Adaptive Nonlinear Control Scheme for Three-Phase Grid-Connected PV Central Inverters

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Abstract—Owing to cost-effectiveness of feeding generated photovoltaic (PV) energy directly into the utility grid, and since grid-connected photovoltaic (GPV) systems have a nonlinear time-varying nature, this paper presents a new control approach for three-phase single-stage GPV systems under uncertainties, using a Lyapunov-based control scheme. The proposed scheme can be utilized in a diverse scope of PV technologies. Simulation results indicate that the suggested strategy improves the efficiency of the system by reducing the total harmonic distortion of the injected current to the grid; and, in addition to having the output current in phase with the voltage of the utility grid, it increases the robustness of the system against uncertainties while rendering the closed-loop system globally stable.

Keywords—three-phase single-stage grid-connected photovoltaic; adaptive controller; lyapunov-based control

I. INTRODUCTION

Climate changes and sustainable electrical power supplies cause renewable energy sources to become more popular than before, and among them, the photovoltaic (PV) system attracts the most attention due to environment-friendly performance [1]. As a result of the feed-in-tariff and the reduction of battery cost, the grid-connected PV system has gained popularity. However, changes in atmospheric conditions affect the intermittent PV generation [2]. Reducing cost-per-watt of PV systems generally is reached by the following [3]:

1) Ameliorating the efficiency of PV cells/modules;
2) Decreasing manufacturing costs of PV cells/modules;
3) Improving the overall PV system efficiency by focusing on the power conditioning elements.

Based on efforts devoted to new PV cell material and manufacturing technologies, high-efficient and cheaper PV panels has been yielded recently. Increasing the efficiency of the overall system using proper power conditioning stage can be an alternative to reduce the cost-per-watt of existing PV systems. Since it is the responsibility of the power conditioning stage to transfer energy properly from the energy source to the load, this stage is an essential part of the PV system. Improving the quality of the power conditioning stage is one of the key issues of future PV applications [4]. Generally, a two-step procedure, namely: 1) selecting the circuit topology and the elements of the power converter properly, and 2) designing control strategy for the chosen power conditioning stage sufficiently should be followed to perceive a PV power conditioning system. In order to have a stable non-oscillatory dynamical behavior of the PV system, the latter task is of high importance. Obviously, there is a long tradition of using linear design techniques found suitable in cases where the power converter operates about a fixed operating point and the disturbances are small. “P Resonant” controllers have mainly been applied in control of power inverters and rectifiers for the sake of a sinusoidal current in phase with the grid voltage [3]. For PV power inverters, control requirements have been generally fulfilled by means of a strategy based on two cascaded control loops using a pulse-width modulation (PWM) scheme [5, 6] where the inner control loop forms the duty ratio to have a sinusoidal output current in phase with the grid voltage. Settling the PV array operating point at its maximum power value for any temperature and irradiance variation, by applying an MPPT algorithm such as Perturb and Observer [7] or more advanced ones [8], [9], is the task of the outer control loop. The current reference amplitude corresponding to the PV array maximum power point is then delivered to the inner control to ensure the power transfer to the grid [10], [11]; however, while using linear techniques, a previous linearization step is required for grid-connected PV inverters which constitutes an approximation of the complete dynamical behavior of the overall system since: 1) the PV source exhibits a strongly nonlinear electrical behavior that affects all variables of the system and 2) electrical characteristics of the PV source are time-varying and therefore the system is not linearizable around a unique operating point or trajectory [3]. Due to the mentioned dilemma in addition to an increasing tendency in the context of nonlinear control of power converters from researchers of both the power electronics and the control community (e.g. see [12]–[15]), we were provoked to emanate a different approach from the usual “classical” control techniques. The Lyapunov-based nonlinear controller technique for power converters proposed in [16] attracts many researchers as renders the closed-loop system globally asymptotically stable, so it has been proved useful for dc-dc converters (e.g., [17]) and ac-dc converters (e.g., [18]).
Several classifications for inverter configurations have been presented with respect to the number of power stages among which a single-stage (central plant) inverter has higher efficiency, lower cost, and higher reliability, since the chance of component failure is lower (with respect to other configurations with higher number of components). Additionally, eliminating a dc-dc converter stage reduces the total cost of grid-connected PV systems and makes this option more attractive on the market. The other feature which affects the design structure of grid-connected PV systems is the use of a single-phase or a three-phase system. From the inverter structure point of view, in high-power applications using a three-phase system has the following advantages [19]:

- Decreasing stresses on inverter switches,
- Reducing the size and ratings of reactive components,
- Increasing the frequency of output current which reduces the size of output filter, and
- Creating a uniform distribution of losses.

Besides, the technology for three-phase inverters can be extended to single-phase inverters [20]. Therefore, a three-phase single-stage grid-connected PV system has been considered in this paper. Following the approach in [3] based on the technique of [16], this paper introduces a nonlinear and adaptive control scheme for a three-phase single-stage grid-connected photovoltaic (GPV) inverter. It is shown that the proposed controller provides a satisfactory closed-loop behavior without neglecting the nonlinear electrical characteristics of the system.

II. PV SYSTEM MODELLING

The three-phase GPV system considered in the present paper is shown in Fig. 1. The considered PV system consists of a PV array, a dc-link capacitor \( C \), a three-phase inverter, a filter inductor \( L \), and the utility grid. In this paper, the main aim is to control the voltage \( v_{dc} \) (which is also the output voltage of PV array \( v_{pv} \)) across the capacitor \( C \) and to make the input current in phase with grid voltage for unity power factor by means of appropriate control signals through the switches of the inverter. Since in GPV systems, the goal is to transfer the PV panels’ energy to the utility grid, delivering a sinusoidal current in phase with the utility grid voltage is the main requirement of the system. However, in standalone PV systems, a sinusoidal voltage is required to be the output of the system, as PV panels’ energy is transferred to a load. In this paper, it is assumed that all PV panels are linked to a unique power inverter unit, known as “central inverter” [3].

A. Photovoltaic cell and array model

A PV cell is a simple p–n junction diode which converts the irradiation into electricity. Fig. 2 shows an equivalent circuit diagram of a PV cell which consists of a light generated current source, a parallel diode, a shunt resistance, and a series resistance.

The typical behavior of a crystalline silicon PV cell is modeled as follows:

\[
i_{pv,cell} = I_{sc,cell}(G) - I_{sat,cell}(T)\exp\left(\frac{v_{pv,cell}(T)}{p_{pv,cell}(T)} - 1\right)\]

where \( i_{pv,cell} \) and \( v_{pv,cell} \) are the cell current and voltage, respectively; \( I_{sc,cell}(G) \) is the generated current due to the incident solar irradiance \( G \); \( \eta \) is the PV cell emission coefficient, \( I_{sat,cell}(T) \) is the reverse saturation current of PV cell p-n junction that varies with temperature \( T \), \( v_{sat}(T) \) is the p-n junction thermal voltage which also changes with temperature. Since the variations of temperature and irradiance are slow compared to the dynamics of practical power inverters, it can be assumed that they do not change.

The electrical behavior of PV array is defined as follows [3]:

\[
i_{pv} = \Lambda - \rho(v_{pv})
\]

where \( v_{pv} \) and \( i_{pv} \) are the PV array voltage and current, respectively, and \( \Lambda \) represents the part of the photovoltaic generator current that depends on the solar irradiance. The last term of (2) denotes the direct link between the voltage of photovoltaic generator and the associated current:

\[
\rho(v_{pv}) = \psi \exp(\alpha v_{pv})
\]

where \( \psi \) and \( \alpha \) represent positive parameters of the photovoltaic generator. Referring to the equation of the PV cell (1), the parameters of this model can be defined as \( \Lambda = (I_{sc,cell} + I_{sat,cell})n_p \cdot \psi = I_{sat,cell}n_p \) and \( \alpha = (n_i)/(n_p p_{cell}) \) where \( n_i \) and \( n_p \) are the number of PV cells connected in series and parallel, respectively.

B. Power conditioning stage

As is clear from Fig.1, the central inverter consists of 6 switches which are triggered via a PWM switching scheme, using a nonlinear controller. Considering the inductor...
According to the assumptions in the simulation of PV array, the only parameter with uncertainty that the controller should be able to deal with is $\Lambda$.

### III. CONTROLLER DESIGN

In order to maximum PV energy amount transferring to the utility grid by the inverter of Fig. 1, the following is required:

- to deliver a sinusoidal current in phase with the utility grid;
- to regulate the input capacitor voltage to a value that assures maximum power extraction from the PV array.

Since MPPT algorithms are slow comparing with dynamic operation of power inverters, augmenting an MPPT algorithm to this control scheme does not affect the system’s closed-loop response.

We consider that the value of $C$ should be sufficiently high, to reduce the oscillations towards the PV array maximum power point. The reference value of $x_1$, $x_2$, is given by an MPPT algorithm, at which the array transfers its maximum power, and $x_2$, is a fraction of utility grid voltage, defined as $\beta v_g$.

$\beta$ will be defined following.

Substituting $x_1$ and $x_2$ in (8), the system dynamical equation will be determined as:

$$C \dot{x}_1 = -u_x x_2 + \hat{A} - \rho(x_1)$$
$$L \dot{x}_2 = u_x x_1 - v_g$$

where $\hat{A}$ is the estimated value of $A$. Therefore, $\beta$ is defined as:

$$\beta = \frac{2x_1(\hat{A} - \rho(x_1))}{A^2}$$

where $A$ is the utility grid voltage amplitude.

If we consider $e_1 = x_1 - x_{1r}$, $e_2 = x_2 - x_{2r}$, $e_u = u - u_r$ and $e_A = A - \hat{A}$, the system dynamics can be written as

$$C(\dot{e}_1 + x_{1r}) = -(e_u + u_r)(e_2 + x_{2r}) + e_A = \rho(x_1) - e_{\rho}(e_1, x_{1r})$$
$$L(\dot{e}_2 + x_{2r}) = (e_u + u_r)(e_1 + x_{1r}) - v_g$$

where $\rho(x_1)$ is decomposed into $\rho(x_1) = \rho(x_1) + e_{\rho}(e_1, x_{1r})$ with $e_{\rho}(e_1, x_{1r}) = \psi[\exp(\omega e_1 + \omega x_{1r}) - \exp(\omega x_{1r})]$.

The control signal, $u$, which fulfills the desired closed loop behavior composed of two elements, a control $u_r$ defined according to (9) and a control $e_u$ designed such that the system error dynamics be eliminated. The error dynamics are obtained by substituting (9) in (11):

$$C \dot{e}_1 = -u_r e_2 - e_{\rho}(e_2, x_{1r}) + e_A - e_{\rho}(e_1, x_{1r})$$
$$L \dot{e}_2 = u_x e_1 + e_u(x_{1r} + e_1)$$

In addition to forming the control $e_u$ that renders the error dynamics (12) stable, we should attain an additional mechanism to estimate $A$, i.e. to make $\hat{A} = A$. The final stability analysis which takes into account the designed signal
\( e_\alpha \) and the dynamics associated to the estimation of \( \Lambda \), validates our proposed control scheme.

The following adaptive law is used to estimate \( \dot{\Lambda} \):

\[
\dot{\Lambda} = \text{Pr} \left\{ |\gamma_1| \right\} \begin{cases} 
|\gamma_1|, & \text{if } \dot{\Lambda} > \varepsilon \\
0, & \text{otherwise}
\end{cases}
\]  
(13)

where \( \gamma \in \mathbb{R}^+ \) is the adaptive gain and \( \text{Pr} \left\{ |\gamma_1| \right\} \) is a projection operator that ensures \( \dot{\Lambda} > \varepsilon > 0 \), with \( \varepsilon \) an arbitrary small constant.

The stability of the error dynamics (12) can be proved by means of the following Lyapunov function

\[
H = \frac{1}{2} C e_\gamma^2 + \frac{1}{2} L e_\alpha^2 + \frac{1}{2\gamma} e_\Lambda^2
\]  
(14)

for which the time derivative along the system trajectories of (12) yields

\[
\dot{H} = e_\mu (x_1 e_2 - x_2 e_1) - e_1 e_\rho (e_1, x_1) + e_\Lambda e_1 + \frac{1}{\gamma} e_\Lambda \dot{e}_\Lambda
\]  
(15)

The closed-loop system will be globally asymptotically stable if the aforementioned expression is negative definite, i.e., if \( \dot{H} \langle 0 \) for all values of \( e_1, e_2, e_\Lambda \) different from zero.

Defining \( e_\alpha \) as

\[
e_\alpha = -K (x_1 e_2 - x_2 e_1)
\]  
(16)

where \( K \) is a control parameter, the first term of (15) remains always non-positive

\[
\dot{H} = -K (x_1 e_2 - x_2 e_1)^2 - e_1 e_\rho (e_1, x_1) + e_\Lambda e_1 + \frac{1}{\gamma} e_\Lambda \dot{e}_\Lambda
\]  
(17)

On the other hand, considering \( \Lambda \) “locally constant”, yields \( \dot{e}_\Lambda = -\dot{\Lambda} \) and according to (13), \( \dot{e}_\Lambda = -\gamma_1 \), and thus, the derivative of the Lyapunov function (17) can be written as

\[
\dot{H} = -K (x_1 e_2 - x_2 e_1)^2 - e_1 e_\rho (e_1, x_1)
\]  
(18)

Being \( e_1 e_\rho (e_1, x_1) \) always positive, which is yielded when \( e_1 = x_1 - x_2 > 0 \), will render the closed-loop system (11) globally asymptotically stable, using the control signal obtained from (9), (16) and adaptive control law (13).

IV. SIMULATION RESULTS

The proposed controller is validated by a series of numerical simulations, and robustness of our proposed controller in front of non-considered uncertainties, i.e., variations of \( \psi \) and \( \alpha \) is observed through simulation results. The considered system is shown in Fig.1 parameters of which are mentioned in Table.1 in details.

The simulation is done for variation of +5% and -5% of \( \alpha \) and \( \psi \). In Fig.3, the effect of +5% variation of \( \alpha \) and \( \psi \) in the capacitor voltage is simulated. The damped line represents the reference value. Fig.4 illustrates the output current of +5% variation of \( \alpha \) and \( \psi \) with respect to the scaled grid voltage. It can be observed that the current is in phase with the grid voltage and harmonic distortion is reduced. In Fig.5 capacitor voltage is shown while having a variation of -5% in \( \alpha \) and \( \psi \). Fig.6 demonstrates the injected current when there is a variation of -5% in \( \alpha \) and \( \psi \). In Fig.3 and Fig.5 it can be seen that the capacitor voltage eventually reaches its desired steady-state value. Results demonstrate that in both cases, system is robust and in addition to keeping the command voltage value, the current is sinusoidal in phase with the grid voltage.

| TABLE I. PARAMETERS OF THE SYSTEM |
|---|---|
| Circuit parameters | values |
| \( L \) | 20mH |
| \( C \) | 2.2mF |
| Grid Voltage | 312V/50Hz |
| \( x_1 \) | 587.8V |
| \( \Lambda \) | 6.1 |
| \( \alpha \) | 0.025 |
| \( \psi \) | \( 1.35 \times 10^{-7} \) |
| \( \gamma \) | 0.05 |
| \( K \) | 2.4 |

Another consideration that can be taken into account is assuming variation in known parameters. Consider the case in which \( L \) is unknown, and assume that \( L \neq \hat{L} \) is the inductance used by the controller. With the reference system

\[
C x_1 = -u_r x_2 + \hat{L} - \rho (x_1)
\]

\[
\hat{L} x_2 = u_r x_1 - v_g
\]

The error dynamic of (12) are modified as

\[
C e_1 = -u_r e_2 - e_\mu (x_2 + e_2) + e_\Lambda - \rho (e_1, x_1)
\]

\[
\hat{L} e_2 = -e_1 x_2 = u_r e_1 + e_\mu (x_1 + e_1)
\]

where \( e_\mu = L - \hat{L} \). Using the defined controllers by (9), (13) and (16) and using the Lyapunov function (14), leads to the Lyapunov derivative

\[
\dot{H} = -K (x_1 e_2 - x_2 e_1)^2 - e_1 e_\rho (e_1, x_1) - e_2 e_\rho (x_1, x_2)
\]  
(21)

The difference of this with (18) is the additional term depending on \( L, \hat{L}, x_1, x_2 \). In order for the controller no to be affected by variations of \( L \), the controller parameter \( K \) should be sufficiently large to dominate the last term of (18).

The contribution of the controller expression that contains the inductance in (9) can be neglected when \( L \ll \hat{L} \). The difference of this with (18) is the additional term depending on \( L, \hat{L}, x_1, x_2 \). In order for the controller no to be affected by variations of \( L \), the controller parameter \( K \) should be sufficiently large to dominate the last term of (18).

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Two cases have been simulated: one in which the complete expression of the controller is used and another one in which the term containing the inductance is neglected. It can be seen from Fig.7 that the injected current in both cases remains in phase with the grid voltage.
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Fig 3. Capacitor voltage: results of +5% variation of $\alpha$ and $\psi$.

Fig 4. Output currents: results of +5% variation of $\alpha$ and $\psi$. The dashed line represents the scaled grid voltages ($\frac{V}{30}$).

Fig 5. Capacitor voltage: results of -5% variation of $\alpha$ and $\psi$. 

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V. CONCLUSIONS

A new control approach for three-phase single-stage grid-connected PV systems is presented in this paper. In order to inject a high quality ac current, and to transfer maximum power into the grid, an adaptive Lyapunov-based controller is applied. The control design renders the closed-loop system globally asymptotically stable while taking the nonlinear time-

Fig6. Output currents: results of -5% variation of \( \alpha \) and \( \psi \). The dashed lines represent the scaled grid voltages \( \frac{v}{30} \).

Fig7. Numerical simulation results of the output currents for the system using the proposed controller with (top figure) and without (bottom figure) the term containing \( L \). The scaled grid voltages \( \frac{v}{30} \), is shown with dashed lines and in volts, the other curve corresponds to \( x_2 \) in (a).
varying characteristic of the system into account. Computer simulation has been carried out using MATLAB/Simulink environment to confirm the system operation. Results illustrate that the injected current into the grid is in phase with the utility grid voltage, even under extreme changes in the system parameters. Additionally, the proposed controller is robust to the system uncertainties. According to the nonlinear nature of PV systems, in order to integrate them to today’s power system, using control algorithms which are accountable to this characteristic will be a solution. Since control strategies based on system parameters’ nonlinear characteristic for single-phase and three-phase inverters are effective and easy to implement, using these strategies in grid-connected distributed generations (DGs) will be demanding.

REFERENCES


