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Voltage regulation with power curtailment in a single-phase grid-connected PV inverter

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Abstract—This work presents the design guidelines of a control for direct regulation of the voltage amplitude at the connection point of a single-phase grid-connected PV inverter. The parameters of the control are designed for ensuring local asymptotic stability for a given range of the impedance. Furthermore, the control includes a strategy of active power curtailment in order to avoid the injection of a large amount of reactive power to the grid. Numerical simulations confirm the expected voltage regulation and the control robustness with respect to the grid impedance variations without the requirement of any estimation or measure of the actual impedance.

I. INTRODUCTION

The penetration of photovoltaic (PV) systems in the electricity network has been increased in the last decades. When operating in a low voltage (LV) network PV installations may produce undesirable voltage fluctuations at the connection point. This problem is specially serious when the network has a high R/X ratio, as usually happens in LV networks. Moreover, this effect is related to the injected active power.

In grid-connected PV inverters the voltage is usually controlled by regulating the reactive power delivered to the grid. In the literature one can find several techniques devoted to design such control [1], [2], [3], [4]. Most of them are based on the droop control method. The regulation of the delivered reactive power and the active power is usually achieved by the design of two different control loops. The inner one is a current loop in charge to ensure the injection of the grid current that provides the desired active and reactive power. The outer loop regulates the powers and generates the reference current for the inner one. The inner loop controller can be designed by using linear control techniques in a rotating frame dq [5], [6], [7] or in a time-variant framework [8], [9], [10], [11], [12], [13] or by applying nonlinear control techniques as Lyapunov-based control [14] or passivity-based control [15].

The outer loop design assumes that the internal PV inverter variables reaches their steady-state regime, but despite this assumption the dynamical description of the complete system is highly nonlinear and the controllers design is even worsened by the unknown impedance that exists between the connection point and the grid source. In order to overcome the aforementioned problems, the droop control method uses an approximation of the voltage fluctuation depending on the resistive and the reactive parts of the grid impedance and evaluates the impact of the grid impedance variation in the

control design. Alternatively, this work develops a rigorous mathematical description of the nonlinear dynamics of the grid-connected PV inverter, first applies a nonlinear control design to ensure the system gets into the steady state regime, and then applies a linearization procedure and designs PI controllers to ensure closed-loop asymptotic stability and the desired voltage regulation. Variations of the grid impedance and the active power delivered to the grid are included in the analysis, thus ensuring the proper power regulation over the whole working range without any measure or estimation of the grid impedance.

When the grid impedance has large values of resistance or very low values of inductance a large amount of reactive power has to be injected to the grid to regulate the voltage at the connection point. In order to overcome this fact some control strategies support the voltage with a battery storage [16], [17] or apply an active power curtailment [18], [19], [20]. The control scheme presented in this work also includes a power curtailment procedure such that the active power is reduced when the reactive power reaches its limit, while maintaining the desired voltage regulation.

The remainder of the paper is organized as follows. The steady-state analysis of the output voltage amplitude of a single-phase PV inverter depending on the injected active and reactive power and the grid impedance is presented in Section II. Section III is devoted to detail the different loops that compose the complete control scheme, to perform a local asymptotic stability analysis and to deliver the control parameters design guidelines. The control is evaluated by means of numerical simulations in Section IV. The tests include changes of the grid impedance and power curtailment operation. The results confirm the expected properties of good voltage regulation, appropriate active power curtailment (when required) and robustness with respect to the impedance variations. Finally, the conclusions are drawn in the last section.

II. PV INVERTER OUTPUT VOLTAGE AMPLITUDE

Fig. 1 shows the circuit scheme of a PV inverter connected to a non-ideal grid, where the non-ideal grid is modelled by an impedance, Z_g , in series with an ideal sinusoidal voltage source, v_g . The state equations (in averaged values) of the PV

Fig. 1. Overall control scheme.

inverter are:

$$C\dot{z}_1 = -uz_2 + f_{pv}(z_1), \quad (1a)$$

$$L\dot{z}_2 = uz_1 - v_{CP}, \quad (1b)$$

where z_1 and z_2 correspond to the capacitor voltage and the inductor current, respectively, L is the inductance, C is the capacitance, $u \in [-1, 1]$ is the control, v_{CP} is the voltage at the connection point (CP) and $f_{pv}(z_1) = \Lambda - \Psi e^{\alpha z_1}$ is the current delivered by the PV array. Here Λ represents the part of the PV generator current that depends on the solar radiation, and α and Ψ are positive parameters of the PV generator.

Assuming the steady-state operation is achieved by an appropriate inner control loop such that the voltage and the current at the CP are, $v_{CP} = A_{CP} \sin(\omega t)$ and $z_2 = A_I \sin(\omega t - \theta)$, respectively, and recalling that $P = \frac{A_{CP} A_I}{2} \cos(\theta)$ is the injected active power and $Q = \frac{A_{CP} A_I}{2} \sin(\theta)$ is the delivered reactive power, the amplitude of the voltage at CP can be determined by evaluating the PV inverter output network equation given by: $v_{CP} = v_{Z_g} + v_g$, where:

- $v_{Z_g} = A_I |Z_g| \sin(\omega t - \theta + \theta_{Z_g})$ is the voltage through the impedance,
- $v_g = A \sin(\omega t + \phi)$ is the ideal grid voltage, being ϕ the phase shift between the grid source and the output voltage of the PV inverter.

From these definitions, the equation can be rewritten as:

$$A_{CP} \sin(\omega t) = A_I |Z_g| \sin(\omega t - \theta + \theta_{Z_g}) + A \sin(\omega t + \phi). \quad (2)$$

Moreover, defining the variables $\Gamma = 2|Z_g| \sqrt{P^2 + Q^2}$ and $\psi = -\arctan(\frac{Q}{P}) + \theta_{Z_g}$, (2) results in:

$$A_{CP} \sin(\omega t) = \Gamma \sin(\omega t + \psi) + A_{CP} A \sin(\omega t + \phi), \quad (3)$$

which, applying trigonometric properties, can be expressed by the set of equations

$$\Gamma \cos(\psi) + A_{CP} A \cos(\phi) = A_{CP}^2, \quad (4a)$$

$$\Gamma \sin(\psi) + A_{CP} A \sin(\phi) = 0. \quad (4b)$$

which has to be solved for A_{CP} and ϕ . Finally, defining the variable $x = A_{CP}^2$, one can get the following second order algebraic equation:

$$x^2 - (A^2 + 2\Gamma \cos(\psi))x + \Gamma^2 = 0. \quad (5)$$

Considering that $\Gamma \geq 0$, the two solutions of (5) are positive real when $|A^2 + 2\Gamma \cos(\psi)| \geq 2\Gamma$. Taking into account that both solutions provide the same active power, it is clear that the upper one is the proper one for the voltage regulation since it requires less injected current [15].

Notice that (4) can also be evaluated to get the values of the required Q , A_I , θ and ϕ that provide $A_{CP} = A$ for a given injected active power and a known impedance.

III. REGULATION OF THE AMPLITUDE OF THE VOLTAGE AT THE CONNECTION POINT

This work proposes the control scheme shown in Fig. 1 for the regulation of the amplitude of the voltage at CP, A_{CP} . The control is composed of three different loops, namely:

- 1) An inner loop to track the reference current such that the required active and reactive power are injected to the grid.
- 2) A mid loop composed by PI controllers that ensures the regulation of the active and the reactive power to their references and generates the signal needed to determine the current reference for the inner loop.
- 3) An outer loop to regulate A_{CP} and to perform the power curtailment when it is required. In a normal operation $|Q^*| < Q_{max}$. Furthermore, the voltage regulation is achieved with the PI controller of the loop related to the reactive power reference, Q^* , see Fig. 1. Moreover, in that case, the integral (I) controller of the loop related with the active power is in reset state and, therefore, $P^* = P_{ref}$. On the other hand, in the power curtailment operation, the reactive power reference is saturated, $|Q^*| = Q_{max}$, the integral controller is enabled and the

voltage regulation is obtained by the loop of the active power. In order to avoid a windup effect the PI controller uses a back-calculation anti-windup with unity gain.

The modelling and the stability analysis of the complete control system are detailed in the following subsections.

A. Inner current control

Several papers have successfully applied passivity-based control in power electronics for regulation and tracking tasks (see [21], [22], [23], [24], among others). This work uses the passivity-based controller designed in [15] to control the grid injected current. The design shows global asymptotic stability achieving the steady-state regime with a very fast transient.

B. Closed-loop system modelling

Assuming that the PV inverter operates in the steady-state framework of its internal variables, i.e., $z_2 = A_I \sin(\omega t - \varphi)$, the model of the grid connected PV inverter in terms of the injected active and reactive power can be obtained as follows. The control signals u_P and u_Q , see Fig. 1, are used by the reference generator to perform the current reference ($A_I = \frac{2}{A_{CP}} \sqrt{u_P^2 + u_Q^2}$, $\varphi = \arctan(\frac{u_Q}{u_P})$) with the required phase shift, φ , to deliver the reactive power, θ , and to compensate the phase shift between the grid source and the voltage (and the current) at the PV inverter output, ϕ . Therefore, since $\varphi = \theta + \phi$, those control signals are given by $u_P = \frac{A_{CP} A_I}{2} \cos(\varphi)$ and $u_Q = \frac{A_{CP} A_I}{2} \sin(\varphi)$. Finally, applying trigonometric properties one can get the relationship between the powers and the control signals:

$$P = u_P \cos(\phi) + u_Q \sin(\phi), \quad (6a)$$

$$Q = u_Q \cos(\phi) - u_P \sin(\phi). \quad (6b)$$

On the other hand, from Fig. 1, the output signals of the mid loop PI controllers are:

$$u_P = \alpha_1 \dot{x}_1 + \beta_1 x_1, \quad \dot{x}_1 = P^* - P, \quad (7a)$$

$$u_Q = \alpha_2 \dot{x}_2 + \beta_2 x_2, \quad \dot{x}_2 = Q^* - Q. \quad (7b)$$

Additionally, the outer loop is characterized by the equations of the controllers, namely, 1- the PI controller:

$$Q^* = \alpha_3 \dot{x}_3 + \beta_3 x_3, \quad \dot{x}_3 = A - A_{CP}, \quad (8)$$

and $P^* = P_{ref}$ when the injected reactive power is not saturated, and 2- the integral controller:

$$P^* = \alpha_4 \dot{x}_4, \quad \dot{x}_4 = A - A_{CP}, \quad (9)$$

and $Q^* = Q_{max}$ in power curtailment operation, with the feasible solution of (5):

$$A_{CP} = \sqrt{\frac{A^2 + 2\Gamma \cos(\psi) + \sqrt{(A^2 + 2\Gamma \cos(\psi))^2 - 4\Gamma^2}}{2}}. \quad (10)$$

The closed-loop systems defined by the above equations are highly nonlinear and their nonlinearities ((6) and (10)) make a global stability analysis rather difficult. Fortunately, numerical analysis of (4) shows that ϕ has low variation around its

equilibrium value, ϕ^* . Therefore one can assume that $\phi \approx \phi^*$ and a linearization procedure can be applied. The figures 2 and 3 show the equivalent closed-loop linear systems when the PV inverter is in a normal operation and when it is in a power curtailment scenario, respectively. The parameters δ_1 and δ_2 correspond to the sensitivity parameters $\delta_1 = \frac{\partial A_{CP}}{\partial P}$ and $\delta_2 = \frac{\partial A_{CP}}{\partial Q}$, evaluated at the reference point, of the linearization of (10).

C. Stability analysis of the closed-loop system

Local stability analysis can be performed on the linearized systems. The block diagrams of figures 2 and 3 can be used to get the active and the reactive power in terms of P_{ref} , Q_{max} and the grid amplitude, A . The analysis of the block diagrams allows to get the closed-loop characteristic polynomials. Specifically, the results are $\Delta_1 = 1 + (G_1 + G_2) \cos(\phi^*) + G_2 G_3 (\delta_1 \sin(\phi^*) + \delta_2 \cos(\phi^*)) + G_1 G_2 (1 + \delta_2 G_3)$ for the system depicted in Fig. 2 and $\Delta_2 = 1 + (G_1 + G_2) \cos(\phi^*) + G_1 G_4 (\delta_2 \sin(\phi^*) + \delta_1 \cos(\phi^*)) + G_1 G_2 (1 + \delta_1 G_4) + \delta_2 G_1^2 G_4 (1 + \delta_1 G_4) \sin(2\phi^*)$ for the one of Fig. 3, where the PI controllers transfer functions are given by $G_i \triangleq G_i(s) = \alpha_i + \frac{\beta_i}{s}$ and the integral controller has been defined as $G_4 \triangleq G_4(s) = \frac{\beta_4}{s}$. Finally, the closed-loop stability analysis can be performed by applying the Routh Stability Criteria to Δ_1 and Δ_2 . Notice that the values of the parameters δ_1 , δ_2 and ϕ^* depend on Z_g , and therefore the coefficients of the control transfer functions G_i have to be designed such that the control systems remain local asymptotically stable for a given range of Z_g .

Fig. 2. Simplified block diagram of the control scheme when the amplitude is regulated by the reactive power.

Fig. 3. Simplified block diagram of the complete control scheme in active power curtailment operation.

IV. SIMULATION RESULTS

The proposed control has been validated by means of numerical simulations using Matlab-Simulink. The PV inverter

parameters are $C = 2.2mF$ and $L = 950\mu H$, the grid source is $v_g = 312\sin(100\pi t)V$ and the PV array has a peak power of $3.3kW$, a short circuit current of $6.1A$, and an open circuit voltage of $678V$ at $1000W/m^2$ ($\Lambda = 6.1$, $\alpha = 0.026$, $\Psi = 1.35e^{-7}$). The grid impedance consists of a series connection of an inductance and a resistance. The controllers PI transfer functions are $G_1(s) = G_2(s) = 0.5 + 10/s$, $G_3(s) = 300 + 2000/s$ and $G_4(s) = 200/s$, which have been designed to ensure locally asymptotic stability for the overall range of the considered grid impedance and the injected active power. In order to point out the power curtailment control operation, the same test has been performed when the reactive power is limited and when it is not. The injected active power is regulated to $P_{ref} = 2kW$ (when it is possible) and a specific pattern, shown in the two bottom plots of Fig. 4, is used for the impedance variation. Fig. 5 presents the results when the power curtailment is inhibited. The top plot of Fig. 4 shows how A_{CP} is properly regulated to the reference value, $A = 312V$, with a good transient when changes in the inductance and resistance come. Fig. 5 plots the behaviours of the injected active power, the reactive power and the power delivered by the PV array. Notice how the active power is regulated to its reference value of $2kW$ and how the reactive power reaches the value of the reactive power that replaced in (10) implies $A_{CP} = A$. The absolute value of the reactive power increases when the grid resistance increases and/or the grid inductance decrease and achieves very large values when $R_g > 1\Omega$ or $L_g < 1mH$. This result can be also confirmed using (10), equalling $A_{CP} = A$ and obtaining Q , thus validating the analysis presented in this work.

Fig. 4. Results: (1st and 2nd plot) A_{CP} (V), (3rd) L_g (mH), (4th) R_g (Ω).

The second plot of Fig. 4 and Fig. 6 show the simulation results when the absolute value of the reactive power is limited to $Q_{max} = 5kVar$. Fig. 6 shows that when needed the reactive power is bounded to $-5kVar$ and the active power is varied such that A_{CP} is properly regulated. On the other hand, the second plot of Fig. 4 presents the behaviour of A_{CP} and confirms that the proper regulation is achieved in both cases,

Fig. 5. Results without power curtailment: PV power (W), P (W) and Q (VAr).

when Q is saturated or not.

Fig. 6. Results with power curtailment: PV power (W), P (W) and Q (VAr).

V. CONCLUSIONS

The design of a control scheme for the output voltage regulation with active power curtailment in a single-phase grid-connected inverter is presented in this work. A rigorous analysis of the nonlinear behaviour relating the injected active power, the reactive power and the grid-connected PV inverter output voltage has been performed and a linearized model has been derived. A design procedure of the control parameters ensuring locally asymptotic stability for a given range of the impedance has been detailed and a set of simulations shows the good voltage regulation and the robustness properties with respect to grid impedance variations, thus confirming the expected control properties.

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