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Integral Backstepping Control of Three-phase Grid-Connected Photovoltaic Systems for Power Optimization

Noureddine Skik, Ahmed Abbou, Rafika El idrissi

Abstract*: We propose in this paper a nonlinear controller to optimize the operation of a photovoltaic device consisting of a PV generator, a three-phase inverter, and an LCL filter. Unlike traditional systems, this system is reliable and is not expensive, thanks to the absence of the DC-DC converter. In reality, we are trying to achieve two goals: (i) Search track and extract the maximum power from the PV generator (MPPT requirement); (ii) Inject this power into the network in the form of an alternating current which has the same pulsation as that of the network (UPF requirement). To achieve these objectives, the proposed controller was designed using non-linear design techniques, based on the nonlinear modeling of the photovoltaic system. Numerical simulation and its results showed the performance of the nonlinear controller and its ability to confront the challenges described in this article (MPP and UPF requirement), external disturbances and abrupt climatic changes.

Keywords*: UPF; MPPT; Integral Backstepping.

I. INTRODUCTION

Recently, the use of renewable energy has increased significantly because of its positive effects on the environment (sources of inexhaustible energy, does not produce waste, completely free, clean), unlike fossil fuels because of the environmental problems they cause (ecosystem contamination, depletion of fossil fuels, environmental concerns about global warming, the need to reduce carbon dioxide emissions), which has prompted many countries to encourage the use of renewable energies such as solar energy and wind energy. Indeed, PV systems are more reliable and generate no noise (absence of mechanical parts), unlike wind systems. Nevertheless, several factors impede the diffusion and use of renewable energies, including the high investment cost and the lower energy conversion efficiency of the PV panels. Solar PV is used in the photo-thermal mode in which the solar energy is transformed into heat; or in the PV mode in which the solar energy is transformed into electricity (direct current). Indeed, the power delivered by the PV systems can be used in different modes: either in an autonomous application mode in which the power is stored in batteries. In application mode, and when connected to the power grid in which the power generated by the PV system must be fed into the network with a unity power factor, these systems gain more interest compared to standalone PV systems. Converters have been proposed and developed such as choppers and inverters to increase the performance of the PV systems. Indeed, several parameters can optimize the efficiency of energy conversion and the transfer of this energy to an electrical network. Among these parameters we quote: the type of converters used, the command by which this converter was controlled, and the way of connection between all the devices of the PV system. In [1]-[2], The PV system is made up of a PV generator, two static converters and an electrical grid (figure 1). The first is a boost converter DC_DC, it is the responsible for MPPT. The second is a DC_AC converter, it is responsible for transforming the direct current into alternating current and transferring this energy to the electrical network (UPF). In [3–4], the PV generator is connected to the mains via an inverter (figure 2); the latter is responsible for performing the two previous functions at the same time as MPPT and UPF. Nonetheless, linking the PV generator and the electrical grid via the only DC AC converter is the best technique because it removes the drawbacks of the boost converter (high weigh , and maintenance costs). The three-phase inverter is operated using this technique to achieve two goals: firstly, to search and extract the maximum power (MPPT) from the PV generator, secondly the synchronization between the injected current and the network voltage at the pulsation level. Besides, the most important in the field of renewable energy is the PV systems linked to the electrical grid. In this context, several control strategies have been proposed and built-in this regard to optimize and improve the efficiency and output of the PV generator connected to the 3-phase grid. In [5], two controllers control the PV system: the first is the adaptive fuzzy logic controller for controlling the DC-DC converter, the second is the predictive current controller for controlling the DC-AC inverter, this control strategy is more costly as it involves a DC-DC converter and the predictive current controller needs accurate circuit parameter information.

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* Correspondence Author

Noureddine Skik*, Department of Electrical Engineering department, Mohammadia School of Engineers, Mohamed V University, Rabat, Morocco. Email: noureddine.skik@gmail.com.

Ahmed Abbou, Department of Electrical Engineering, Mohammadia School of Engineers, Mohamed V. University, Rabat, Morocco. Email: abbou@emi.ac.ma,

Rafika El idrissi, Department of Electrical Engineering, Mohammadia School of Engineers, Mohamed V. University, Rabat, Morocco. Emails: abbou@emi.ac.ma, rafika.elidrissi@gmail.com.

In [6], two controllers controlled the PV system: one is the back-stepping used to control the DC-DC converter, while the other is the PI controller used to control the phase inverter. This strategy of control is costly because a DC-DC converter is needed. Indeed, the PI controller used in this technique may be sluggish in low frequency at times and pose a risk of instability which limits its use in nonlinear systems control. Sliding mode control and discrete–time integral sliding mode control have been Suggested in [7–8] to transfer the power of the PV generator to the grid. The sliding mode control operating principle is to push the system's trajectories to hit the sliding surface and stay there. Nevertheless, with considerable uncertainty, this control technique has a high gain that leads to high amplitude of oscillation (chatter).

The purpose of this article is to control a generator connected to the public network through a 3-phase inverter and an LCL filter. In line with the above, the primary purpose is to extract the PV generator's maximum power by using the algorithm perturb and observe, secondly inject this power into the network as a sinusoidal current with the same pulsation as that of the grid and with a harmonic distortion rate of less than 5 percent. The control strategy proposed in this study is based on the "Integral Back-stepping" technique while considering the modeling of the nonlinear system studied. In order to reinforce the robustness of the PV system, and to increase its resistance against internal and external disturbances and parasites, and to eliminate the uncertainties of the modeling of the studied system, an integral action has been used. To demonstrate the stability of the proposed controller, the analysis of Lyapunov was called. Indeed, this control technique forces the output voltage of the PV generator to follow the reference voltage generated by the algorithm (P&O), and keeps the current injected into the network in phase with the network voltage. In addition, it seems that this is the best solution to the disadvantages of the previous controllers, it is robust, insensitive to internal and external disturbances, and also accurate and stable.

The rest of the article will be structured as follows: -A description of the PV system consisting of a PV generator connected to the single-phase grid will be presented in section 2; section 3 will be dedicated to the design and analysis of the non-linear controller using the back-stepping technique; and section 4 will present the discussion and analysis of the effects of numerical simulation. A conclusion and a reference will be given at the end of the article.

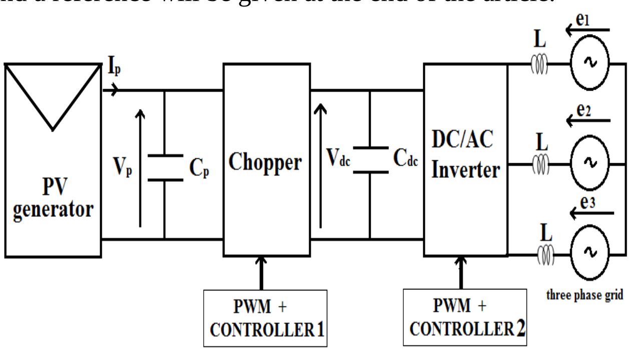

Fig. 1.PV system connection structure with DC-DC converter

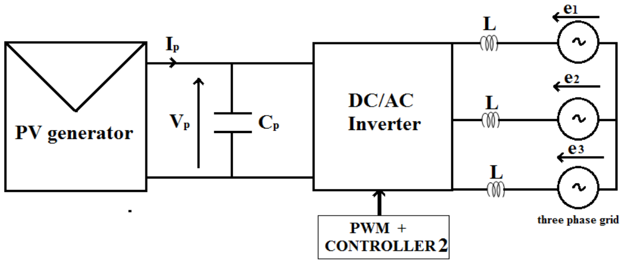

Fig. 2.PV system connection structure without DC-DC converter

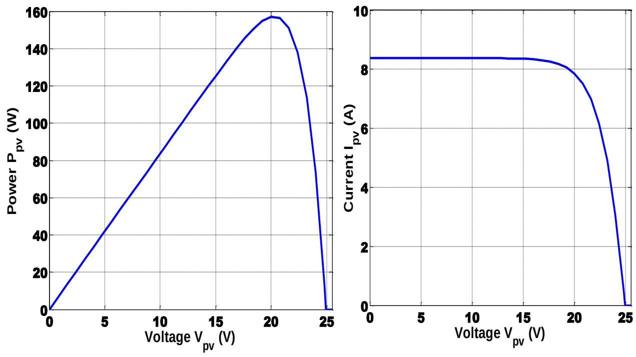

Fig. 3.P = f (vp) and Ip = f (vp)

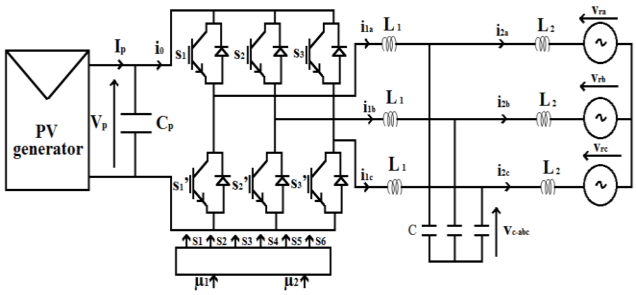

Fig. 4.system connection structure of the three phase grid system

II. THE MODELING OF A THREE PHASE GRID CONNECTED TO A PV ARRAY

As illustrated in figure 4, the actual PV system used in this study. This system consists of a PV generator, capacitor C_p, a three-phase inverter, an LCL filter and a public network.

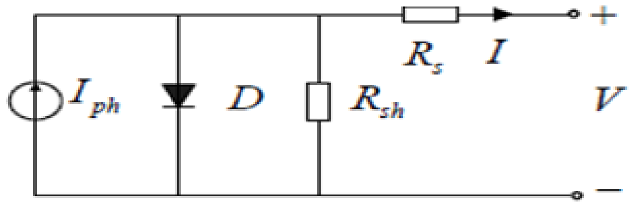

Fig. 5.System connection of the PV cell.

A. PV panel model

As illustrated in figure 5, the electric model of the solar cell used in this article. Indeed, this model consists of a diode connected anti-parallel with a current generator, and two resistors connected in parallel and in series.

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This cell converts solar energy into electrical energy using the PV effect.

The solar cell studied can be modeled by the following mathematical equation [9]:

$$I = I_{ph} - I_s\left[\exp\left(\frac{V + IR_s}{NnV_T}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}$$

(1)

Where, I_{ph} represents the photocurrent, I_s represents saturation current of the diode, n represents the ideality factor, V_T represents the thermal voltage KT/q, K is the Boltzmann's constant, T is the temperature in Kelvin, q is the charge of an electron, R_s and R_{sh} are the series and parallel resistors that, due to the connection of the devices, model energy loss. In this paper, the PV module considered has linked cells serially to N=36.

To obtain the desired voltage and inject it into the network, several PV modules are connected in series and parallel. A PV generator can be modeled by the following mathematical equation:

$$I_p = I_{php} - I_{sp}\left[\exp\left(\frac{V_p + I_p R_{sp}}{N_s NnV_T}\right) - 1\right] - \frac{V_p + I_p R_{sp}}{R_{shp}}$$

(2)

Where V_p and I_p are the PV generator's output voltage and current. I_{sp}= N_n I_s and I_{php}= N_p I_{ph} are the PV generator photocurrent and saturation current respectively. The parallel and series resistances of the PV generator are R_{shp}= $R_{sh}(N_s / N_p)$ and R_{sp}= $R_s(N_s / N_p)$. The PV module is composed of N_s panels in serial and N_p panels in parallel. Depending on the solar irradiation and the temperature of the cell, each PV cell delivers a variable current (photocurrent). The following mathematical equation describes this current:

$$I_{ph} = \left[I_{ph,ref} + C_T\left(T - T_{ref}\right)\right]\left(\frac{S}{1000}\right)$$

(3)

Where S stands for the direct solar radiation (W/m^2). I_{phref} is the short-circuit current of the cell. T_{ref} represents the reference temperature of the cell. The C_T represents the coefficient of temperature (A/K). Nevertheless, a diode's saturation current varies by temperature and can be given by the following mathematical equation:

$$I_s = I_{s,ref}\left(\frac{T}{T_{ref}}\right)^3\left[\exp\left(\frac{qE_g}{nK}\right)\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$$

(4)

Where I_{sref} at T_{ref} temperature is the cell's reverse saturation current. E_g is the band-gap energy of the semiconductor (ev) of the cell.

B. Dynamic model of the inverter DC/AC

In this paragraph, we address the study and the mathematical modeling of the three-phase inverter shown in figure 4. The dynamic system shown in figure 4 is modeled by the following dynamic state equations:

$$L_1\frac{d\left[i_{1\text{-}abc}\right]}{dt} - R_1\left[i_{1\text{-}abc}\right] = v_p\left[S_{123}\right] - \left[v_{c\text{-}abc}\right] \quad (5)$$

$$L_2\frac{d\left[i_{2\text{-}abc}\right]}{dt} - R_2\left[i_{2\text{-}abc}\right] = \left[v_{c\text{-}abc}\right] - \left[v_{r\text{-}abc}\right] \quad (6)$$

$$C\frac{d\left[v_{c\text{-}abc}\right]}{dt} = \left[i_{1\text{-}abc}\right] - \left[i_{2\text{-}abc}\right]$$

(7)

$$C_p\frac{dv_p}{dt} = I_p - i_0$$

(8)

$$i_0 = \left[S_{123}\right]^T\left[i_{1\text{-}abc}\right]$$

(9)

Where I_p, v_p, i_0, ($[i_{1\text{-}abc}] = [i_{1a}\ i_{1b}\ i_{1c}]^T$, $[i_{2\text{-}abc}] = [i_{2a}\ i_{2b}\ i_{2c}]^T$) and ($[v_{c\text{-}abc}] = [v_{ca}\ v_{cb}\ v_{cc}]^T$, $[v_{r\text{-}abc}] = [v_{ra}\ v_{rb}\ vr_c]^T$) are respectively the PV array current, the DC link's voltage, the input current inverter, the two three-phase components of the current traversing the inductances L_1 and L_2 and the two components of the voltage across the capacitor and the grid side (with known constant frequency ω and amplitude v_r). C_p, L_1, C, L_1, R_1 and R_2 are respectively the input capacitor of the inverter, the inductance of the LCL filter on the three-phase inverter side, the capacity of the LCL filter, the inductance of the LCL filter on the three-phase grid side, and the equivalent series resistance of inductances R_1 and R_2.

$$S_i = \begin{cases} 1 \text{ if } s_i \text{ in on and } s'_i \text{ is off} \\ 0 \text{ if } s_i \text{ in on and } s'_i \text{ is off} \end{cases} \quad i = 1, 2, 3 \quad (10)$$

We will now apply the park transformation to (5_9) to simplify the representation and modeling of three phases. The grid voltage and current are linked to the d_q transformation, therefore $V_{rd} = V_r$ and $V_{rq} = 0$.

$$\frac{di_{1d}}{dt} = -\frac{R_1}{L_1}i_{1d} + \frac{1}{L_1}\mu_1.v_p + \omega i_{1q} - \frac{1}{L_1}v_{cd} \quad (11)$$

$$\frac{di_{1q}}{dt} = -\frac{R_1}{L_1}i_{1q} + \frac{1}{L_1}\mu_2.v_p - \omega i_{1d} - \frac{1}{L_1}v_{cq} \quad (12)$$

$$\frac{di_{2d}}{dt} = -\frac{R_2}{L_2}i_{2d} + \frac{1}{L_2}v_{cd} + \omega i_{2q} - \frac{1}{L_2}v_{rd} \quad (13)$$

$$\frac{di_{2q}}{dt} = -\frac{R_2}{L_2}i_{2q} + \frac{1}{L_2}v_{cq} - \omega i_{2d} - \frac{1}{L_2}v_{rq} \quad (14)$$

$$\frac{dv_{cd}}{dt} = \left(\begin{array}{l}\left(\frac{1}{C} - \frac{R_1R_c}{L_2}\right)\left(i_{1d} - i_{2d}\right) - R_c\left(\frac{1}{L_1} + \frac{1}{L_2}\right)v_{cd} \\ +\omega v_{cq} + \frac{R_c}{L_1}\mu_1 v_p + \frac{R_c}{L_2}v_{rd}\end{array}\right) \quad (15)$$

$$\frac{dv_{cq}}{dt} = \left(\begin{array}{l}\left(\frac{1}{C} - \frac{R_1R_c}{L_2}\right)\left(i_{1q} - i_{2q}\right) - R_c\left(\frac{1}{L_1} + \frac{1}{L_2}\right)v_{cq} \\ -\omega v_{cd} + \frac{R_c}{L_1}\mu_2 v_p + \frac{R_c}{L_2}v_{rq}\end{array}\right) \quad (16)$$

$$C_p\frac{dv_p}{dt} = I_p - i_0 \quad (17)$$

The goal now is to build a controller for the three-phase inverter using the following state equations and considering the following state variables: $\left(\bar{i}_{1d}; \bar{i}_{1q}; \bar{i}_{2d}; \bar{i}_{2q}; \bar{v}_{cd}; \bar{v}_{cq}; \bar{v}_p^2\right) = \left(x_{1d}; x_{1q}; x_{2d}; x_{2q}; x_{3d}; x_{3q}; x_p\right)$.

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Let us now change the expression of the current i_0 by the new expression $i_0 = \mu_1 x_{1d} + \mu_2 x_{1q}$; and multiply both sides of the equation (8) by the variable $2v_p$.

$$\dot{x}_{1d} = -\frac{R_1}{L_1} x_{1d} + \frac{1}{L_1}\mu_1.v_p + \omega x_{1q} - \frac{1}{L_1} x_{3d} \quad (18)$$

$$\dot{x}_{1q} = -\frac{R_1}{L_1} x_{1q} + \frac{1}{L_1}\mu_2.v_p - \omega x_{1d} - \frac{1}{L_1} x_{3q} \quad (19)$$

$$\dot{x}_{2d} = -\frac{R_2}{L_2} x_{2d} + \frac{1}{L_2} x_{3d} + \omega x_{2q} - \frac{1}{L_2} v_{rd} \quad (20)$$

$$\dot{x}_{2q} = -\frac{R_2}{L_2} x_{2q} + \frac{1}{L_2} x_{3q} - \omega x_{2d} - \frac{1}{L_2} v_{rq} \quad (21)$$

$$\dot{x}_{3d} = \begin{pmatrix} \left(\frac{1}{C} - \frac{R_1 R_c}{L_2}\right)(x_{1d} - x_{2d}) - R_c\left(\frac{1}{L_1} + \frac{1}{L_2}\right) x_{3d} \\ +\omega x_{3q} + \frac{R_c}{L_1}\mu_1 v_p + \frac{R_c}{L_2} v_{rd} \end{pmatrix} \quad (22)$$

$$\dot{x}_{3q} = \begin{pmatrix} \left(\frac{1}{C} - \frac{R_1 R_c}{L_2}\right)(x_{1q} - x_{2q}) - R_c\left(\frac{1}{L_1} + \frac{1}{L_2}\right) x_{3q} \\ -\omega x_{3d} + \frac{R_c}{L_1}\mu_2 v_p + \frac{R_c}{L_2} v_{rq} \end{pmatrix}$$

(23)

$$C_p \dot{x}_p = 2P - 2v_p\left(\mu_1 x_{1d} + \mu_2 x_{1q}\right)$$

(24)

Where the expression $P = v_p * i_p$.

III. THE DESIGN OF THE PROPOSED CONTROLLER

This segment aims at achieving two main goals: (i) MPPT achievement. (ii) UPF achievement.

A. Unity Power Factor and the DC voltage of the PV generator controller:

In this paragraph two loops were considered. In the first loop, the main objective is to realize the UPF which is based on the injection of a sinusoidal current and on the same frequency as that of the network. In the second loop, the goal is to achieve the MPP and regulate the voltage across the PV generator v_p at its reference voltage $v_{p,ref}$ generated by the algorithm (P&O). These two loops will be designed using the Integral backstepping technique [10-12].

B. UPF controller design:

The objective here is to design a nonlinear controller that forces the signal x_p to zero $\left(x_{2q}^* = 0\right)$ (UPF achieved). Let us considered the error ε_{1q}:

$$\varepsilon_{1q} = x_{2q} - x_{2q}^*$$

(29)

Using (21), the time derivative of ε_{1q} is given by:

$$\dot{\varepsilon}_{1q} = -\frac{R_2}{L_2} x_{2q} + \frac{1}{L_2} x_{3q} - \omega x_{2d} - \frac{1}{L_2} v_{rq} - \dot{x}_{2q}^*$$

(30)

Let us define the Lyapunov candidate function:

$$V_{1q} = 0.5*\left(\gamma_{1q}\xi_{1q}^2 + \varepsilon_{1q}^2\right)$$

(31)

Using (30), the time derivation of (31) is given by:

$$\dot{V}_{1q} = \varepsilon_{1q}\begin{pmatrix} \gamma_{1q}\xi_{1q} - \frac{R_2}{L_2} x_{2q} + \frac{1}{L_2} x_{3q} - \omega x_{2d} \\ -\frac{1}{L_2} v_{rq} - \dot{x}_{2q}^* \end{pmatrix} \quad (32)$$

Consider the following equation:

$$\begin{pmatrix} \gamma_{1q}\xi_{1q} - \frac{R_2}{L_2} x_{2q} + \frac{1}{L_2} x_{3q} - \omega x_{2d} \\ -\frac{1}{L_2} v_{rq} - \dot{x}_{2q}^* \end{pmatrix} = -K_{1q}\varepsilon_{1q}$$

(33)

Therefore, we will have:

$$\dot{V}_{1q} = -K_{1q}\varepsilon_{1q}^2$$

(34)

While $\gamma_{1q} \succ 0$ and $K_{1q} \succ 0$. ξ_{1q} is given by (35).

$$\xi_{1q} = \int_0^t \varepsilon_{1q}(\tau)d\tau$$

(35)

Thus, the x_{3q}^* stabilization function is given by:

$$x_{3q}^* = \begin{pmatrix} -L_2 K_{1q}\varepsilon_{1q} - L_2\gamma_{1q}\xi_{1q} + R_2 x_{2q} + L_2\omega x_{2d} \\ +v_{rq} + L_2\dot{x}_{2q}^* \end{pmatrix} \quad (36)$$

Consider the new tracking error ε_{2q} defined by:

$$\varepsilon_{2q} = x_{3q} - x_{3q}^*$$

(37)

Using the expressions (36) and (37), the expressions (30) and (32) will have a new definition as follows:

$$\dot{\varepsilon}_{1q} = \frac{\varepsilon_{2q}}{L_2} - K_{1q}\varepsilon_{1q} - \gamma_{1q}\xi_{1q}$$

(38)

$$\dot{V}_{1q} = -K_{1q}\varepsilon_{1q}^2 + \frac{\varepsilon_{1q}\varepsilon_{2q}}{L_2}$$

(39)

Using (23), the time derivation of ε_{2q} is given by:

$$\dot{\varepsilon}_{2q} = \begin{pmatrix} \left(\frac{1}{C} - \frac{R_1 R_c}{L_2}\right)(x_{1q} - x_{2q}) - R_c\left(\frac{1}{L_1} + \frac{1}{L_2}\right) x_{3q} \\ -\omega x_{3d} + \frac{R_c}{L_1}\mu_2 v_p + \frac{R_c}{L_2} v_{rq} - \dot{x}_{3q}^* \end{pmatrix}$$

(40)

Let us define the new tracking error ε_{3q}:

$$\varepsilon_{3q} = x_{1q} - x_{1q}^*$$

(41)

Therefore, the new expression of (40) is given by:

$$\dot{\varepsilon}_{2q}=\begin{pmatrix}\left(\frac{1}{C}-\frac{R_1R_c}{L_2}\right)\left(\varepsilon_{3q}+x_{1q}^*-x_{2q}\right)-\omega x_{3d}\\ +\frac{R_c}{L_1}\mu_2 v_p+\frac{R_c}{L_2}v_{rq}-\dot{x}_{3q}^*-R_c\left(\frac{1}{L_1}+\frac{1}{L_2}\right)x_{3q}\end{pmatrix}$$
(42)

Consider the new Lyapunov function defined by:

$$V_{2q}=V_{1q}+\frac{1}{2}\varepsilon_{2q}^2$$
(43)

Using (42), the time derivation of (43) is given by:

$$\dot{V}_{2q}=-K_{1q}\varepsilon_{1q}^2+\varepsilon_{2q}\begin{pmatrix}\left(\frac{1}{C}-\frac{R_1R_c}{L_2}\right)\left(\varepsilon_{3q}+x_{1q}^*-x_{2q}\right)\\ -\omega x_{3d}+\frac{R_c}{L_1}\mu_2 v_p+\frac{R_c}{L_2}v_{rq}\\ -\dot{x}_{3q}^*-R_c\left(\frac{1}{L_1}+\frac{1}{L_2}\right)x_{3q}+\frac{\varepsilon_{1q}}{L_2}\end{pmatrix}$$
(44)

The equilibrium (ε_{1q} , ε_{2q}) = (0 , 0) is globally asymptotically stable if:

$$\begin{pmatrix}\frac{\varepsilon_{1q}}{L_2}+\left(\frac{1}{C}-\frac{R_1R_c}{L_2}\right)\left(\varepsilon_{3q}+x_{1q}^*-x_{2q}\right)\\ -\omega x_{3d}+\frac{R_c}{L_1}\mu_2 v_p+\frac{R_c}{L_2}v_{rq}\\ -R_c\left(\frac{1}{L_1}+\frac{1}{L_2}\right)x_{3q}-\dot{x}_{3q}^*\end{pmatrix}=-K_{2q}\varepsilon_{2q}$$
(45)

With $K_{2q}\succ 0$. If $\varepsilon_{3q}=0$, the x_{1q}^* stabilization function will have the following new expression:

$$x_{1q}^*=\left(\frac{CL_2}{L_2-C\left(R_1R_c\right)}\right)\begin{pmatrix}-K_{2q}\varepsilon_{2q}-\frac{R_c}{L_1}\mu_2 v_p\\ +R_c\left(\frac{1}{L_1}+\frac{1}{L_2}\right)x_{3q}\\ +\dot{x}_{3q}^*-\frac{\varepsilon_{1q}}{L_2}+\omega x_{3d}\\ -\frac{R_c}{L_2}v_{rq}\end{pmatrix}+x_{2q} \qquad (46)$$

By combining (42) and (46), the new expression of (42) and (44) is given by:

$$\dot{\varepsilon}_{2q}=-K_{2q}\varepsilon_{2q}-\frac{\varepsilon_{1q}}{L_2}+\left(\frac{1}{C}-\frac{R_1R_c}{L_1}\right)\varepsilon_{3q} \qquad (47)$$

$$\dot{V}_{2q}=-K_{1q}\varepsilon_{1q}^2-K_{2q}\varepsilon_{2q}^2+\left(\frac{1}{C}-\frac{R_1R_c}{L_1}\right)\varepsilon_{2q}\varepsilon_{3q} \qquad (48)$$

By combining (19) and (41), the new expression of $\dot{\varepsilon}_{3q}$ is given by:

$$\dot{\varepsilon}_{3q}=-\frac{R_1}{L_1}x_{1q}+\frac{1}{L_1}\mu_2.v_p-\omega x_{1d}-\frac{1}{L_1}x_{3q}-\dot{x}_{1q}^*$$
(49)

Let's bring Lyapunov function:

$$V_{3q}=V_{2q}+\frac{1}{2}\varepsilon_{3q}^2$$
(50)

By combining (48) and (49), the new expression of (50) is given by:

$$\dot{V}_{3q}=-K_{1q}\varepsilon_{1q}^2-K_{2q}\varepsilon_{2q}^2+\varepsilon_{3q}\begin{pmatrix}\left(\frac{1}{C}-\frac{R_1R_c}{L_1}\right)\varepsilon_{2q}\\ -\frac{R_1x_{1q}}{L_1}-\frac{x_{3q}}{L_1}\\ -\omega x_{1d}-\dot{x}_{1q}^*+\frac{\mu_2.v_p}{L_1}\end{pmatrix} \qquad (51)$$

Therefore, the signal μ_2 is given by:

$$\mu_2=\frac{L_1}{v_p}\begin{pmatrix}-K_{3q}\varepsilon_{3q}-\left(\frac{1}{C}-\frac{R_1R_c}{L_1}\right)\varepsilon_{2q}+\frac{x_{3q}}{L_1}\\ +\frac{R_1}{L_1}x_{1q}+\omega x_{1d}+\dot{x}_{1q}^*\end{pmatrix} \qquad (52)$$

With $K_{3q}\succ 0$. Thus:

$$\dot{V}_{3q}=-K_{1q}\varepsilon_{1q}^2-K_{2q}\varepsilon_{2q}^2-K_{3q}\varepsilon_{3q}^2$$
(53)

Thus, the objective UPF is achieved with $THD\prec 5\%$.

C. The DC-link voltage of the PV GENERATOR controller design:

We proposed in this section the signal μ_1 to push the voltage v_p to follow the reference $v_{p,ref}$. This technique of regulation must achieve two goals at the same time: (i) Creating an internal loop so that the current x_{2d} follows its reference current x_{2d}^* correctly. (ii) Using an external loop, the reference signal x_{2d}^* is designed to set the voltage v_p to follow its reference $v_{p,ref}$.

- The realization of the inner loop of the current x_{2d}:

The tracking error ε_{1d} is given by:

$$\varepsilon_{1d}=x_{2d}-x_{2d}^*$$
(54)

Using (20), the time derivative of ε_{1d} is given by:

$$\dot{\varepsilon}_{1d}=-\frac{R_2}{L_2}x_{2d}+\frac{1}{L_2}x_{3d}+\omega x_{2q}-\frac{1}{L_2}v_{rd}-\dot{x}_{2d}^* \qquad (55)$$

Let's bring Lyapunov function:

$$V_{1d}=0.5*\left(\gamma_{1d}\xi_{1d}^2+\varepsilon_{1d}^2\right) \qquad (56)$$

Using (55), the time derivation of (56) is given by:

$$\dot{V}_{1d}=\varepsilon_{1d}\begin{pmatrix}\gamma_{1d}\xi_{1d}-\frac{R_2}{L_2}x_{2d}+\frac{1}{L_2}x_{3d}+\omega x_{2q}\\ -\frac{1}{L_2}v_{rd}-\dot{x}_{2d}^*\end{pmatrix}$$
(57)

Consider the following equation:

$$\begin{pmatrix} \gamma_{1d}\xi_{1d} - \frac{R_2}{L_2}x_{2d} + \frac{1}{L_2}x_{3d} + \omega x_{2q} \\ -\frac{1}{L_2}v_{rd} - \dot{x}_{2d}^{*} \end{pmatrix} = -K_{1d}\varepsilon_{1d} \tag{58}$$

Therefore, we will have:

$$\dot{V}_{1d} = -K_{1d}\varepsilon_{1d}^{2}$$

(59)

While $\gamma_{1d} \succ 0$ and $K_{1d} \succ 0$. ξ_{1d} is is given by (60).

$$\xi_{1d} = \int_0^t \varepsilon_{1d}(\tau)d\tau \tag{60}$$

Consider the new expression of x_{3d}^{*} :

$$x_{3d}^{*} = \begin{pmatrix} -L_2K_{1d}\varepsilon_{1d} - L_2\gamma_{1d}\xi_{1d} + R_2x_{2d} - L_2\omega x_{2q} \\ +v_{rd} + L_2\dot{x}_{2d}^{*} \end{pmatrix} \tag{61}$$

The new expression of ε_{2d} is given by:

$$\varepsilon_{2d} = x_{3d} - x_{3d}^{*} \tag{62}$$

Using the expressions (61) and (62), the expressions (55) and (57) will have a new definition as follows:

$$\dot{\varepsilon}_{1d} = \frac{\varepsilon_{2d}}{L_2} - K_{1d}\varepsilon_{1d} - \gamma_{1d}\xi_{1d}$$

(63)

$$\dot{V}_{1d} = -K_{1d}\varepsilon_{1d}^{2} + \frac{\varepsilon_{1d}\varepsilon_{2d}}{L_2}$$

(64)

Using (22), the time derivation of ε_{2d} is given by:

$$\dot{\varepsilon}_{2d} = \begin{pmatrix} \left(\frac{1}{C} - \frac{R_1R_c}{L_2}\right)(x_{1d} - x_{2d}) - R_c\left(\frac{1}{L_1} + \frac{1}{L_2}\right)x_{3d} \\ +\omega x_{3q} + \frac{R_c}{L_1}\mu_1 v_p + \frac{R_c}{L_2}v_{rd} - \dot{x}_{3d}^{*} \end{pmatrix} \tag{65}$$

Let us define the new tracking error ε_{3d} :

$$\varepsilon_{3d} = x_{1d} - x_{1d}^{*} \tag{66}$$

Therefore, the new expression of (65) is given by:

$$\dot{\varepsilon}_{2d} = \begin{pmatrix} \left(\frac{1}{C} - \frac{R_1R_c}{L_2}\right)\left(\varepsilon_{3d} + x_{1d}^{*} - x_{2d}\right) + \frac{R_c}{L_2}v_{rd} - \dot{x}_{3d}^{*} \\ -R_c\left(\frac{1}{L_1} + \frac{1}{L_2}\right)x_{3d} + \omega x_{3q} + \frac{R_c}{L_1}\mu_1 v_p \end{pmatrix}$$

(67)

Consider the new Lyapunov function defined by:

$$V_{2d} = V_{1d} + \frac{1}{2}\varepsilon_{2d}^{2}$$

(68)

Using (67), the time derivation of (68) is given by:

$$\dot{V}_{2d} = -K_{1d}\varepsilon_{1d}^{2} + \varepsilon_{2d}\begin{pmatrix} \left(\frac{1}{C} - \frac{R_1R_c}{L_2}\right)\left(\varepsilon_{3d} + x_{1d}^{*} - x_{2d}\right) \\ +\frac{R_c}{L_2}v_{rd} - \dot{x}_{3d}^{*} + \frac{\varepsilon_{1d}}{L_2} + \omega x_{3q} \\ -R_c\left(\frac{1}{L_1} + \frac{1}{L_2}\right)x_{3d} + \frac{R_c}{L_1}\mu_1 v_p \end{pmatrix} \tag{69}$$

In this expression, the equilibrium $\left(\varepsilon_{1d};\varepsilon_{2d}\right) = (0;0)$ is proved to be globally asymptotically stable if:

$$-K_{2d}\varepsilon_{2d} = \begin{pmatrix} \left(\frac{1}{C} - \frac{R_1R_c}{L_2}\right)\left(\varepsilon_{3d} + x_{1d}^{*} - x_{2d}\right) \\ +\frac{R_c}{L_1}\mu_1 v_p - R_c\left(\frac{1}{L_1} + \frac{1}{L_2}\right)x_{3d} \\ +\frac{R_c}{L_2}v_{rd} - \dot{x}_{3d}^{*} + \frac{\varepsilon_{1d}}{L_2} + \omega x_{3q} \end{pmatrix} \tag{70}$$

With $K_{2d} \succ 0$ .In the case where $\varepsilon_{3d} = 0$, the stabilization function x_{1d}^{*} will have a new expression as follows:

$$x_{1d}^{*} = \left(\frac{CL_2}{L_2 - CR_1R_c}\begin{pmatrix} -K_{2d}\varepsilon_{2d} - \frac{R_c}{L_1}\mu_1 v_p \\ +R_c\left(\frac{1}{L_1} + \frac{1}{L_2}\right)x_{3d} + \dot{x}_{3d}^{*} \\ -\frac{R_c}{L_2}v_{rd} - \frac{\varepsilon_{1d}}{L_2} - \omega x_{3q} \end{pmatrix} + x_{2d} \right) \tag{71}$$

By combining (67) and (71), the new expression of $\dot{\varepsilon}_{2d}$ *and* $\dot{V}_{2d}$ is given by:

$$\dot{\varepsilon}_{2d} = -K_{2d}\varepsilon_{2d} - \frac{\varepsilon_{1d}}{L_2} + \left(\frac{1}{C} - \frac{R_1R_c}{L_2}\right)\varepsilon_{3d} \tag{72}$$

$$\dot{V}_{2d} = -K_{1d}\varepsilon_{1d}^{2} - K_{2d}\varepsilon_{2d}^{2} + \left(\frac{1}{C} - \frac{R_1R_c}{L_1}\right)\varepsilon_{2d}\varepsilon_{3d} \tag{73}$$

By combining (18) and (66), the new expression of $\dot{\varepsilon}_{3d}$ is given by:

$$\dot{\varepsilon}_{3d} = -\frac{R_1}{L_1}x_{1d} + \frac{1}{L_1}\mu_1.v_p + \omega x_{1q} - \frac{1}{L_1}x_{3d} - \dot{x}_{1d}^{*} \tag{74}$$

Let's bring in Lyapunov function:

$$V_{3d} = V_{2d} + \frac{1}{2}\varepsilon_{3d}^{2} \tag{75}$$

By combining (73) and (74), the new expression of (75) is given by:

$$\dot{V}_{3d} = -K_{1d}\varepsilon_{1d}^{2} - K_{2d}\varepsilon_{2d}^{2} + \varepsilon_{3d}\begin{pmatrix} \left(\frac{1}{C} - \frac{R_1R_c}{L_1}\right)\varepsilon_{2d} \\ -\frac{R_1x_{1d}}{L_1} - \frac{x_{3d}}{L_1} \\ +\frac{\mu_1.v_p}{L_1} + \omega x_{1q} - \dot{x}_{1d}^{*} \end{pmatrix} \tag{76}$$

Thus, the signal μ_1 is given by:

$$\mu_1 = \frac{L_1}{v_p}\begin{pmatrix} -K_{3d}\varepsilon_{3d} - \left(\frac{1}{C} - \frac{R_1R_c}{L_1}\right)\varepsilon_{2d} + \frac{x_{3d}}{L_1} \\ +\frac{R_1}{L_1}x_{1d} - \omega x_{1q} + \dot{x}_{1d}^{*} \end{pmatrix} \tag{77}$$

With $K_{1d} \succ 0$.

$$\dot{V}_{3d} = -K_{1d}\varepsilon_{1d}^{2} - K_{2d}\varepsilon_{2d}^{2} - K_{3d}\varepsilon_{3d}^{2}$$

(78)

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Thus, the signal x_{2d} follows the reference $x_{2d,ref}$.

- The external loop of the PV generator voltage v_p :

Using (52) and (77), equation (24) becomes:

$$C_p \dot{x}_p = \begin{pmatrix} 2L_1 x_{1d} K_{3d} \varepsilon_{3d} + 2L_1 x_{1d} \left(\frac{1}{C} - \frac{R_1 R_c}{L_1} \right) \varepsilon_{2d} \\ -2x_{1d} x_{3d} - 2R_1 x_{1d}^2 - 2L_1 x_{1d} \dot{x}_{1d}^* \\ +2L_1 x_{1q} K_{3q} \varepsilon_{3q} + 2L_1 x_{1q} \left(\frac{1}{C} - \frac{R_1 R_c}{L_1} \right) \varepsilon_{2q} \\ -2x_{1q} x_{3q} - 2R_1 x_{1q}^2 - 2L_1 x_{1q} \dot{x}_{1q}^* + 2P \end{pmatrix} \quad (79)$$

The reference signal of the PV generator $v_{p,ref}$ is given by :

$$x_{p,ref} = \overline{v}_{p,ref}^2$$

(80)

Then, we define the tracking error ε_p by :

$$\varepsilon_p = C_p (x_p - x_{p,ref})$$

(81)

Using (79), the time derivative of ε_p is given by:

$$\dot{\varepsilon}_p = \begin{pmatrix} \begin{pmatrix} 2L_1 x_{1d} K_{3d} \varepsilon_{3d} + 2L_1 x_{1d} \left(\frac{1}{C} - \frac{R_1 R_c}{L_1} \right) \varepsilon_{2d} \\ -2x_{1d} x_{3d} - 2R_1 x_{1d}^2 - 2L_1 x_{1d} \dot{x}_{1d}^* \\ +2L_1 x_{1q} K_{3q} \varepsilon_{3q} + 2L_1 x_{1q} \left(\frac{1}{C} - \frac{R_1 R_c}{L_1} \right) \varepsilon_{2q} \\ -2x_{1q} x_{3q} - 2R_1 x_{1q}^2 - 2L_1 x_{1q} \dot{x}_{1q}^* + 2P \end{pmatrix} \\ -C_p \dot{x}_{p,ref} \end{pmatrix} \quad (82)$$

Let's bring in Lyapunov function:

$$V_p = 0.5 * \left(\gamma_p \xi_p^2 + \varepsilon_p^2 \right)$$

(83)

Using (82), the time derivation of (83) is given by:

$$\dot{V}_p = \varepsilon_p \begin{pmatrix} \begin{pmatrix} 2L_1 x_{1d} K_{3d} \varepsilon_{3d} + 2L_1 x_{1d} \left(\frac{1}{C} - \frac{R_1 R_c}{L_1} \right) \varepsilon_{2d} \\ -2x_{1d} x_{3d} - 2R_1 x_{1d}^2 - 2L_1 x_{1d} \dot{x}_{1d}^* \\ +2L_1 x_{1q} K_{3q} \varepsilon_{3q} + 2L_1 x_{1q} \left(\frac{1}{C} - \frac{R_1 R_c}{L_1} \right) \varepsilon_{2q} \\ -2x_{1q} x_{3q} - 2R_1 x_{1q}^2 - 2L_1 x_{1q} \dot{x}_{1q}^* + 2P \end{pmatrix} \\ -C_p \dot{x}_{p,ref} + \gamma_p \xi_p \end{pmatrix} \quad (84)$$

Let's make the following change:

$$K_p \varepsilon_p = \begin{pmatrix} \begin{pmatrix} -2L_1 x_{1d} K_{3d} \varepsilon_{3d} - 2L_1 x_{1d} \left(\frac{1}{C} - \frac{R_1 R_c}{L_1} \right) \varepsilon_{2d} \\ +2x_{1d} x_{3d} + 2R_1 x_{1d}^2 + 2L_1 x_{1d} \dot{x}_{1d}^* \\ -2L_1 x_{1q} K_{3q} \varepsilon_{3q} - 2L_1 x_{1q} \left(\frac{1}{C} - \frac{R_1 R_c}{L_1} \right) \varepsilon_{2q} \\ +2x_{1q} x_{3q} + 2R_1 x_{1q}^2 + 2L_1 x_{1q} \dot{x}_{1q}^* - 2P \end{pmatrix} \\ +C_p \dot{x}_{p,ref} - \gamma_p \xi_p \end{pmatrix} \quad (85)$$

Therefore, we will have:

$$\dot{V}_p = -K_p \varepsilon_p^2$$

(86)

While $\gamma_p \succ 0$ and $K_p \succ 0$. ξ_p is given by

$$\xi_p = \int_0^t \varepsilon_p(\tau) d\tau$$

(87)

Thus, the voltage v_p follows the reference $v_{p,ref}$.

The variable X is defined by:

$$X = \begin{pmatrix} K_p \varepsilon_p + 2P + 2L_1 x_{1d} K_{3d} \varepsilon_{3d} - 2x_{1d} x_{3d} \\ -2L_1 x_{1d} \dot{x}_{1d}^* + 2L_1 x_{1q} K_{3q} \varepsilon_{3q} - 2R_1 x_{1d}^2 \\ +2L_1 x_{1q} \left(\frac{1}{C} - \frac{R_1 R_c}{L_1} \right) \varepsilon_{2q} - 2x_{1q} x_{3q} - 2R_1 x_{1q}^2 \\ -2L_1 x_{1q} \dot{x}_{1q}^* + \gamma_p \xi_p - C_p \dot{x}_{p,ref} \end{pmatrix} \quad (88)$$

Using a combination of the above equation (88) with equations (54), (63) and (85), the expression of the $x_{2d,ref}$ is given by using the backstepping control regulator:

$$\dot{x}_{2d}^* = \begin{pmatrix} \dfrac{X}{2L_1 L_2 x_{1d} \left(\frac{1}{C} - \frac{R_1 R_c}{L_1} \right)} \\ -K_{1d} x_{2d}^* + \dot{x}_{2d} + K_{1d} x_{2d} + \gamma_{1d} \xi_{1d} \end{pmatrix}$$

(89)

IV. SIMULATION AND RESULTS

In this part, we will test and examine the performance and the efficiency of the non-linear controller designed in Section 3 by numerical simulations. We modeled the PV system studied by a system of nonlinear equations [18-24].

Table- I: Table Styles

Parameters	Name	Value
R_s	Series resistance	0.002Ω
R_p	Parallel resistance	1000Ω
N_s	Number series PV	20
N_p	Number Parallel PV	5
η	Ideality factor	1.7
I_{scr}	Short circuit current at T_r	8.3758A
I_{rr}	Cell saturation current at T_r	5.3μA
T_r	Reference temperature	298.15K

Table- II: DC_AC Inverter, LCL Filter and Grid Parameters

Parameters	Name	Value
C_f	Capacitance of LCL filtre	3μF
R_{sd}	damping resistor of the capacitance of LCL filter	7.5 Ω
$V_{p,ref}$	DC link voltage reference	500V
L_f	inverter side inductance	2.4mH
L_g	grid side inductance	4mH
R_f, R_g	equivalent series resistance of inductances L_f and L_g	0.005Ω
C_p	DC-link capacitor	3000μF
f	grid frequency	60Hz
v_{abc}	the utility grid's amplitude	230
P_n	Inverter power	1000W
f_{sw}	Switching frequency	10KHz

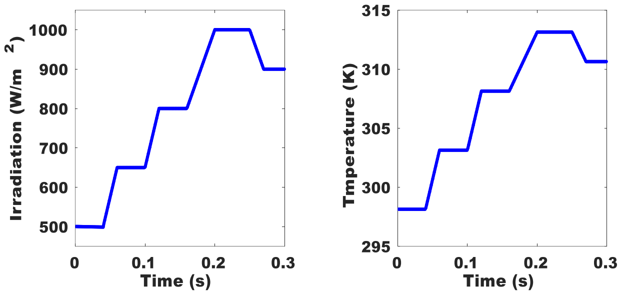

Fig. 6.Change of solar irradiation and Temperature

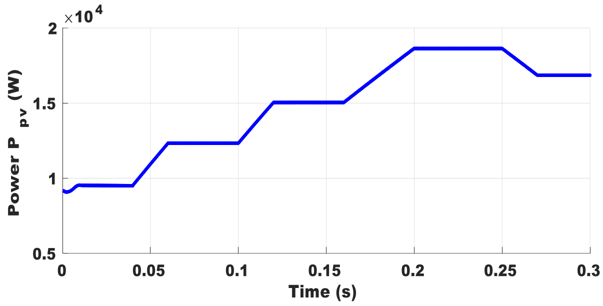

Fig. 7.Output power p_p of PV generator

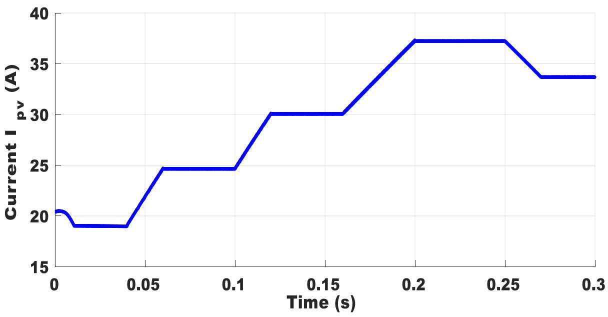

Fig. 8.Output current i_p of PV generator

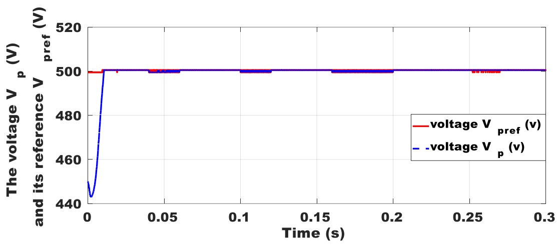

Fig. 9.Output current v_p of PV generator

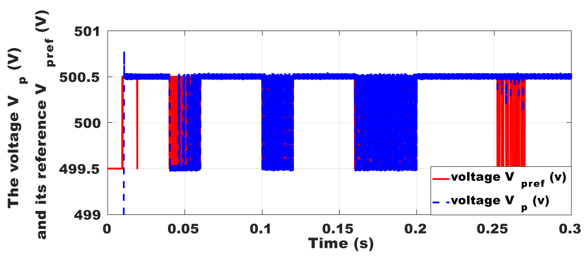

Fig. 10. Output voltage v_p of PV generator

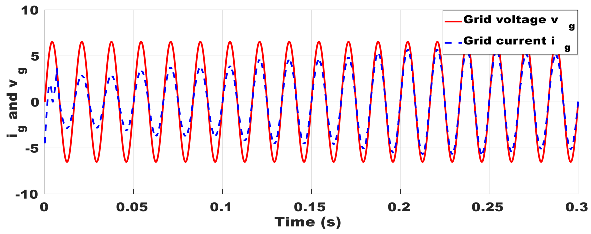

Fig. 11. Current i_g and voltage v_g

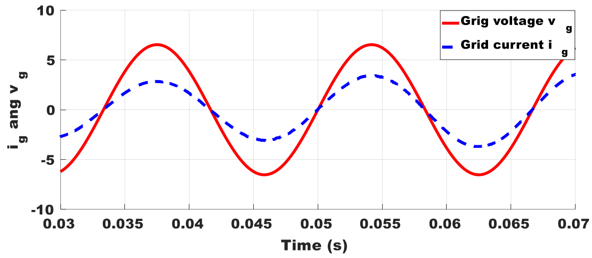

Fig. 12. Current i_g and voltage v_g

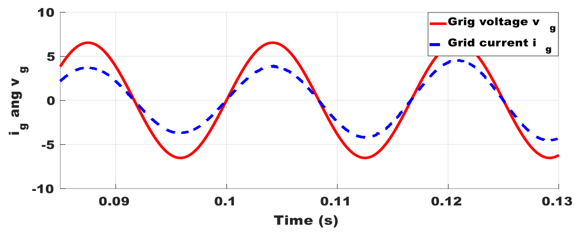

Fig. 13. Current i_g and voltage v_g

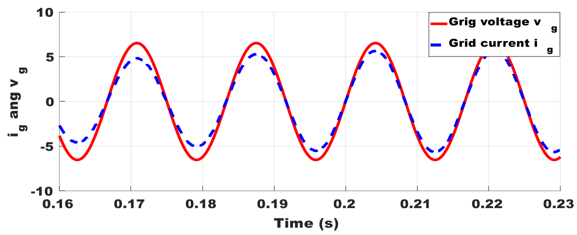

Fig. 14. Current i_g and voltage v_g

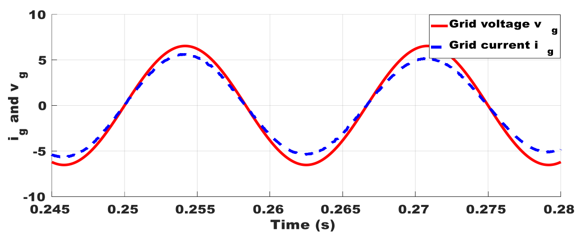

Fig. 15. Current i_g and voltage v_g

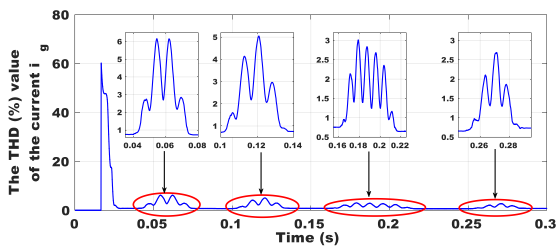

Fig. 16. THD of current i_g

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Figure 6 indicates the solar radiation and temperature fluctuations. Figure 7 shows the power P_p generated from the PV generator, it is apparent that this power is always at its maximum regardless of the weather. It means that the PV generator's maximum power extraction target has been achieved. As shown in figure 8, the PV generator's current i_p varies depending on solar radiation. The DC-link voltage v_p is constant, as shown in figure 9, and follows its reference $v_{p,ref}$, regardless of the environmental conditions. The current i_g injected into the grid electrical, is illustrated in figures 10, 11, 12, 13, 14 and 15. The injected current i_g and grid voltage v_g frequencies are found to be equal. Regardless of weather conditions, the injected current i_g remains sinusoidal and in phase with grid voltage v_g (UPF achieved). Indeed, figure 16 shows that the THD of the current i_g is less than 5% (0,7%)

V. CONCLUSION

In this paper, we proposed a nonlinear advanced controller for optimizing, increasing and improving the efficiency of a public grid-connected PV network. The main benefit of the system being studied is the absence of the DC_DC converter. Under the Matlab-Simulink, the simulation showed that the desired goals were achieved in this article. Also, the controller allowed the maximum power to be extracted and injected into the grid. Whatever the weather conditions, the total harmonic distortion rate of the current injected into the grid is minimal (THD < 5 percent). Nevertheless, the nonlinear controller suggested in this article has the following advantages: fast response, accurate tracking, and robustness. This controller is proven to have a minimal harmonic ratio, high efficiency, and asymptotic stability overall.

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AUTHORS PROFILE

Noureddine Skik, received the M.S. degree in industrial electronics from the Faculty of Sciences-Fez, in 2014. He is currently pursuing his Ph.D. in Electrical Engineering department at Mohammed V University, Mohammadia School of Engineers, Rabat, Morocco. His research interests include static converters, power electronics, power systems, Smart Grid, Renewable Energy and Artificial Intelligence.

Ahmed ABBOU, He received the B.E. degree from ENSET in Rabat, the M.E. degree from Mohammed V University in Rabat and the Ph.D. degree from Mohammed V University in Rabat, in 2000, 2005 and 2009, respectively, all in electrical engineering. Since 2009, he has been working at Mohammadia School of engineers, Mohammed V University in Rabat, Department of electric Power Engineering, where he is a Professor of Power Electronics and Electric drives.

He published numerous papers in scientific international journals and conferences proceedings. His current research interests include induction machine control systems, self-excited induction generator, power electronics, sensorless drives for AC machines and renewable energy (PV and wind energy).

Rafika El idrissi, was born in Sidi Bennour, Morocco, in 1990. She received the B.S. degree in Electronics and Industrial Computing and M.S. degree in Information processing from Hassan II University, Casablanca, Morocco, in 2012 and 2014, respectively. She is currently pursuing her PH.D. in Electrical Engineering department at Mohammadia School of Engineers, Mohamed V University, Rabat, Morocco. Her research interests include nonlinear control theories, Power Systems, and photovoltaic systems.