Nonlinear controller design for maximum power tracking in grid connected photovoltaic systems.

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Abstract: - This work presents a new control method to track the maximum power point of a single-phase grid-connected photovoltaic (PV) system. This converter is built on two stages: a DC/ DC stage and a DC/ AC stage. The two blocks are bound by a DC voltage intermediate bus. We seek the achievement of three control objectives: (i) maximum power point tracking (MPPT) of (PV) module. (ii) tight regulation of the DC bus voltage and (iii) unity power factor (PF) in the grid.
To meet these objectives, a multi-loop controller is designed using the backstepping technique based on an averaged nonlinear model of the whole controlled system.
It is formally shown, through theoretical analysis and simulation results that the developed strategy control actually meets its objectives.

Key-Words: - photovoltaic system; maximum power point (MPP); boost converter; backstepping technique, unity power factor, lyapunov.

1 Introduction

Due to the requirement for environmental preservation and dramatic increase in energy consumption over the last decades, most countries have decided to strongly promote and develop clean and sustainable power generation sources. Also, governments encourage resorting to such energy solutions through significant tax credits.

Nowadays, renewable energy sources are widely used and particularly (PV) energy systems have become widespread everywhere. Indeed, PV systems present several features e.g high dependability, simplicity of allocation, absence of fuel cost, low maintenance and lack of noise due to the absence of moving parts. All these considerations assure a promising role for PV generation systems in the near future.

The grid-connected PV systems consist of an array of solar module, a DC-DC power converter, a DC-AC converter and a control system, the complete scheme is presented in fig 1.

Due to the switching functions of the converters and inverters, Grid-connected PV systems are highly nonlinear systems. Advanced and efficient control schemes are essential to ensure the operation over a wide range of operating points.

Furthermore, dependence of the power generated by a PV array and its MPP(maximum power point) on atmospheric conditions is readily be seen in the power-voltage (P-V) characteristics of PV arrays as shown in Fig. 4 and Fig. 5.

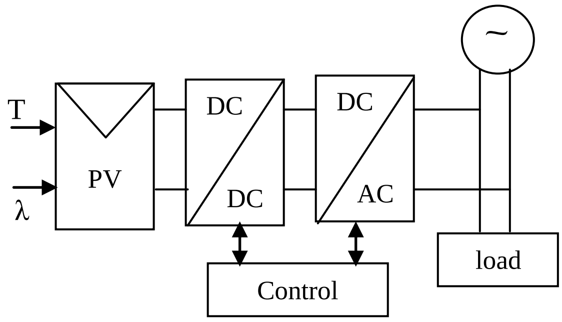

Fig.1: General diagram of the PV single-phase grid system (T: temperature, λ: irradiance)

In the literature, different techniques to maximize (PV) power transfer to various loads have been reported, including: perturb and observe (P&O) method ([1], [2]), the incremental conductance method (IncCond) ([3],[4], [5]), the open circuit voltage method, the short circuit method, the Ripple Correlation Control (RCC) method [6] and artificial neuronal networks based algorithms([7]-[8]), amongst others.

In the first method mentioned above, (P&O), the output power has an oscillatory behavior about the maximum power point (MPP) which can be minimized by reducing the perturbation step size. However, a small perturbation size slows down the MPPT. Also, the equilibrium point is not always achieved, obtaining a local maximum instead of a global maximum. The artificial neuronal network has an involved structure and a singularity problem in (RCC) and (IncCond) methods

In this paper, a new control method for MPPT is proposed. A nonlinear backstepping controller ([9]-[10]) has been designed to track the maximum power point in the sense to extract the maximum power from photovoltaic generator regardless of temperature and solar radiation. In addition, the control of the DC-AC power inverter of the PV system has been designed to inject electrical power to the electrical network by means of a PI control. So, the global control makes possible extract the maximum power of the PV system, inject active power and regulate the input voltage of the DC-AC power inverter.

The rest of the paper is organized as follows: in Section 2, the system modeling is presented; Sections 3 is devoted to the controller design; the controller tracking performances are illustrated through numerical simulations in Section 4. A conclusion and a reference list end the paper.

2 Presentation and Modeling of Grid connected PV system:

The configuration of a single-phase grid connected photovoltaic system is shown in Fig 2, it consists of a solar array, an input capacitor C_i, a boost DC-DC converter which is used for boosting the array voltage and achieving MPPT for PV array, a DC link capacitor C_{dc}, a single phase full-bridge inverter (including fours power semiconductors) with filter inductor $L_g$which converters a DC input voltage into an AC sinusoidal voltage, and finally an isolation transformer. By means of appropriate switch signals u_1 and u_2, the converter is controlled to make the output current in phase with the utility voltage $e_g$and so obtain a power factor (PF) of unity.

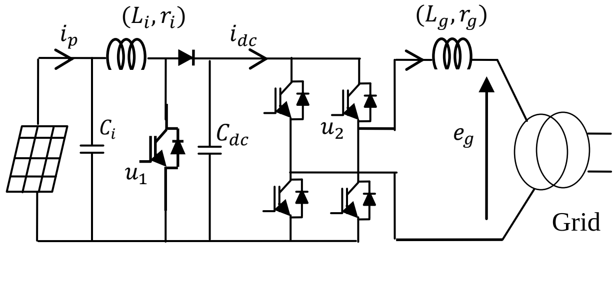

Fig.2: typical configuration of single stage grid connected pv system

2.1 Photovoltaic generator model

The direct conversion of the solar energy into electrical power is obtained by solar cells. The equivalent circuit of PV module is shown in fig 3. (see e.g. [11], [12], [13]).

The traditional $(I_p - V_p)$ ideal characteristics (i.e $R_s = 0, R_{sh} = \infty$) of a solar array are given by the following equation:

$$I_p = I_{ph} - I_O\{\exp(AV_p) - 1\} \quad (1)$$

Where

$$A = \frac{q}{\gamma KT}$$

$$I_{ph} = [I_{SOR} + K_1(T - T_r)]\frac{\lambda}{1000}$$

$$I_O = I_{or}\left[\frac{T}{Tr}\right]^3 exp\left[\frac{qE_{GO}}{\gamma K}\left(\frac{1}{Tr} - \frac{1}{T}\right)\right]$$

Where I_{ph} is the photocurrent (generated current under a given radiation), I_O is the cell reverse saturation current, I_{SOR} is the cell saturation current at T_r, I_{SOR} is the short circuit current at 298.15 k and 1KW/m², K is the short circuit current temperature coefficient at I_{SOR}. λ is the solar radiation, E_{GO} is the band gap for silicon, γ is the ideality factor , T_r is the reference temperature, T is the cell temperature, K is the Boltzmans constant and q is the electron charge, the analytical expressions of I_{ph} and I_{or} can be found in many places, see [9]. Here let us just note that these only depend on the temperature T and radiation λ. The pv array module considered in this paper is the NU-183E1

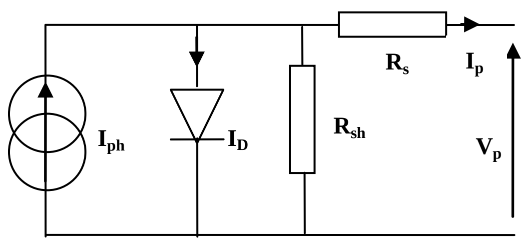

Fig.3: PV module circuit

Table1. Electrical specifications for the solar module NU-183E1

Parameter	Symbol	value
Maximum power	Pm	183,1w
Short circuit current	Iscr	8,48A
Open circuit voltage	Voc	30,1 V
Maximum power voltage	Vm	23,9 V
Maximum power current	Im	7,66A
Number of parallel modules	NP	1
Number of series modulesNs	48	

The associated power-voltage (P-V) characteristics under changing climatic conditions (temperature and radiation) are shown in fig 4 and 5.

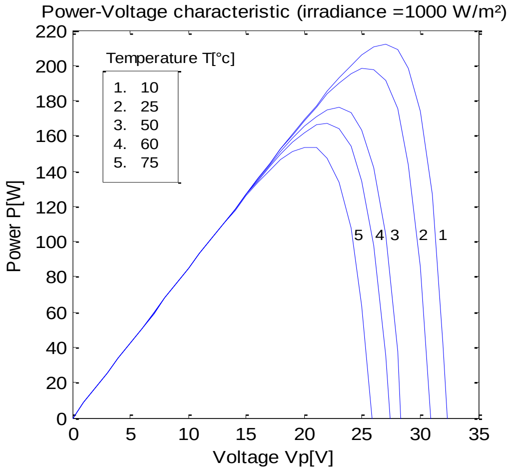

Fig.4: (*P-V*) characteristics of The PV module NU-183E1 with constant radiation and varying temperature

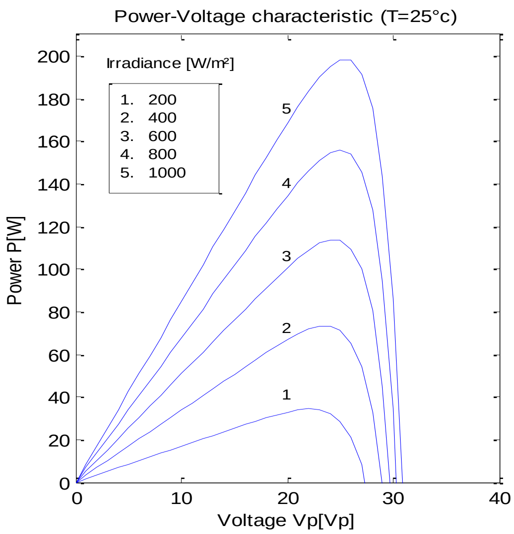

Fig.5: (*P-V*) characteristics of The PV module NU-183E1 with constant temperature and varying radiation

2.2 Overall system model

The control input u_1 and u_2 of the boost converter and for the inverter respectively are a PWM signals (pulse width modulation) taking values in the set $\{-1,1\}$, they vary from one period to another and their variations can determine the trajectories of the state variables of the converter.

Applying the kirchoff's laws, one obtains the following averaged model [14].

$$C_i\dot{x}_1 = -x_2 + \bar{\iota}_p \tag{2.a}$$

$$L_i\dot{x}_2 = -r_i x_2 + x_1 + \frac{1-u_1}{2}x_3 \tag{2.b}$$

$$C_{dc}\dot{x}_3 = -u_2 x_4 + \frac{1-u_1}{2}x_2 \tag{2.c}$$

$$L_g\dot{x}_4 = -r_g x_4 - \bar{e}_g + u_2 x_3 \tag{2.d}$$

Where $x_1, x_2, x_3, x_4, u_1, u_2$ and $\bar{\iota}_p$ denote respectively the means values, over a period of cutting of variables $v_p, i_{ci}, V_{dc}, i_g, \mu_1, \mu_2$ and i_p.

Note that the mathematical model (2a-d) is non linear because of the products involving the state variables and input signals. Taking into account these nonlinearities, a nonlinear controller using the backstepping approach ([9], [10]) will be done in the next paragraph.

3 Controller design

The converter control strategy must be developed to:

- Ensure a global stability of closed loop system
- Achieve the MPPT (maximum power tracking) side of the PV cell by setting the operating point power/voltage
- Ensure the setting of the DC bus voltage
- Obtain unity power factor and low harmonic distortion at the output

3.1 Controlling the boost converter to meet MPPT

Recall that the control objective is to enforce the output power $p(w) = v_p i_p$ to track as accurately as possible its optimal point (p_{opt}, v_{popt}) whatever the radiation λ and the temperature T. Specifically, if the derivative $y = \frac{dp}{dv_p}$ is made equal to $y_{ref} = 0$, then maximal power P_{opt} is captured. The control circuit must steer the derivative y to zero by acting on the duty cycle μ_1. At the optimal point, one has

$$\frac{dp}{dv_p} = \bar{\iota}_p + v_p\frac{d\bar{\iota}_p}{dv_p} = 0 \tag{3}$$

The controller is designed in two steps.

Design step 1: consider the tracking error z_1 defined by

$$z_1 = y - y_{ref} \quad (4)$$

In view of (1), its dynamics is given by

$$\dot{z}_1 = -\frac{AI_0}{C_i} exp(Ax_1)(2 + Ax_1)(\bar{\imath}_p - x_2) \quad (5)$$

In the above equation, the quantity x_2 stands as a virtual control variable. Let us use the lyapunov candidate function

$$V_1 = 0.5\, z_1^2 \quad (6)$$

As its derivative with respect to time, is given by

$$\dot{V}_1 = -z_1 \frac{AI_0}{C_i} exp(Ax_1)(2 + Ax_1)(\bar{\imath}_p - x_2) \quad (7)$$

Setting $\Delta = \frac{AI_0}{C_i} exp(Ax_1)(2 + Ax_1)$, It can be easily checked that Δ is a positive definite function, then equation (7) shows that the tracking error z_1 can be regulated to zero if $x_2 = \alpha_1$ where α_1 is a stabilizing function defined by

$$\alpha_1 = \bar{\imath}_p - c_1 z_1 \quad (8)$$

Where c_1 is a positive design parameter, since x_2 is not the actual control input, one can only seek the convergence of the error $(x_2 - \alpha_1)$ to zero. We then define the following second error variable

$$z_2 = x_2 - \alpha_1 \quad (9)$$

Using (9), equation (5) becomes

$$\dot{z}_1 = -\Delta(c_1 z_1 - z_2) \quad (10)$$

Also, the derivative (7) is rewritten

$$\dot{V}_1 = -\Delta z_1(c_1 z_1 - z_2) \quad (11)$$

The next step is to determine a variation law for the control signal u_1 so that the set of errors z_1 and z_2 vanish asymptotically.

Design step 2: the objective now is to enforce the error variables $(z_1, z_2) = (0,0)$, to this end, let us first determine the dynamics of z_2. Deriving (9) and using (2.b) and (10) one obtains:

$$\dot{z}_2 = \left(\frac{1 - u_1}{2}\right)\frac{x_3}{L_i} - \frac{r_i x_2}{L_i} + \frac{x_1}{L_i} - \frac{d\bar{\imath}_p}{dt} - c_1(c_1 z_1 - z_2)\Delta \quad (12)$$

To stabilize the whole system with state vector is (z_1, z_2) , we consider the augmented lyapunov function candidate

$$V_2 = V_1 + 0.5\, z_2^2 = 0.5 z_1^2 + 0.5 z_2^2 \quad (13)$$

Our goal is to make $\dot{V}_2$ non-positive definite

$$\dot{V}_2 = -c_1 \Delta z_1^2 - c_2 z_2^2 + z_2[\Delta z_1 + c_2 z_2 + \dot{z}_2] \quad (14)$$

Where $c_2 > 0$ is a design parameter.

Equation (14) shows that the equilibrium $(z_1, z_2) = (0,0)$ is globally asymptotically stable if

$$\dot{z}_2 = -c_2 z_2 + \Delta z_1 \quad (15)$$

Combining (12) and (15), one gets the following control law

$$u_1 = 1 - \frac{2}{x_3}\left(L_i\left((1 - c_1^2)\Delta z_1 + (c_1\Delta^2 - c_2) z_2\right) - x_1 - r_i x_2\right) \quad (16)$$

3.2 Controlling the inverter to meet unity PF in the grid

- Unity PF objective

The unity PF objective means that the grid current i_g should be sinusoidal and in phase with the (AC) grid supply voltage $\overline{e_g}$. It amounts to ensuring current harmonics rejection. We therefore seek a regulator that enforces the current x_4 to tack a reference signal x_4^* of the form

$$x_4^* = \beta\, \overline{e_g} \quad (17)$$

When $\beta \in IR^+$

The regulator will now be designed using the backstepping technique [10], consider the tracking error z_3 defined by

$$z_3 = x_4 - x_4^* \quad (18)$$

Its dynamics is given by

$$\dot{z}_3 = \dot{x}_4 - x_4^*$$

$$= u_2 \frac{x_3}{L_g} - \frac{r_g}{L_g} x_4 - \frac{\bar{e}_g}{L_g} - \dot{x}_4^* \quad (19)$$

To get a stabilizing control law for this system (18), consider the quadratic lyapunov function

$$V_3 = 0.5 z_3^2 \quad (20)$$

As its derivative with respect to time is giving by $\dot{V}_3 = \dot{z}_3 z_3$. It can be easily checked that $\dot{V}_3$ is negative definite function of z_3 if the control input u_2 is chosen to be

$$u_2 = \frac{1}{x_3}\{r_g x_4 + \bar{e}_g + L_g(-c_3 z_3 + x_4^*\} \quad (21)$$

Where c_3 is a positive constant parameter
Therefore global asymptotic stability is achieved and z_3 tends exponentially to zero. And the PF is asymptotically achieved.

- DC bus voltage regulation

The aim is now to design a tuning law for the ratio β in (17) in such a way that the DC bus voltage x_2 be regulated to a given reference $x_2^* > 0$, to this end, the following PI control law is used:

$$\beta = F(s)\varepsilon \quad (22)$$

Where

$$F(s) = k_p + k_i \frac{1}{s} \quad (23)$$

$$\varepsilon = x_2 - x_2^* \quad (24)$$

Where s denotes the Laplace variable.

The bode diagram of figure 6 shows the frequency response of the transfer function $F(s)$.

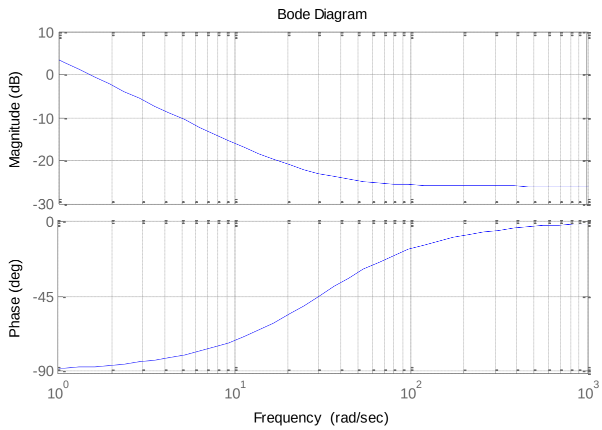

Fig. 6 Bode diagram of F(s)

The main results of the paper are now summarized in the following proposition.

Proposition 1. Consider the closed loop system consisting of the single phase grid-connected PV system, of fig. 2 represented by its averaged model (2a-d), and the controller composed of the control laws (16), (21) and (22). Then one has the following results:

- The closed loop system is globally asymptotically stable
- The tracking error z_1 vanishes exponentially, implying MPPT achievement.
- The error $(x_2 - x_2^*)$ converge to zero guaranteeing a tight regulation of the DC bus voltage.
- The error z_3 converge to zero ensuring a unity PF

5 Simulation results

The performances, described by proposition 1 of the proposed nonlinear controller are now illustrated by simulation using the MATLAB software. The characteristics of the controlled system are listed in table II. The control design parameter which proved to be convenient are given values of table III. The resulting control performances are shown by Figs 7 to 9.

TABLA II. Characteristics of controlled system

Parameter	*symbol*	*value*
PV array	*PV model*	*NU-183E1*
Boost converter	C_i	*4700uF*
	L_i	*1mH*
	r_i	*0.65 Ω*
Dc link capacitor	C_{dc}	*6800uF*
Grid filter inductor	L_g	*2.2mH*
	r_g	*0.47 Ω*
Grid	*Transformer ratio*	*22:220*
	AC source	*220 V*
	Line frequency	*50 Hz*

TABLE III. Controller parameters

Parameter	*symbol*	*value*
Design parameter	c_1	*1.5x102*
	c_2	*1.5x102*
	c_3	*2 x102*
PI- regulator	k_p	*5 1x0-2*
	k_i	*1.51*
Desired DC bus voltage	x_2^*	*48V*

Fig 7 illustrates the behavior of controlled system in presence of temperature change. The change are carried out between 298.15 K and 333.15K (25°C and 60°C), meanwhile the radiation λ is kept constant, equal to 1000W/m². The figures shows that the captured PV power varies between 198.5W and 167W, these values correspond (see fig. 4) to the maximum power point of the curves associated to the mentioned temperatures, respectively. The figure shows also that the DC bus voltage x_3 is regulated to its desired value (48V). fig 8 shows that the grid current i_g remains most time in phase with the supply voltage $e_g$complying with the PFC requirement.

Fig. 9 illustrates the controller behavior when facing radiation changes, specifically, the radiation varies between 1000W/m² and 400W/m²; while the temperature is constant equal to 298.15K (25°C). It is seen that the captured power P achieves the values 198.3W and 73.17W corresponding to the maximum power point associated to the considered radiation (see Fig. 5). We can see also that the DC bus voltage x_3 is regulated to its desired value (48V). Fig. 10 shows that the current i_g is sinusoidal and in phase with the source voltage e_g. Which proves the required unity PF.

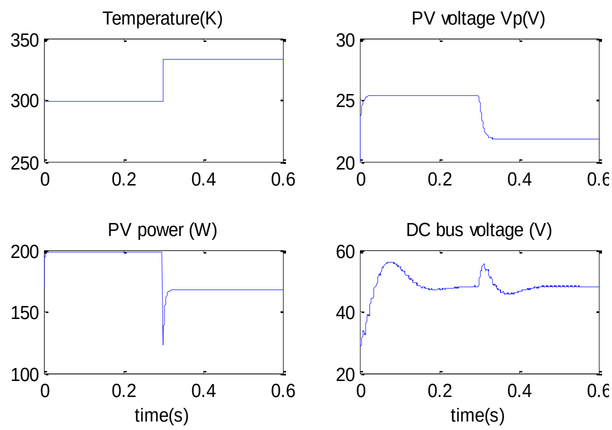

Fig.7: PV power and DC bus voltage in presence of temperature change

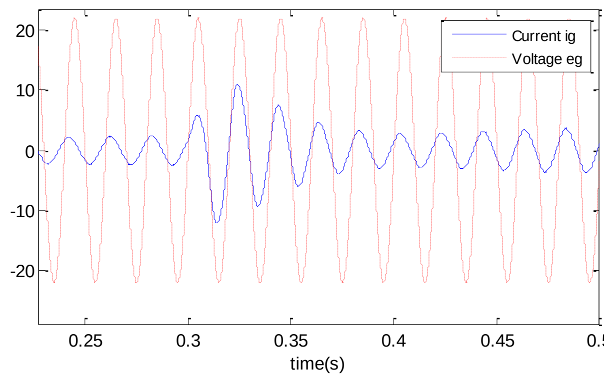

Fig 8. Unity PF behavior in presence of temperature changes

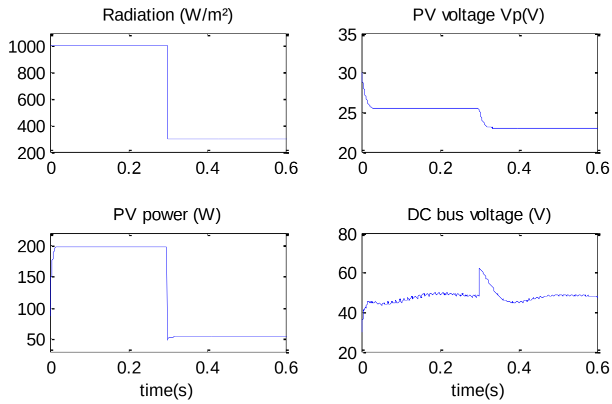

Fig.9 PV power and DC bus voltage in presence of radiation changes

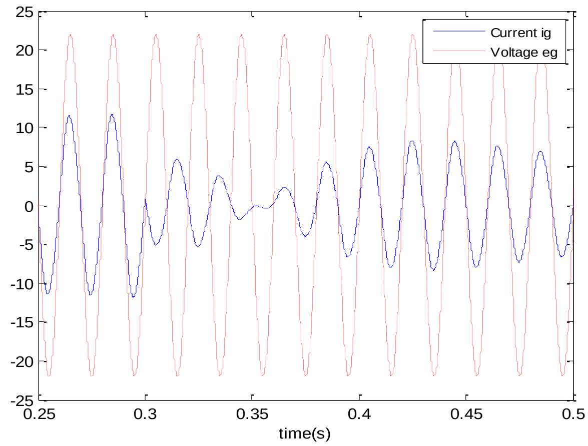

Fig 10. Unity PF behavior in presence of radiation changes

6 Conclusion

In this paper, the problem of achieving MPPT in single phase grid- connected photovoltaic systems has been addressed. A new control strategy has been developed using the backstepping design approach. Based on the system nonlinear model (2.a-d), the developed controller is resorted to cope with the changing operating conditions (temperature and radiation) and to remedy to disadvantages of (RCC), (INCOND) and (P&O) methods, the realized MPPT controller is shown to meet its objectives, despite the climatic conditions, this performances are cheked by simulations.

References :

[1] Enrico Bianconi, Javier Calvente, Roberto Giral, Emilio Mamarelis, Giovanni Petrone, Carlos Andres Ramos-Paja, Giovanni Spagnuolo, Massimo Vitelli. (2013) "Per-turb and Observe MPPT algorithm with a current con-troller based on the sliding mode". *International Journal of Electrical Power and Energy Systems (IJEPES)*, Vol.44, pp: 346-356.

[2] Yong Yang, Fang Ping Zhao. (2011) "Adaptive perturb and observe MPPT technique for Grid connected Pho-tovoltaic Inverters." *Procedia Engineering*,Vol.23,pp:468-473.

[3] Panagiotis E. Kakosimos, Antonios G. Kladas. (2011) "Im-plementation of photovoltaic array MPPT through _xedstep predictive control technique*".Renewable Energy, El-sevier*, Vol. 36, pp: 2508-2514.

[4] Lalili D, A. Mellit, N. Lourci, B. Medjahed, E.M. Berkouk.(2011) "Input output feedback linearization control and variable step size MPPT algorithm of a grid-connectedphotovoltaic inverter". *Renewable Energy, Elsevier*,Vol.36,pp:3282-3291.

[5] Georgios Tsengenes, Georgios Adamidis. (2011) "Investi-gation of the behavior of a three phase grid-connected photovoltaic system to control active and reactive power*". Electric Power Systems Research*, Vol. 81, pp: 177-184.

[6] Trishan Esram, Jonathan W. Kimball, Philip T. Krein, Patrick L. Chapman, Pallab Midya. (2006) "Dynamic Maximum Power Point Tracking of Photovoltaic Arrays Using Ripple Correlation Control". *IEEE TransactionsOn Power Electronics*, Vol. 21, No. 5, pp: 1282-1291.

[7] T. Hiyama and K. Kitabayashi, "Neural network based estimation of maximum power generation from PV module using environment information,"*IEEE Trans. Energy Conv.,* vol. 12, no. 3, pp. 241–247, Sep.1997.

[8] A. B. G. Bahgat, N. H. Helwa, G. E. Ahmad,

[9] and E. T. E. Shenawy, "MPPT controller for PV systems using neural networks," *Renew. Energy*, vol. 30, no. 8, pp. 1257–1268, 2005.

[10] Khalil H Nonlinear Systems. Prentice Hall, NJ, USA.

[11] Krstic M, I. Kanellakopoulos and P. Kokotovic. (1995) "Nonlinear and Adaptive Control Design". *JohnWilley&Sons,Inc*.

[12] Enrique J.M., 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.

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

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