Nonlinear Control Design for Maximum Power Point Tracking and Unity Power Factor of a Grid-Connected Photovoltaic Renewable EnergySystems

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***Abstract:** This paper deals with the design of a nonlinear controller for single-phase grid-connected photovoltaic (PV) renewable energy systems to maintain the current injected into the grid in phase with grid voltage and to regulate the DC link voltage and to extract maximum power point tracking (MPPT).The system configurationincludes a photovoltaic generator, DC-DCconverter, DC-AC inverter coupled to grid network. The controller is designed using thebackstepping control to optimize the PV energy extraction and to achieve unity power factor, the controller is based on an averaged nonlinear state space model of the controlled system. This is carried out via controlling the duty ratio of the DC-DC converter and DC-AC inverter. An integral action was added in order to robustify the controller with respect to parameter variations and disturbances.The synthesis of the regulator wasachieved by having recourse to advanced tools of nonlinearcontrol such as asymptotic stability in the sense of Lyapunov. The performance of the proposed controller is evaluated through numerical simulation in terms of delivering maximum power and synchronization of grid current with grid voltage under changes in atmospheric conditions.*

***Keywords:** Grid-connected photovoltaic systems, Maximum power point tracking (MPPT), Unity power factor, Backstepping controller, Asymptotic stability.*

I.   Introduction

Solarenergyhasnonoiseandnopollutionandissustainablewith a series of advantages. It has become one of the mostpotentialgreenenergiesfordevelopment.Photovoltaicrenewableenergy sources has been initiallyused in stand-alone applications, nevertheless, PV systems thatsupply energy directly to the utility grid are becoming more popular because ofthe cost reduction due to the lack of a battery subsystem.Moreover, governmental laws and policies recently created thatfavors grid-connected PV systems have proved to be aneffective way to encourage the use of solarenergy. Photovoltaic grid-connected system needs to use the grid-connectedinverter as power conversion device of the DCoutput of the PV array into AC power.

Grid-connected PV systems still have many technicalproblems to be solved. Firstly, since the output power ofthe solar cell is easily influenced by environmental factorswith obvious nonlinear factor, the photovoltaic cell is a veryunstable power supply, so designing an efficient and reliablemaximum power tracking control strategyis required to match the PV panelpower to the irradiation and temperature changes.Many algorithms have been developed for trackingmaximum point of a PV panel such as Perturb and Observation [1], and Incremental Conductance [2], neural network [3], fuzzy logic control [4] and slidingmode controller [5], [6], [7], [8]. Secondly, since the inverter is running excessive harmoniccurrents injected into the grid, the power system harmonicpollution problem is getting worse. Grid system becomesabnormal and false, and another equipment is also adverselyaffected, so various control strategy is proposed to solve this problem; power controlled [9], current controlled grid connected PV system [10] andhysteresis current control [11].

In this paper, a backsteppingcontrol strategy isdeveloped to track the maximum power of the PV array and to synchronize the grid current with the grid voltage by ensuring the tight regulationof the DC-bus voltageand further reduce the harmonic content of the network current.The concept is to calculate an appropriate controllaw to guarantee the global asymptotic stability of the closedloop system. Thecontrol inputs of the grid-connected PV system are the duty cycles of the DC-DC converter and DC-AC inverter.Thecontrol input of the DC-DC converter achieves the maximum power pointtracking, according to atmospheric condition changes.The control input of the DC-AC inverter achieves the unity power factor with regulationof the DC-link voltage and assure that the output currentpresents both low harmonic distortion and robustnessin front of system's perturbations.

II. Grid-Connected PV System Modelling

The configuration of single-phase grid-connected photovoltaic system is shown in Fig.1. It consists of PV array connected to the DC bus via a DC-DC boost converter, and then to the AC grid via a DC-AC inverter. The boost converter is used for boosting the array voltage and achieving maximum power point tracking for the PV array. The inverter with filter inductor converts a DC input voltage into an AC sinusoidal, by means of appropriate switch signals to make the output current in phase with the utility voltage and so obtain a power factor unity.
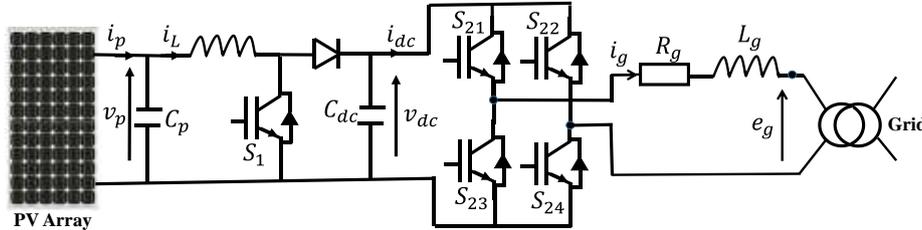
Fig. 1. Single-phase grid connected PV system.

2.1. Photovoltaic Array Modelling

Typically, aPVcell isasimple p-n junctiondiode, which converts solar irradiation intoelectricity. Fig. 2 illustrates a simple equivalent circuit diagram of a PV cell.ThismodelconsistsofacurrentsourceI_{ph} whichrepresentsthelight generated currentfromPVcell,a diode in parallel with the current source, a shunt resistanceR_{sh}, and a series resistanceR_s.
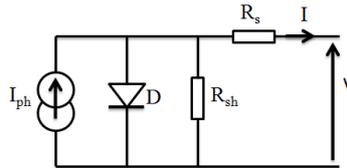
Fig. 2. Equivalent circuit of a PV cell.

The terminal equation for the PV current i_p and PV voltage v_p of the solar cell is given as follows:

$$i_p = I_{ph} - I_s \left[\exp\left(\frac{v_p + R_s i_p}{\gamma V_T} \right) - 1 \right] - \frac{v_p + R_s i_p}{R_{sh}} \qquad (1)$$

where I_s is the saturation current, $V_T = K_B T/q$ is the thermal voltage, K_B is the Boltzmann's constant, q is the charge of electron, T is the cell's absolute working temperature, γ is the p-n junction ideality factors. The light generated current I_{ph} depends on the solar irradiation and temperature, which can be related by the following equation:

$$I_{ph} = [I_{scr} + K_i(T - T_r)] \frac{G}{1000} \qquad (2)$$

where, I_{scr} is the short circuit current, G is the solar irradiation, K_i is the cell's short circuit current coefficient and $T_r = 298.15K$ is the reference temperature of the cell.The cell's saturation current I_s varies with the temperature according to the following equation:

$$I_s = I_{rr} \left[\frac{T}{T_r} \right]^3 \left[\exp \frac{q E_G}{\gamma K_B} \left(\frac{1}{T_r} - \frac{1}{T} \right) \right] \qquad (3)$$

where, E_G is the band-gap energy of the semiconductor used in the cell and I_{rr} is the reverse saturation current of the cell at reference temperature and solar irradiation.

PV cells, usually considered to have the same characteristics, are arranged together in series and parallel to form arrays inordertoobtainahighervoltage andcurrent. The mathematical equation relating the PV array current to the PV array voltage becomes:

$$i_p = N_p I_{ph} - N_p I_s \left[\exp \frac{1}{\gamma V_T} \left(\frac{v_p}{N_s} + \frac{R_s i_p}{N_p} \right) - 1 \right] - \frac{N_p}{R_{sh}} \left(\frac{v_p}{N_s} + \frac{R_s i_p}{N_p} \right) \qquad (4)$$

whereN_s is the number of cells in series and N_p is the number of modules in parallel.

The PV array considered in this paper is the Siemens SM55. The corresponding electrical characteristics are listed in Table 1.

Nominal voltage	12V
Maximum power	55W
Current at the maximum power point	3.15A
Voltage at the maximum power point	17.4V

Maximum current (short circuit output)	3.45A
Maximum voltage (open circuit)	21.7V
Current temperature coefficient	+1.2mA/°C
Number of series cells N_s	36
Number of parallel modules N_p	1

Table 1: Parameter values of the PV array Siemens SM55.

Figs. 3 and 4 show the constitutive curves of the PV array for different values of temperature and solar incident irradiance. Two important electricalcharacteristics of the PV array are observed in those figures:That there is an operating point, marked in the figures, in which the PV array generates more power than the other points. That there are different maximum power points for each curve.The aforementioned observations imply that during one day the maximum powerpoint of a PV array varies according to the solar incident irradiance and temperaturechanges.
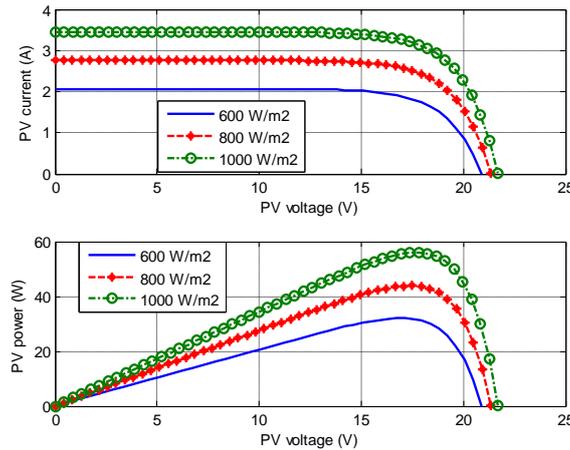
Fig. 3. PV array current–voltage and PV array power–voltage at 25°C at different irradiance levels.
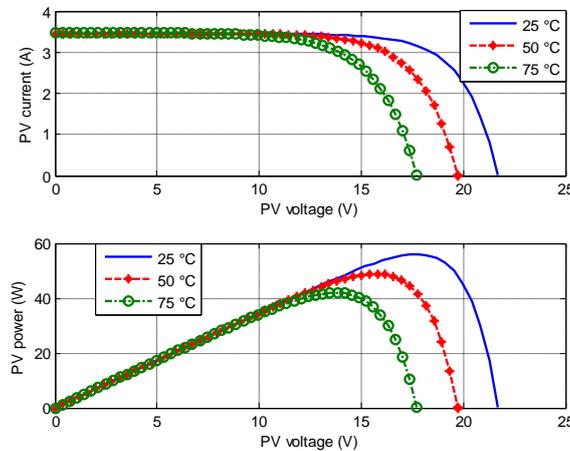
Fig. 4. PV array current–voltage and PV array power–voltage at 1000W/m^2 at different temperature levels.

Based on the solar array characteristic curves shown in Figs. 3 and 4, it can be found that a maximum power point occurs when the derivative of PV output power$P = v_p i_p$ with respect to terminal voltagev_p equals zero. Therefore:

$$\left.\frac{\partial P}{\partial v_p}\right|_{MPP} = \frac{\partial(v_p i_p)}{\partial v_p} = i_p + v_p \frac{\partial i_p}{\partial v_p} = 0 \qquad (5)$$

2.2. Single-phase Grid-connected PV System Modelling

Thepower converter structure used tointerface the photovoltaic array with the power gridas shown in Fig 2.In the specific architecture consideredin this work, the PV panel is connected to the inputof a single full-bridge power inverter by means of a DC-DC converter and a DC-link capacitor. The DC-DC boost converter consists of the switchS_1 controlled by a switching signal $\mu_1 \in \{0, 1\}$(i.e., OFF or ON respectively) and the full-bridge inverter consists of four switches$\{S_{21}, S_{22}, S_{23}, S_{24}\}$ controlled bya switching signal$\mu_2 \in \{0, 1\}$. The

switching signal μ_1 and μ_2 can also be generated via a pulse-width modulator (PWM)scheme with an input signal $u_i (i = 1,2) \in [0, 1]$ outputted by the controller. In this case, if theswitching frequency is sufficiently high, the dynamical behavior of the PV system canbe approximated by the following set of differential equations:

$$
\begin{cases}
\dfrac{dv_p}{dt} = \dfrac{1}{C_p}i_p - \dfrac{1}{C_p}i_L \\[2mm]
\dfrac{di_L}{dt} = \dfrac{1}{L}v_p - \dfrac{1}{L}(1 - u_1)v_{dc} \\[2mm]
\dfrac{dv_{dc}}{dt} = \dfrac{1}{C_{dc}}(1 - u_1)i_L + \dfrac{1}{C_{cd}}(1 - 2u_2)i_g \\[2mm]
\dfrac{di_g}{dt} = -\dfrac{1}{L_g}R_g i_g - \dfrac{1}{L_g}e_g - \dfrac{1}{L_g}(1 - 2u_2)v_{dc} \\[2mm]
y_1 = \dfrac{\partial P}{\partial v_p} = i_p + v_p \dfrac{\partial i_p}{\partial v_p} \\[2mm]
y_2 = i_g
\end{cases}
\qquad (6)
$$

where C_p is the input capacitor and L is the inductor of the boost converter. C_{dc} is the DC link capacitor, L_g is the filter inductor and R_g is the equivalent series resistance of the filter inductor. i_p, v_p, i_L, v_{dc}, i_g and e_g are respectively, the average values over switching period of the PV array current, PV array voltage, boost inductor current, DC bus voltage, grid current and grid voltage, y_1 and y_2 are the controlled outputs of the power system. The control inputs u_1 and u_2 are the average values (duty cycles) of the binary input switching signals μ_1 and μ_2. The utility grid voltage $e_g = A\sin(\omega t)$ is assumed to be sinusoidal with a constant amplitude A and a constant frequency $\omega = 2\pi f$.

III.   Controller Design

The control strategy of the power converter and power inverter that interface the PV array with theutility grid needs to accomplish the following control objectives in order to assure anefficient energy transfer:

- The maximum power extraction from the PV array by means of tracking the solar array maximum power point (MPP) that varies with the solar irradiance and the PV array temperature.
- The proper conversion of the DC input power into an AC output current, which has to be injected to the grid. This current has to exhibit low harmonic contents and must be in phase to the grid voltage in order to perform the power transfer at unity power factor.
- The tight regulation of the DC-bus voltage.

To accomplish the previous objectives, a nonlinear controller is developed using the backstepping technique based on the averaged nonlinear state space model of the controlled system. The proposed control system will have the structure shown in Fig.5. The MPPT controller and unity power factor controller will be synthesized using backstepping approach [12], [13], [14], [15] and the third will bedone by a simple proportional-integral corrector.
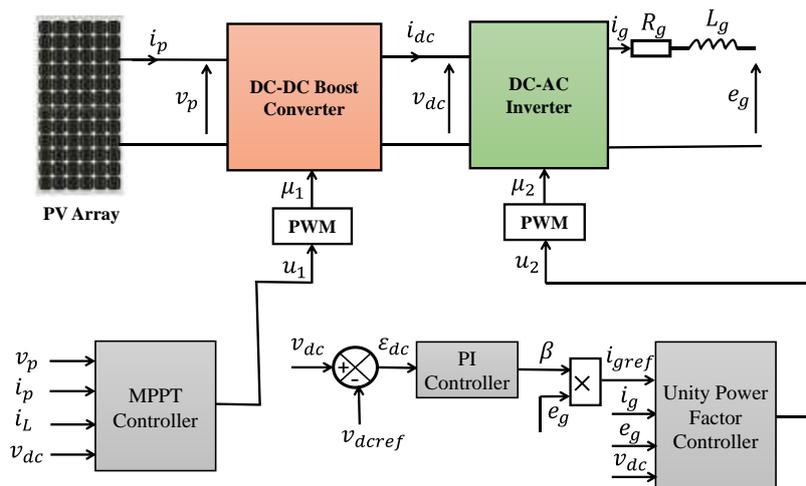
Fig. 5. Control scheme of the grid-connected PV system.

3.1. MPPT Controller

The maximum power point tracking controlhas to settle the PV array operating pointat itsmaximumpower valuefor anytemperatureandirradiance variation, bymeansof the input signal u_1 that controls

the switch of the boost converter. The control objective is to regulate the controlled output $y_1 = \frac{\partial P}{\partial v_p}$ of the photovoltaic array to its reference $y_{1ref} = \frac{\partial P}{\partial v_p}\Big|_{MPP} = 0$.

Backstepping design procedure:

Design Step: Let us introduce the following tracking error $\varepsilon_1 = y_1 - y_{1ref}$ and including integral action $\xi_1(t) = \int_0^t (y_1(\tau) - y_{1ref}(\tau)) d\tau$.

Deriving ε_1 with respect to time and accounting for (5) and (6), implies:

$$\dot{\varepsilon}_1 = \frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p} + v_p \frac{\partial^2 i_p}{\partial v_p^2}\right)(i_p - i_L) \qquad (7)$$

Treating the boost inductor current i_L as a virtual control signal for (7) and considering the first Lyapunov function positive definite:

$$V_1(\xi_1, \varepsilon_1) = \frac{1}{2}\xi_1^2 + \frac{1}{2}\varepsilon_1^2 \qquad (8)$$

The derivative of V_1 with respect to time, is given by:

$$\dot{V}_1 = \varepsilon_1\left[\xi_1 + \frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p} + v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)(i_p - i_L)\right] \qquad (9)$$

As i_L is just a state variable and not an effective control input, the stabilization of ξ_1 and ε_1 can be obtained by introducing a new virtual control $\alpha_1 = (i_L)_d$, where $(i_L)_d$ is the desired value of the boost inductor current. The virtual control law would be:

$$\xi_1 + \frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p} + v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)(i_p - \alpha_1) = -k_1\varepsilon_1 \qquad (10)$$

Where $k_1 > 0$ being a design parameter. The desired value α_1 is called a stabilization function, is given by:

$$\alpha_1 = i_p + \frac{C_p}{2\frac{\partial i_p}{\partial v_p} + v_p\frac{\partial^2 i_p}{\partial v_p^2}}(k_1\varepsilon_1 + \xi_1) \qquad (11)$$

The Lyapunov candidate function whose dynamics is negative definite: $\dot{V}_1 = -k_1\varepsilon_1^2 < 0$.

Design Step 2: We define the following second error variable of the boost inductor current error $\varepsilon_2 = i_L - \alpha_1$, where the inductor current should reach the desired value α_1 to make the error vanish in order to achieve the control aim. The time derivative of this error is:

$$\dot{\varepsilon}_2 = \frac{di_L}{dt} - \dot{\alpha}_1 = \frac{1}{L}\left(v_p - (1 - u_1)v_{dc}\right) - \dot{\alpha}_1 \qquad (12)$$

Substituting $i_L = \varepsilon_2 + \alpha_1$ into equation (7), $\dot{\varepsilon}_1$ becomes:

$$\dot{\varepsilon}_1 = \frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p} + v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)(i_p - \varepsilon_2 - \alpha_1) \qquad (13)$$

Introducing (11), we obtain the time derivative of ε_1 and V_1:

$$\dot{\varepsilon}_1 = -k_1\varepsilon_1 - \xi_1 - \frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p} + v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)\varepsilon_2 \qquad (14)$$

$$\dot{V}_1 = -k_1\varepsilon_1^2 - \frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p} + v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)\varepsilon_1\varepsilon_2 \qquad (15)$$

The time derivative of the stabilising function α_1 is given by:

$$\dot{\alpha}_1 = \left[\frac{\partial i_p}{\partial v_p}\frac{\partial v_p}{\partial t} + C_p\left(\frac{(k_1\dot{\varepsilon}_1 + \varepsilon_1)}{\left(2\frac{\partial i_p}{\partial v_p} + v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)} - \frac{(k_1\varepsilon_1 + \xi_1)}{\left(2\frac{\partial i_p}{\partial v_p} + v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)^2}\left(3\frac{\partial^2 i_p}{\partial v_p^2} + v_p\frac{\partial^3 i_p}{\partial v_p^3}\right)\frac{\partial v_p}{\partial t}\right)\right] \qquad (16)$$

Consider the augmented Lyapunov function candidate:

$$V_2(\xi_1, \varepsilon_1, \varepsilon_2) = V_1 + \frac{1}{2}\varepsilon_2^2 \qquad (17)$$

The time derivative of the second Lyapunov function is obtained by combining equations (12) and (15):

$$\dot{V}_2 = -k_1\varepsilon_1^2 + \varepsilon_2\left[-\frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p} + v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)\varepsilon_1 + \frac{1}{L}\left(v_p - v_{dc}\right) + \frac{1}{L}u_1 v_{dc} - \dot{\alpha}_1\right] \qquad (18)$$

The control law u_1 which guarantees the negativity of the dynamics of the Lyapunov candidate function V_2, is given by:

$$u_1 = \frac{L}{v_{dc}}\left[-k_2\varepsilon_2 + \frac{1}{C_p}\left(2\frac{\partial i_p}{\partial v_p} + v_p\frac{\partial^2 i_p}{\partial v_p^2}\right)\varepsilon_1 - \frac{1}{L}\left(v_p - v_{dc}\right) + \dot{\alpha}_1\right] \qquad (19)$$

where $k_2 > 0$ is a positive constant. The above choice yields:

$$\dot{V}_2 = -k_1\varepsilon_1^2 - k_2\varepsilon_2^2 < 0 \qquad (20)$$

which ensures that the state vector error $(\xi_1, \varepsilon_1, \varepsilon_2)$ converges asymptotically to the origin, which implies that $\varepsilon_1 = y_1 - y_{1ref} = \partial P / \partial v_p$ converges asymptotically to the origin, Therefore, the maximum power extraction from the PV array is achieved.

3.2. Unity Power Factor Controller

The unity power factor controller input signal u_2 that controls the inverterhave been carried out by means of on two cascaded control loops, where theinner current control loop is in charge to establish the duty ratio for the generation of a sinusoidal output current in phase with the grid voltage and ensuring current harmonics rejection. In turn, the outer voltagecontrol loop has to settle the DC bus voltage regulating at its desired value,this loop delivers to the inner control loop the currentreference amplitude corresponding to the PV array maximum power, thereby ensuringthe power transfer to the grid.

The inner controllerallows the grid current i_g to track a reference signal i_{gref} of the form:

$$i_{gref} = \beta e_g = \beta A \sin(\omega t) \qquad (21)$$

Whereβ isanadjustmentpositive parameter anditcanbeadjustedbyaPIcontrol.

Let us introduce thefollowing tracking current error$\varepsilon_3 = y_2 - y_{2ref} = i_g - i_{gref}$. Itsdynamics is given by:

$$\dot{\varepsilon}_3 = -\frac{1}{L_g} R_g i_g - \frac{1}{L_g} e_g - \frac{1}{L_g}(1 - 2u_2)v_{dc} - \frac{di_{gref}}{dt} \qquad (22)$$

Let us use the Lyapunov candidate function by introducing the integral action $\xi_2(t) = \int_0^t (i_g(\tau) - i_{gref}(\tau))d\tau$:

$$V_3(\xi_2, \varepsilon_3) = \frac{1}{2}\xi_2^2 + \frac{1}{2}\varepsilon_3^2 \qquad (23)$$

As its derivative with respect to time, is given by:

$$\dot{V}_3 = \varepsilon_3 \left[\xi_2 - \frac{1}{L_g}R_g i_g - \frac{1}{L_g}e_g - \frac{1}{L_g}(1 - 2u_2)v_{dc} - \frac{di_{gref}}{dt}\right] \qquad (24)$$

The stabilizing control law by making $\dot{V}_3$ negative definite is given by:

$$u_2 = \frac{1}{2}\left[1 + \frac{1}{v_{dc}}\left(R_g i_g + e_g + L_g\left(\frac{di_{gref}}{dt} - k_3\varepsilon_3 - \xi_2\right)\right)\right] \qquad (25)$$

where$k_3 > 0$ is a positive parameter; which yields$\dot{V}_3 = -k_3\varepsilon_3^2 < 0$, then the tracking error ε_3 converges asymptotically to zero.Therefore, thegrid current is sinusoidal and in phase with the grid voltage.

The aim of the outer voltage loopis to design a variation law for the ratio βin equation (21) sothat the inverter DC input voltagev_{dc}issteered to a given constant referencev_{dcref}.This regulatorisgiven by the following PI controllaw:

$$\beta(t) = k_4(v_{dc}(t) - v_{dcref}(t)) + k_5 \int_0^t (v_{dc}(\tau) - v_{dcref}(\tau))d\tau \qquad (26)$$

wherek_4 and k_5 are respectively the proportional and integral gain.

IV.   Simulation Results and Discussions

Numerical simulations were made in the Simulink/Matlabplatform to verify the performance of thecontroller;all parameters of thephotovoltaic system componentsand controller are depicted in Table 2.Two scenarios were simulated. In the first one,realistic variations were applied to the irradiance from $500 W/m^2$ to $1000 W/m^2$at 0.5swhile maintainingthe cell temperature constant at $25°C$.Theresulting control performances are illustrated by Fig. 6 to Fig. 9.The reference DC bus voltage valueis held at$v_{dcref} = 40V$.Thesecondscenario was simulated for temperature changes from $25°C$ to $50°C$ at 0.5s while the radiation is constant equal to$1000 W/m^2$.The corresponding performances are illustrated by Fig. 10 to Fig. 13.

From these Figures, it is clear that the maximum power point is always reached very quickly with excellent accuracy and good performances according to atmospheric condition changes.The grid current is sinusoidal and in phase with the grid voltage, which proves the unity power factor achievement. Noting that the DC bus voltage is regulated to its desired value.In addition to that,this controller has tobe used in orderto achieve the synchronization tothe grid and to perform the power managementbetween the PV system and the electrical grid.

Photovoltaic array parameters	Boost converter, inverter and grid parameters	Controller parameters
$R_s = 0.1124\Omega$	$C_p = 4700\mu F$	$k_1 = 900$
$R_{sh} = 6500\Omega$	$C_{dc} = 470\mu F$	$k_2 = 900$
$\gamma = 1.7404$	$L = 3.5mH$	$k_3 = 200$
$I_{scr} = 3.45A$	$L_g = 2.2mH$	$k_4 = 0.01$
$I_{rr} = 4.842\mu A$	$R_g = 0.7\Omega$	$k_5 = 1$
$N_s = 36$	$A = 22\sqrt{2}V; f = 50Hz$	
$N_p = 1$	$v_{dcref} = 40V$	

Table 2: Power system and controller parameters.
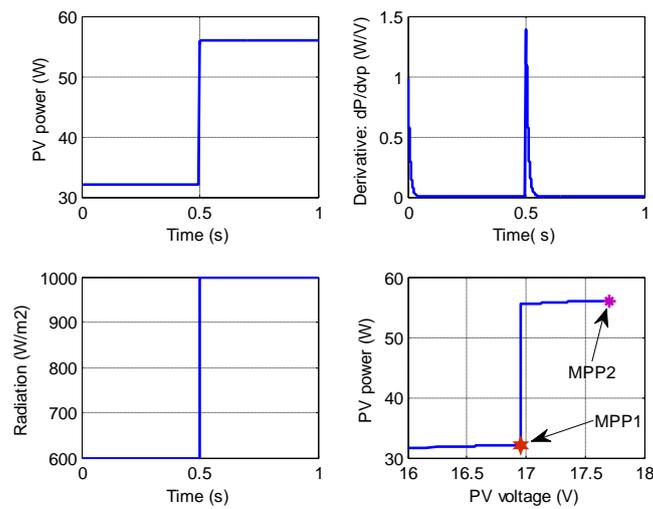
Fig. 6. PV power, controlled output, radiation and PV array power-voltage characteristic in presence of radiation changes.
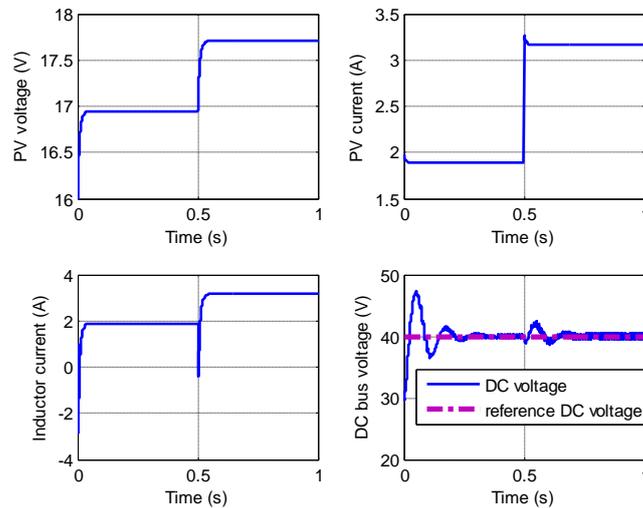
Fig. 7. PV array voltage, PV array current, boost inductor current and DC bus voltage in presence of radiation changes.
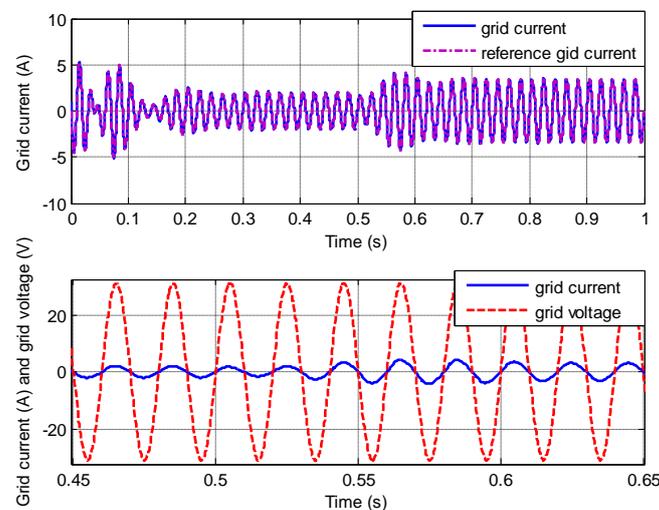
Fig. 8. Grid current and its reference and grid voltage in presence of radiation changes.
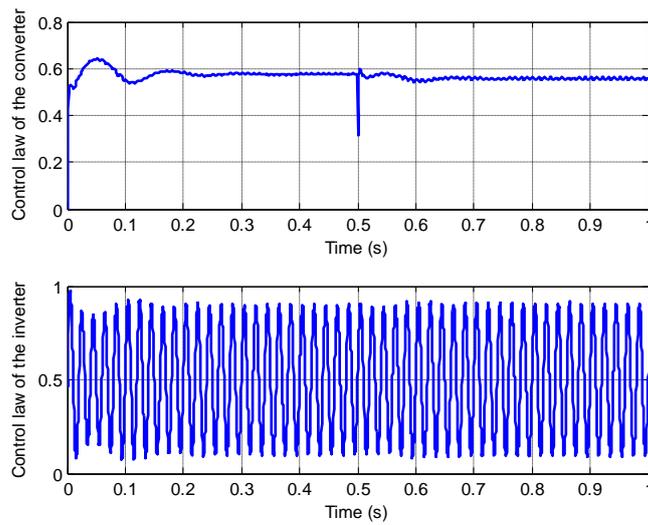
Fig. 9. Input controls of the converter and inverter in presence of radiation changes.
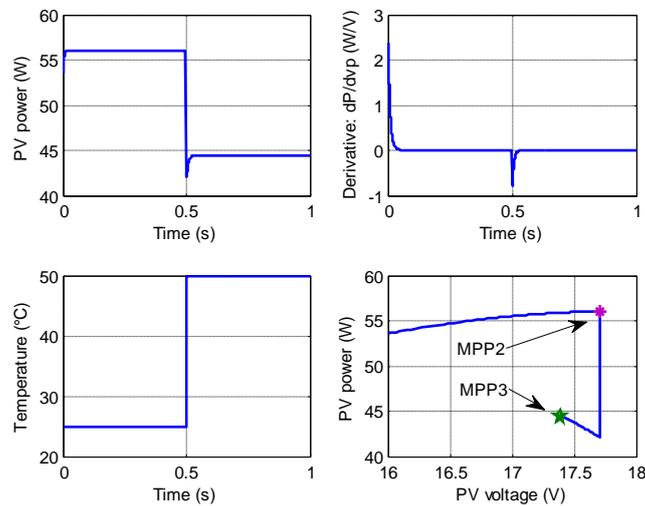
Fig. 10. PV power, controlled output, temperature and PV array power-voltage characteristic in presence of temperature changes.
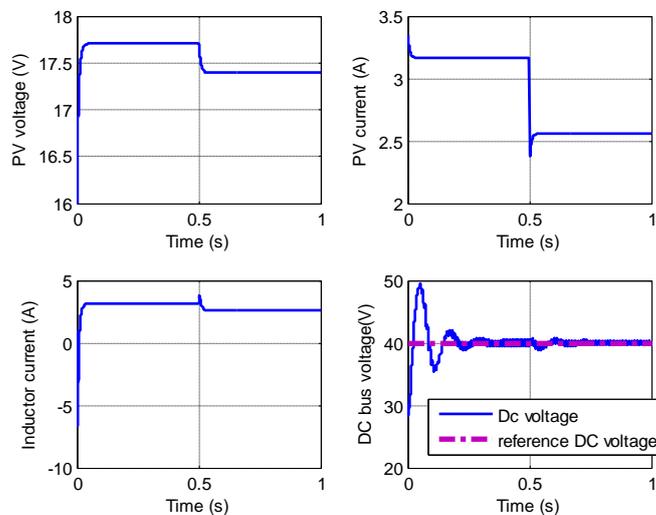
Fig. 11. PV array voltage, PV array current, boost inductor current and DC bus voltage in presence of temperature changes.
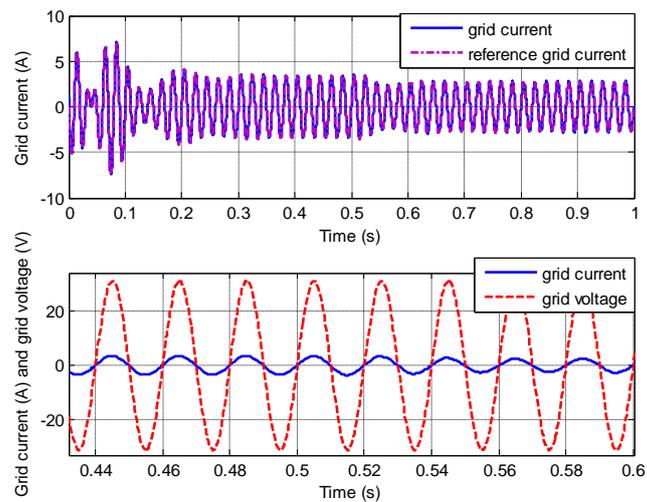
Fig. 12. Grid current and its reference and grid voltage in presence of temperature changes.
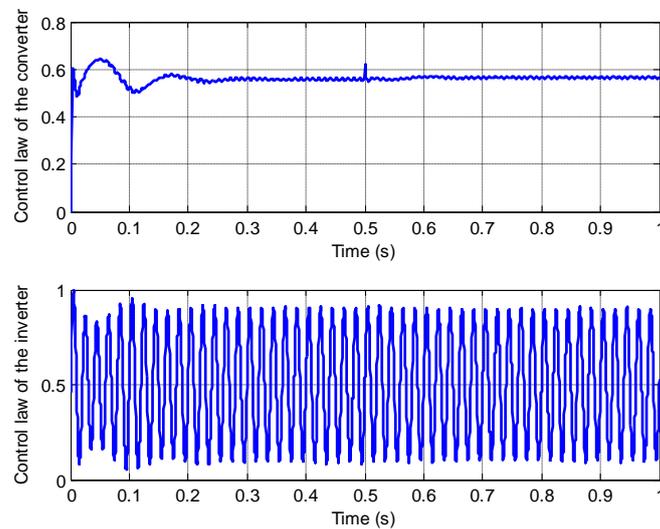
Fig. 13. Input controls of the converter and inverter in presence of temperature changes.

V.   Conclusion

This paper presents a new nonlinear control strategy of single-phase grid-connected PV generation system. The controller is designed to extract maximum power from the PV array and to inject a sinusoidal current in the grid with unity power factor and regulating the DC bus voltage. The studied system is described by a representation of nonlinear state space average model. To track the designed trajectory, a tow backstepping controller and a proportional-integral corrector are developed to modulate the duty cycle of the interleaved boost converter and inverter. The controller is proven to yield asymptotic stability with respect to the tracking errors via Lyapunov analysis. The proposed controller has the advantages of robustness, accurate tracking, fast response and good performance. Simulationresults, obtained under Matlab/Simulink environment, show the controlperformance and dynamic behavior of grid-connected photovoltaic system providesgood results and show that the control system is robust and efficiency.

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