Grid Voltage-sensorless Current Control of LCL-filtered Grid-connected Inverter based on Gradient Steepest Descent Observer

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ABSTRACT

This paper presents a grid voltage-sensorless current control design for an LCL-filtered grid-connected inverter with the purpose of enhancing the reliability and reducing the total cost of system. A disturbance observer based on the gradient steepest descent method is adopted to estimate the grid voltages with high accuracy and light computational burden even under distorted grid conditions. The grid fundamental components are effectively extracted from the estimated gird voltages by means of a least-squares algorithm to facilitate the synchronization process without using the conventional phase-locked loop. Finally, the estimated states of inverter system obtained by a discrete current-type full state observer are utilized in the state feedback current controller to realize a stable voltage-sensorless current control scheme. The effectiveness of the proposed scheme is validated through the simulation results.

1. Introduction

A grid-connected voltage source inverters (VSIs) with LCL filter are commonly adopted to inject currents from renewable energy sources (RES) to the grid. However, the unity grid condition is normally polluted by low-older harmonic components. Thus, the control scheme of interfacing system should have a capability to produce high quality currents even under non-ideal grid conditions.

Regarding the system cost and reliability enhancement, it is highly desirable to realize a grid interfacing scheme with a minimized number of sensing devices. A recent research work in [1] adopts a full-state observer to replace the measurement devices in an LCL-filtered VSI. In this study, only the grid-side current and grid voltage sensors are utilized. To further reduce the sensing devices in system, one feasible option is to replace the grid voltage sensors by a software-based grid voltage estimator. The study in [2] represents a grid voltage estimator which has a capability to construct the real grid voltages accurately from the gird-side current information. However, the presented sensorless scheme is applied to L-filtered converter system.

In this paper, a grid voltage-sensorless current control for a grid-connected inverter with LCL filter is presented. Firstly, a discrete current-type full-state observer is employed to estimate all the state variables of LCL filter inverter system, which facilitates the full-state feedback current controller. Secondly, to eliminate the grid voltage sensors without affecting the inverter control performance, the proposed scheme employs a disturbance observer based on the gradient steepest descent (GSD) method to estimate the grid voltages with high accuracy and light computational burden even under adverse distorted conditions. For the purpose of synchronizing between VSI and the unity grid, the conventional phase-locked loop (PLL) is implemented popularly. However, the performance of the PLL method is quite degraded by polluted harmonics in grid. In order to address this problem, a filter based on least-squares algorithm is presented in this study to obtain a precise grid phase angle by effectively extracting the grid fundamental component from estimated quantities. Furthermore, to achieve the control objectives such as reference tracking and harmonic compensation, this study adopts the integral-resonant state feedback current control as presented in [1]. Finally, the simulation results under adverse grid condition are provided to demonstrate the validity of the proposed control scheme.

2. Proposed Control Scheme

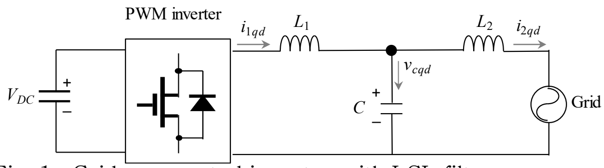

Fig. 1 Grid-connected inverter with LCL filter.

Fig. 1 shows a three-phase inverter connected to the grid through LCL filters. Only the DC link voltage sensor and grid-side current sensors are used to implement the control algorithm and to synchronize the inverter system with the utility grid. The inverter model of in the stationary reference frame can be written in discrete domain as

$$\mathbf{x}_s^\alpha(k+1) = \mathbf{A}_{sd}\mathbf{x}_s^\alpha(k) + \mathbf{B}_{sd}v_i^\alpha(k) + \mathbf{D}_{sd}e^\alpha(k) \quad (1)$$
$$y^\alpha(k) = \mathbf{C}_{sd}\mathbf{x}_s^\alpha(k)$$

where $\mathbf{x}_s^\alpha = [i_1^\alpha \ v_c^\alpha \ i_2^\alpha]^T$ is state vector, $\mathbf{C}_{sd}$, $\mathbf{A}_{sd}$, $\mathbf{B}_{sd}$, $\mathbf{D}_{sd}$ are discrete-time counterparts of $\mathbf{C}_{sc} = [0\ 0\ 1]$,

$$\mathbf{A}_{sc} = \begin{bmatrix} -R_1/L_1 & -1/L_1 & 0 \\ 1/C & 0 & -1/C \\ 0 & 1/L_2 & -R_2/L_2 \end{bmatrix}, \mathbf{B}_{sc}\begin{bmatrix} 1/L_1 \\ 0 \\ 0 \end{bmatrix},$$

and $\mathbf{D}_{sc} = [0\ 0\ -1/L_2]^T$, respectively.

Because the equations in the α-axis and β-axis are independent of each other, the control design can be accomplished by considering only one axis without the loss of generality.

2.1 Discrete current-type full-state observer

To enhance the stable operation of observer, the discrete current-type observer is introduced, in which the estimated states are determined based on the current estimation error [1] as

$$\hat{\mathbf{x}}_d(k) = \hat{\mathbf{x}}_d(k) + \mathbf{L}_e(y^\alpha(k) - \mathbf{C}_{sd}\hat{\mathbf{x}}_d(k)) + \mathbf{D}_{sd}\hat{e}^\alpha \quad (2)$$

$$\tilde{\mathbf{x}}_d(k+1) = \mathbf{A}_{xd}\tilde{\mathbf{x}}_d(k) + \mathbf{B}_{xd}v_i^\alpha(k)$$
$$+\mathbf{A}_{zd}\mathbf{L}_{zd}(y^\alpha(k) - \mathbf{C}_{zd}\tilde{\mathbf{x}}_d(k)) \quad (3)$$

where $\tilde{\mathbf{x}}_d$ is new estimated state vector computed by the prediction form in (3), and $\hat{e}^\alpha$ is the output of grid voltage estimator as presented in next section. In this case, the error dynamics are described by

$$\mathbf{e}_{zd}(k+1) = (\mathbf{A}_{zd} - \mathbf{L}_{zd}\mathbf{C}_{zd}\mathbf{A}_{zd})\mathbf{e}_{zd}(k)\,. \quad (4)$$

By choosing the poles of matrix $(\mathbf{A}_{zd} - \mathbf{L}_{zd}\mathbf{C}_{zd}\mathbf{A}_{zd})$ in stable region, the estimated system and disturbance states reach to the actual values asymptotically.

2.2 Grid voltage estimator based on GSD

A high accurate estimator of the grid voltages based on GSD is presented to realize a voltage-sensorless control scheme. To construct a grid voltage estimator based on GSD, the grid-side currents estimator is first designed from (1) as

$$\bar{i}_2^\alpha(k+1) = \mathbf{C}_{sd}\mathbf{A}_{sd}\bar{\mathbf{x}}_s^\alpha(k) + \mathbf{C}_{sd}\mathbf{B}_{sd}v_i^\alpha(k) + \mathbf{C}_{sd}\mathbf{D}_{sd}\hat{e}^\alpha(k) \quad (5)$$

where $\bar{\mathbf{x}}_s^\alpha(k) = [\hat{i}_1^\alpha \;\; \hat{v}_c^\alpha \;\; \bar{i}_2^\alpha]^T$, $\bar{i}_2^\alpha$ is the output of the GSD based observer, $\hat{i}_1^\alpha$ and $\hat{v}_c^\alpha$ are estimated inverter-side current and capacitor voltage from the discrete current-type full-state observer, and $\hat{e}^\alpha$ is estimated grid voltage. Based on the GSD algorithm, $\hat{e}^\alpha$ is asymptotically converged to the actual value once the quadratic error function $E(k)$ is minimized, where $E(k) = \frac{1}{2}(i_2^\alpha - \bar{i}_2^\alpha)^2$.

Then $\hat{e}^\alpha$ is calculated as follows [2]:

$$\hat{e}^\alpha(k+1) = \hat{e}^\alpha(k) - \mu\nabla E(k)$$
$$= \hat{e}^\alpha(k) + \mu(i_2^\alpha(k) - \bar{i}_2^\alpha(k))\mathbf{C}_{sd}\mathbf{D}_{sd} \quad (6)$$

where μ is a positive gain.

2.3 Grid voltage filter by least-squares algorithm

The grid voltage fundamental components are extracted from the estimated quantities $\hat{e}^\alpha$ by means of a least square algorithm-based filter. First, an estimated fundamental component $\hat{e}_{LS}^\alpha$ as the output of filter is obtained by $\hat{e}_{LS}^\alpha = \hat{\mathbf{X}}\mathbf{D}(k)$, where $\hat{\mathbf{X}} = [E_1\cos(\varphi_1) \,\vdots\, -E_1\sin(\varphi_1)]$ and $\mathbf{D}(k) = [\cos(\omega_1 kT_s) \,\vdots\, \sin(\omega_1 kT_s)]^T$.

Obviously, the grid voltage is a linear combination of unknown weight matrix $\hat{\mathbf{X}}(k)$ and a fixed sinusoidal matrix $\mathbf{D}(k)$. Relying on the least squares algorithm, the estimate $\hat{\mathbf{X}}(k)$ can be calculate as

$$\hat{\mathbf{X}}(k+1) = \hat{\mathbf{X}}(k) + \frac{\eta\nabla(\hat{e}^\alpha - \hat{e}_{LS}^\alpha)}{\varepsilon + \nabla^T(\hat{e}^\alpha - \hat{e}_{LS}^\alpha)\nabla(\hat{e}^\alpha - \hat{e}_{LS}^\alpha)} \quad (7)$$

where η is a positive gain and ε is a small value to avoid division by zero. As a result, once $\hat{\mathbf{X}}(k)$ converges to $\mathbf{X}(k)$, the fundamental component of grid voltage $\hat{e}_{LS}^\alpha$ is obtained as the output of the filter. The grid phase angle is simply calculated by from estimated fundamental grid voltage α- and β-components.

3. Simulation Results

To demonstrate the performance of the proposed scheme, the simulation results are presented. Fig. 2 shows the measured and estimated grid voltages in the stationary frame. It is clearly confirmed that the proposed grid voltage estimator based on GSD can estimate exactly the actual quantities even under distorted grid environment. The performance of the least squares-based filter is presented in Fig. 3, which well extracts the fundamental components of grid voltages.

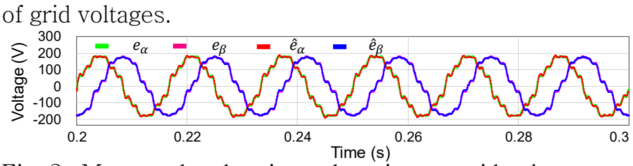

Fig. 2 Measured and estimated stationary grid voltages.

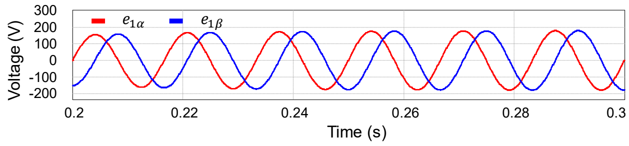

Fig. 3 Estimated fundamental grid voltages.

4. Conclusion

This paper has presented a grid voltage-sensorless current control scheme, which is realized by a current-type full-state observer to estimate grid-connected VSI state variables, and a GSD-based grid voltage observer. By means of the fundamental grid voltage components extracted by least squares-based filter, the synchronization of VSI is guaranteed without using the conventional PLL. The simulation has confirmed the validity of the proposed scheme.

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References

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