Observer-based Control for Grid-connected LCL-filtered Inverter with Only Grid Current Feedback

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Abstract. This paper presents an observer-based control scheme for a grid-connected LCL-filtered inverter with only grid-side current feedback. The proposed control scheme is composed of a state feedback regulator and an augmented state observer. The augmented state observer is used to estimate the inverter states which are then employed to construct the regulator. In addition to inverter states, the observer also estimates the grid voltages which are utilized to remove the effects of abnormal grid voltage and system parameter variations, as well as to synchronize the inverter with the grid. As a result of using the observer, only grid-side current sensors are required to control the inverter system even under unbalanced and distorted grid voltages. The effectiveness of the suggested control approach is verified through numerical results.

Introduction

With the increasing penetration of renewable energy, grid-connected inverters have drawn much interest for their flexibility and reliability [1]. Due to the better harmonic attenuation and smaller physical size, LCL-filters are being more and more popular [2]. However, the complicated structure of LCL-filters has introduced more difficulty in designing the control system. Moreover, grid voltage sensors are often required to synchronize the inverter with the grid.

For the purpose of performing grid synchronization without using grid voltage sensors, several voltage sensorless control schemes have been proposed [3-5]. In [3], the grid-side currents are controlled by a predictive controller and the grid voltage is estimated by an adaptive estimator. Despite considerably good results under the ideal grid voltage condition, test results under abnormal grid voltage conditions were not provided in this study. A control scheme which uses the Kalman filter and sliding mode control is presented in [4]. In this study, the system states including grid voltage are estimated using the Kalman filter. These estimated states are then used for three decoupled sliding mode controllers to control the inverter. Even though this scheme shows reasonable results under abnormal grid conditions, it still suffers from the chattering problem as a result of using the sliding mode controller. As another approach, the literature [5] presents a line-voltage sensorless control scheme which is based on an extended-state estimator. In this work, the estimator is formed using a change of variables. The use of a new set of variables enables this control scheme to cope with the observer dynamics and system parameter uncertainties separately. However, capacitor current sensors are required to perform the active damping in this control scheme.

To control LCL-filtered inverters even under abnormal grid voltage conditions, this paper proposes a line-voltage sensorless control scheme which is based on an augmented observer. The observer, which is constructed using not only inverter model but also grid voltage model, estimates the states of the inverter system as well as the grid voltage. While the estimated inverter states are used for a state feedback regulator to stabilize the system, the estimates of grid voltage are employed to reject the grid voltage disturbance as well as to remove the effects of parameter mismatches in the control design. Simulation results under different grid conditions are provided to prove the validity of the proposed control scheme.
System Modeling

Figure 1(a) shows the circuit diagram of a three-phase inverter which is connected to the grid through LCL filters. In this diagram, $R_1$, $R_2$, $L_1$, and $L_2$ represent the resistance and inductance of the filters, respectively, $C_f$ represents the filter capacitance. The inverter system can be mathematically described in the stationary reference frame as

$$\dot{x}(t) = Ax(t) + Bu(t) + B_d w(t)$$

$$y(t) = Cx(t)$$

where $x = [i_i \: \: v_{cf} \: \: i_q]^T$, $u = v$, $w = e$, and the parametric matrices are given by

$$A = \begin{bmatrix} -R_1/L_1 & -1/L_1 & 0 \\ 1/C_f & 0 & -1/C_f \\ 0 & 1/L_2 & -R_2/L_2 \end{bmatrix}, \quad B = \begin{bmatrix} 1/L_1 \\ 0 \\ 0 \end{bmatrix}, \quad B_d = \begin{bmatrix} 0 \\ 0 \\ -1/L_2 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}.$$  \hspace{1cm} (3)

Proposed Control Scheme

To control the inverter under normal as well as abnormal grid condition using only the grid-side current information, the proposed control consists of a state feedback regulator and an augmented state observer as shown in Figure 1(b). The regulator is used to stabilize the inverter system and is formulated by feeding back the system states as

$$u_i(k) = Kx(t).$$  \hspace{1cm} (4)

In order to construct the observer which is able to eliminate the effect of grid voltage, internal model of the grid voltage is employed. In general, grid voltage can be modeled using state-space equations as

$$\dot{x}_w(t) = Fx_w(t)$$

$$w(t) = Hx_w(t)$$

where

$$x_w = \begin{bmatrix} x_{w1} \\ \vdots \\ x_{wn} \end{bmatrix}, \quad F = \begin{bmatrix} F_1 \\ \vdots \\ F_n \end{bmatrix}, \quad H = \begin{bmatrix} H_1^T \\ \vdots \\ H_n^T \end{bmatrix}, \quad F_i = \begin{bmatrix} 0 & 1 \\ -\omega_i & 0 \end{bmatrix} \quad \text{and} \quad H_i = \begin{bmatrix} 1^T \\ 0 \end{bmatrix}.$$  \hspace{1cm} (7)

The system model in Eq. 1 and Eq. 2 can be augmented with the grid model in Eq. 5 and Eq. 6 as
\[
\begin{bmatrix}
\dot{x}(t) \\
\dot{x}_w(t)
\end{bmatrix} = \begin{bmatrix}
A & B_dH \\
0 & F_d
\end{bmatrix} \begin{bmatrix}
x(t) \\
x_w(t)
\end{bmatrix} + \begin{bmatrix}
B \\
0
\end{bmatrix} u(t)
\]  
\tag{8}

\[y(t) = [C \ 0] \begin{bmatrix}
x(t) \\
x_w(t)
\end{bmatrix} \tag{9}\]
or in a compact form

\[\dot{x}_e(t) = A_e x_e(t) + B_e u(t) \tag{10}\]

\[y(t) = C_e x_e(t). \tag{11}\]

The observer which estimates the system states and grid voltages form inverter inputs and grid-side inverter currents can be given as

\[\dot{x}_e(t) = A_e x_e(t) + B_e u(t) + L_e (C_e x_e(t) - y(t)). \tag{12}\]

The feedback gain \(K\) and observer gain \(L\) are chosen such that the resonance of LCL filter is properly damped and the system is stable. The estimated states are composed of system states and grid voltages. While the estimated inverter states are used to construct the regulator, the estimated grid voltage is fed back to the inverter system to cancel out the effect of the real grid voltage. Also, this feedback grid voltage compensates the parameter mismatch in controller design as shown in Figure 1(b). Therefore, only a constant feed forward gains are sufficient to perform the reference tracking task.

Simulation Results

![Simulation results](image)

Figure 2. Simulation results of the proposed control scheme: (a) three-phase grid voltages, (b) measured and estimated grid voltage in \(\alpha\beta\)-frame, (c) measured and estimated angle of grid voltage, (d) three-phase grid-side currents, (e) reference and measured grid-side currents in \(\alpha\beta\)-frame, (f) grid-side currents in \(dq\)-frame.
To verify the proposed control scheme, simulations have been carried out for a three-phase grid-connected inverter under different grid conditions. In addition to fundamental component, the unbalanced and distorted grid voltage is assumed to contain 10% of 5\textsuperscript{th} and 7\textsuperscript{th}, and 5% of 11\textsuperscript{th} harmonics, respectively, as well as 20% of voltage reduction in one phase.

Figure 2 shows the simulation results of the proposed control scheme. As can be observed from Figure 2a, Figure 2b, and Figure 2c, the estimated variables are merely influenced by the sudden change of the grid voltage. Also, the current waveforms in Figure 2d, Figure 2e, and Figure 2f show stables and fast responses of the proposed control scheme under a sudden change of grid voltage as well as reference currents. Furthermore, considerable sinusoidal phase currents illustrate the superior steady-state performance of the proposed control scheme even under adverse grid voltage condition.

Summary

An observer-based voltage sensorless control scheme for LCL-filtered grid-connected inverters has been proposed in this paper. The proposed control scheme features an augmented state observer which estimates not only system states but also grid voltages. While the estimated system states are used to form a state regulator, the estimated grid voltages are used to remove the influences of the grid voltages and system parameter mismatch on the injected currents. As a result of using the observer, only the grid-side current measurements are required to accomplish the proposed control scheme. Simulation results of the proposed control scheme under different grid conditions are given to illustrate the effectiveness of the proposed control scheme.

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