Ripple correlation MPPT and Robust Controller for Grid-Connected Photovoltaic Systems

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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 grid-connected photovoltaic (PV) systems. To maximize the steady-state input-output energy transfer ratio of a backstepping controller is designed to assure output unity power factor and a Maximum Power Point Tracking (MPPT) algorithm to optimize the PV energy extraction. The achievement of the DC-AC conversion at unity power factor and the efficient PV’s energy extraction are validated with simulation results.

Keywords: MPPT, unity power factor, backstepping controller, Lyapunov

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, wind, and tidal power. 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 power system and grid-connected power system. Both systems have several similarities, but are different in terms of control functions. 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 de 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 [1]-[2]. 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, backstepping mode control techniques have been proposed as an alternative to PWM control strategies in dc–ac switching regulators since they make these systems highly robust to perturbations, namely variations of the input voltage. A power conditioning system linking the solar array and the 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 amount of energy from the PV and to assure that the output current presents both low harmonic distortion and robustness in front of system's perturbations [3].

In order to extract the maximum amount of energy the PV system must be capable of tracking the solar array’s maximum power point (MPP) that varies with the solar radiation value and temperature. Several MPPT algorithms have been proposed, namely, Perturbation and Observation (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 [4].

Several controller strategies have been used in the literature, citing the PI in [5] that is generally suitable for linear systems, the sliding mode in [6] for which the chattering problem, and the fuzzy logic proposed
adjustment in adapted to systems without a mathematical model [7].

In this paper, a backstepping control strategy is developed to maximize the power of a solar generating system and to assure that the output current presents both low harmonic distortion and robustness in front of system’s perturbations. The desired array voltage is designed online using a RCC (Ripple Correlation Control) MPP tracking algorithm [8]. The proposed strategy ensures that the MPP is determined and the system errors are globally asymptotically stable. The stability of the control algorithm is verified by Lyapunov analysis [9].

The rest of the paper is organized as follows. The dynamic model of the global system (GPV, buck inverter (PWM)) is described in Section II. A backstepping controller is designed along with the corresponding closed-loop error system and the stability analysis is discussed in Section III. In Section IV, a simulation results proves the robustness of the controller with respect solar radiation and temperature change.

2. MPPT System Modeling

The solar generation model consists of a PV array module, dc-to-de boost converter and a dc-to-ac buck inverter as shown in Fig1.

![Fig 1: Cascade connection of a boost converter with a full-bridge buck inverter](image)

### II.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 is shown in Fig2. In this model, it consists of a light-generated source, diode, series and parallel resistances. Where Rs is relatively small and Rp is relatively large, which are neglected in the equation in order to simplify the simulation [10]-[11].

![Fig 2: equivalent model of solar cell](image)

### II.2 Inverter model

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 (CCI). Noticing that $u$ stand for the control signal of buck inverter, the system can be represented by differential equations (1) [3].

$$
\begin{align*}
  c_2 \cdot i_{c_2} &= i_d - i_b \\
  L_2 \cdot i_r &= u_s - u_f \\
  u_s &= (2u - 1) \cdot u_{c_2} \\
  i_r &= (2u - 1) \cdot i_b
\end{align*}
$$

Where $u \in [0,1]$

Where $u_{c_2}, u, u$ designs a DC voltage, output inverter voltage and AC grid voltage, respectively. And $i_{c_2}, i_b, i_r$ are converter output current, inverter input current and grid current, respectively.

Using the state averaging method (on cutting period), the switched model can be redefined by the average PWM model as follows:

$$
\begin{align*}
  c_2 \cdot \dot{i}_{c_2} &= i_d - u_{c_2} \cdot \frac{i_f}{u_s} \\
  L_2 \cdot \dot{i}_r &= \beta \cdot u_{c_2} - u_f
\end{align*}
$$

Where $\beta$ is averaging value of $(2u - 1)$

3. Control design

The backstepping approach is a recursive design methodology. It involves a systematic construction of both feedback control laws and associated Lyapunov functions. The controller design is completed in a number of steps, which is never higher than the system order.

Two main objectives have to be fulfilled in order to transfer efficiently the photovoltaic generated energy
into the utility grid are tracking the PV’s maximum power point (MPP) and obtain unity power factor and low harmonic distortion at the output. Figure 3 shows the control scheme used to accomplish the previous objectives.

The boost converter is governed by control signal \( a \) generated by a RCC (Ripple correlation control) maximum power point tracking (MPPT). RCC MPPT correlates the time derivative of the time-varying PV array power \( \dot{P} \) with the time derivative of the time-varying PV array voltage \( \dot{u}_{pv} \) to drive the power gradient to zero [9], thus reaching the MPP. if \( u_{pv} \) is increasing (\( \dot{u}_{pv} > 0 \)) and \( P \) is increasing (\( \dot{P}_{pv} > 0 \)), then the operating point is below the MPP (\( u_{pv} < u_{MPP} \)). On the other hand, if \( u_{pv} \) is increasing and \( P \) is decreasing (\( \dot{P}_{pv} < 0 \)), then the operating point is above the MPP (\( u_{pv} > u_{MPP} \)). Combining these observations, we see that \( \dot{P}_{pv} \dot{u}_{pv} \) are positive to the left of the MPP, negative to right of the MPP, and zero at the MPP.

When the power converter is a boost, increasing the duty ratio increases the inductor current \( i \), but decreases the PV array voltage. Therefore, the duty ratio control input is:

\[
\alpha(t) = -k \int \dot{P}_{pv} \dot{u}_{pv} \, dt
\]

The unity power factor controller input signal \( u \) that controls the buck inverter. This controller consists of an inner current loop and an outer voltage loop. The inner current loop is responsible of obtaining a unity power factor. The outer voltage loop assures a steady-state maximum input-output energy transfer ratio and a desired steady-state averaged DC-link voltage guarantying proper Buck inverter dynamics [3].

\[
\epsilon_1 = u_{c2} - \frac{u_{c2} \ast}{c_2} \tag{4}
\]

Where \( u_{c2} \ast \) is a reference signal of DC voltage which is equal to the nominal value of input inverter voltage (must be higher than the grid voltage). Deriving \( \epsilon_1 \) with respect to time and accounting for (2) and (4) implies:

\[
\dot{\epsilon}_1 = \frac{i_d}{c_2} - \frac{u_{c2}}{u_s} \frac{i_r}{c_2} \tag{5}
\]

In equation (5), \( i_r \) behaves as a virtual control input. Such an equation shows that one gets \( \dot{\epsilon}_1 = -k_1 \epsilon_1 \) \((k_1 > 0 \text{ a design parameter})\) provided that:

\[
i_r = \frac{u_s}{u_{c2}} (k_1 c_2 \epsilon_1 + i_d) \tag{6}
\]

As \( i_r \) is just a variable and not (an effective) control input, (5) cannot be enforced for all \( t \geq 0 \). Nevertheless, equation (5) shows that the desired value for the variable \( i_r \) is:

\[
\alpha_1 = i_r \ast - \frac{u_s}{u_{c2}} (k_1 c_2 \epsilon_1 + i_d) \tag{7}
\]

The equality of average (on cutting period) inverter output power \( \langle P_l \rangle = \langle u_i i \rangle \) and grid input power \( \langle P_e \rangle = \langle u_i i \rangle \) implies \( \langle u_i \rangle = \langle u_o \rangle \).

Indeed, if the error:

\[
e_2 = i_r - i_r \ast \tag{8}
\]

vanishes (asymptotically) then control objective is achieved i.e. \( e_1 = u_{c2} - u_{c2} \ast \) vanishes in turn. The desired value \( \alpha_1 \) is called a stabilization function.

Now, replacing \( i_r \) by \( (i_r \ast + e_2) \) in (5) yields:

\[
\dot{\epsilon}_1 = \frac{i_d}{c_2} - \frac{u_{c2}}{u_r} \frac{(i_r \ast + e_2)}{c_2} \tag{9}
\]

which, together with (7), gives:

\[
\dot{\epsilon}_1 = -k_1 \epsilon_1 - \frac{e_2}{c_2} \frac{u_{c2}}{u_r} \tag{10}
\]

**Step 1.** Let us introduce the input error:

**Step 2.** Let us investigate the behavior of error variable \( e_2 \).
In view of (1), time-derivation of \( c_2 \) turns out to be:

\[
\dot{e}_2 = \dot{i}_r - \dot{i}_r^* = \frac{\beta u_{c_2} - u_{r}}{L_2} - i_r^*
\]  

(11)

From (7) one gets:

\[
\dot{e}_1 = \dot{i}_r^* = \frac{(k_1 e_2 + i_d) (u_{r} u_{c_2} - u_{r} i_d) + u_{r} u_{c_2} (k_1 e_1 + i_d)}{(u_{c_2})^2}
\]  

(12)

which together with (11) implies:

\[
\dot{e}_2 = \frac{\beta u_{c_2} - u_{r}}{L_2} \frac{(k_1 e_2 + i_d) (u_{r} u_{c_2} - u_{r} i_d) + u_{r} u_{c_2} (k_1 e_1 + i_d)}{(u_{c_2})^2}
\]  

(13)

In the new coordinates \((e_1, e_2)\), the controlled system is expressed by the couple of equations (10) and (13). 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:

\[
V = \frac{1}{2} e_1^2 + \frac{1}{2} e_2^2
\]  

(14)

The time-derivative of the latter, along the \((\alpha 1, \alpha 2)\) trajectory, is: (substituting (2)-(3) in (13) and using (12))

\[
\dot{V} = e_1 \dot{e}_1 + e_2 \dot{e}_2
\]

\[
\dot{V} = -k_1 e_1^2 - k_2 e_2^2 + e_1 \left[ \frac{\beta u_{c_2} - u_{r}}{L_2} - i_r^* + k_2 e_2 \right]
\]  

(15)

where \( k_2 > 0 \) is a design parameter and \( i_r^* \) is to be replaced by the right side of (12). Equation (15) shows that the equilibrium \((e_1, e_2) = (0, 0)\) is globally asymptotically stable if the term between brackets in (15) is set to zero. So doing, one gets the following control law:

\[
\beta = \frac{-k_2 e_2}{u_{c_2} L_2 + u_{r}}
\]  

(16)

Proposition: Consider the control system consisting of the average PWM Buck model in closed-loop with the controller (12), where the desired DC voltage reference \( u_{c_2}^* \) is sufficiently smooth. Then, the equilibrium \( i_r \to i_r^* \), \( u_{c_2} \to u_{c_2}^* \) and \( \beta \to \mu \)

is locally asymptotically stable where:

\[
\mu = L_2 \left[ \frac{(u_{r} u_{c_2} - u_{r} u_{c_2}^*) + u_{r} u_{c_2} (k_1 e_1 + i_d)}{(u_{c_2})^3} \right] \frac{u_{r}}{u_{c_2}}
\]  

(17)

II. Simulation result:

The PV model, boost-buck inverter model, and proposed MPPT approach are implemented in Matlab/Simulink as illustrated in Figure 3. In the study, RSM-60 PV module has been selected as PV power source, and the parameter of the components are chosen to deliver maximum 1kW of power generated by connecting 16 module of RSM-60 in parallel. The specification of the system and PV module are respectively summarized in the following table.

<table>
<thead>
<tr>
<th>Control parameters used in the simulation</th>
<th>parameters</th>
<th>Value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_1 )</td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>( k_2 )</td>
<td></td>
<td>1130</td>
<td></td>
</tr>
</tbody>
</table>

| Characteristics of the photovoltaic generator | Maximum power | P_{max} | 60 w |
| Output voltage at | \( u_{pv,max} \) | 16v |

Open-circuit voltage | Voc | 21.5v |

A Matlab® simulation of the complete system with the backstepping controller and the RCC MPPT has been carried out using the following parameters:

- L1=1mH, L2=2mH, \( c_1=220\mu\text{F} \), \( c_2=2\text{mF} \)
- Buck switching frequency = 25kHz
- RCC MPPT frequency = 100kHz

The proposed controller is evaluated from two aspects: robustness to irradiance and temperature. In each figures, two different values of irradiance and temperature are introduced in order to show the robustness. Figure 4 shows the simulation results of the designed inverter when the solar radiation changes from 500W/m² to 1000W/m² and then the temperature.
change from 25°C to 30°C at t=2s and t=2.5s respectively. Notice that according to figure 4.c the maximum power point is always reached after a smooth transient response and that the power of photovoltaic generator (GPV) reaches the commanded value according to radiation change and temperature and that the DC-link capacitor voltage reaches the commanded value of 450V which is greater than AC grid voltage.

From figure 5.a, it can be seen that the output current is in phase with the utility grid voltage.

V. Conclusions

A backstepping control strategy has been developed for a solar generating system to inject the power extracted from a photovoltaic array and obtain unitary power factor in varying weather conditions. A desired array voltage is designed online using an MPPT searching algorithm to seek the unknown optimal array voltage. To track the designed trajectory, a tracking controller is developed to modulate the duty cycle of the boost-buck inverter. The
proposed controller is proven to yield global asymptotic stability with respect to the tracking errors via Lyapunov analysis. Simulation results are provided to verify the effectiveness of this approach.

References:


