Nonlinear Control of Single-Phase Grid Connected PV Generator through Multicellular Inverter

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Abstract— A nonlinear control methodology for single-phase grid connected of photovoltaic generator is presented in this paper. It consists of a PV arrays, a voltage source Multicellular inverter, a grid filter and an electric grid. The controller objectives are threefold: i) ensuring the Maximum power point tracking (MPPT) in the side of PV panels, ii) guaranteeing a power factor unit in the side of the grid, iii) ensuring a good convergence of the voltages across the flying capacitors. On the basis of the nonlinear model of the entire system, the controller is carried out using an approach of Lyapunov. The simulation results have been performed through Matlab/Simulink environment and show that the designed controller meets its objective.

Keywords— single-phase PV grid-connected inverters; nonlinear control, MPPT; Backstepping approach; Lyapunov stability.

I. INTRODUCTION

The world energy supply is still dominated by fossil fuels. In fact, according to recent published statistics [1], these resources constitute more than 80% of total primary energy. Power generation based on fossil-fuel combustion releases about 10 billion tons of carbon emissions per year and thus contributes to climate change with severe and irreversible consequences on the environment. Therefore, ensuring a secure and sustainable energy supply is one of the most important challenges facing the world, especially with the population growth and the improvement of living standards [2-3]. In this respect, photovoltaic (PV) based renewable energy presents several features e.g. simplicity of allocation, high dependability, absence of fuel cost, low maintenance and lack of noise and wear due to the absence of moving parts. In addition to these benefits, the recent progress made in the PV technology has resulted in quite lower cost and more efficient PV cells. This evolution is expected to continue in the future due to economies scale [4-6]. A comprehensive discussion about single-phase grid connected PV system with power conditioning capability has been given in [7,8]. Multilevel converters are proper alternatives for medium and high power applications and possess some advantages like increased number of output voltage levels, which improves output voltage spectrum with low harmonic distortion and reduces filter requirements.

In this work the flying capacitor multicellular (FCM) converter [9] is the only power converter interfacing the PV generator and single-phase grid, (see Fig. 1). This simpler structure prevents the disadvantages of using chopper (additional losses, investment and maintenance).

Several strategies for control have been proposed in the literature in order to improve the characterization of this topology for example: sliding modes in [10-12] hybrid control in [13-15] predictive control in [16-19] and passivity based control in [20].

The rest of the paper is organized as follows: in section 2, the description and the modeling of the system are presented, sections 3 is devoted to the controller design and the controller performances are illustrated through simulations under MATLAB/Simulink software in Section 4.

II. SYSTEM DESCRIPTION AND MODELING

A. System description

The main circuit of single phase grid-connected photovoltaic system is shown in Fig. 1. It consists of a PV arrays; two DC link capacitor C1 and C2; a single phase inverter (including 3 elementary switching cells in series, each switching cell of the converter is composed of pairs of complementary switches); a LCL filter is used in order to minimize the harmonics distortion of current and voltage and an electric grid.

![Fig. 1 Single-phase grid connected PV system](image_url)

As there is no DC-DC converter between the PV generator and the inverter, the PV array configuration should be chosen such that the output voltage of the photovoltaic generator is adapted to the requirements of the inverter, so the inverter would need at least 780V DC bus in order to be able to operate...
The PV array was found to require 22 series connected modules per string. Each solar module has the following Electrical specifications: Maximum Power $P_m = 200$ W. Short circuit current $I_{sc} = 8.21$ A. Open circuit voltage $V_{oc} = 32.9$ V. Maximum power voltage $V_{mp} = 26.3$ V. Maximum power current $I_{mp} = 7.61$ A.

### B. Converter and filter modeling

Applying Kirchhoff’s laws, the system under study is described by the following set of differential equations:

$$L_g i_g = v_c - r i_g$$

(a)

$$C_f \dot{v}_c = i_{Lf} - \dot{i}_g$$

(b)

$$L_f \ddot{i}_{Lf} = (\mu_1 - \mu_2) v_{cl} + (\mu_2 - \mu_3) v_{c2} + \mu_3 v_1 - v_c$$

(c)

$$C \dot{v}_{cl} = (\mu_2 - \mu_1) i_{Lf}$$

(d)

$$C \dot{v}_{c2} = (\mu_3 - \mu_1) i_{Lf}$$

(e)

$$C \dot{v}_1 = i_{pv} - \mu_1 i_{Lf}$$

(f)

$$C \dot{v}_2 = i_{pv} - (l - \mu_1) i_{Lf}$$

(g)

where $\mu_i \in [0,1], i = 1,2,3$.

The model (1a-c): However, it cannot used in the control design as it involves a binary control input, namely $\mu$. For control design purpose, it is more convenient to consider the following averaged model:

$$L_g \dot{x}_1 = x_2 - v_g - r_g x_1$$

(a)

$$C_f \dot{x}_2 = x_3 - x_1$$

(b)

$$L_f \ddot{x}_3 = (u_1 - u_2) x_4 + (u_2 - u_3) x_5 + u_3 x_6 - x_2$$

(c)

$$C \dot{x}_4 = (u_2 - u_1) x_3$$

(d)

$$C \dot{x}_5 = (u_3 - u_2) x_3$$

(e)

$$C \dot{x}_6 = i_{pv} - u_3 x_3$$

(f)

$$C \dot{x}_7 = i_{pv} - (l - u_1) x_3$$

(g)

where $x_1, x_2, x_3, x_4, x_5, x_6, x_7$ denote the average values, over cutting periods, of the signals $i_g, v_c, i_{Lf}, v_{cl}$, $v_c, v_1$, and $\mu_i$.

### III. Controller Design

#### A. Control Objectives

- **i)** ensuring the (MPPT) in the side of PV panels, the controller must enforce the average value of the voltage $x_7 = V_{pv}$ provided by the solar array to track as possible a given desired value of the reference voltage $x_7 = V_{pv}^*$.

- **ii)** guaranteeing a power factor unit in the side of the grid, by injecting (in the grid) a current with sinusoidal shape and in phase with a grid voltage, $x_1 = \beta V_g$.

- **iii)** ensuring a good convergence of the voltages across the flying capacitors at its desired reference values:

$$x^*_3 = \frac{V_{pv}^*}{3} \quad (5)$$

$$x^*_4 = \frac{2V_{pv}^*}{3} \quad (4)$$

#### B. Nonlinear control design

Following the backstepping technique, the controller is designed in three steps.

- **Step 1:**

  Let us define the following tracking error:

  $$z_j = C(x_j - x_j^*) \quad (5a)$$

  $$z_3 = C(x_3 - x_3^*) \quad (5b)$$

  $$z_3 = L_g (x_1 - x_1^*) \quad (5c)$$

  with $x_3^*, x_4^*$ and $x_1^*$ represent respectively the desired trajectories of $x_3, x_4$, and $x_1$.

  Deriving $z_1, z_2$ and $z_3$ with respect to time yields and accounting for (1a) and (1c-d), implies:

  $$\dot{z}_1 = (u_2 - u_1) x_3 - C \dot{x}_4$$

  $$\dot{z}_2 = (u_3 - u_2) x_3 - C \dot{x}_5$$

  $$\dot{z}_3 = x_2 - v_g - r_g x_1 - L_g \ddot{x}_1$$

  We need to select a Lyapunov function for such system. As the objective is to drive its state ($z_1, z_2, z_3$) to zero, it is natural to choose the following function:

  $$V_j = 0.5 z_1^2 + 0.5 z_2^2 + 0.5 z_3^2$$

  Its time derivative is given by the following equation:

  $$\dot{V}_j = z_1 \dot{z}_1 + z_2 \dot{z}_2 + z_3 \dot{z}_3$$

  The choice $\dot{V}_j = -\lambda_1 z_1^2 - \lambda_2 z_2^2 - \lambda_3 z_3^2$, where $\lambda_i (i = 1, \ldots, 3)$ are positive constants of synthesis, leads to a Lyapunov candidate function whose dynamics is negative definite.

  In view of (7b) and using (6) this suggests the following choices:

  $$(u_2 - u_1) x_3 - C \dot{x}_4 = -\lambda_1 z_1$$

  $$(u_3 - u_2) x_3 - C \dot{x}_5 = -\lambda_2 z_3$$

  $$x_2 - v_g - r_g x_1 - L_g \ddot{x}_1 = -\lambda_3 z_3$$

  if we choose $x_2$ as virtual control input, we deduce the stabilizing function namely $x_2^*$:

  $$x_2^* = -\lambda_3 z_3 + v_g + r_g x_1 + L_g \ddot{x}_1$$

  as $x_2$ is not the control input, a new error variable $z_4$ between $x_2$ and its desired value $x_2^*$ is introduced:

  $$z_4 = C_f (x_2 - x_2^*)$$

  using (10) and (9), dynamics of error $z_4$ becomes:

  $$\dot{z}_4 = \frac{z_4}{C_f} - \lambda_3 z_3$$

  In the same way

  $$V_1 = -\lambda_1 z_1^2 - \lambda_2 z_2^2 - \lambda_3 z_3^2 + \frac{z_2^2 z_4}{C_f}$$

- **Step 2:**
The objective now is to enforce the error variables \((z_1, z_2, z_3, z_4)\) to vanish. To this end, let us first determine the dynamics of \(z_4\), we obtain:

\[
\dot{z}_4 = x_4 - x_1 - C_f x_2^* 
\] (13)

Consider the augmented Lyapunov function candidate.

\[
V_2 = V_f + 0.5 z_4^2 
\] (14.a)

Using (12)-(14.a), its dynamics is given by:

\[
\dot{V}_2 = -\lambda_z z_2^* - \lambda_z z_3^* - \lambda_4 z_4^* - z_4 \left( \frac{\dot{z}_4}{C_f} + \frac{\dot{z}_4}{L_f} \right) 
\] (14.b)

As our goal is to make \(V_2\) non-positive definite \(V_2 = -\lambda_z z_2^* - \lambda_z z_3^* - \lambda_4 z_4^* - \lambda_4 z_4^2 \leq 0\), this suggests choosing that the bracketed term, in (14.C), is equal to \(-\lambda_4 z_4^2\):

\[
\dot{z}_4 = -\lambda_4 z_4 - \frac{\dot{z}_4}{C_f} \quad \text{(15)}
\]

where \(\lambda_4\) is a positive constant of synthesis. if we choose \(x_3\) as virtual control input, we deduce the stabilizing function namely \(x_3^*\):

\[
x_3^* = x_1 + C_f x_2^* - \lambda_4 z_4 - \frac{\dot{z}_4}{C_f} \quad \text{(16)}
\]

As \(x_3\) is not the control input, a new error variable \(z_5\) between \(x_3\) and its desired value \(x_3^*\) is introduced:

\[
z_5 = L_f (x_3 - x_3^*) \quad \text{(17)}
\]

using (11) and (16), dynamics of error \(z_4\) became:

\[
\dot{z}_4 = \frac{\dot{z}_5}{L_f} - \lambda_4 z_4 - \frac{\dot{z}_4}{C_f} \quad \text{(18)}
\]

In the same way

\[
\dot{V}_2 = -\lambda_z z_2^2 - \lambda_z z_3^2 - \lambda_z z_3^2 - \lambda_4 z_4^2 + \frac{\dot{z}_4 z_5}{L_f} \quad \text{(19)}
\]

- **Step 3:**

The objective now is to enforce the error variables to vanish. To this end, let us determine the dynamics of \(z_5\), we obtain:

\[
\ddot{z}_5 = \left( u_2 - u_1 \right) x_4 + \left( u_2 - u_1 \right) x_3 + u_3 x_0 - x_2 - L_f \dot{x}_1 \quad \text{(20)}
\]

We are finally in a position to make a convenient choice of the parameter update law and feedback control to stabilize the whole system with state vector \((z_1, z_2, z_3, z_4, z_5)\). Consider the augmented Lyapunov function candidate.

\[
V_3 = V_f + 0.5 z_5^2 
\] (21.a)

Using (19)-(21.a), its dynamics is given by:

\[
\dot{V}_3 = -\lambda_z z_2^2 - \lambda_z z_3^2 - \lambda_z z_3^2 - \lambda_4 z_4^2 + z_5 \left( \frac{\dot{z}_4}{L_f} + \frac{\dot{z}_5}{L_f} \right) \quad \text{(21.c)}
\]

As our goal is to make \(V_3\) non-negative definite \(V_3 = -\lambda_z z_2^2 - \lambda_z z_3^2 - \lambda_z z_3^2 - \lambda_4 z_4^2 - \lambda_4 z_4^2 \leq 0\), this suggests choosing that the bracketed term, on the right side of (21.c), is equal to \(-\lambda_5 z_5\):

\[
\dot{z}_5 = -\lambda_5 z_5 - \frac{\dot{z}_4}{L_f} \quad \text{(22)}
\]

Finally, the control input can be solved from the following system equations.

\[
f_1 = \left( u_2 - u_1 \right) x_4 + \left( u_2 - u_1 \right) x_3 + L_f \dot{x}_1 \quad \text{(23)}
\]

\[
u_2 = u_3 - C_f \left( x_3 - z_3^* \right) - \lambda_5 \frac{x_3}{L_f} \quad \text{(24)}
\]

\[
u_1 = u_2 - C \left( x_3 - z_3^* \right) \quad \text{(25)}
\]

where \(\lambda_5\) is a positive constant of synthesis.

**C. MPPT CONTROLLER DESIGN**

Maximum power point tracking, or MPPT, is the automatic adjustment of the load of a photovoltaic system to achieve the maximum possible power output. The output of the PV cells is expressed as the current-voltage characteristic of the PV cell. The maximum power point tracking (MPPT) can be addressed by different ways, in this paper we worked with the algorithm perturb and observe (P&O) which is the most method used due to its simplicity and a fewer measured parameter, it has two input signals. The algorithm steps are described as shown in the following flowchart (Fig.3). [21]

**IV. SIMULATION RESULTS**

The proposed control scheme, presented in Fig. 4, is validated through simulations performed using the Matlab/Simulink and its SimPower System Toolbox.

![Control block for multicellular inverter](image)

The proposed control scheme, presented in Fig. 4 is validated through simulations performed using the Matlab/Simulink environment. The simulation results have been obtained under standard climatic conditions \((\lambda=1000 \text{ W/m}^2 \text{ and } T=25^\circ \text{C})\) with the following parameters: Flying capacitor \(C_2\) and Dc link capacitors \(C_2=C=4 \text{ mF}\) Filter capacitor \(C=5 \text{ mF}\), Filter inductor \(L_f=2 \text{ mH}\) and grid inductors \(L_g=30 \text{ mH}\), \(R=35 \Omega\)

The control design parameter are given: \(\lambda_1=400\), \(\lambda_2=200\), \(\lambda_3=20000\), \(\lambda_4=200\), \(\lambda_5=900\), \(\beta=10/\left(220^*\sqrt{2}\right)\) and the Switching frequency \(f_s=10 \text{ kHz}\).
The resulting control performances are shown by Fig 5 to 8. Fig. 5 shows the PV voltage with its reference generated by the “P&O” algorithm. The voltage of the PV array \( V_{pv} \) after 0.18s varies between \( V_{pv}=600V \) and \( V_{pv}=700V \) and then returns to 780V, which correspond very well to the optimum voltage.

The capacitor voltages \( v_{c1} \) and \( v_{c2} \) shown in Fig (6-7) converge towards their desired values, after 0.21 seconds they reach the reference voltages. Fig 8 shows that the current \( i_2 \) and the grid voltage \( V_g \) are sinusoidal and in phase. As a result, a unit power factor is achieved.

### REFERENCES