Observer−based Voltage Sensorless Control Scheme for an LCL−filtered Grid−connected Inverter

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ABSTRACT

To synchronize the distributed generation (DG) unit with the grid, the voltage sensors are generally employed to obtain the grid phase angle. This paper presents an observer−based voltage sensorless control scheme for a three−phase inverter connected to the grid through an LCL filter. The proposed control scheme consists of an augmented state observer and a feedback controller. The augmented state observer is used to estimate the grid voltages and states of the inverter system, which are then employed to determine the grid voltage angle and to construct the feedback controller. As a result of using the observer, only the grid current sensors are required to accomplish the control scheme. The simulation results are given to prove the validity of the proposed control scheme.

1. Introduction

Grid−connected inverters have been playing an important role in delivering renewable energy to the utility grid[1]. Recently, LCL filters are preferred over L filters since they provide better harmonic attenuation capability with smaller physical size and lower cost. However, the resonant characteristic of LCL filters poses a challenge in controlling the inverter. Also, to facilitate the grid synchronization, voltage sensors are required. The use of voltage sensing devices often increases system cost and complexity.

The resonant nature of the LCL filter can be tolerated using active or passive damping methods[2]. Since the passive damping methods decrease the overall system efficiency due to losses associated with damping elements, active damping methods are preferably chosen. To eliminate the need of voltage sensors, a grid voltage sensorless control scheme is proposed in [3]. In this work, an adaptive observer is employed to estimate the frequency, angle, and magnitude of the grid voltage. Despite having reasonable control performance, the learning algorithm used in the adaptive observer complicates the control system.

This paper proposes an observer−based voltage sensorless control scheme for an LCL−filtered grid−connected inverter system, which is composed of a state observer and a feedback controller. The proposed control scheme is to eliminate the need of voltage sensor and at the same time to cope with damping nature of the LCL filter. The effectiveness of the proposed approach is confirmed through numerical results.

2. Modeling of Inverter System

The continuous−time description of a three−phase inverter connected to the grid through LCL filters is given in the stationary reference frame as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}u(t) + \mathbf{B}_d w(t) \tag{1}$$

$$y(t) = \mathbf{C}\mathbf{x}(t) \tag{2}$$

where $\mathbf{x} = [i_i \quad u_c \quad i_g]^T$ is the system state vector with i_i, u_c, i_g being the inverter side current, capacitor voltage, and grid side current, respectively, u is inverter output voltage, $w = e$ is grid voltage, and

$$\mathbf{A} = \begin{bmatrix} -R_1/L_1 & -1/L_1 & 0 \\ 1/C & 0 & -1/C \\ 0 & 1/L_2 & -R_2/L_2 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 1/L_1 \\ 0 \\ 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ -1/L_2 \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}^T .$$

3. Proposed Voltage Sensorless Control Scheme

To stabilize the inverter system, the system states are fed back to the input through a feedback gain vector K. The state equation can be written as

$$\dot{\mathbf{x}}(t) = (\mathbf{A} + \mathbf{B}\mathbf{K})\mathbf{x}(t) + \mathbf{B}_d w(t) . \tag{3}$$

The feedback regulator in (3) is designed under an assumption that the information on all the states is available. However, for the chosen inverter system, only the grid side currents are measured. To estimate the system states, a state observer is used. In addition to the system states, grid voltages can be also estimated along with system states since its frequency ω is known. The grid voltages can be described as

$$\dot{\mathbf{x}}_d(t) = \begin{bmatrix} 0 & 1 \\ -\omega^2 & 0 \end{bmatrix} \mathbf{x}_d(t) = \mathbf{A}_d \mathbf{x}_d(t) \tag{4}$$

$$w(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} x_d(t) = \mathbf{C}_d x_d(t) . \tag{5}$$

Equation (4) and (5) can be augmented with the inverter model as

$$\begin{bmatrix} \dot{\mathbf{x}}(t) \\ \dot{\mathbf{x}}_d(t) \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B}_d\mathbf{C}_d \\ \mathbf{0} & \mathbf{A}_d \end{bmatrix} \begin{bmatrix} \mathbf{x}(t) \\ \mathbf{x}_d(t) \end{bmatrix} + \begin{bmatrix} \mathbf{B} \\ \mathbf{0} \end{bmatrix} u(t) \tag{6}$$

$$y(t) = [\mathbf{C} \quad 0] \cdot [\mathbf{x}(t) \quad \mathbf{x}_d(t)]^T . \tag{7}$$

A state observer can be constructed to estimate the states of augmented system as

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$$\begin{bmatrix} \dot{\bar{\mathbf{x}}}(t) \\ \dot{\bar{\mathbf{x}}}_d(t) \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B}_d\mathbf{C}_d \\ \mathbf{0} & \mathbf{A}_d \end{bmatrix} \begin{bmatrix} \bar{\mathbf{x}}(t) \\ \bar{\mathbf{x}}_d(t) \end{bmatrix} + \begin{bmatrix} \mathbf{B} \\ \mathbf{0} \end{bmatrix} u(t) + \mathbf{L}\left(y(t) - \mathbf{C}\bar{\mathbf{x}}(t) \quad 0\right) \tag{8}$$

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. Also, to track the reference currents, a feed−forward term included in the control scheme is derived from the system model as $\overline{N} = N_u + \mathbf{K}\mathbf{N}_x$ where N_u and N_x are calculated as

$$\begin{bmatrix} \mathbf{N}_x \\ N_u \end{bmatrix} = \begin{bmatrix} \mathbf{A}-\mathbf{I} & \mathbf{B} \\ \mathbf{C} & 0 \end{bmatrix}^{-1} \cdot \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix}. \tag{9}$$

The block diagram of the proposed control scheme is illustrated in Fig. 1, in which $\bar{\mathbf{x}}(t)$ and $\overline{w}(t)$ represent the estimated system state vector and the estimated grid voltage. The estimated voltage is used to determine the grid angle and to feed back to the system input to cancel out the grid voltage.

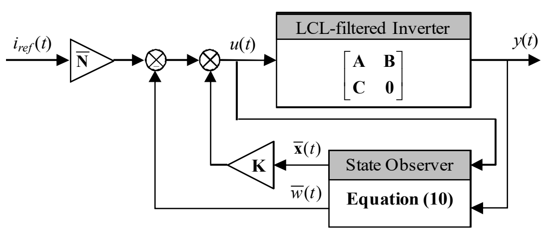

Fig. 1 Block diagram of the proposed current controller.

4. Simulation Results

To highlight the effectiveness of the proposed controller, the simulations have been carried out. The system includes three−phase inverter connected to utility grid through LCL filters. Fig. 2 shows the gird voltage used in the simulations.

Fig. 3 shows the grid voltage and estimated grid voltage in the stationary reference frame using the proposed observer. As can be seen, the estimated grid voltages rapidly approach the real grid voltage. The steady−state errors are negligibly low after 10 ms.

The simulation results for the inverter currents with the proposed control scheme are presented in Fig. 4. As can be observed from the q−axis current waveform, the inverter current instantly reaches to the steady state. Also, the sinusoidal waveforms of α−axis and β−axis currents indicate a good state−state performance.

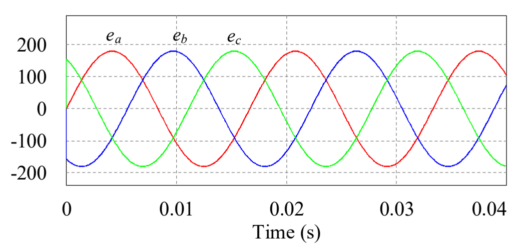

Fig. 2 Waveforms of the three−phase gird voltages.

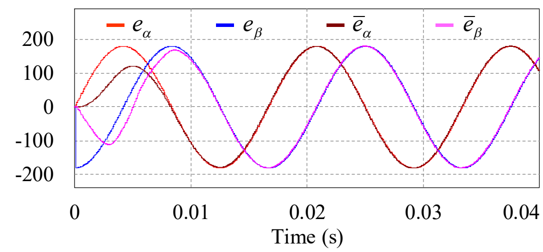

Fig. 3 Grid voltages and estimated grid voltages.

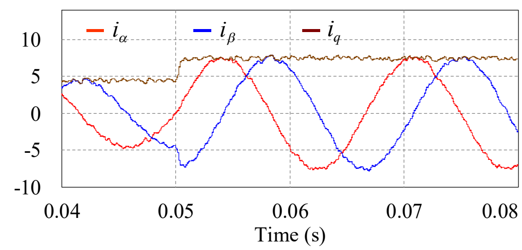

Fig. 4 Simulation results for the inverter currents.

5. Conclusion

This paper has presented a voltage sensorless control scheme for LCL−filtered grid−connected inverters. The proposed control scheme is based on an augmented state observer, which estimates the system states as well as the grid voltage. By using the observer, the inverter can be synchronized with the grid without using any voltage sensors. Also, due to the simple control structure, the resonant nature of the LCL filter can be easily damped by choosing appropriate gains. Superior transient and steady−state performance confirmed the validity of the proposed control scheme.

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6. References

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