INTEGRAL BACKSTEPPING CONTROLLER DESIGN OF PHOTOVOLTAIC SYSTEM CONNECTED TO THE GRID

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Abstract: *In this paper, the problem of the controlling of the photovoltaic (PV) generators connected to a single-phase grid is addressed. The PV system presented consists of a PV generator, a DC_AC inverter and a single-phase grid. Unlike the conventional systems, the great benefits of the proposed system are reduced cost as it involves no temperature/irradiation sensors and no chopper, in addition to a higher reliability. We seek to achieve three control objectives: (i) extracting the maximum power from the PV generator, (ii) regulating the DC voltage to a desired value ($V_{pv,ref}$) (iii) injecting a sinusoidal current and in phase with the grid voltage (unit power factor UPF), while ensuring a total harmonic distortion (THD) less than 5%. The control strategy is based on the design of a nonlinear controller Integral Backstepping robust to be applied to the DC-AC inverter in order to optimize the PV energy extraction and to achieve unity power factor (UPF). In order to improve the robustness of the nonlinear controller, an integral action is introduced. The stability of the nonlinear control is demonstrated by means of Lyapunov's analysis. The representative computer simulations show the performance of the control strategy to track the maximum power point of the photovoltaic panel and network synchronization of the grid's current with the mains voltage in different climatic conditions.*

Key words: *photovoltaic (PV) array, unity power factor (UPF), Maximum Power Point (MPP), Lyapunov, Integral Backstepping Control.*

1. Introduction

In order to reduce the utilization of fossil fuels for energy conversion in the world, several sources of renewable energy are proposed, photovoltaic systems have been concerned, as one of the fastest growing new energy sources, it is unfailing and non-polluting; it presents a solution to the growth of energy demand and pollution from the utilization of fossil fuels, they generate DC electric power from sunlight by using the photovoltaic effect of semiconductor materials [1]. In order to obtain high power PV generators, the PV modules should be combined in parallel and in series. The photovoltaic generator releases its electricity as a DC current between its terminals.

Different PV grid connection structures are researched and utilized, literally, single phase grids are typically used. In [2], [3], [4], [5], the PV generator is connected to the grid via a chopper and a single phase inverter (fig 1). In this case, the chopper is used in order to extract the maximum of power from the PV panel, to regulate and increase the input voltage across the terminals of the inverter. In [6], [7], the inverter is the only DC/AC converter connecting the PV generator and single-phase grid (fig 2). There, the inverter is used for both functions, to extract the maximum power from PV generator and transfer it to the electrical grid simultaneously. This structure avoids the inconveniences caused by using a chopper (heavier in weight, in investment as well as maintenance, more expensive, plus additional losses). By using this structure, the inverter is controlled in order to achieve two objectives, (i) extracting the maximum power point (MPP) and (ii) the power factor correction (PFC) requirement.

The use of PV energy can be divided into two parts, a stand-alone power system and a grid-connected one. Even though they have many similarities, there is a difference between them in terms of control functions. The stand-alone system (used in an off-grid application) requires a battery to store the energy, but in high power application, PV grid connected systems are used. The main aim of the grid connected system is to synchronize the grid's current with its voltage under various climatic conditions. As illustrated in (fig 3) and (fig 4), the power generated by a PV array depends by its MPP on atmospheric conditions and the array power depends nonlinearly on the array terminal operating voltage. Furthermore, the MPP varies depending on the radiation and temperature; this requires the continuous adjustment of the array terminal voltage. Different approaches to track the MPP have been addressed in many literatures in [8]. In this sense, several studies have focused on the PV systems. They tried to develop algorithms to extract the maximum energy converted by the panel and then allowing the optimal operation of the PV system [9]. Such as Perturb and Observe (P&O) [10]-[11], the increment conductance (Inc-Con) [12]-[13], a fuzzy logic controller type Mamdani was also studied [14], [15]. The advantage of the (P&O) is that the characteristics of the PV generator are not required. However, in a stable state, the system oscillates around the MPP, but it can be minimized by reducing the perturbation's step size. Nevertheless, a short perturbation size slows down the MPP and the Perturb and Observe method fails most of the time under rapidly changing atmospheric conditions. The strategy of increment conductance is founded on the

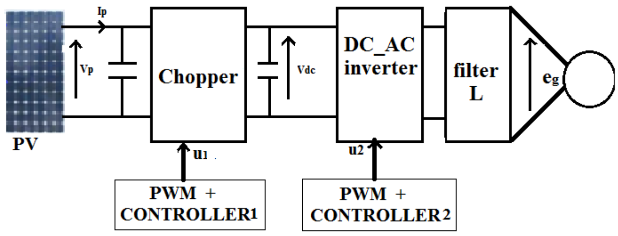

Fig1. PV-grid connection structure with Chopper

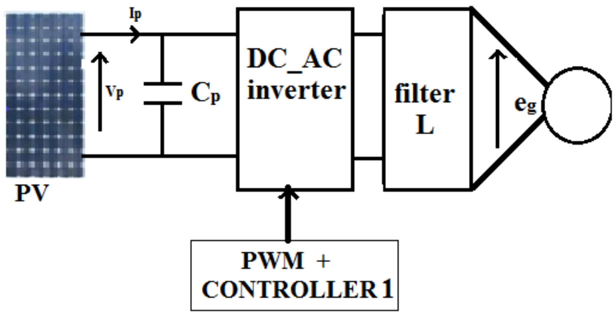

Fig2. PV-grid connection structure without Chopper

fact that the slope of the PV array power curve is negative on the right, zero at the MPP and positive on the left (fig 3), and it needs a complex control circuit. To solve all these problems, the Sliding Mode Control (SMC) is an adequate technique for the variable structure of the PV generator and the DC_DC boost converter, to track the maximum power of PV system [16]-[17], the SMC is designed for a class of nonlinear dynamic systems to deal the problems concerning the model uncertainties, parameters fluctuations and external disturbances. By this control, the bounds of the uncertainties are not required to be known in advance [18]-[19]-[20]. However, in the presence of large uncertainties, the controller has a higher switching gain and produces higher amplitude of chattering. The fuzzy logic controller is used very successfully in the implementation for the MPP searching. The fuzzy controller improves the efficiency of the PV systems by reducing: energy loss, response time of the system and also eliminating fluctuations around the optimal point. This technique shows the quality, robustness, and efficiency of the fuzzy logic controller for the PV systems under fast changing environmental conditions.

This article deals with the problem of controlling the PV system which is composed of a PV generator connected to the single-phase-grid through the DC_AC inverter PWM and an inductor (L_g). The main objective is to design a nonlinear controller in order to: (i) extract the maximum power from the PV generator; (ii) inject a sinusoidal current and in phase with the grid voltage (UPF), and with a low distortion harmonic ratio (THD<5%) without using the DC_DC converter in order to minimize the costs of the PV system. This technique was carried out by using the optimum voltage reference that is designed online using the algorithm (P&O).

In this work, the proposed strategy of the non-linear controller is designed by the Integral Backstepping technique based on the nonlinearity of the studied system. The integral action was introduced in order to reinforce the system's robustness against the modeling uncertainty of the studied one and against internal and external disturbances. The Analysis of Lyapunov was introduced in order to prove the stability of the proposed non-linear controller.

This command forces the voltage across the PV generator to perfectly follow its reference whatever the weather; it also keeps the grid's current in phase with its voltage. Moreover, this technique is robust, insensitive to the variations of both internal and external system parameters, and very accurate and stable.

The rest of the paper is organized as follows: in section 2, we present a model of the PV system that is composed of a PV generator connected to the single-phase-grid. Section 3 will be consecrated to the design and analysis of the nonlinear controller by using the Integral Backstepping technique. As for section 4, in it are presented the discussion and analysis of the results of the numerical simulation. At the end of the article, a conclusion and a reference are given.

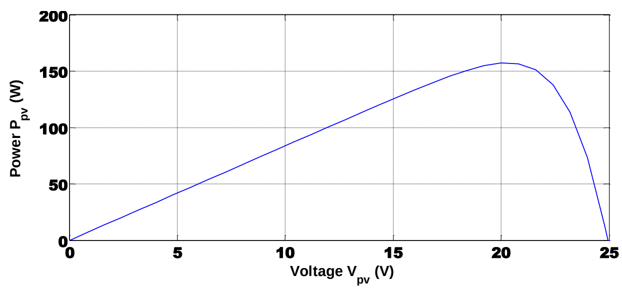

Fig3. Characteristic $P_{pv} = f(V_{pv})$

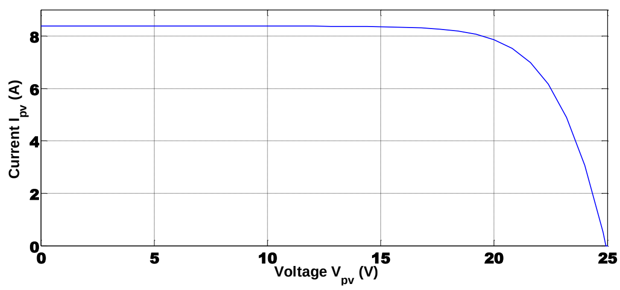

Fig4. Characteristic $I_{pv} = f(V_{pv})$

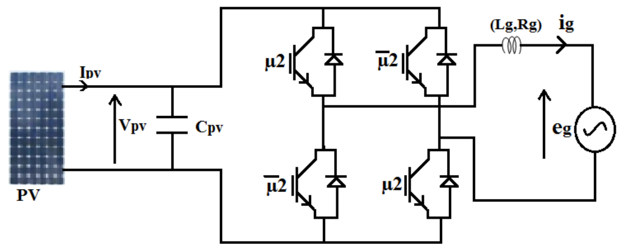

Fig5. General diagram of the PV single-phase grid system.

2. System modelling

The PV system is shown in (fig 5). It consists of 36 series photovoltaic modules, a DC-AC inverter which is used to achieve the maximum power point (MPP) and to provide energy to the grid. The filter (L_g) is employed to reduce the ripple components due to the PWM switching operation.

2.1 PV generator model

The solar PV array technology is a p-n junction semiconductor, which allows the direct conversion of sunlight into electrical power without any moving parts, noise or pollution. The absorption of photons by materials when the incoming solar energy overtakes the band-gap energy of the module enables to generate electricity. Fig 2 shows the equivalent circuit of photovoltaic (PV), it consists of a light-generator source, diode, series and parallel resistances [21]-[22].

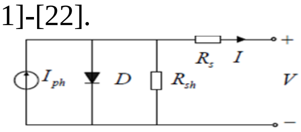

Fig6. equivalent circuit diagram of a PV cell.

The characteristic equation for the current and voltage of the PV module is given as follows [23]-[24].

$$I = I_{ph} - I_s\,[exp\,((V+IR_s) / (NnV_T)) - 1] - ((V+IR_s)) / R_{sh} \quad (1)$$

Where, I_{ph} is the photocurrent, I_s is the diode saturation current, n is the ideality factor, V_T is the thermal voltage (kT/q), k is the Boltzmann constant, T is the temperature in Kelvin, q is the charge of an electron, R_s and R_{sh} are series and parallel resistors modeling the losses due to connections. The PV module considered in this paper has N=36 series connected cells.

The PV generator consists of several chains of PV module in series, connected in parallel, in order to inject the desired values of output voltage and grid current of the single-phase-grid connected to the PV system. The PV array model is represented by the equation:

$$I_p = I_{php} - I_{sp}\,[exp\,(\frac{Vp+IpRsp}{NsNnVt}) - 1] - \frac{Vp+IpRsp}{Rshp} \quad (2)$$

Where V_p and I_p are the PVG output voltage and its output current; $I_{sp}=N_pI_s$ and $I_{php}=N_pI_{ph}$ are the saturation current of the PVG and the photocurrent; $R_{shp}=R_{sh}(N_s/N_p)$ and $R_{sp}=R_s(N_s/N_p)$ are the PVG parallel resistance and series resistance; N_p and N_s are the number of the PV module in parallel and its number in series.

Photocurrent is the function of solar radiation and cell temperature described as:

$$I_{ph} = [I_{ph,\,ref} + C_T\,(T - T_{ref})]\,(S / 1000) \quad (3)$$

Where, S is the real solar radiation (W/m^2), $I_{ph,ref}$ is the cell's short-circuit and radiation, T_{ref} is the cell's reference temperature's, C_T is the temperature coefficient (A/K).

Diode saturation current varies with the cell temperature:

$$I_s = I_{s,ref}\,[T / T_{ref}]^{\wedge 3}\,[exp((qE_g / n\,K)\,(1/T_{ref} - 1/T))] \quad (4)$$

Where, $I_{s,ref}$ is the cell reverse saturation at temperature T_{ref}, E_g is the band-gap energy of the cell semiconductor (eV).

2.2 Characteristics of the Power-Voltage & Current-Voltage:

In (fig 7) and (fig 8), the constitutive curves of the PV array with different values of solar irradiation and temperature are illustrated. There, in those figures, two considerable electrical characteristics of the PV array can be observed: indeed, in the operating point, the PV array generates more power than the other points. Thus, for each curve, there are different maximum power points. The above observations show that the maximum power point of a PV cell varies according to the temperature changes and the solar incident irradiance.

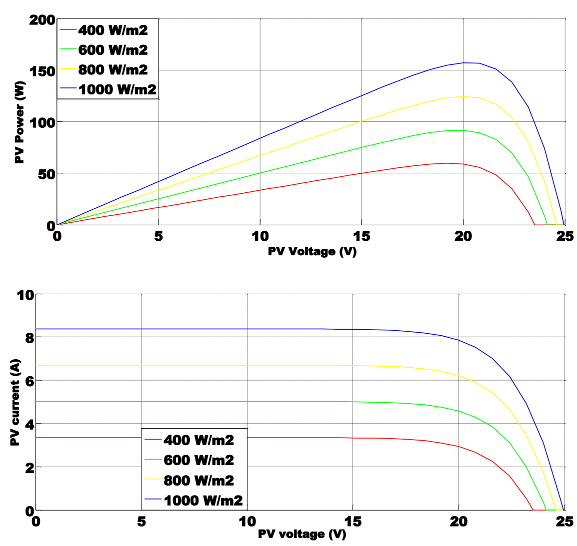

Fig7. PV array current–voltage and PV array power–voltage at 25°C at different irradiance levels.

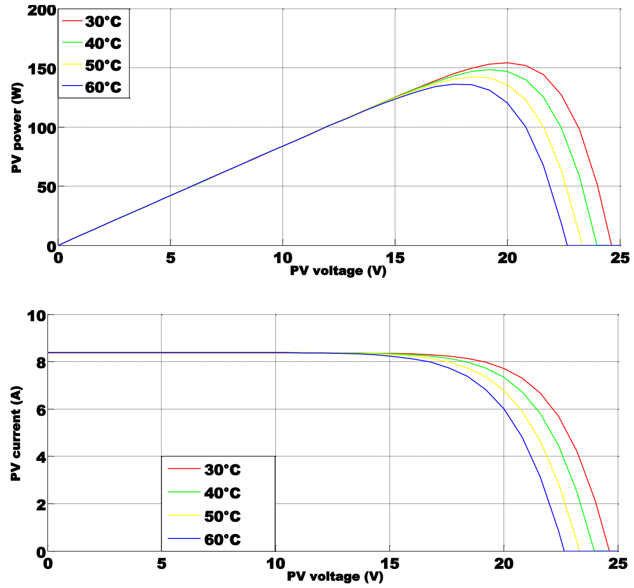

Fig8. PV array current–voltage and PV array power–voltage at 1000W/m2 at different temperature levels.

The PV Model performance can be determined through the characteristic curves. (fig 3) and (fig 4) present the current-voltage output characteristics and power-voltage output characteristics of the PV array with constant solar irradiation G = 1000 W/m2 and temperature T = 25 °C.

In general, the PV arrays have nonlinear voltage-current characteristics, and there is only one PV operating point with a maximum output power under particular conditions. Based on the characteristic curve shown in (fig 3) and (fig 4), the condition of maximum power point is given by:

$$(\partial P/\partial v_{pv}) = i_{pv}+(\partial i_p/\partial v_{pv}) = 0 \qquad (5)$$

Where $P=i_{pv}*v_{pv}$ is the output power of the PV array.

2.3 A grid connected to the PV System model

Fig.5 shows the photovoltaic array output connected to the single-phase grid via the DC/AC inverter, which consists of a two phase converter that has 4 semiconductors (IGBT with anti-parallel diodes) displayed in two legs 1 and 2. The 4 semiconductors are considered as ideal switches, and at the same time, one switch on the same leg can be conducted.

The dynamic model of the solar power generation system presented in (fig 5) can be expressed by an instantaneous switching model as follows [25]-[26]:

$$C_{pv}\,\dot{x}_1 = I_{pv} - (\,2\mu - 1\,)\,x_2 \qquad (6)$$

$$L_g\,\dot{x}_2 = (\,2\mu - 1\,)\,x_1 - R_g\,x_2 - V_g \qquad (7)$$

Where x_1, x_2, I_{pv} and V_g are respectively, the means values, over a period of cutting of the PV array voltage (V_{pv}), grid current (i_g), PV array current and grid voltage. The control input of the DC_AC inverter is a PWM signal (pulse width modulation) taking the discrete values 0 (switch open) and 1 (switch closed). C_{pv} is the input capacitor of the inverter. L_g is the filter inductor and R_g is the equivalent series resistance of the filter inductor.

3. The controller design

3.1 Control objectives

The main objectives of this section are designing a:

(i) DC-link voltage reference: DC link voltage v_{pv} must track as accurately as possible the voltage reference $v_{pv,ref}$. The desired array voltage designed online by using an MPPT algorithm as illustrated in (fig 10).

(ii) PFC requirement: The grid current (i_g) must be of a sinusoidal form with the same frequency as the supplied power grid (V_g), and in phase with the grid voltage.

In order to attain the previous objectives, a direct nonlinear integral backstepping controller is designed to control the duty ratio of the DC_AC inverter. The integral action is introduced in order to improve the system's robustness against external disturbance and modeling uncertainties. The global controller of the maximum power point tracking and unity power factor controller will be synthesized using the backstepping approach [27]-[28]-[29], and the second will be done by a simple PI corrector. Fig 9 illustrates the structure of the whole controlled system.

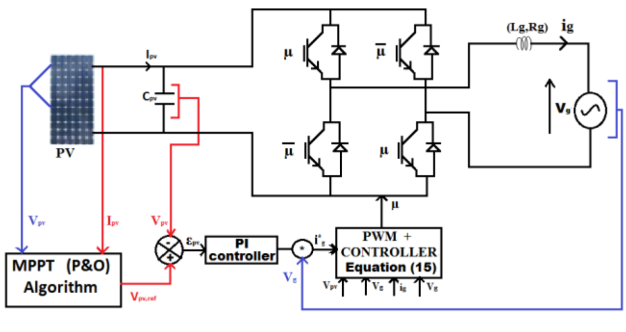

Fig9. PV system with multiple controllers.

3.2 DC-link voltage reference

The main objective of this section, is designing a voltage-reference by using the (P&O) algorithm (fig 10). In particular, the (P&O) algorithm is used to compute on-line the optimal voltage value $V_{pv,ref}$ as follows, if the voltage V_{pv} is made equal to $V_{pv,ref}$ then, the maximal power is captured, and transmitted to the grid through the DC/AC inverter. The operating principle of the algorithm (P&O) is as the following: the voltage of the PV array must be disturbed in a given sense and if the power generated by the PV array increases, then, the operating point is moved toward the MPP and, therefore, the operation voltage must still be disrupted in the same sense.

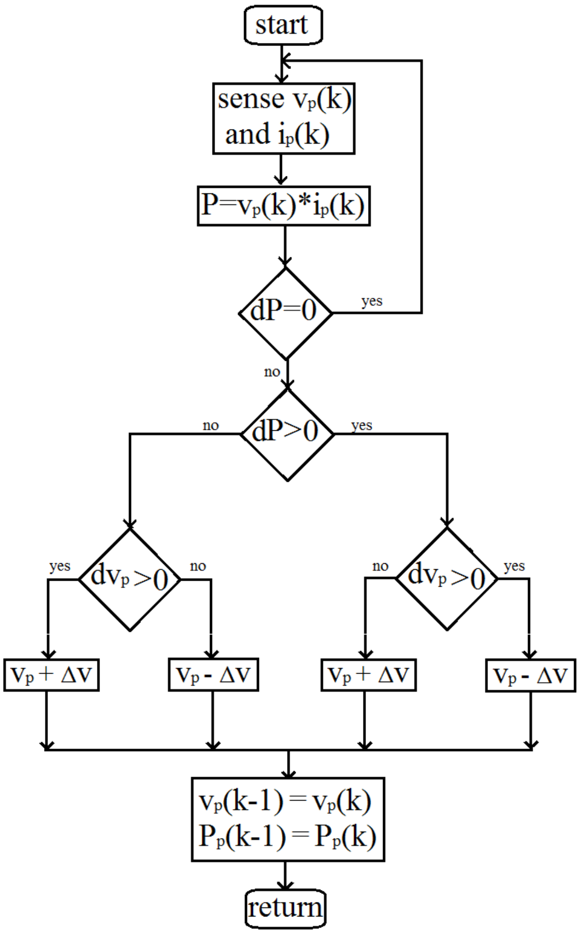

Fig10. The flowchart of P&O MPPT algorithm

Where, $dP = P(k) – P(k\text{-}1)$, $dV_p = V_p(k) – V_p(k\text{-}1)$.

Furthermore, if the power generated by the PV array decreases, consequently the operating point has moved away from the MPP and, thus, the sense of the operating voltage perturbation must be reversed.

3.3 Controlling inverter output current to achieve PFC.

We should recall that the control objectives are: i) unitary power factor, ii) injecting a sinusoidal current in the network, iii) ensuring current harmonics rejection. Therefore, the aim is to directly enforce the current x_2 to track a given reference current x_2^* of the form:

$$i^*_g = x^*_2 = \lambda v_g = \lambda \, . \, A \, .sin\,(\omega t) \quad (8)$$

Where λ is a positive parameter and it can be adjusted by a PI control.

Consider the tracking error ε_1 defined by:

$$\varepsilon_1 = x_2 - x_2^* \quad (9)$$

Its dynamics is given by:

$$\dot{\varepsilon}_3 = -\,(1/L_g)\,(R_g x_2 + V_g + (1-2\mu)\,x_1) \;-\; (dx_2^*/dt) \quad (10)$$

We define the Lyapunov candidate function:

$$V_1 = \frac{\gamma}{2}\,\xi_1^{\;2} + \frac{1}{2}\,\varepsilon_1^{\,2} \quad (11)$$

Its derivative with respect to time is given by:

$$\dot{V}_1 = \varepsilon_1\,[\gamma\xi_1 - (1/L_g)\,(R_g x_2 + V_g + (1-2\mu)\,x_1) - (dx_2^*/dt)] \quad (12)$$

Where γ, is a positive constant at the disposal of the designer, $\xi_1 = \int_0^t \varepsilon_1(\tau)\,d\tau$ is the integral of the position tracking error.

Thus the equation (12) leads to the development of the regulator's Backstepping control.

$$\mu = 0.5[1 + (1/x_1)\,(R_g x_2 + V_g + L_g((dx_2^*/dt) - k_1\varepsilon_1 - \gamma\xi_1))] \quad (13)$$

Where $k_1 > 0$ is a design parameter. Then, we obtain: $\dot{V}_1 = -k_1\,\varepsilon_1^{\;2} < 0$. Therefore global asymptotic stability is achieved and ε_1 tends exponentially to zero. Consequently the grid current (i_g) is sinusoidal and in phase with the grid voltage (V_g).

Proposition: Consider the control system consisting of the average PWM Inverter model (6)-(7) in closed-loop with the controller (13), where the desired DC link voltage reference x_1^* ($V_{pv,ref}$) is sufficiently smooth. Thus, the equilibrium $x_1 \longrightarrow x^*_1$, $x_2 \longrightarrow x^*_2$, $\mu \longrightarrow \mu_0$ is asymptotically stable where:

$$\mu_0 = 0.5[1 + (1/x^*_1)\,(R_g x^*_2 + V_g)] \quad (14)$$

3.4 DC link bus voltage control.

In order to design a tuning law for the ratio in (8) in such a way that the DC link voltage x_1 be regulated to a given reference x_1^* ($V_{pv,ref}$), to this end, the following PI control law is used:

$$\lambda(t) = K_p.\varepsilon(t) + K_i.\int_0^t \boldsymbol{\varepsilon}\,(\boldsymbol{\tau})\,\mathbf{d\tau} \quad (15)$$

With $\varepsilon = V_{pv,ref} - x_1$ and (K_p, K_i) are design parameters at the disposal of the designer.

4. Simulation Results

The objective of this section is to test the experimental setup described by (fig 9) and the nonlinear controller that has been designed in the above section under the environment Simulink / Matlab.

Table 1 illustrates all parameters of the PV components and controller.

TABLE I. POWER SYSTEM AND CONTROLLER PARAMETERS

Photovoltaic array parameters	**dc-ac inverter, L filter and grid parameters**	**Controller parameters**
R_s=0.002Ω	C_{pv}=51mF	k_1=500000
R_p=1000Ω	L_g=2mH	k_p=8
n=1.7	R_g=0.005Ω	k_i=200
I_{scr}= 8.3758A	$A=220\sqrt{2}$	$\gamma = 1$
I_{rr}=5.3μA	f=50Hz	
N_s=20	V^*_{dc}=400V	
N_p=5		
P_{max}=157.165W		
V_{max}= 20V		
V_{ov}= 24.947V		
I_{sc}= 8.3758A		

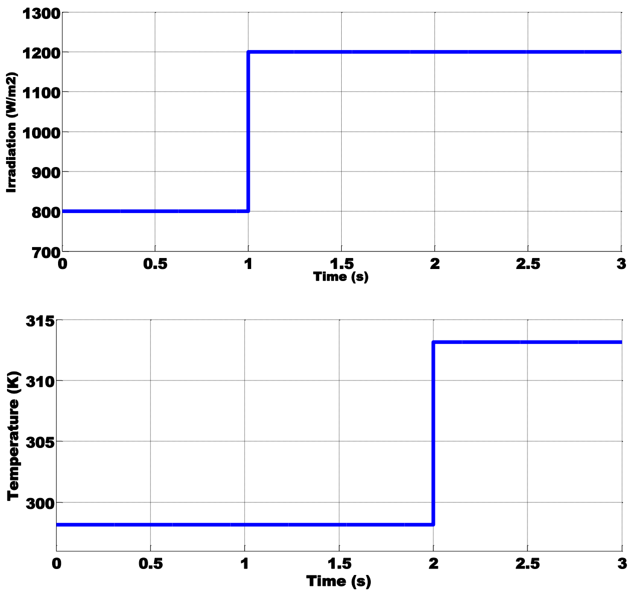

Fig11. Change of solar irradiation, Change of temperature.

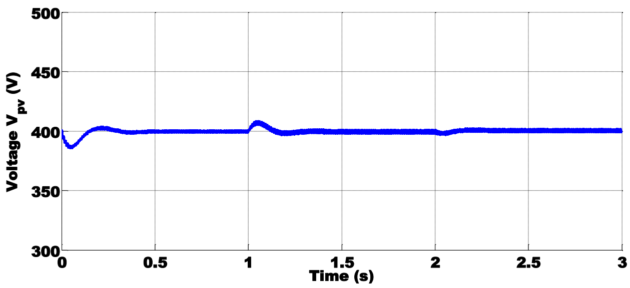

Fig12. The solar array voltage V_{pv} (V)

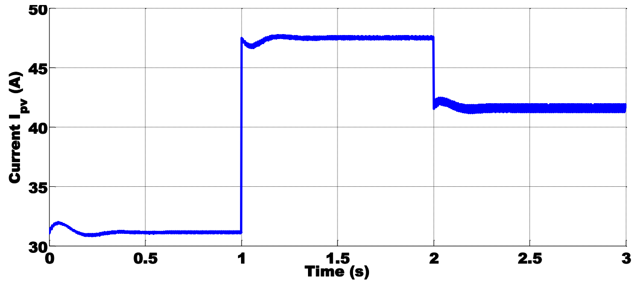

Fig13. The solar array current I_{pv} (A)

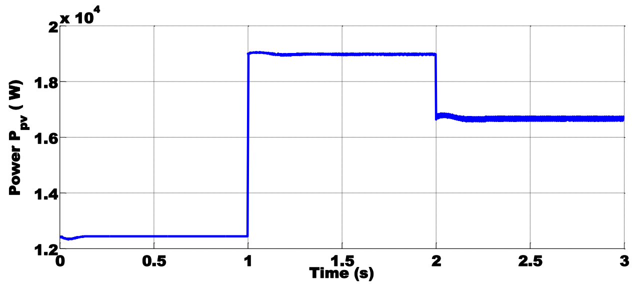

Fig14. The solar array power P_{pv} (W)

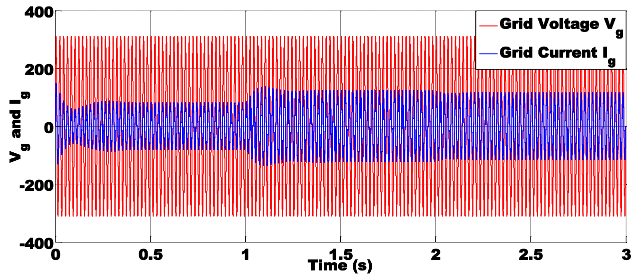

Fig15. Grid voltage (V), Output current (A).

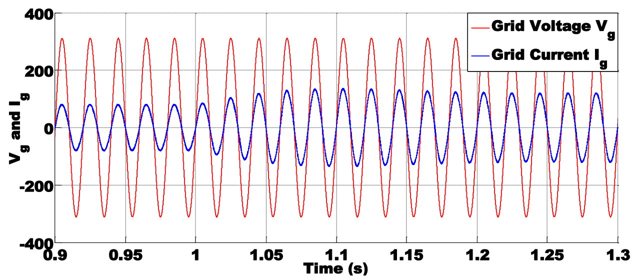

Fig16. Unity PF behavior in presence of radiation changes.

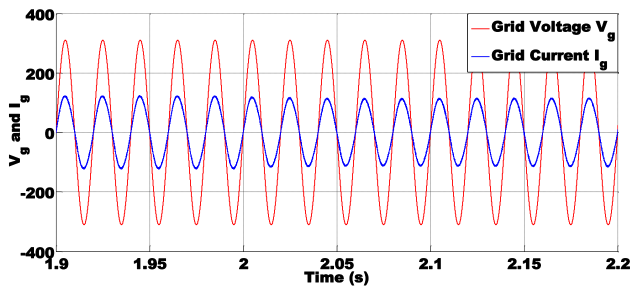

Fig17. Unity PF behavior in presence of temperature changes.

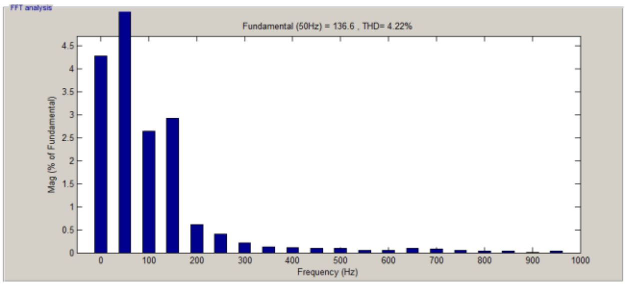

Fig18. Harmonic spectrum of the grid current

In order to verify the performances of the controller; a numerical simulation was made in the Simulink/Matlab-platform. Indeed, the initial value of irradiation is chosen as 800 W/m^2 (low radiation) between 0 and 1s, then steps to 1200 W/m^2 at t = 1s (high radiation), while the temperature steps from 25°C to 40°C at 2s.

The radiation and temperature variation is shown by (fig 11). Fig. 12 shows that the DC Link-voltage is regulated to its desired value and tracks quickly its reference (400V) after each change in radiation. Fig. 13 shows the photovoltaic current I_{pv}. It is clearly seen that the current amplitude changes significantly in function of the radiation. Fig. 14 shows that the maximum power point of PV is achieved quickly with great precision and strong performances regardless to radiation variation. Fig. 15, (fig 16) and (fig 17) show the measured output grid current i_g response. It is clearly seen that the current frequency is constant and equal to the voltage v_g frequency. More precisely, the current remains most of the time in phase and in a sinusoidal form with the supply net voltage, consequently, the unity power factor (UPF) is achieved. Furthermore, the measured THD of the grid current (i_g) in the steady state is 4.22% as shown in (fig 18), this shows that the current harmonic distortion is less thaan 5%.

5. Conclusion

In this article, an Integral Backstepping controller has been proposed in order to optimize the operation of a PV system connected to the single-phase grid described by the nonlinear state space model (6)-(7). The main advantage of the system presented is that it does not require a DC-DC converter as an intermediary between the PV generator and the DC _AC inverter because the action of extracting the maximum power of the PV generator will be made by the only DC-AC converter used. The results of the simulation showed that the developed nonlinear controller meets the objectives of this article. Indeed, the maximum power has been extracted and it was injected into the single-phase grid, in the form of a sinusoidal current and in phase with the grid voltage, and with a very low total harmonic distortion (THD<5%) regardless of the weather conditions. Consequently, the main objectives have been achieved and therefore, this controller is proven for a minimum harmonic ratio, high efficiency and global asymptotic stability.

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