Harmonic Suppression and Stability Enhancement of a Voltage Sensorless Current Controller for a Grid-connected Inverter under Weak Grid

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ABSTRACT

This paper presents the harmonic suppression and stability enhancement of a grid voltage sensorless current controller for a grid-connected inverter under weak grid conditions. Given that inductive-capacitive-inductive (LCL) filters represented as higher-order dynamics cause resonance problems, a considerate resonance frequency damping process is required. In particular, the resonance phenomenon of the LCL filter crucially influences the current quality when the grid-connected inverter is connected to a weak grid with uncertain grid impedance and distorted harmonics. Additionally, there is a possibility that the control system will become unstable due to changes in system parameters, even after considerate resonance frequency damping. In order to solve these problems, this paper presents an active damping (AD) method by using integral variables in an integral state feedback current controller for a grid voltage sensorless inverter system, which significantly improves the current harmonics and stability of the grid-connected inverter under weak grid condition. The presented closed-loop current control scheme only requires the measurement of the injected grid currents and DC-link voltage. Compared to the traditional state feedback control methods, the reliability and robustness of the proposed control scheme are much improved even with reduced system cost. The stability and current control performance of the closed-loop system are investigated in the presence of uncertainty in the grid impedance and filter capacitor parameter under distorted grids. In order to support the theoretical analyses, the comprehensive simulation results are presented in terms of the grid current quality and control stability in an environment with both uncertain grid impedance and a distorted grid. Experimental results are also presented by using a 32-bit digital signal processor (DSP) TMS320F28335 controller for a 2 kVA grid-connected inverter to validate the feasibility of the proposed scheme practically.

INDEX TERMS

Active damping, distorted grid, grid-connected inverter, LCL parameter uncertainty, stability enhancement, voltage sensorless control, weak grid

I. INTRODUCTION

Due to the rapidly growing demand for energy and environmental problems related to conventional fossil fuels, renewable energy sources from wind turbines or photovoltaic systems are considered as promising alternatives for power generation in the global energy market. The progress of distributed power generation systems based on renewable energy sources is mainly facilitated by the development of power electronics technology [1], [2].

Pulse width modulation (PWM) grid-connected inverters which fulfill existing grid standards are widely used and adopted to deliver power from the renewable energy resources to the utility grid [3]. To meet the necessary criteria, a filter that effectively attenuates the current harmonics caused by the PWM switching frequency must
be designed properly. For this purpose, an inductive (L) filter with high inductance can be used in the inverter output stage as it simplifies the control design. On the other hand, compared to an L filter, inductive-capacitive-inductive (LCL) types of filters are more attractive due to their smaller physical size and better harmonic attenuation capability of high-order harmonics. Nevertheless, a third-order LCL filter introduces a resonant peak into the system, which may cause output resonance. To ensure the stable and reliable operation of the inverter system, a proper damping method, either passive or active, should be considered in system design [4].

A wide variety of resonance damping techniques have thus been developed with the trend generally favoring active damping (AD) techniques owing to the additional power losses experienced by passive damping techniques [5]-[7]. To effectively suppress the resonance frequency from LCL filters, single loop damping methods which use several types of digital notch filter have been extensively developed in [8]-[10]. In these methods, active damping strategies are simply realized by using the notch filter to deal with the variation of the grid impedance. In [8], the frequency of the notch filter is selected apart from the nominal resonance frequency to consider the variation of the resonance frequency. On the other hand, the researches in [9] and [10] present the resonance frequency estimators based on the fast Fourier transform and extended Kalman filter for tuning the notch filter frequency. Since these methods can deal with the resonance frequency variation, they are robust against the negative effects of weak grid condition. However, these methods are vulnerable when the resonance frequency severely deviates from the nominal setup or when distorted harmonics are applied at the PCC.

On the other hand, an effective AD can also be achieved by the multiloop damping method. The multiloop AD method can be constructed by the following techniques: the capacitor current or voltage feedback methods [11]-[19], observer-based AD methods [20]-[22], full-state feedback methods [23]-[25], and the hybrid damping methods [27]-[30]. Capacitor current or voltage feedback methods are presented in [11]-[19]. The digital filters constructed by the lead-lag network or the high pass filter are utilized with the capacitor current or voltage feedback to enhance the system stability and performance effectively. However, additional sensors raise the concerns on hardware system complexity and cost increase. In order to implement the capacitor current-based AD, high-precision current sensors are needed. Also, the capacitor voltage-based AD requires additional voltage sensors with high bandwidth switching devices and a digital differentiator, which often results in amplification of noises. To overcome this problem, the capacitor current or voltage estimators are presented based on the measured grid-side currents and system model to eliminate the extra sensors in [20]-[22]. The observer eigenvalue locations can be assigned to yield the desired observer dynamics. However, those methods do not work well under weak grid conditions with distorted grid voltages, or system parameter uncertainties.

As another approach, observer-based full-state feedback schemes have been presented [23]-[26]. In these methods, feedback control of the capacitor voltage and the inverter-side current is used actively to damp the resonance phenomenon. The advantages of using these control methods are that the design procedure is quite standard and straightforward, thereby eliminating the need for trial-and-error processes. However, certain drawbacks still exist, such as the computational burden and limited harmonic compensation [7]. Furthermore, the controller gain is designed based on the system model, which is vulnerable to disturbances caused by parameter changes in a weak grid. To address these vulnerabilities, feedback control systems can be designed with a wide gain margin, but such a design may degrade the current quality in a steady state.

In order to achieve high robustness against the grid impedance variations and to reduce the impact of processing delay, hybrid damping methods are also proposed to achieve AD by combining both the active and passive damping methods. However, the hybrid damping methods discussed in [27]-[30] require a trade-off between the power losses and the damping robustness [31].

Cable overload, long radial distribution feeders, saturation, and temperature effects are all possible causes of variation in the interfacing impedance and LCL filter parameters in the inverter system [32], [33]. Therefore, the grid impedance and filter parameters should be carefully considered when designing the controller parameters, especially when the inverter system operates under a weak grid condition. Under a weak grid condition in which the grid impedance or filter parameters can vary, the performance of AD scheme as well as harmonic compensation can deteriorate severely, causing serious grid current harmonics or even system instability [34].

To improve the harmonic suppression capabilities and the stability of state feedback controllers, this paper presents a control design methodology for a grid-connected inverter with an LCL filter in the discrete-time state-space. In the proposed control scheme, the current control design is accomplished by an integral full-state feedback control in which the proposed AD algorithm is incorporated by using the integral variable. The controller is implemented in the synchronous reference frame (SRF) so that integral control of the DC quantities can ensure zero steady state current errors. Furthermore, an AD algorithm using the integral terms can effectively compensate for uncertain disturbances from variations in the LCL filter parameters and grid impedance.

Additionally, to reduce the system cost and hardware complexity, the grid voltage sensorless control is further taken into consideration in the inverter design process. By
means of a discrete current-type observer, the system state variables can be estimated precisely to accomplish the full-state feedback current control. Also, the grid voltage phase angle estimator is designed by using the \( d \)-axis current and capacitor voltage estimates from the state observer [35]. This method provides accurate estimates of the grid voltage phase angle and frequency even under severe grid conditions such as the harmonic distortion and system parameter change. Thus, the proposed current controller can be implemented successfully without the grid voltage measurements. Only the grid-side currents and DC-link voltage sensors are utilized to control the inverter system.

A system stability analysis is conducted by investigating the closed-loop frequency responses when the grid impedance and filter parameters vary. The stability analysis for the proposed control scheme is validated by a PSIM software-based simulation and experimental results obtained from a prototype three-phase grid-connected inverter under adverse grid conditions. The analytical assessment shows that a grid voltage sensorless full-state feedback current controller with AD scheme can effectively assess the grid voltage sensorless current control scheme measures only two grid-side currents and DC-link voltage, and the grid voltage phase and frequency even under severe grid parameter change. Thus, the proposed current controller can be implemented successfully without the grid voltage measurements. Only the grid-side currents and DC-link voltage sensors are utilized to control the inverter system.

This paper is organized as follows: Section II describes the system model. Section III presents the design of the proposed grid voltage sensorless current controller with the AD scheme. Section IV presents the closed-loop system stability under system parameter uncertainty by using the frequency responses. The simulation and experimental results for the proposed control scheme is validated by a PSIM software-based simulation and experimental results obtained from a prototype three-phase grid-connected inverter under adverse grid conditions. The analytical assessment shows that a grid voltage sensorless full-state feedback current controller with AD scheme can effectively assess the grid voltage sensorless current control scheme measures only two grid-side currents and DC-link voltage, and the grid voltage phase and frequency even under severe grid parameter change. Thus, the proposed current controller can be implemented successfully without the grid voltage measurements. Only the grid-side currents and DC-link voltage sensors are utilized to control the inverter system.

II. SYSTEM DESCRIPTION

Fig. 1 shows the configuration of an LCL-filtered grid-connected inverter connected to a weak grid, in which \( V_{DC} \) denotes the DC-link voltage, \( R_1, R_2, L_1, \) and \( L_2 \) are the filter resistance and filter inductance values, respectively, \( C_f \) is the filter capacitance, and \( L_g \) is the grid inductance caused by the weak grid. In Fig. 1, the proposed grid voltage sensorless current control scheme measures only two grid-side currents and DC-link voltage. When grid impedance does not exist in Fig. 1, the inverter system can be expressed mathematically in the SRF as

\[
p_i^d = (-R_i / L_i) i_d^d - \omega L_i v_i^q - (1 / L_i) e^q
\]

\[
p_i^q = (-R_i / L_i) i_d^q + \omega L_i v_i^d + (1 / L_i) e^d
\]

\[
p_c^d = (-R_c / L_c) i_d^c - \omega L_c v_c^q - (1 / L_c) e^q
\]

\[
p_c^q = (-R_c / L_c) i_d^q + \omega L_c v_c^d + (1 / L_c) e^d
\]

\[
p_v^d = e^q - (1 / C_f) i_d^q + (1 / C_f) i_d^c
\]

\[
p_v^q = e^d - (1 / C_f) i_d^q + (1 / C_f) i_d^c
\]

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FIGURE 1. Configuration of a grid-connected inverter and a current control scheme.

where the superscripts “q” and “d” denote the \( q \)-axis and \( d \)-axis variables, respectively, \( p \) represents the differential operator, \( i_1 \) is the inverter-side current, \( i_2 \) is the grid-side current, \( v_i \) is the capacitor voltage, \( e \) is the grid voltage, \( v_i \) is the inverter output voltage, and \( \omega \) is the angular frequency of the grid voltages. From (1)-(6), the state-space model of the inverter system is expressed as

\[
\dot{x}(t) = Ax(t) + Bu(t) + De(k)
\]

\[
y(t) = Cx(t)
\]

where \( x = [i_1^q, i_1^d, i_2^q, i_2^d, v_i^q, v_i^d] \) is the state system vector, \( u = [v_i^q, v_i^d] \) is the input system vector, \( e = [e^q, e^d] \) is the grid voltage vector, and the system matrices \( A, B, C \) and \( D \) are expressed as

\[
A = \begin{bmatrix}
-R_1 / L_1 & -\omega & 0 & 0 & 1 / L_1 & 0 \\
\omega & -R_2 / L_2 & 0 & 0 & 0 & 1 / L_2 \\
0 & 0 & -R_1 / L_1 & -\omega & -1 / L_1 & 0 \\
0 & 0 & \omega & -R_2 / L_2 & 0 & -1 / L_2 \\
-1 / C_f & 0 & 1 / C_f & 0 & 0 & -\omega \\
0 & -1 / C_f & 0 & 1 / C_f & 0 & \omega
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 1 / L_2 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 / L_1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

For the purpose of a digital implementation, a discretized model of the continuous-time inverter system expressed by (7) and (8) is obtained using the zero-order hold (ZOH) method with sampling time \( T_s \), as follows:

\[
x(k+1) = Ax(k) + Bu(k) + De(k)
\]
\[ y(k) = C_x x(k) \]  
(11)

where \( A_x = e^{A_x T}, B_x = (\int_0^T e^{A_x t} \, dt)B, C_x = C. \)

III. GRID VOLTAGE SENSORLESS CURRENT CONTROLLER WITH ACTIVE DAMPING

A. INTEGRAL STATE FEEDBACK CONTROL WITH RESONANT CONTROLLER

To ensure asymptotic reference tracking as well as disturbance rejection, the integral terms are augmented in inverter state model to constitute an integral state feedback controller. By incorporating the integral action in (10) and (11), the entire system model can be combined as follows [23], [24]:

\[
\begin{bmatrix}
    x(k+1) \\
    x_1(k+1)
\end{bmatrix} = 
\begin{bmatrix}
    A_x & 0_{6 \times 2} \\
    -B_x C_x & A_x
\end{bmatrix}
\begin{bmatrix}
    x(k) \\
    x_1(k)
\end{bmatrix} + 
\begin{bmatrix}
    B_x & 0_{6 \times 2}
\end{bmatrix}
\begin{bmatrix}
    u(k) \\
    e(k)
\end{bmatrix}
\]

\[
+ \begin{bmatrix}
    D_x \\
    0_{2 \times 2}
\end{bmatrix}
\begin{bmatrix}
    e(k) \\
    r(k)
\end{bmatrix}
\]

\[
y_s(k) = \begin{bmatrix}
    C_x & 0_{1 \times 2}
\end{bmatrix}
\begin{bmatrix}
    x(k) \\
    x_1(k)
\end{bmatrix}
\]

where \( x_1(k+1) = A_x x_1(k) + B_x e(k) \)

\[ \varepsilon = [e^T e^T]^T = r - C_x x, A_x = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, B_x = \begin{bmatrix} T_s & 0 \\ 0 & T_s \end{bmatrix} \]

\( x_1 = [x_1^T x_1^T]^T \) is the integral state vector, \( 0_{6 \times 2} \) is a zero matrix with appropriate dimensions, and \( \bullet \bullet \bullet \) denotes the reference quantities.

Considering an augmented system in (12) and (13), integral state feedback control is designed as follows:

\[
u(k) = K_x \begin{bmatrix} x(k) \\ x_1(k) \end{bmatrix}
\]

\[
K_x = \begin{bmatrix}
    K_{ix} & K_{ix} \\
    K_{ix} & K_{ix}
\end{bmatrix}
\]

(14)

where \( K_x \) is the set of state feedback gains. The full-state feedback control gain is systematically determined through the linear quadratic regulator (LQR) approach by minimizing the discrete quadratic cost function. A detailed block diagram of the state feedback current controller augmented with the integral control terms is available in the literature [23].

Additionally, to track the grid-side current reference and to compensate for grid voltage disturbances in the fifth- and seventh-order harmonic components, the proposed scheme uses parallel resonant controllers. The resonant control scheme is realized in the discrete-time domain by using the transfer function given as

\[ G_{h=5,7}(z) = \frac{z^2 - \cos(h o T_s)z}{z^2 - 2 \cos(h o T_s)z + 1}. \]

B. VOLTAGE SENSORLESS CURRENT CONTROL

This section presents a current-controller-based grid voltage sensorless algorithm that effectively estimates the phase angles and frequencies of three-phase grid voltages. The traditional phase-locked loop method is used to obtain the grid phase angles, and to adjust the phase angle between the grid voltage and grid-injected current. However, inspired by the earlier work [35], this paper extracts the grid phase angles from the integral term of \( d \)-axis current without the grid voltage measurements to regulate the AC line currents. In addition, to implement the resonant controllers in (15), the grid frequency is also estimated. For this purpose, the grid phase angle and grid frequency estimator is designed.

When the exact grid phase angle is not known, an LCL-filtered grid-connected inverter system is transformed to the reference frame which rotates with the estimated grid phase angle \( \hat{\theta} \). The discretization of the continuous-time inverter model at the SRF produces the state equation in (10). On the other hand, when the continuous-time model at the rotating reference frame with \( \hat{\theta} \) is discretized, the inverter model in (10) is modified to

\[ x(k+1) = A_x x(k) + B_x u(k) + D_x \hat{e}(k) \]

(16)

where \( \hat{e} = [\hat{e}_q \hat{e}_d]^T = [e_q \cos(\hat{\theta}) e_q \sin(\hat{\theta})]^T \) is the grid voltage error vector as a result of using the transformation with unknown grid phase angle, and \( \hat{\theta} = \theta - \hat{\theta} \) is the difference between the actual grid voltage phase angle \( \theta \) and the estimated value \( \hat{\theta} \). It is obvious that once the difference \( \hat{\theta} \) reaches zero, the representation of (16) is reduced to the LCL-filtered inverter model in the SRF as presented in (10).

To estimate \( \hat{e}_d \), the \( d \)-axis current error is used as follows:

\[ \frac{d}{dt} \hat{e}_d = \lambda (t_d^* - t_d^\hat{\theta}) \]

(17)

where \( \bullet \bullet \bullet \) denotes the estimated quantities and \( \lambda \) is the estimation gain. By using the estimate of \( \hat{e}_d \), \( \hat{\theta} \) can be obtained with the assumption of \( \hat{\theta} \approx \sin(\hat{\theta}) \) as follows:

\[ \hat{\theta} \approx \sin(\hat{\theta}) = \frac{\hat{e}_d}{e_q}. \]

(18)
The phase angle difference \( \hat{\theta} \) is used to estimate the phase angle and frequency of the grid voltage by constructing the Luenberger observer based on the grid model as follows:

\[
\frac{d}{dt} \hat{\theta} = \omega_0 \quad (19)
\]

\[
\frac{d}{dt} \theta = \omega \quad (20)
\]

From the model in (19) and (20) with the phase angle difference \( \hat{\theta} \) as an estimator input, the dynamic of the observer is constructed as follows:

\[
\frac{d}{dt} \begin{bmatrix} \hat{\theta} \\ \hat{\omega} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{\theta} \\ \hat{\omega} \end{bmatrix} + \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \delta.
\]

(21)

where \( \alpha \) and \( \beta \) are the observer gains. The observer in (21) is implemented in the discrete-time domain after a discretization process based on the Euler method with the sampling time \( T_s \). The observer gains, \( \alpha \) and \( \beta \) are designed such that the observer poles are located inside the unit circle. In addition, since the proposed scheme does not measure the grid voltages for grid voltage sensorless operation, the estimated \( q \)-axis capacitor voltage is used instead of the \( q \)-axis grid voltage magnitude thanks to a negligible voltage drop via a small-size inductor [36]. As a result, the grid phase error in (18) is replaced with the equation as below

\[
\hat{\theta} \approx \frac{\hat{\omega}_d}{e^\omega} \approx \frac{\hat{\omega}}{\hat{\omega}_d}.
\]

(22)

C. ACTIVE DAMPING SCHEME

In order to ensure the control stability of LCL-filtered grid-connected inverters, the state-feedback-based AD methods are preferred to repress the peak at resonance frequency from the LCL filter, which provides the advantages of flexibility, robustness, and zero power loss. However, the existence of grid impedance or the variation of LCL filter parameters introduces a large resonance frequency derivation. This may degrade the resonance suppression capability and control performance of the state feedback current controller.

In this section, to enhance the system stability and robustness against the negative impacts from the external perturbation as weak grid condition or the internal parameter uncertainties, an AD method is integrated into the full-state feedback controller. Resonance damping performance is generally degraded when the designed resonance frequency is mismatched with actual one. Thus, the AD scheme should be designed in order to maintain a good performance under a wide range of resonance frequency.

To achieve this goal, the proposed AD scheme uses a technique of injecting the anti-phase oscillation into the inverter control inputs. The system oscillation is extracted from the output of the integral control terms via the high pass filters (HPFs). HPFs can be realized by means of low-pass filters, which is known to avoid the delay in high frequency domain [36]. To take the advantage of a systematic controller design in an integral state feedback control, additional AD scheme is designed using the integral control outputs of the state feedback controller in this paper. In addition, the AD terms are augmented into the system model in (12) to constitute an entire state-space inverter model.

The AD transfer function to design an additional AD scheme is presented as follows:

\[
G_{h}(s) = \frac{\hat{\omega}_d}{\omega_d} = \frac{\omega_c^2}{s^2 + 2\xi \omega_c s + \omega_c^2}.
\]

(23)

where \( \omega_c \) is the cutoff frequency and \( \xi \) is damping ratio. To augment (23) with the system model in (12), the above transfer function is expressed in the discrete-time state space, as follows:

\[
x_h(k+1) = A_h x_h(k) + B_h u_h(k)
\]

(24)

\[
y_h(k) = C_h x_h(k)
\]

(25)

where

\[
A_h = \begin{bmatrix} A_{h1} & A_{h2} \\ A_{h3} & A_{h4} \end{bmatrix}, \quad B_h = \begin{bmatrix} B_h \\ 0 \end{bmatrix}, \quad C_h = \begin{bmatrix} C_{h1} & C_{h2} \end{bmatrix}.
\]

To implement the AD scheme, the integral control output \( u_h(k) \) in (14) which is expressed again as

\[
u_h(k) = K x_h(k) = \begin{bmatrix} K_{h1} & K_{h2} \\ K_{h3} & K_{h4} \end{bmatrix} \begin{bmatrix} x_{h1} \\ x_{h2} \end{bmatrix}.
\]

(26)

is applied to the input in (24). The \( q \)-axis and \( d \)-axis integral control output signals are combined as

\[
x_h(k+1) = A_h x_h(k) + B_h u_h(k)
\]

(27)

\[
y_h(k) = -C_h x_h(k)
\]

(28)

where \( x_h = [x_{h1} \ x_{h2} \ x_{h3} \ x_{h4}]^T \) is the HPF state vector for the \( q \)-axis and \( d \)-axis, and the system matrices \( A_h, B_h, \) and \( C_h \) are expressed as follows:

\[
A_h = \begin{bmatrix} A_h & 0 \\ 0 & A_h \end{bmatrix}, \quad B_h = \begin{bmatrix} B_h \\ 0 \end{bmatrix}, \quad C_h = \begin{bmatrix} C_{h1} & C_{h2} \\ 0 & C_{h1} \end{bmatrix}.
\]
The HPF state equation in (27) is combined with the integral state equation in (12) to produce the entire system model as follows:

\[
\begin{bmatrix}
    x(k+1) \\
    q_x(k+1) \\
    x_y(k+1)
\end{bmatrix} = 
\begin{bmatrix}
    A_{ij} & 0 & 0 \\
    -B_{C_j} & A_i & 0 \\
    0 & 0 & A_{ij}
\end{bmatrix}
\begin{bmatrix}
    x(k) \\
    q_x(k) \\
    x_y(k)
\end{bmatrix} + 
\begin{bmatrix}
    B_{D_j} \\
    0 \\
    0
\end{bmatrix} u(k) + 
\begin{bmatrix}
    0_{6 \times 2} \\
    0_{6 \times 2} \\
    0_{6 \times 2}
\end{bmatrix} e(k) + 
\begin{bmatrix}
    B_i \\
    0 \\
    0
\end{bmatrix} r(k)
\]

\[B_{ij} \equiv \begin{bmatrix}
    K^d_{x} B_h & K^e_{x} B_h \\
    0 & 0 \\
    K^d_{x} B_h & K^e_{x} B_h \\
    0 & 0
\end{bmatrix}.
\]

(29)

The proposed current control with the AD scheme is achieved by the state feedback control for the entire system model in (29). Nevertheless, the proposed AD technique can cause the problem of the high frequency harmonic amplification by the HPFs. To solve this problem, the magnitude of the anti-phase frequency is adjusted by multiplying a factor \( \zeta \) \((0 < \zeta < 1)\) in the control law. The effects of the AD according to the value of \( \zeta \) will be covered in section 4. From the augmented system in (29), the entire control law is composed of the state feedback control term, integral state feedback control term, and AD term as follows:

\[
u(k) = \begin{bmatrix}
    K_{x} & K_{y} & \zeta C_{y}
\end{bmatrix}
\begin{bmatrix}
    x(k) \\
    q_x(k) \\
    x_y(k)
\end{bmatrix}
\]

(30)

where the control term \( \zeta C_{y} x_y(k) \) provides additional AD for the system, and \( \zeta \) is the AD gain.

The proposed AD algorithm utilizes the information of the integral control term \( K_{y} x_y(k) \) in (26) to suppress the impact of the resonance phenomenon. In addition, the whole grid voltage sensorless control scheme is accomplished by using only the information of the grid-side current \( i_2 \). In this regard, the proposed scheme is attractive given that it is scarcely dependent on the grid parameters, and the tuning procedure of the AD scheme is very simple.

Fig. 2 shows the detailed block diagram of the proposed grid voltage sensorless control scheme with the grid phase angle estimator and AD scheme for three-phase grid-connected inverter. The control block diagram shows that the proposed scheme is composed of the integral full-state feedback controller with the AD method, grid phase angle estimator for a grid voltage sensorless operation, and resonant controller for the compensation of the harmonic distortion in grid voltages. To design the state feedback controller, proper set for the feedback gain matrices \( K_{x} \) and \( K_{y} \) is chosen systematically by the LQR approach.

The complete design step for the proposed grid voltage sensorless current control with the AD scheme proceeds as follows: 1. The system parameters and sampling time should be first set to obtain the accurate discrete-time system mode in (12) and state feedback controller in (14) by the LQR method.; 2. The additional AD scheme in (24) is next augmented with the system model to compensate for the LCL filter resonance and negative impact of system parameter variations.; 3. The frequency-domain characteristics of the closed-loop system in (29) are determined to obtain the desired AD gain.; 4. If necessary, the integral gains are further adjusted to ensure the stable margin.

IV. CLOSED-LOOP SYSTEM STABILITY UNDER SYSTEM PARAMETER UNCERTAINTY

In this section, the closed-loop system stability of the current controller is investigated under system parameter variations. To evaluate the reference tracking performance of the proposed current controller with the AD method, the frequency responses are obtained by using the closed-loop transfer function from reference \( i_2^* \) to output grid current \( i_2^* \). To demonstrate the effectiveness of the AD scheme, the frequency responses for the proposed current controller with the AD scheme in (29) and (30) are compared with those for the conventional integral state feedback current controller without the AD scheme in (12) and (14). The stability and current control performance of the AD scheme are evaluated under uncertain grid impedance and filter capacitor variations.

Fig. 3 shows the closed-loop frequency responses for the system model with the nominal LCL filter parameters with and without the AD scheme for different AD gains, in which the response for AD gain \( \zeta = 0 \) corresponds to the case without the AD scheme. The dynamics of the resonant
controller are included in the closed-loop frequency responses of Fig. 3. However, the influence of the grid phase angle estimator and full state observer is not considered. In these figures, it is observed that the magnitude-frequency response curve with the AD decreases more in high frequency regions with the nominal LCL parameter set as the AD gain is increased. On the other hand, the phase-frequency response curve does not vary significantly under the change of the AD gain. This result shows that the controller stabilizes the system regardless of AD function.

However, when the system parameters vary, the proposed AD method plays a major role in enhancing the stability of the system. Also, it is worth to note that the magnitudes of the closed-loop frequency response get smaller as the AD gain $\zeta$ increases in Fig. 3. From the above discussions, the proposed AD scheme can suppress well the LCL filter resonance peak when the inverter system has the nominal LCL filter parameters.

In order to verify the necessity of additional AD scheme and analyze the drawbacks of the state feedback-based damping methods, a comprehensive comparison is conducted in Fig. 4 and Fig. 5 when the system parameters vary from the nominal values without the AD scheme. Fig. 4 shows the closed-loop frequency responses when $L_g$ varies from 0 to 5 mH without the AD scheme. Obviously, the frequency response characteristics are changed according to the system parameter variations. It can be clearly observed from Fig. 4 that the magnitudes of the frequency responses exceed 0 dB without using the AD scheme in the conventional integral state feedback control. The magnitude increase of the frequency responses beyond 0 dB is more severe as $L_g$ increases. The magnitude of the frequency responses greater than 0 dB amplifies high
frequency noise, which may cause the output oscillation, or even system instability.

Fig. 5 presents the closed-loop frequency responses under variations of the filter capacitors without the AD scheme. In Fig. 5(a), the filter capacitor is gradually increased to 30 μF from the nominal value 20 μF. In Fig. 5(b), the filter capacitor is gradually decreased to 14 μF from the nominal value. Similarly, the filter capacitor variations also alter the frequency response characteristics. In fact, the filter capacitor variations force the magnitude of the frequency responses to move toward unstable regions. It can be seen from these figures that for a small variation of the filter capacitor, the stability is maintained. However, as the filter capacitor varies further, the magnitudes of the frequency responses are increased beyond 0 dB. This clearly proves that additional AD scheme is necessary in the conventional integral state feedback controller to improve the system stability under the uncertainty in the grid impedance and LCL filter parameters.

Fig. 6 shows the comparison of the closed-loop frequency responses under the system parameter variations with and without the AD scheme by using the system model in (12) and (29) with different system parameters. The closed-loop frequency responses in Fig. 6 are obtained under $C_f = 30 \, \mu F$, $C_f = 15 \, \mu F$, and $L_g = 5 \, mH$. To realize the current controller without the AD scheme, the conventional integral state feedback controller is designed based on the system (12) and (14). On the other hand, the proposed AD scheme is achieved by the system (29) and (30). In all cases, the closed-loop frequency responses exhibit the magnitude responses higher than 0 dB in certain frequency range without the AD scheme, which may amplify high frequency components. In addition, the system is very sensitive to the disturbances and the system cannot maintain the stability. On the contrary, the current controller with the proposed AD scheme can effectively suppress the LCL filter resonance peak even in the presence of the parameter uncertainty. As a result, the magnitudes of the closed-loop frequency responses always remain less than 0 dB. It is confirmed from this analysis result that augmenting the proposed AD method into the conventional controller produces a more robust system under parameter deviations. Simulations and experimental results are presented in the following sections.

V. EVALUATION RESULTS

A. SYSTEM CONFIGURATION

In order to verify the validity of the theoretical analyses in the previous section, both the PSIM software-based simulations and experiments are carried out using a three-phase prototype grid-connected inverter system. The system parameters are presented in Table I. Fig. 7 shows the experimental configuration of the system. The overall system is composed of a three-phase inverter connected to the grid through an LCL filter, a magnetic contactor for grid-connecting operations, and an AC power source to
emulate three-phase grid voltages in ideal as well as distorted grid conditions. The entire control algorithm is implemented on a 32-bit floating-point digital signal processor (DSP) TM320F28335 [37]. Only two current sensors and DC-link voltage sensor are used to measure the grid-side currents and DC-link voltage, respectively for the implementation of the proposed voltage sensorless current control with the AD scheme. Additional inductors are employed to implement grid impedance changes. The sampling and inverter switching frequencies are set as 10 kHz. Fig. 8 presents a photograph of the experimental hardware test setup.

**B. SIMULATION RESULTS**

In order to simulate the worst operation condition that can occur in a utility grid, the proposed current control scheme is tested under severe distorted grid voltages containing fifth- and seventh-order harmonic components, with a 5% magnitude of the fundamental grid voltage, as represented in Fig. 9(a). Fig. 9(b) shows the simulation results of three-phase grid-side currents for the proposed grid voltage sensorless current control with the AD scheme in a steady state under the grid condition in Fig. 9(a). Fig. 9(c) shows the fast Fourier transform (FFT) result of the phase-a current in Fig. 9(b) with the harmonic limits specified by the grid interconnection regulation IEEE Std. 1547 [38]. The simulation results show that the proposed current controller suitably rejects the distorted harmonics from the grid to produce clean output currents. As shown in Fig. 9(c), the total harmonic distortion (THD) of the grid-side phase currents is only 3.08%.

To verify the usefulness of the proposed scheme under the weak grid condition, additional inductors \( L_g \) of 1.5 mH are connected in series with the grid-side filter inductors \( L_2 \) as shown in Fig. 7. Fig. 10 presents the responses of three-phase grid-side currents and FFT result with the proposed grid voltage sensorless control with the AD scheme. In Fig. 10(a), even though the additional inductors are suddenly...
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To clearly highlight negative effects of weak grid condition, Fig. 11 shows the responses of three-phase grid-side currents without AD scheme. Fig. 11(a) shows the transient responses of the current controller under the grid inductance change from 0 mH to 1.5 mH at 0.2 s when the AD function is disabled. It is clearly shown in Fig. 11(a) that high frequency oscillations in the grid currents are increased as soon as \( L_g \) is added. Steady state current waveforms in Fig. 11(b) still shows high frequency current oscillations due to insufficient damping. Moreover, the FFT result for the a-phase grid-side current in Fig. 11(c) shows THD = 2.98%.

To further assess the robustness and current control performance under system parameter changes, Fig. 12(a) and Fig. 12(b) present the responses of grid-side three-phase currents with the proposed grid voltage sensorless control with the AD scheme under variations of the filter capacitance to 15 \( \mu \)F and 30 \( \mu \)F, respectively. Even in the presence of the filter parameter variations, the entire system maintains a stable operation without using the grid voltage measurements. The grid-side phase currents show a reasonably sinusoidal current quality due to the use of an effective AD scheme. In addition, to evaluate the robustness and reliability under very weak grid condition, additional inductors \( L_g \) of 1.5 mH are connected in series with the grid-side filter inductors \( L_2 \) similar to Fig. 10. In Fig. 12(c), three-phase grid-side currents still show sinusoidal currents even in this condition, which is matched well with the closed-loop frequency response in Fig. 6(a).

To clearly demonstrate the effectiveness of the proposed grid voltage sensorless current control with the AD scheme, Fig. 13 shows the transient responses of the current controller under system parameter uncertainties when the AD function is suddenly removed at 0.3 s. In Fig. 13(a), the filter capacitance \( C_f \) changes from 20 \( \mu \)F to 15 \( \mu \)F, which results in a higher LCL resonance frequency than that of the nominal system model. As is clearly shown in Fig. 13(a), as soon as the AD scheme is removed at 0.3 s, high frequency oscillations due to insufficient damping.
oscillations in the grid currents are considerably increased, which is matched well with the closed-loop frequency response in Fig. 6(a). Fig. 13(b) and Fig. 13(c) show the simulation results when the filter capacitance \( C_f \) changes from 20 \( \mu \)F to 30 \( \mu \)F, and \( L_g \) of 5 mH exists due to a weak grid condition, respectively. Similarly, the AD function is suddenly removed at 0.3 s. In these tests, the nominal LCL filter parameter, \( L_g = 5.0 \) mH.

To verify the dynamic performance of both the proposed current controller and grid phase angle estimator, the transient simulation results are shown in Fig. 14 under a step change of the q-axis reference current from 4 A to 7 A at 0.25 s. In these tests, the nominal LCL filter parameter, \( C_f \) variation, and uncertain \( L_g \) are considered under the distorted grid condition shown in Fig. 9(a). In all cases, the currents quickly track the new reference without a significant overshoot, which proves a stable and desirable transient response of the proposed control scheme.

In addition, to demonstrate the estimating performance of the grid phase angle by the proposed sensorless scheme, Fig. 14 also shows the comparison results of the estimated phase angle \( \hat{\theta} \) with the phase angle obtained by the conventional phase-locked loop (PLL) with measured grid voltages, \( \theta_{PLL} \).

In these figures, \( \theta_{PLL} \) is used only for monitoring purpose. The estimated phase angle is aligned well with the phase angle obtained by the PLL with measured grid voltages even in the presence of the uncertainty in the grid impedance and LCL filter parameters.

Additionally, to investigate grid phase and frequency estimation performance under voltage dip condition, Fig. 15.
shows the simulation results for the proposed control when the grid voltages have distortion and voltage dip with $L_g$ variation. Initially, the grid voltages have the nominal magnitude only with harmonic distortion. Then, the grid voltages have 20% voltage dip at 0.2 s, additional inductors $L_g$ of 5 mH are added at 0.25 s, and the grid voltages are recovered to the nominal values at 0.35 s. Even though the grid currents have overshoot at the instant of the voltage dip at 0.2 s, the sensorless algorithm which estimates the grid phase and angular frequency is quite stable and the grid currents reach sinusoidal steady state rapidly. Noticeable transient responses are observed when large uncertain grid impedance is added to the system at 0.25 s. The grid currents show severe oscillation before reaching steady state, which also affects the estimation performance of the grid phase and angular frequency. However, the proposed grid voltage sensorless control maintains the system stability and ensures high current quality at steady state. Finally, when the grid voltages are recovered to the nominal values at 0.35 s with $L_g$ of 5 mH, the proposed scheme still shows a good current quality and a satisfactory estimation performance of the grid phase and angular frequency.

To further test the proposed control scheme under more severe voltage dip condition, Fig. 16 simulates the proposed control when the grid voltages have distortion, voltage dip, and 60° phase jump.
the grid voltages have 20% voltage dip and 60° phase angle jump at the same time at 0.2 s. In this instant, there exists a phase difference between $\hat{\theta}$ and $\theta_{PLL}$ due to the sudden voltage drop and phase angle jump. Moreover, the estimated angular frequency deviates severely from the nominal value. However, as shown in these simulation tests, the proposed control method effectively stabilizes the system even under such a severe grid disturbance. As a result, the grid-side phase currents are restored to stably sinusoidal currents.

C. EXPERIMENTAL RESULTS

In this section, the experimental results are presented to evaluate the control performance and robustness of the proposed grid voltage sensorless current control with the AD scheme under both the system parameter changes and model uncertainty by using the experimental system in Fig. 7 and Fig. 8. A programmable AC power source is used to implement distorted grid voltages.

Fig. 17 shows the experimental results for the proposed grid voltage sensorless current control with the AD scheme under distorted grid voltages. (a) Distorted grid voltages and FFT result for the a-phase voltage. (b) Grid-side three-phase currents and FFT result for the a-phase current.

In order to verify experimentally the usefulness of the proposed AD scheme in a grid voltage sensorless current control, Fig. 18 shows the experimental results of grid-side three-phase currents under the parameter uncertainty. Similar to the simulation in Fig. 12, the filter capacitance $C_f$ varies to 15 μF and 30 μF, respectively, in Fig. 18(a) and Fig. 18(b). Also, an external inductor $L_g$ of 5 mH is applied in Fig. 18(c) to emulate the grid impedance caused by a weak grid condition. It can be seen in Fig. 18 that the proposed scheme damps well the inherent LCL resonance phenomenon even in the presence of parameter variations as well as model uncertainty. In addition, it effectively attenuates the external disturbance caused by the grid harmonic distortion even without using the grid voltage measurements. This confirms that the proposed sensorless grid-side current waveforms and FFT result for the a-phase grid current under the nominal conditions when a current reference is 5 A. As expected, the proposed scheme suppresses well the disturbance caused by a distorted grid, and provides high-quality grid currents.

FIGURE 17. Experimental results for the proposed grid voltage sensorless current control with AD scheme under distorted grid voltages. (a) Distorted grid voltages and FFT result for the a-phase voltage. (b) Grid-side three-phase currents and FFT result for the a-phase current.

FIGURE 18. Experimental results of grid-side three-phase currents for the proposed grid voltage sensorless current control with AD scheme under distorted grid voltages and parameter variation. (a) $C_f$ changes from 20 μF to 15 μF. (b) $C_f$ changes from 20 μF to 30 μF. (c) $L_g = 5.0$ mH.

FIGURE 19. Experimental results of grid-side three-phase currents for the proposed scheme with and without AD method under nominal system parameter.

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control with the AD scheme greatly enhances the system stability and reliable operation of inverter.

To emphasize the usefulness of the proposed AD method by comparison, the experimental transient test results are presented when the proposed AD method becomes suddenly inactive in the grid voltage sensorless integral state feedback current controller. Fig. 19 shows the experimental results of grid-side three-phase currents under the nominal system parameters, and Fig. 20 shows the experimental results under the filter parameter variations and uncertain grid impedance, respectively. In all figures, the green waveforms represent the transition signal to remove the AD scheme in the current controller. It is obvious from Fig. 19 that the proposed AD scheme is effective in the grid voltage sensorless integral state feedback current controller even under the nominal LCL filter parameter case to improve the current quality of the inverter system. A remarkable contribution of the proposed AD scheme in maintaining the system stability and ensuring high current quality is observed in Fig. 20, when the filter parameters vary, or uncertain grid impedance exists in the system. As soon as the proposed AD scheme is deactivated, the quality of grid-injected currents is significantly degraded, showing highly oscillating phase currents. In an extreme case, the inverter system could lose the stability. These results clearly demonstrate that the proposed AD scheme is necessary for a grid voltage sensorless integral state feedback current controller to enhance the system stability. Also, these experimental results are in good agreement with the stability analyses in Fig. 4 to Fig. 6, as well as the simulation results in Fig. 13.

The transient responses of the proposed grid voltage sensorless current control with AD scheme are validated by experiments. Fig. 21 shows the experimental results for the proposed grid voltage sensorless current control with AD scheme under step change in q-axis current reference from 3 A to 5 A. \( \hat{\theta} \) is the phase angle detected by the conventional PLL with measured grid voltages, and \( \hat{\theta} \) is the estimated phase angle by the proposed sensorless scheme. (a) With nominal LCL filter parameters. (b) With \( C_f = 15 \, \mu F \). (c) With \( L_g = 5.0 \, mH \).

VI. CONCLUSION

This paper has presented harmonic suppression and stability enhancement method of a grid voltage sensorless current controller for a grid-connected inverter operating under a distorted weak grid. Based on the conventional integral state feedback current controller, the additional AD terms are
augmented to enhance the system stability and to ensure current control performance under the uncertainties of grid impedance and parameter changes with weak grid conditions. A stability analysis has been carried out by investigating the closed-loop frequency responses for discrete-time system model when the grid impedance and filter parameters vary. In addition, to reduce the system cost and hardware complexity, the grid voltage sensorless control scheme is taken into consideration. Thus, the proposed controller can be implemented with only the measurements of grid-side currents and DC-link voltage. For this purpose, a discrete current-type state observer and a grid voltage phase angle estimator are designed.

In order to support the theoretical stability analysis of the proposed control scheme, the entire control algorithm that includes a grid voltage sensorless current control and AD method has been implemented on a 32-bit DSP TMS320F28335 to control a 2 kVA grid-connected inverter. The proposed control scheme has been tested in terms of grid current harmonic attenuation and resonance damping, in the presence of the harmonic distortion of grid voltages as well as the uncertainties of grid impedance and LCL parameters. It is confirmed from test results under various conditions that the proposed grid voltage sensorless full-state feedback current controller with the AD scheme can effectively solve the issues of current harmonic attenuation and resonance damping at the same time even without using the grid voltage sensors. The proposed scheme highly improves the robustness with reduced system cost, especially in an environment containing uncertain grid impedance caused by the weak grid.

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