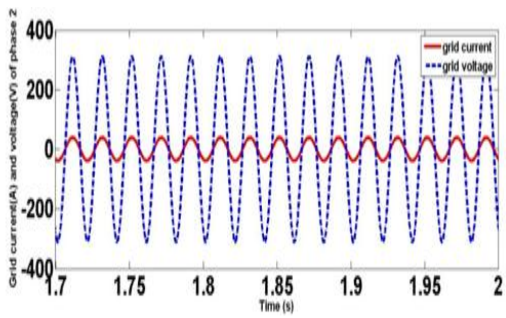

Figure 6. Zoomed injected current i_2 and grid voltage e_2 of the phase 2 (UPF achievement during a parameters disturbance)

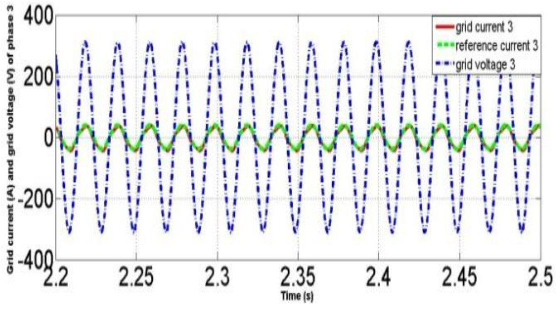

Figure 7. Zoomed injected current i_3 and grid voltage e_3 of the phase 3 (UPF achievement during a harmonic pollution)

The Figure 6 and Figure 7 demonstrate the robustness of the proposed control successively in front the parameter's disturbance and grid perturbation.

It can be seen that the MPPT and the UPF are reached under atmospheric conditions changes and system's perturbation with a very good performance. That proves the efficiency and the robustness of the integral backstepping control proposed in this paper.

5. CONCLUSION

This paper describes an integral backstepping control of a three phase grid connected photovoltaic system with a boost converter, where the behavior of the whole system is represented by a mathematical model and the controller is developed by using an instantaneous model in the d-q reference frame. The aims of this strategy are tracking the maximum power generated by the PV Generator and injecting this power to the grid with a maximum active power, a null reactive power and a low harmonic distortion of the injected currents. So, the simulation results prove that the backstepping control has reached all of these goals under atmospheric conditions changes with a very good precision and a very fast response.

Furthermore, the introduced integral action gave the controller more robustness in front the system's perturbation. Moreover, the system is globally asymptotically stable.

The next work will be consecrated to elaborate a control strategy of this system with a non-linear load.

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