

# THREE PHASE GRID-CONNECTED PHOTOVOLTAIC SYSTEM USING MPPT AND BACKSTEPPING-BASED CONTROL IN A BOOST CONVERTER

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**Abstract**—*The present work describes the analysis, modeling and control of a Boost-Buck power inverter used as a DC-DC and DC-AC power conditioning stage for three phase grid-connected photovoltaic (PV) systems.*

*To maximize the steady-state input-output energy transfer ratio a backstepping controller is designed to assure output unity power factor, extract and transfer a Maximum Power extracted from photovoltaic generator. The achievement of the DC-AC conversion at unity power factor and the efficient PV's energy extraction are validated with simulation results.*

**Key words:** MPPT, unity power factor, PI controller, backstepping, PV

## 1.Introduction

Many renewable energy technologies today are well developed, reliable, and cost competitive with the conventional fuel generators. The cost of renewable energy technologies is on a falling trend as demand and production increases. There are many renewable energy sources such as solar, biomass and wind. The solar energy has several advantages for instance clean, unlimited, and its potential to provide sustainable electricity in area not served by the conventional power grid.

However, the solar energy produces the dc power, and hence power electronics and control equipment are required to convert dc to ac power. There are two types of the solar energy system: stand-alone and grid-connected power system. Both systems have several similarities, but are different in terms of control functions [1].

The stand-alone system is used in off-grid application with battery storage. Its control algorithm must have an ability of bidirectional operation, which is battery charging and inverting. The grid-connected system, on the other hand, inverts dc to ac and transfers electrical energy directly to power grid. Its control function must follow the voltage and frequency of the utility-generated power presented on the distribution line. With a GCI (grid connected inverter) excess power is bought and credited by the utility, and grid power is available at times when the local demand exceeds the PV system output [1].

Usually, the power stage circuits in charge of performing the dc-ac conversion are based on a full-bridge buck switching converter topology. Regarding the control subsystem, several control schemes oriented to ensure a proper tracking of an external sinusoidal reference have been suggested. For instance, many tracking control techniques based on high-frequency pulse width modulation (PWM) have been proposed in the past for buck based dc-ac converters.

On the other hand, linear mode control techniques have been proposed as an alternative to PWM control strategies in dc-ac switching regulators. The advantage of a linear control is the simplicity of implementation and its ability to meet the need of adjustment of state variables.

A power conditioning system linking the solar array and the three phase utility grid is needed to facilitate an efficient energy transfer between them, this implies that the power stage has to be able to extract the maximum of energy from the PV panels and to assure that the output current presents both low harmonic distortion.

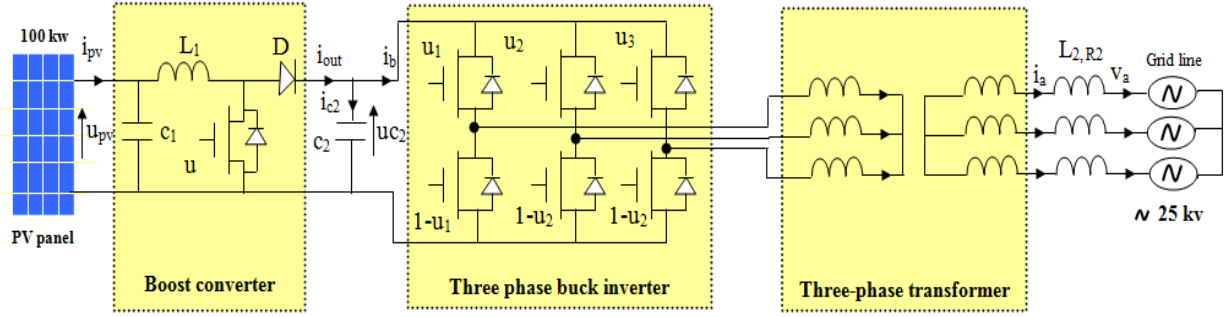


Fig. 1. Cascade connection of a boost converter with a three phase full-bridge buck inverter

In order to extract the maximum of energy, the PV system must be capable of tracking the solar arrays maximum power point (MPP) that varies with the solar radiation and temperature. Several MPPT algorithms have been proposed, namely, Perturb and Observe (P&O), incremental conductance, fuzzy based algorithms, etc. They differ from its complexity and tracking accuracy but they all required sensing the PV current and/or the PV voltage [2].

Several controller strategies have been used in the literature, citing the PI that is generally suitable for linear systems, the sliding mode for which the chattering problem and fuzzy logic adapted to systems without a mathematical model .

In this paper, a linear PI control strategy is developed to extract and transfer maximum power of a PV system and assure that the output current presents both low harmonic. The desired array voltage is designed online using a P&O (Perturb and Observe) MPP tracking algorithm. The rest of the paper is organized as follows. The dynamic model of the global system (PV, boost converter and buck inverter) are described in Section II. A linear controllers are designed along with the corresponding closed-loop error are discussed in Section III. In Section IV, a simulation results of the controller with respect solar radiation change.

## 2. MPPT System Modeling

The PV system model consists of a PV array panel, dc-to-dc boost converter, and three phase dc-to-ac buck inverter and three phase transformer as shown in Figure1.

### 2.1 PV model

PV array is a p-n junction semiconductor, which converts light into electricity. When the incoming solar energy exceeds the band-gap energy of the module, photons are absorbed by materials to generate electricity. The equivalent-circuit model of PV cell is shown in Figure 2. It consists of a light-generated source, diode, series and parallel resistances [3].

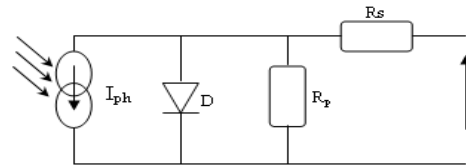


Fig.2. equivalent model of solar cell

### 2.2 Boost model

The dynamic model of the boost converter (figure 3 ) can be expressed by an instantaneous switched model as follows [5]:

$$\begin{aligned} C_1 \cdot \dot{u}_{pv} &= i_{pv} - i_{L1} \\ L_1 \cdot \dot{i}_{L1} &= u_{pv} - (1 - u) \cdot u_{c2} \end{aligned} \quad (1)$$

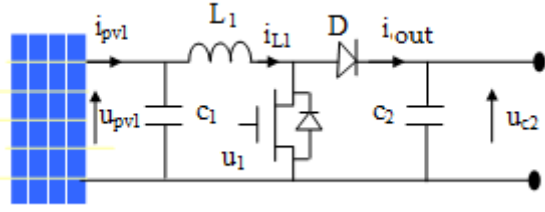


Fig 3: PV array connected to boost circuit

where  $L_1$  and  $i_{L1}$  represents the dc-to-dc converter storage inductance and the current across it,  $u_{c2}$  is the DC bus voltage and  $u$  is the switched control signal that can only take the discrete values 0 (switch open) and 1 (switch closed).

Using the state averaging method, the switched model can be redefined by the average PWM model as follows:

$$\begin{aligned} C_1 \dot{\bar{u}}_{pv} &= \dot{\bar{i}}_{pv} - \dot{\bar{i}}_{L1} \\ L \dot{\bar{i}}_L &= \bar{u}_{pv} - \alpha \bar{u}_{c2} \end{aligned} \quad (2)$$

Where  $\alpha$  is averaging value of  $u$ ,  $u_{pv}$  and  $i_{pv}$  are the average states of the output voltage and current of the solar cell,  $i_{L1}$  is the average state of the inductor current.

### 2.3 Current control modeling

The active power transfer from the PV panels is accomplished by power factor correction (line current in phase with grid voltage). The inverter operates as a current-control inverter.

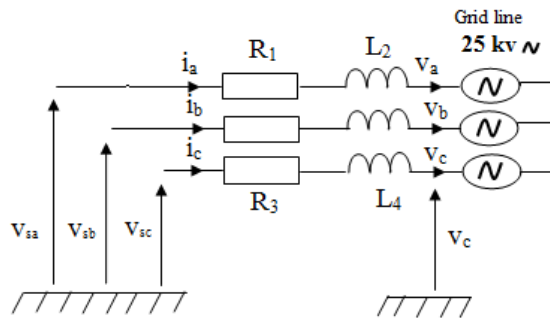


Fig. 4. Simplified circuit from AC output

The converter modeling is relatively simple and is accomplished through  $dq0$  transformation. The modeling for the current control is obtained considering the AC output.

When the circuit is observed from the AC output, it is possible to make some initial considerations that result in a simplified circuit, shown in Fig. 4. The line voltages are presented in (3) considering  $L2=L3=L4=L$ ,  $R1=R2=R3=R$

$$\begin{cases} v_{sa} = Ri_a + L \frac{di_a}{dt} + v_a \\ v_{sb} = Ri_b + L \frac{di_b}{dt} + v_b \\ v_{sc} = Ri_c + L \frac{di_c}{dt} + v_c \end{cases} \quad (3)$$

Where  $v_{sa}$ ,  $v_{sb}$  and  $v_{sc}$  are the voltages at the output of the three-phase transformer respectively.  $v_a$ ,  $v_b$  and  $v_c$  are the grid voltage.

Applying  $dq0$  transformation and developing the equations system (3), it is possible to find the differential equations (4) :

$$\begin{cases} v_d = Ri_d + L \frac{di_d}{dt} + L\omega i_q + V_d \\ v_q = Ri_q + L \frac{di_q}{dt} - L\omega i_d + V_q \end{cases} \quad (4)$$

The expression of the active and reactive power injected to the grid are :

$$\begin{cases} P = V_d i_d + V_q i_q \\ Q = V_d i_q - V_q i_d \end{cases} \quad (5)$$

Where  $(V_d, V_q)$  are the direct and quadrature components of the grid voltage.  $(i_d, i_q)$  are the

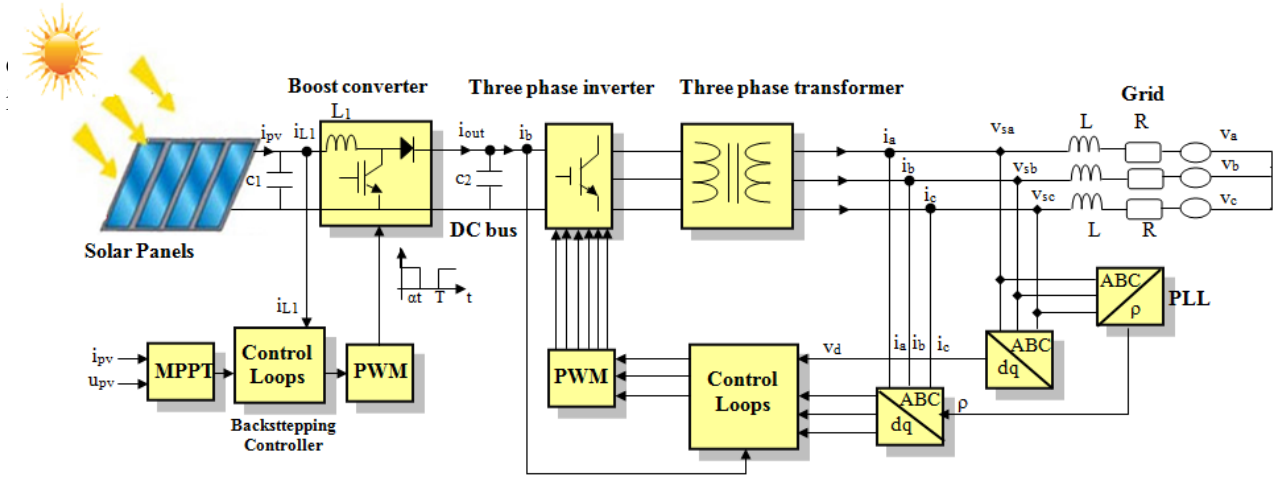


Fig. 5. Simulated three phase grid-connected photovoltaic system

The term  $-\omega.L.i_q + V_d$  and  $\omega.L.i_d$  are compensated by a feed-forward action. By applying the Laplace transform to the compensated system, the transfer function of the inverter is given as:

$$G_i(p) = \frac{v_d}{i_d} = \frac{v_q}{i_q} = \frac{1}{L.P+R} \quad (6)$$

Where the inputs are the the voltages  $v_d$  and  $v_q$  and the outputs are the currents  $i_d$  and  $i_q$ .

The DC bus dynamics is given as :

$$C_2 \cdot \dot{u}_{c2} = i_{out} - i_b \quad (7)$$

The application of the Laplace transform to (8)

result in :

$$C_2 \cdot P \cdot \dot{u}_{c2} = i_{out}(P) - i_b(P) \quad (8)$$

The term  $i_{out}$  is a disturbance in the control. It is assumed in this work that the DC bus loop is sufficiently fast, as to eliminate the perturbation

term. For this reason, the DC bus function will be:

$$G_u(p) = \frac{u_{c2}}{i_b} = -\frac{1}{C_2 \cdot P} \quad (9)$$

### 3. MPPT and Backstepping controller

The boost converter is governed by control signal  $\alpha$  generated by a backstepping controller that allow to extract maximum of photovoltaic generator control by regulating the voltage of the photovoltaic generator to its reference provided by conventional P&O MPPT algorithm [4].

Step 1. Let us introduce the input error:

$$e_1 = u_{pv} - u_{pv}^* \quad (10)$$

Deriving  $e_1$  with respect to time and accounting for (2) , implies:

$$\dot{e}_1 = \dot{u}_{pv} - \dot{u}_{pv}^* = \dot{u}_{pv} - \left( \frac{\bar{i}_{pv}}{C_1} - \frac{\bar{i}_{L1}}{C_1} \right) - C_1 \cdot \dot{u}_{pv} \quad (11)$$

In equation (11),  $i_{L1}$  behaves as a virtual control input. Such an equation shows that one gets  $\dot{e}_1 = -k_1 \cdot e_1$  ( $k_1 > 0$  being a design parameter) provided that:

$$\bar{i}_{L1} = -k_1 \cdot C_1 \cdot e_1 + \bar{i}_{pv} - C_1 \cdot \dot{u}_{pv}^* \quad (12)$$

As  $\bar{i}_{L1}$  is just a variable and not (an effective) control input, (11) cannot be enforced for all  $t \geq 0$ . Nevertheless, equation (11) shows that the desired value for the variable  $i_{L1}$  is:

$$\beta = i_{L1}^* = -k_1 \cdot c_1 \cdot e_1 + \bar{i}_{pv} - c_1 \cdot \dot{u}_{pv}^* \quad (13)$$

Indeed, if the error:

$$e_2 = i_{L1} - i_{L1}^* \quad (14)$$

vanishes (asymptotically) then control objective is achieved i.e.  $e_1 = u_{pv} - u_{pv}^*$  vanishes in turn. The desired value  $\beta$  is called a stabilization function.

Now, replacing  $i_{L1}$  by  $(e_2 + i_{L1}^*)$  in (11) yields:

$$\dot{e}_1 = \dot{u}_{pv} - \left( \frac{\bar{i}_{pv}}{c_1} - \frac{\bar{i}_{L1} + e_2}{c_1} \right) \quad (15)$$

which, together with (14), gives:

$$\dot{e}_1 = -k_1 \cdot e_1 + \frac{e_2}{c_1} \quad (16)$$

Step 2. Let us investigate the behaviour of error variable  $e_2$ .

In view of (14) and (2), time-derivation of  $e_2$  turns out to be:

$$\dot{e}_2 = \dot{i}_{L1} - \dot{i}_{L1}^* = \frac{\bar{u}_{pv}}{L_1} - \frac{\alpha \cdot \bar{u}_{c2}}{L_1} - \dot{i}_{L1}^* \quad (17)$$

From (13) one gets:

$$\dot{i}_{L1}^* = -k_1 \cdot c_1 \cdot \dot{e}_1 + \dot{\bar{i}_{pv}} - c_1 \cdot \ddot{u}_{pv}^* \quad (18)$$

which together with (17) implies:

$$\dot{e}_2 = \frac{\bar{u}_{pv}}{L_1} - \frac{\alpha \cdot \bar{u}_{c2}}{L_1} + k_1 \cdot c_1 \cdot \dot{e}_1 - \dot{\bar{i}_{pv}} + c_1 \cdot \ddot{u}_{pv}^* \quad (19)$$

In the new coordinates  $(e_1, e_2)$ , the controlled system (2) is expressed by the couple of equations (16) and (19). We now need to select a Lyapunov function for such a system. As the objective is to drive its states  $(e_1, e_2)$  to zero, it is natural to choose the following function:

$$v = \frac{1}{2} \cdot e_1^2 + \frac{1}{2} \cdot e_2^2 \quad (20)$$

The time-derivative of the latter, along the  $(e_1, e_2)$ -trajectory, is:

$$\dot{v} = -k_1 \cdot e_1^2 - k_2 \cdot e_2^2 + e_2 \cdot \left[ \frac{\bar{u}_{pv}}{L_1} - \frac{\alpha \cdot \bar{u}_{c2}}{L_1} + k_1 \cdot c_1 \cdot \dot{e}_1 - \dot{\bar{i}_{pv}} + c_1 \cdot \ddot{u}_{pv}^* + k_2 \cdot e_2 \right] \quad (21)$$

where  $k_2 > 0$  is a design parameter and  $\dot{e}_2$  is to be replaced by the right side of (19). Equation (21) shows that the equilibrium  $(e_1, e_2) = (0, 0)$  is globally asymptotically stable if the term between brackets in (21) is set to zero. So doing, one gets the following control law:

$$\alpha = \frac{L_1}{\bar{u}_{c2}} \left[ \frac{\bar{u}_{pv}}{L_1} + k_1 \cdot c_1 \cdot \dot{e}_1 - \dot{\bar{i}_{pv}} + c_1 \cdot \ddot{u}_{pv}^* + k_2 \cdot e_2 \right] \quad (22)$$

### **Proposition :**

Consider the control system consisting of the average PWM Boost model (2) in closed-loop with the controller (22), where the desired input voltage reference  $u_{pv}^*$  is sufficiently smooth and satisfies  $u_{pv}^* > 0$ . Then, the equilibrium  $i_{L1} \rightarrow i_{L1}^*$ ,  $u_{pv} \rightarrow u_{pv}^*$  and  $\alpha \rightarrow \alpha_0$  is asymptotically stable where :

$$\alpha_0 = \frac{\bar{u}_{pv}}{\bar{u}_{c2}} \quad (23)$$

### 4. Design of current and voltage controller

The control loops of the inverter are shown in figure (6). Externally, there is the reactive power loop that controls the power factor and the loop to regulate the DC bus voltage. The current control loops use proportional-integral controllers. The controller gains are adjusted by the poles allocation method.

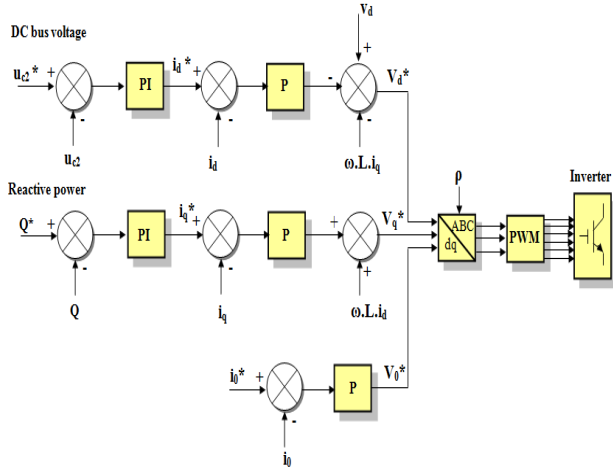


Fig.6. Control loops of the inverter

### 5. Simulation result

The PV model, boost-buck inverter model, backstepping and PI controller are implemented in Matlab/Simulink as illustrated in Figure 5. In the study, SPR 305 PV module has been selected as PV power source, and the parameter of the components are chosen to deliver maximum 100kW of power generated by connecting of 330 panels, in a connection of 5 panels in series and 66 blocks in parallel. The specification of the system and PV module are respectively summarized in the table.

TABLE I  
MAIN CHARACTERISTICS OF THE PV GENERATION SYSTEM

Maximum power	Output voltage at $P_{max}$	Open-circuit voltage	Short current circuit
305w	54.7v	64.2v	5.96A

TABLE II  
CONTROL PARAMETERS USED IN THE SIMULATION

Boost converter		Inverter	
$c_1$	220 $\mu$ F	$L_2$	2mH
$c_2$	4700 $\mu$ F	R	10m $\Omega$
$L_1$	1mH	$V_d$	25kv
f	20kHz	f	10kHz

TABLE II  
PARAMETERS USED IN INVERTER CONTROLLER

Parameters	Value
Backstepping controller $k_1, k_2$	10, 1000
PI (DC bus voltage) $K_i, K_p$	30, 100
PI (reactive power) $K_i, K_p$	2, 2000
P (direct current) $K_p$	5
P (quadrature current) $K_p$	5

The proposed controller is evaluated from robustness to irradiance change.

Figure 6 shows the simulation results of the designed system.

Figure 6.b and 6.c illustrate the variables of the solar panel (voltage and power) according to the irradiation change (fig 6.a). The backstepping based control allows the solar panel to work in the MPPT.

Figure 6.d show the DC-link capacitor voltage. The DC bus voltage reaches the commanded value of 450V which is greater than AC grid voltage.

Figure 6.e and 6.f shows the injected current in the grid. It can be observed that the inverter's control regulate the amplitude of the current in function of the generated power. Figure 6.e shows the current injected into the network and the grid voltage are in phase, so the power factor is almost unitary.

Figure 6.g shows the active power injected into the three-phase network. It can be seen that this power is highly depend on variation of the solar radiation. The active power injected in the grid is very close to the generated value. The difference is due to the internal losses in the system.

Figure 6.h illustrate the reactive power injected by the three-phase inverter. The reactive power oscillate around zero.

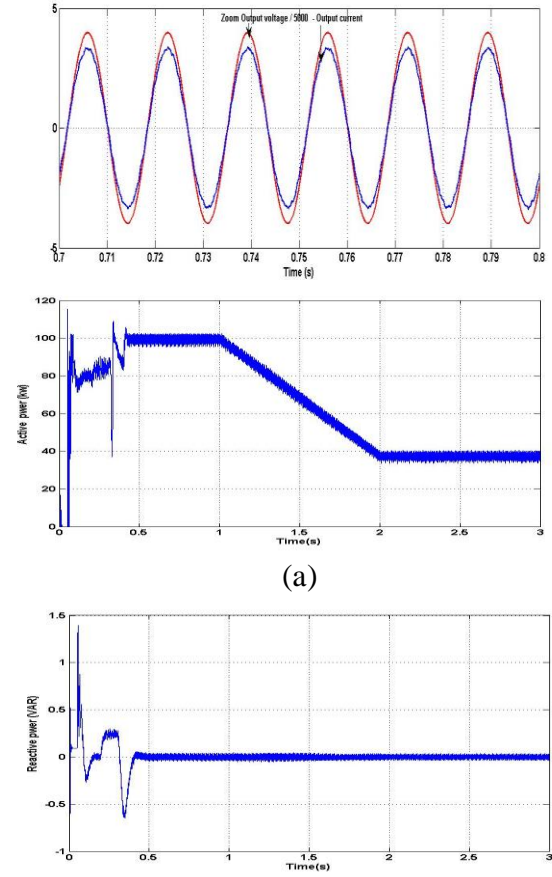
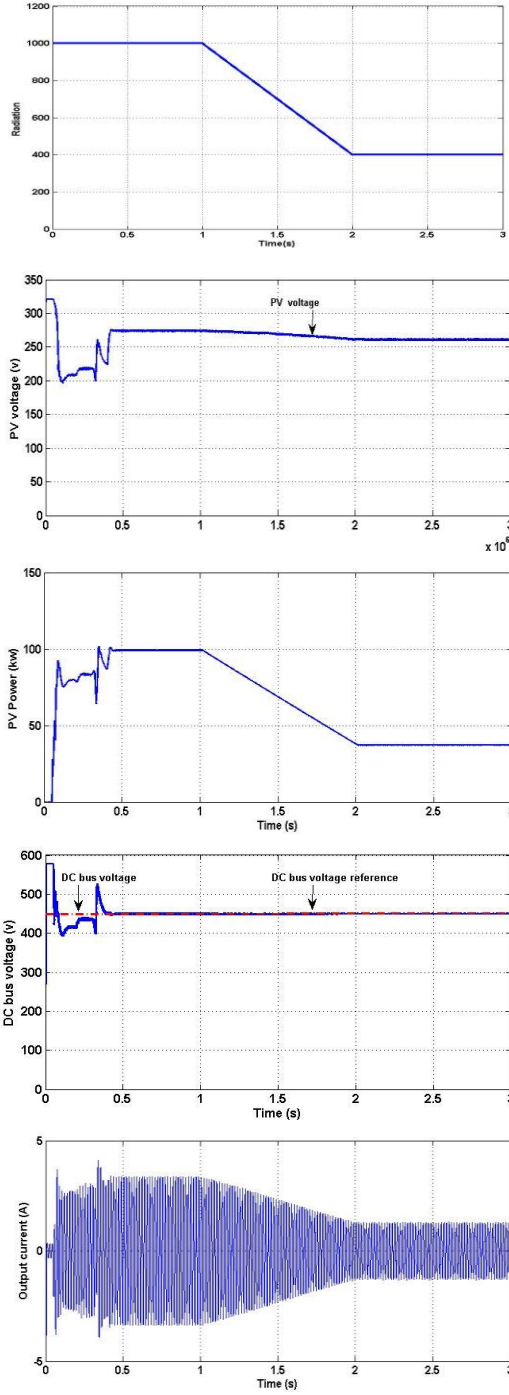


Figure 6. (a) radiation, (b) PV voltage, (c) PV power, (d) DC bus voltage (e) grid current, (f) grid voltage and current [0.7s to 0.8s], (g) Active grid power, (h) Reactive power

## Conclusions

The presented results show that the backstepping controller applied to the boost converter allows to extract the maximum power in PV panel with fast dynamic response. The control of the inverter allows to connect the system to the grid, inject the power extracted and obtain unitary power factor.

The proposed controller is proven to yield global asymptotic stability and high efficiency with low harmonic distortion.

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