International Conference on Automation, Control Engineering and Computer Science (ACECS)
Proceedings of Engineering and Technology – PET
Vol.20 pp.65 - 70

Nonlinear Control Based on a Combination Between Sliding mode and Backstepping of Grid Connected Photovoltaic System

Hajar Dammah #1, Ibtissam Lachkar #2, Saad Lissane Elhaq #3

Engineering Research Laboratory (LRI), Optimization of Production System & Energy Team
University Hassan II, Superior National School of Electricity and Mechanics ENSEM
Casablanca, Morocco
1hajardammah@gmail.com

***Abstract*— This paper involves the nonlinear control of single phase grid connected to the photovoltaic system through an adaptation circuit based on a half bridge inverter and L filter. The control objectives are threefold: i) Perfect MPPT: extracting the Maximum power from the PV array by acting on the DC-DC converter ii) Unity power factor in the grid: provide a sinusoidal current in phase with the grid voltage by controlling DC/AC converter iii) Regulating the output voltage to a desired reference value. The problem is dealt with by designing a nonlinear controller using a combination between Sliding mode, Backstepping approach and Lyapunov stability based on an averaged nonlinear model of 5th order of the whole system. The system configuration includes a photovoltaic generator, DC-DC converter, DC-AC half bridge inverter coupled to grid. The system is controlling via the input control of the DC-DC converter and DC-AC inverter. It is easy to shown, that the proposed controller achieves its objectives, through theoretical analysis and simulation results. The simulation results have been performed through Matlab/Simulink environment.**

***Keywords*— Photovoltaic system, Single-phase half-bridge inverter, Maximum power point tracking (MPPT), Unity power factor, Nonlinear control Sliding mode and Backstepping approach.**

I. INTRODUCTION

With the growing need for electrical energy, scientific development has found a good alternative for classical methods of generating electricity, this alternative is renewable energy specially photovoltaic energy. The most advantage of photovoltaic energy are characterise by their high efficiency and low cost. The principe of solar energy is transforming free solar radiation into electricity, so it is one of the most useful natural energy sources. PV energy has grown at an average rate of 60% in last five years [13]. We can find two types of PV system application, the first one is a stand-alone with needs presence of battery, the second one is direct connection to the grid, and composed by a dc-dc converter controlled to meet the MPPT and the dc-ac converter controlled to meet unity PF.

The goal of this work is controlling a grid connected photovoltaic system based on a half bridge inverter by a nonlinear control based on sliding mode strategy, to track the maximum power of the PV array and to obtain a unity power factor by ensuring the tight regulation of the DC-bus voltage. The half bridge inverter, used in this paper, present many advantage, such as the low cost because reducing of number of interrupters and the current in output is the double compared to the inverter full-bridge. The concept of the control is to calculate an appropriate control law to guarantee the global asymptotic stability of the system. The control input of the DC/DC converter achieves the maximum power point tracking, despite changing of the climatic conditions. The control input of the DC/AC inverter achieves the unity power factor with regulation of the DC-link voltage and assures that the output current must be sinusoidal and in phase with the grid voltage. A theoretical analysis is developed to show that the controller actually meets its objectives a fact that is confirmed by simulation. The paper is organized as follows: part II describe and model the single phase grid connected PV system. Part III is devoted to controller design and analysis. Part IV illustrates the controller tracking performances by numerical simulation.

II. PRESNTATION OF THE SYSTEM

Fig.1 represents the single-phase grid connected photovoltaic system under study. This system composed by a solar array, a DC/DC boost converter used for boosting the PV voltage level of photovoltaic array and to feed DC side of the DC/AC inverter. The single phase half-bridge inverter (with two IGBT) used to supply the energy to the grid, and a filter inductor Lg in order to minimize the harmonics distortion of current and voltage.

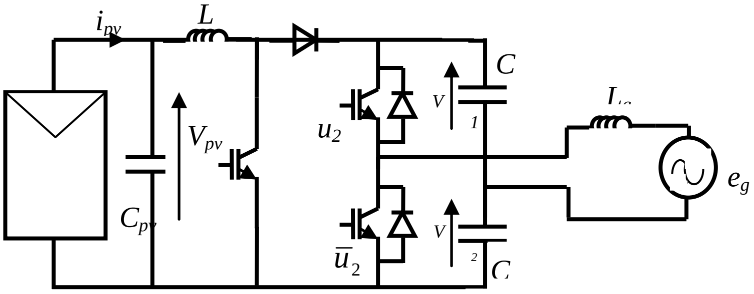

Fig. 1 A Single phase grid connected PV system

ISSN 2356-5608

III. MATHEMATICAL MODEL

A. *Photovoltaic Array Model*

Equation (1) describes the behavior of the curve for any PV array under different values of temperature and solar irradiance.

$$I_{pv} = N_p I_{ph} - N_p I_o \left\{ \exp\left[A(V_{pv} + \frac{N_s I_{pv} R_s}{N_p} \right] - 1 \right\} - \frac{N_p}{R_{sh}} \left(\frac{V_{pv}}{N_s} + \frac{I_{pv} R_s}{N_p} \right) \quad (1)$$

The meaning and values of the parameters in (1) can be found in many places (see e.g. [1], [2], [3]). The PV array module considered in this paper is the 1STH-215-P. The corresponding electrical characteristics are listed in Table 1.

TABLE I
ELECTRICAL SPECIFICATIONS FOR THE SOLAR MODULE 1STH-215P

Parameter	**Symbol**	**Value**
Maximum power	Pm	213.15 W
Short circuit current	Isc	7.84 A
Open circuit voltage	Voc	36.3 V
Maximum power voltage	Vm	29 V
Maximum power current	Im	7.35 A
Number of series modules	Ns	6
Number of parallel modules	Np	7

The current-voltage (I-V) and power-voltage (P-V) characteristics under changing temperature are shown in Fig.2 and 3.

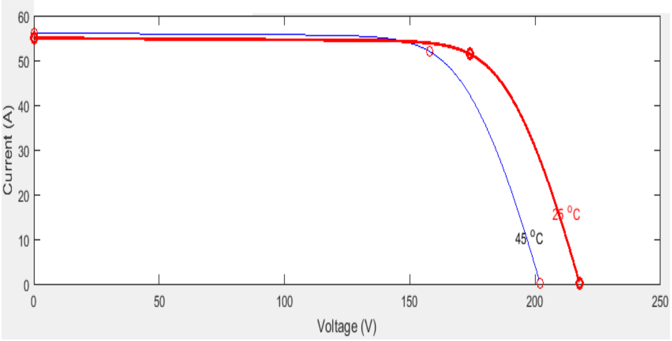

Fig. 2 (I-V) characteristics of The PV module 1STH-215-P with varying temperature.

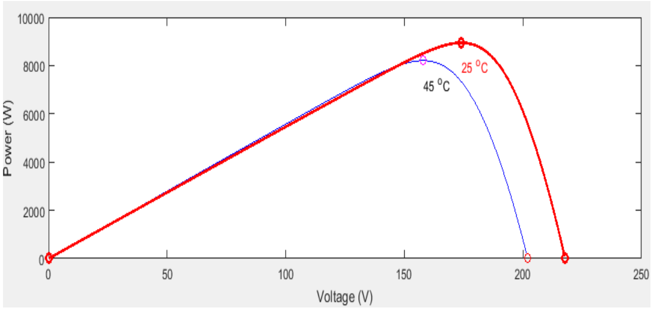

Fig. 3 (P-V) characteristics of The PV module 1STH-215-P with varying temperature.

B. *Boost Converter Modelling*

The control input u1 of the boost converter is a PWM signals with values in the set {0,1}. Applying the Kirchhoff's laws to the boost converter presented in fig. 1, one obtains the following instantaneous model;

$$C_{pv} \frac{dv_{pv}}{dt} = i_{pv} - i_l \qquad (2a)$$

$$L \frac{di_l}{dt} = v_{pv} - (1 - u_1)(v_1 + v_2) \qquad (2b)$$

C. *Single Phase Half-Bridge Inverter Modelling*

The control input u_2 for the single-phase half-bridge inverter is also a PWM signal taking values in the set {-1,1}. Applying the Kirchoff's laws, to the inverter circuit of Fig. 1 one obtains the following instantaneous model:

$$C \frac{dv_1}{dt} = (1 - u_1) i_l - \frac{u_2 + 1}{2} i_g \qquad (3a)$$

$$C \frac{dv_2}{dt} = (1 - u_2) i_l - \frac{u_2 - 1}{2} i_g \qquad (3b)$$

$$L_g \frac{di_g}{dt} = -r_g i_g + \frac{1 + u_2}{2} v_1 - \frac{1 - u_2}{2} v_2 - e_g \qquad (3c)$$

D. *Overall System Model*

Performing a following transformation

$$v_1 + v_2 = v_o$$

$$v_1 - v_2 = v_d$$

Combining systems of equation (2) et (3), the model comes:

$$C_{pv} \frac{dv_{pv}}{dt} = i_{pv} - i_l \qquad (4a)$$

$$L \frac{di_l}{dt} = v_{pv} - (1 - u_1) v_o \qquad (4b)$$

$$C \frac{dv_o}{dt} = 2(1 - u_1) i_l - u_2 i_g \qquad (4c)$$

$$C \frac{dv_d}{dt} = -i_g \qquad (4d)$$

$$L_g \frac{di_g}{dt} = -r_g i_g + \frac{v_d}{2} + \frac{u_2}{2} v_o - e_g \qquad (4e)$$

This model cannot be based upon to design a continuous control law as it involves a binary control input, u_1 and u_2. To overcome this difficulty, it is usually resorted to the averaging model [7].

$$C_{pv} \frac{dx_1}{dt} = \bar{i}_{pv} - x_2 \qquad (5a)$$

$$L \frac{dx_2}{dt} = x_1 - (1 - \mu_1) x_3 \qquad (5b)$$

$$C \frac{dx_3}{dt} = 2(1 - \mu_1) x_2 - \mu_2 x_5 \qquad (5c)$$

$$C \frac{dx_4}{dt} = -x_5 \qquad (5d)$$

ISSN 2356-5608

$$L_g \frac{dx_5}{dt} = -r_g x_5 + \frac{x_4}{2} + \frac{\mu_2}{2} x_3 - e_g \tag{5e}$$

TABLE II
MODEL AVERAGED VALUES

Physical variable	**Averaged values**
PV voltage v_{pv}	x_1
Inductor current i_l	x_2
Sum of Voltage v_o	x_3
Difference of Voltage v_d	x_4
Grid current i_g	x_5
PV current i_{pv}	$\bar{i}_{pv}$
Converter binary control input u_1	μ_1
Inverter binary control input u_2	μ_2

IV. CONTROLLER DESIGN

The objective of this section is to be able to ensure: (i) a perfect MPPT whatever the position of the panel, the controller must enforce the voltage x_1 to track the optimal voltage V_m whish depend on temperature and solar variation Ir. (ii) a unity PF in the grid. (iii) a tight regulation of the voltage x_3.

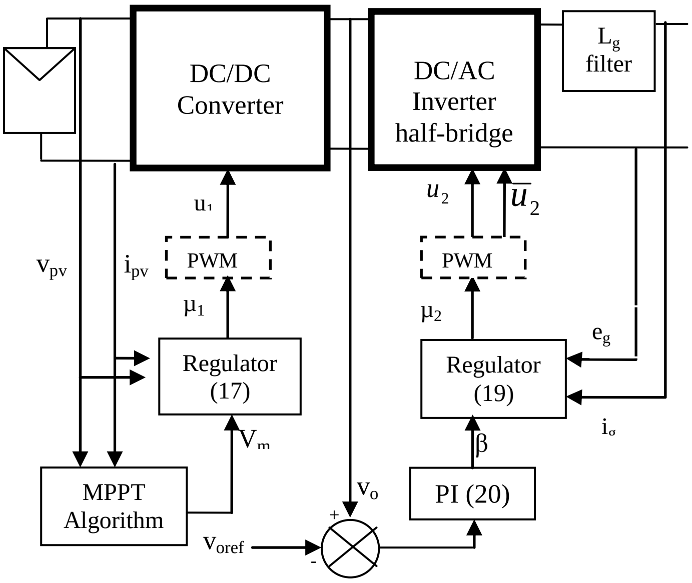

Fig. 4 control structure

A. *PV voltage controller design*

The control object is to enforce the voltage x_4 across the solar panel to track a given optimal voltage V_m . To meet this objective we use the combination between backstepping & sliding mode techniques for controller design and the "P&O algorithm" to generate the optimal voltage signal.

Considering the sub-system (5a-b):

$$C_{pv} \frac{dx_1}{dt} = \bar{i}_{pv} - x_2$$

$$L \frac{dx_2}{dt} = x_1 - (1-\mu_1) x_3$$

Let us introduce the following sliding manifold:

$$S_1 = C_{pv}(x_1 - V_m) \tag{6}$$

We define the Lyapunov function : $V_1 = \frac{1}{2} S_1$

The time derivative of S_1 is:

$$\dot{S}_1 = i_{pv} - x_2 - C_{pv} \dot{V}_m \tag{7}$$

In (7), the quantity x_2 stands as a virtual control variable. So the algorithm of control can be defined as follow:

$$x_2 = x_{2eq} + x_{2N} \tag{8}$$

With x_{2eq} is the equivalent control law, it consist to find a continuous value of the control variable such as state vector trajectory is maintained on the sliding surface $S_1(t) = 0$. And x_{2N} is the discontinuous component.

The Equivalent control law is a way to determine the system performance when restricted to the surface $S_1(t) = 0$, which implies $\dot{S}_1(t) = 0$, so the equivalent control law is:

$$x^*_{2eq} = i_{pv} - C_{pv} \dot{V}_m \tag{9}$$

The convergence condition is defined by the Lyapunov function, it makes the surface attractive and invariant, then $S_1(t)\dot{S}_1(t) < 0$. This condition will be satisfied if

$$x^*_{2N} = -K_1 sign(S_1) \tag{10}$$

with K_1 a positive constant and the signe function is defined like as:

$$sign(s(t)) = 1 \quad if \quad s(t) > 0$$

$$sign(s(t)) = 0 \quad if \quad s(t) = 0$$

$$sign(s(t)) = -1 \quad if \quad s(t) < 0$$

Combining (9) and (10), we obtain:

$$x_2^* = i_{pv} - C_{pv} \dot{V}_m - K_1 sign(S_1) \tag{11}$$

Since x_2 is not the actual control input, a new surface S_2 between the virtual control and its desired value x_2^* is introduced:

$$S_2 = L(x_2 - x_2^*) \tag{12}$$

So, $x_2 = \frac{S_2}{L} + x_2^*$

Then $\dot{S}_1 = i_{pv} - x_2^* - \frac{S_2}{L} - C_{pv} \dot{V}_m$

$$\dot{S}_1 = -\frac{S_2}{L} + K_1 sign(S_1) \tag{13}$$

Consider the Lyapunov function:

$$V_2 = V_1 + \frac{1}{2} S_2^2 \tag{14}$$

$$\dot{V}_2 = K_1 S_1 sign(S_1) - S_2 (\frac{S_1}{L} - \dot{S}_2)$$

The focus is to make the derivative negative definite:

$$\frac{S_1}{L} - \dot{S}_2 = \lambda_2 S_2 \quad \Longrightarrow \quad \dot{S}_2 = \frac{S_1}{L} - \lambda_2 S_2 \qquad (15)$$

The derivative of S_2 is:

$$\dot{S}_2 = x_1 - (1 - \mu_1) x_3 - L\dot{x}_2^* \qquad (16)$$

Combining (15) and (16), the control law comes:

$$\mu_1 = 1 - \frac{x_1 - L\dot{x}_2^* - \frac{S_1}{L} + \lambda_2 S_2}{x_3} \qquad (17)$$

B. *Generation of the optimal voltage*

The voltage and current delivered by the PV array are affected by the not stable climate conditions. So to ensure the correct operation of PV module at its maximum power point we use the “perturb and observe algorithm (P&O)”. P&O is simple and use a few measured parameters. This method consists of two input signals: the PV voltage and the current, and one output signal which is optimal voltage that must be applied to the regulator. The algorithm steps are described as shown in the following figure.

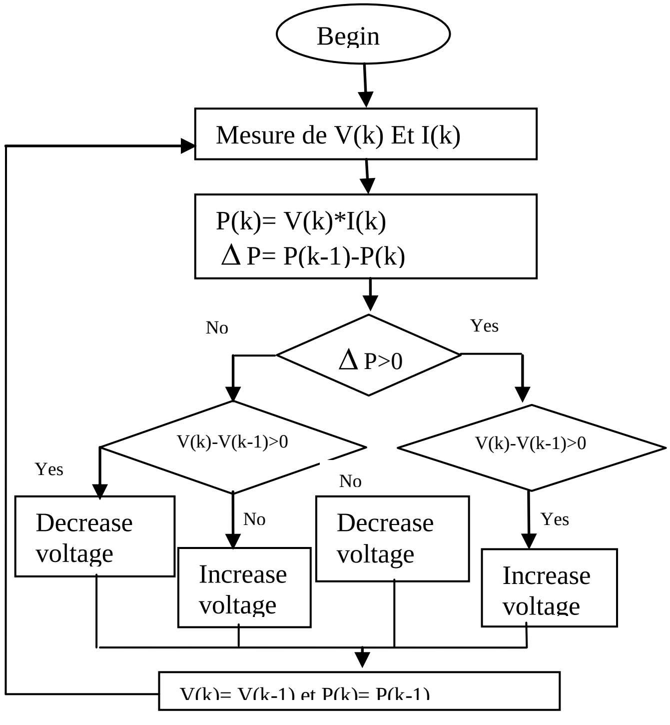

Fig. 6 P&O Algorithm

C. *PFC controller*

The PFC objective means that the output current should be sinusoidal and in phase with the network supply voltage. The regulator has to enforce the current x_5 to track a reference signal of the form

$$x_5^* = \beta e_g \qquad (18)$$

The nonlinear sliding mode control is used to design the regulator.

Let us introduce the following sliding surface:

$$S_3 = L_g (x_5 - x_5^*)$$

The equivalent control law when restricted to the surface $S_3(t) = 0$ is:

$$u_{2eq} = 2 * \frac{r_g i_g - \frac{v_d}{2} + e_g + L_g i_g^*}{v_0}$$

To make the surface attractive and invariante, the product $S_3(t)\dot{S}_3(t)$ must be negative, so:

$$u_{2N} = -K_3 sign(S_3)$$

The control law u_2 is:

$$u_2 = 2 * \frac{r_g i_g - \frac{v_d}{2} + e_g + L_g i_g^*}{v_0} - K_3 sign(S_3) \qquad (19)$$

D. *DC link voltage regulation*

To ensure the PFC objective, we need to control DC bus voltage to track its desired voltage reference, to do that, a simple PI regulator is required.

$$\beta = G_2(s) \xi_{dc} \qquad (20a)$$

$$G_2(s) = k_p + \frac{k_i}{s} \qquad (20b)$$

$$\xi_{dc} = x_3 - V_{oref} \qquad (20c)$$

V. SIMULATION

The performances of regulators previously established are now numerically evaluated using a MATLAB/Simulink environment with the following system characteristics.

TABLE III
CHARACTERISTICS OF CONTROLLED SYSTEM

Parameter	**Symbol**	**Value**
PV array	Power	213.15W
	Modul	1STH-215-P
DC/DC converter	L	2mH
	Cpv	4mF
DC/AC converter	C	4mF
Grid filter inductor	Lg	10mH
	rg	0.7Ω
PWM	Switching frequency	10kHz
Grid	AC Source	220V
	Frequency	50Hz

The following values of the controllers design parameters proved to be suitable:

TABLE IV. CONTROLLER PARAMETER

Parameter	Symbol	Value
Regulator U_1	λ_1	1e4
Regulator U_2	K_2	1e14
Regulator PI	k_p	1e-6
	k_i	4e-7
Desired v_o voltage	v_{oref}	1000V

A. *Radiation Change Effect*

Fig. 6 shows that the PV voltage converges to its reference with good accuracy, comparing to results obtain with sliding mode strategy, and ensuring the perfect MPPT in presence of radiation changes. Specifically, the radiation varies between 400 W/m2 and 1000 W/m2 , meanwhile the temperature is kept constant, equal to 298.15K (i.e. 25°C). The figure, also shows that the DC bus voltage vo is regulated to its desired value. Fig. 8 shows that the grid current ig is sinusoidal and therefore demonstrates the good performance of the inner loop.

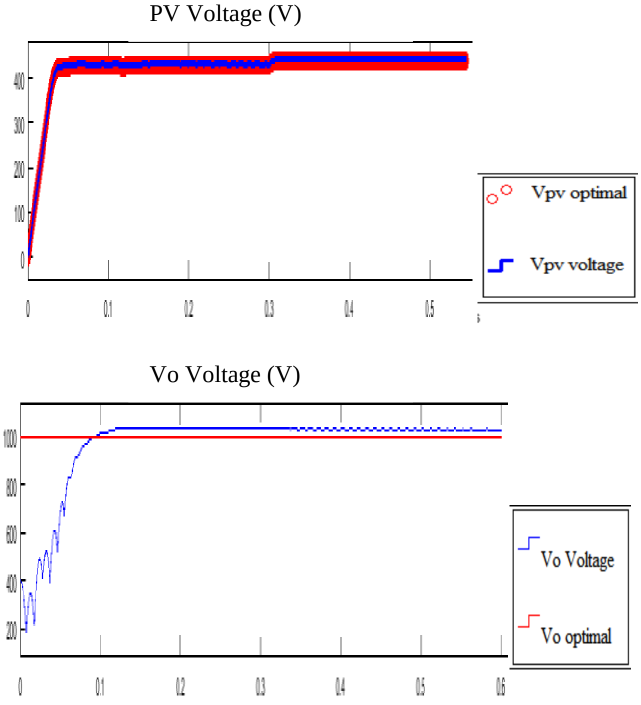

Fig. 6 MPPT & Vo voltage in presence of radiation change.

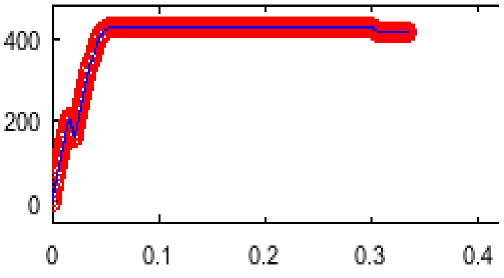

Fig. 7 MPPT with sliding mode strategy in presence of radiation change.

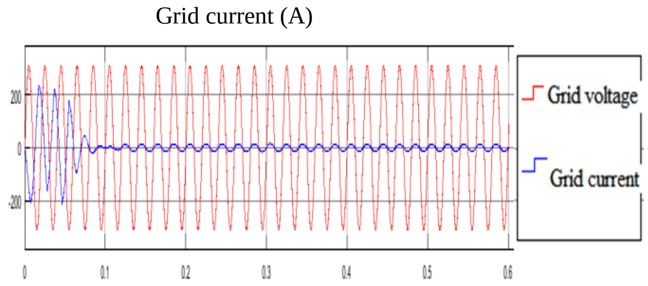

Fig.8 Unity PF in presence of temperature changes.

B. *Temperature changes effect*

From Fig. 9, it is clear that the maximum power point is reached with excellent accuracy and good performances according to temperature changes, comparing with performances obtain with backstepping strategy. Specifically, the temperature T varies between 25°C and 35°C, while the radiation maintained constant at 1000W/m². Noting that the DC bus voltage is regulated to its desired value voref. The last figure shows clearly that the grid current ig is sinusoidal and in phase with the grid voltage eg, which proves the unity power factor achievement.

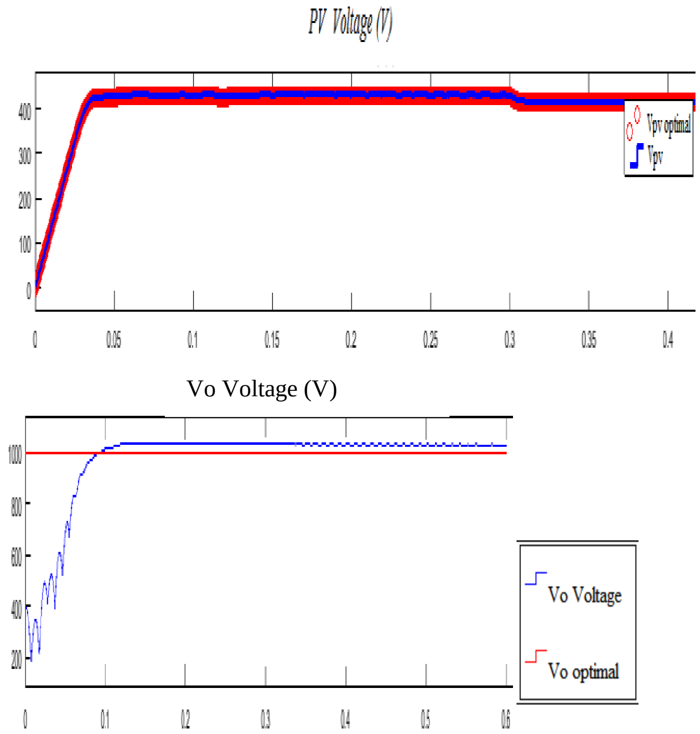

Fig. 9 MPPT & Vo voltage in presence of temperature change.

Fig. 10 MPPT with backstepping strategy in presence of temperature change.

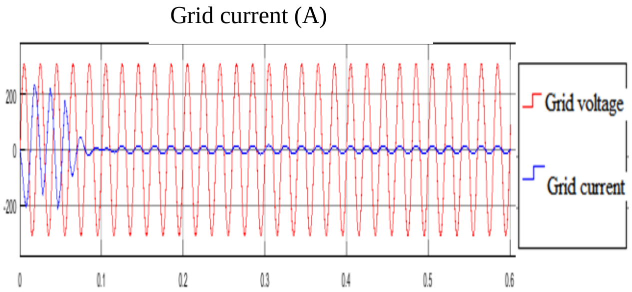

Fig.11 Unity PF in presence of temperature changes.

VI. CONCLUSIONS

In this paper, a new nonlinear controller has been developed for PV grid connected system. The controller design is made based on combination between backstepping & sliding mode techniques and Lyapunov stability. The present controller has the advantage such as robustness against changes in system parameters, and insensitivity to external perturbations. Both analysis and simulation studies prove that the proposed controllers meet the objectives.

REFERENCES

[1] C. Chen-Chi, C. Chieh-Li. “Robust maximum power point tracking method for photovoltaic cells: A sliding mode control approach”. Solar Energy, 83, pp. 1370–1378, 2009.

[2] H .El Fadil, and F. Giri, “Climatic sensorless maximum power point tracking in PV generation systems”. Control Engineering Practice (ELSEVIER), Vol. 19, N.5, pp. 513–521, May 2011.

[3] J.M Enrique, E. Duran, M. Sidrach-de-Cardona, J.M. Andujar. “Theoritical assessment of the maximum power point tracking efficiency of photovoltaic facilities with different converter topologies”. Solar Energy, 81, pp. 31-38, 2007.

[4] H.N. Zainudin, Saad Mekhilef “Comparison Study of Maximum Power Point Tracker Techniques for PV Systems “. Proceedings of the 14th International Middle East Power Systems Conference (MEPCON’10), Cairo University, Egypt, December 19-21, 2010, Paper ID 278.

[5] H. Abbes, H. Abid, K. Loukil, A. Toumi, M. Abid.(2013). “Etude comparative de cinq algorithmes de commande MPPT pour un système photovoltaïque « . Conférence Internationale des Energies Renouvelables (CIER’13) Sousse, Tunisie –(2013)

[6] C. Hua, J. Lin, H. Tzou, 2003. “MPP control of a photovoltaicenergy system.” ETEP 13 (4), July/August 2003.

[7] P.T. Krein, J. Bentsman, R.M. Bass, R. M., & B. Lesieutre, “On the use of averaging for analysis of power electronic system”. IEEE Transactions on Power Electronics, 5(2), pp. 182–190, 1990.

[8] V.I Utkin “variable structure systems with sliding mode”. IEEE transactions on Automatoc Control, vol. AC, No.2,pp. 212-222

[9] J.H. Lee; H.S. Bae; B.H. Cho, “Advanced Incremental Conductance MPPT Algorithm with a Variable Step Size”, Power Electronics and Motion Control Conference EPEPEMC 12th International, Sept 2006, pp. 603 – 607...

[10] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, “Optimization of Perturb and Observe maximum power point tracking method”, Power Electronics, IEEE Transactions, Vol. 20, n.4, July 2005, pp. 963–973

[11] N.Patcharaprakiti,S.Premrudeepreechacharn,Y.Sriuthaisiriwong, “Maximum power point tracking using adaptive fuzzy logic control for grid-connected photovoltaic system”, Renewable Energy, Vol 30 n.11, Sept 2005, pp. 1771–1778.

[12] M. Krstic, I. Kanellakopoulos and P.V. Kokotovic (1995). “Nonlinear and adaptive control design” (John Willy & Sons, NY).

[13] S.Kouro, J.I.Leon, D.Vinnikov, L.G.Franquelo, “Grid-connected photovoltaic systems”, An overview of recent research and emerging PV converter technology. March 2015