Linear ADRC direct current control of grid-connected inverter with LCL filter for both active damping and grid voltage induced current distortion suppression

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Abstract: The conversion and utilisation of renewable energy generations often require grid-connected inverters. When applying LCL filter to remove power electronic chopping harmonics, the power quality faces two issues of resonance damping and grid voltage induced current distortion. Conventionally, two separate control algorithms are required to treat the two issues, requiring an additional current sensor, increasing control complexity and limiting performance. This study demonstrates that linear active disturbance rejection control (ADRC) is able to treat both resonance damping and grid voltage induced current distortion as overall disturbance at the same time through a single structure, while achieving higher power quality for dynamic, steady-state, small and large parameter setup, as well as parameter variations, as validated by experimental results. In principle, the ADRC can be configured with or without knowledge of the system model. This study also reveals that it is the measurement noise tolerance that makes the two configurations different in practice. By using model information in ADRC algorithm, the required bandwidth can be reduced, offering more tolerance to measurement noise. Moreover, the ADRC controller has only two parameters to tune for ‘fast’ or ‘slow’, which makes it easy for implementation.

1 Introduction

Grid-connected inverters transform direct current (DC) energy to alternating current (AC) energy. In the context of increasing renewable energy distributed generation, such as photovoltaic and wind energy, more and more grid-connected inverters are being connected to the grid. Besides, such inverters are also essential for uninterrupted power supply, microgrid, as well as for future potential demand of electric vehicular to grid (V2G) scenario [1].

To avoid switching harmonics and to ensure high-quality current injection, the chopping output voltage of power electronic devices must be filtered. Compared with traditional L filter, LCL filter has less volume, better filtering performance, lower cost and less inertia. LCL filter is widely used for renewable energy conversion applications. However, when using LCL filters, the injected current quality faces two issues: resonance and grid voltage induced distortion. Resonance is the nature of the three-order LCL filter, which requires either extra passive damping resistor or active damping techniques in control algorithm. The grid voltage induced current distortion is due to insufficient controller gain, which is limited by the stability of the three-order system. Without sufficient controller gain, the disturbance in the control loop, i.e. the grid voltage influence, cannot be sufficiently rejected. The grid voltage induced distortion is especially obvious in low-current operation, presented by large phase and amplitude error, as well as a distorted waveform. Existing studies mainly focus on rated power operation and low current condition, such as high current power quality has not drawn much attention. In the literature, the above two issues are often separately studied.

Firstly, to resolve resonance problem, active damping by control algorithm is preferred over passive damping resistors for the advantage of no extra damping loss. The existing active damping techniques can be divided into two groups: open-loop and closed-loop. Open-loop techniques filter the controller output, thereby eliminating resonant harmonic components so that the resonance cannot be induced by inverter output voltage. The often used filters include Notch filter [2, 3] and high-pass filter [4]. However, the open-loop techniques are not effective on current resonance induced by grid voltage harmonics. Closed-loop techniques usually modify system dynamics by establishing extra feedbacks, such as virtual impedance, pole-placement [5], capacitor current feedback etc. After block diagram transformations of the feedback system, it can be found that such feedback is equivalent as virtual impedance presented in the plant, such as virtual Resistor-Capacitor (RC) [6] and virtual Resistor-Inductor (RL) [7]. It is worth noting that the often used capacitor current inner loop feedback is equivalent to a virtual resistor connected in parallel with the capacitor [6]. Capacitor voltage differentiation feedback is an alternative to capacitor current feedback, but discrete-time issue and noise must be handled. Lead-lag [8] and non-ideal integrator [9] are proposed for better extraction of differentiation signal. Resonant integrator based second order filter is also proposed to extract capacitor current for low switching to resonance frequency ratio case [10]. As the extra feedback requires additional sensors, efforts have also been done to merged extra feedback with grid current feedback through block diagram transformation, such as in [7].

Secondly, for grid injection current control, the controller gain cannot be set sufficiently large due to stability limits for such a three-order system. Thus, the controller is not able to completely attenuate the grid voltage disturbance on the output current. The limitations for the injected grid current harmonics are given in IEEE standard [11]. When using the LCL filter, such limitations can be more easily satisfied at rated power operation. However, due to the nature of solar and wind power, light and medium load range operations are unavoidable [12, 13]. Under low-current conditions, current waveform distortion induced by grid-voltage is more obvious in the form of phase error and harmonics. For example, even current Total Harmonic Distortion (THD) can be satisfied at rated power, in case of 1 A peak current injection to 220 V/50 Hz grid with grid voltage THD <5%, the current power factor can degrade to 0.6 with the current THD >25% and the injection current amplitude can reach almost 2 A [12]. Such degradation cannot be improved by only tuning controller gain. In
different current feedback configurations, grid voltage feedforward compensations are found out to be effective for this issue [12, 14–16].

For the most often used control structure that taking grid current feedback with capacitor current inner feedback loop, the full feedforward compensation involves proportional, derivative and second derivative of grid voltage [16]. It is also found out the using part of the grid voltage feedforward can also help improve the power quality. When using an inverter current feedback control structure, the feedforward compensation can take the form of grid voltage proportional feedback combined with capacitor current feedback [14], simple grid voltage derivative with low-pass filter [12], or capacitor voltage through a proportional resonance transfer function [17]. However, such a feedforward compensation path is directly dependent on grid voltage measurement and plant parameters. Sampling noise and the imprecise parameter may directly degrade the compensation performance. Moreover, in a weak grid case, grid feedforward compensation is not as effective as linear, non-linear, optimal in different system order. ADRC is able to treat the external and internal disturbance together by two major innovations: using cascade-integral-model and extended state observer (ESO). Gradually in recent years, ADRC’s superior performance has been proved in various industrial and military applications [24–30]. This work gives a detailed study of linear ADRC for a grid-connected inverter with an LCL filter. Using fewer sensors, ADRC achieves better dynamic and steady-state performance than conventional techniques. The results are validated by experiment results. As the proof of the disturbance rejection ability, the power quality is improved. The remainder of this paper is organised as follows: Section 2 gives the plant description. The ADRC concept and the proposed control strategy and analysis are given in Section 3. Experimental results are given in Section 4. Section 5 concludes this paper.

2 LCL-type single-phase grid-connected inverter description

The grid-connected inverter with an LCL filter is shown in Fig. 1a. $L_i$, $R_i$, $L_G$, and $C$ are filter parameters, respectively, inductance and resistance of inverter-side inductor, inductance and resistance of grid-side inductor, and filter capacitance. $u_{DC}$, $i_C$, and $u_L$ are, respectively, DC bus voltage, inverter output voltage, capacitor branch voltage, and grid voltage, $i_L$, $i_C$, and $i_G$ are inverter-side current, capacitor branch current, and grid injection current.

![Fig. 1 Grid-connected inverter with LCL filter plant model and control algorithms](image)

(a) Grid-connected inverter with LCL filter, (b) Block diagram of LCL filter, (c) Conventional control scheme using two separate algorithms to handle resonance ($i_C$ inner loop damping) and grid induced distortion (full grid voltage feedforward), (d) Proposed linear ADRC control scheme to handle resonance and grid induced distortion.
The plant consists of an inverter, LCL filter, and power grid. The ignored, thus (1) turns into more obvious in phase shift and distortion for low-current active damping, which requires two current sensors to measure both active damping and grid voltage induced distortion are treated considering the control structure [16].

Equation (2) shows more evidently that grid current suffers from resonance problem, as characterised by purely imaginary poles, and grid voltage influence.

Classic capacitor current feedback inner loop is often used for active damping, which requires two current sensors to measure both grid and capacitor current. As the controller gain cannot be infinite, the grid voltage influence on the output current, which is more obvious in phase shift and distortion for low-current amplitude operation, and requires full grid voltage compensation as $G_{\text{COMP}}(s) = ((L_sC_s^2 + u_{pc}CH_c + 1)/u_{pc})$ after taking into consideration the control structure [16]. $H_c$ is the damping coefficient.

The conventional control algorithm is shown in Fig. 1c. In the following section, the ADRC-based control strategy is proposed, both active damping and grid voltage induced distortion are treated together as overall disturbance and only using grid injection current sensor.

### 3 Proposed control strategy based on ADRC

The overview of the proposed control strategy is shown in Fig. 1d. The plant consists of an inverter, LCL filter, and power grid. The controller includes measurement, grid synchronisation module and ADRC module.

After measurement, phase-locked-loop is used to extract the phase \( \theta \) of \( u_{\text{FC}} \). Given desired amplitude $I_{\text{AMP}}$, the grid current reference \( \tilde{i}_g \) is generated by the phase \( \theta \) and sine function as in the following equation:

$$
\tilde{i}_g = I_{\text{AMP}} \sin(\theta).
$$

In the ADRC module, \( \tilde{i}_g \) is processed by tracking differentiator [23] to get its derivative $\dot{\tilde{i}}_g$ and second-order-derivative $\ddot{\tilde{i}}_g$. The ESO gives the estimations of virtual variables $[\xi_2, \xi_3]$ and the estimation of overall disturbance $d_{\text{Overall}}$ which will be discussed later. Then, the error term between $\dot{\tilde{i}}_g \xi_2^2 \xi_3^2$ and $[\xi_2, \xi_3]$ are combined by linear form to get the virtual control signal $u'$, which is compensated by $d_{\text{Overall}}$ to get the final output $u_{\text{Control}}$. Finally, $u_{\text{Control}}$ ranging $-1$ to 1 generates pulse-width modulation signals for the inverter.

### 3.1 Concept of ADRC

The main concept of ADRC is disturbance rejection. Unlike conventional technique, the use of cascade integral plant model and ESO makes ADRC unique. In the literature, the equations of ADRC makes it difficult to understand the concept of disturbance rejection, it is illustrated by figures in this study.

Firstly, any arbitrary general third-order system, as presented in Fig. 1b can be transformed into the following cascade integral form, which is an order-based model instead of a precise model

$$
\begin{align*}
\dot{x}_1 &= \dot{x}_2, \\
\dot{x}_2 &= \dot{x}_3, \\
\dot{x}_3 &= f(x_1, x_2, x_3, u) + h_{at} + w, \\
y &= x_1,
\end{align*}
$$

where, $x_1, x_2, x_3$ and $x_4$ are the state variables of the cascade integral form, $f(x_1, x_2, x_3, u)$ represents the dynamics of the system, which is the so-called ‘internal disturbance’, $u$ is the control variable, $y$ is the output variable, $w$ is an external disturbance, $b_0$ is the coefficient describing the influence from $u$ to the cascade integral system. The relation can be expressed as in Fig. 2a.

There is no need to distinguish ‘internal disturbance $f’ or ‘external disturbance $w’’, they can be treated together as a single state variable, the ‘overall disturbance’, noted as $d_{\text{Overall}}$. It is worth noting that $d_{\text{Overall}}$ need not to be known explicitly (it is also difficult to do so). If $d_{\text{Overall}}$, the estimation of $d_{\text{Overall}}$, can be obtained, the plant turns to be a purely cascade integral, regardless of the system dynamic and external disturbance, as presented in Fig. 2b. For a grid-connected inverter with an LCL filter, active damping and grid-voltage induced distortion are both parts of $d_{\text{Overall}}$

$$
d_{\text{Overall}} = d_{\text{Overall}}/b_0.
$$

The $d_{\text{Overall}}$ cannot be implemented directly in the model, it can only be implemented in the control signal $u$ as shown in Fig. 2c.

### 3.2 Extended state observer

ESO was proposed by Prof. Han Jingqing [23]. ESO has made a significant breakthrough that the observer variables can be selected other than real state variables, and even unknown function can be chosen as an observer variable, where the term ‘extended state’ comes from. Recently, the authors of [31] also reveal another advantage that ESO provides more robust observer dynamics by separating conventionally coupled observer dynamic error and parameter mismatch error, and succeed in reconstructing LCL filter full state variables using a single inverter current sensor to realise grid voltage sensorless control even for parameter mismatch, which might be suitable to adopt grid impedance variation in a weak grid case.

By the concept of ‘extended state’, the ESO can be used to extract $d_{\text{Overall}}$ for ADRC. For three-order system, four-order ESO must be used, as the overall disturbance is treated as another state variable. Depending on whether known system dynamics $f$ is used or not, the ESO structure and $d_{\text{Overall}}$ calculation can take two different forms as expressed in (6). The two forms work on the same principle to get $d_{\text{Overall}}$, and the differences between the two forms are further discussed later in Section 4.

ESO takes the input value $x_1$ and gives the estimation variables $\tilde{z}_1, \tilde{z}_2, \tilde{z}_3, \tilde{z}_4$, which are, respectively, the estimation of $x_1, x_2, x_3$ and $d_{\text{Overall}}$ (or $d_{\text{Overall}}$ without $f$). By selecting the feedback coefficients $b_1, b_2, b_3, b_4$ properly, the estimation error converges to a sufficiently small value.

$$
\begin{align*}
\text{ESO without } f & \quad \text{ESO with } f \\
e &= \tilde{z}_1 - x_1, & e &= \tilde{z}_1 - x_1, \\
\tilde{z}_1 &= \tilde{z}_2 - b_1 e, & \tilde{z}_1 &= \tilde{z}_2 - b_1 e, \\
\tilde{z}_2 &= \tilde{z}_3 - b_2 e, & \tilde{z}_2 &= \tilde{z}_3 - b_2 e, \\
\tilde{z}_3 &= \tilde{z}_4 + \hat{b}_1 e - b_3 e, & \tilde{z}_3 &= \tilde{z}_4 + \hat{b}_1 e - b_3 e, \\
\tilde{z}_4 &= -b_4 e, & \tilde{z}_4 &= -b_4 e, \\
\dot{d}_{\text{Overall}} &= \tilde{z}_4/b_0, & \dot{d}_{\text{Overall}} &= [f + \tilde{z}_4]/b_0.
\end{align*}
$$

### 3.3 State variables and disturbance estimation based on ESO

With the inputs of grid-injected current and grid voltage signal, the overall disturbance and other states used in ADRC can be obtained by ESO with the following procedure.

The state-space description of the LCL-type inverter is given in the following equation:
where

\[ k_1 \]  

By substituting

\[ L_2 G_k x_1 + (R_l G + R_C L_2) C s^2 + (R_l R_C C + L_4 + L_2)s + (R_l + R_C) \]

\[ \frac{d}{dt}[u(t) - \alpha e - b]\].

The equations can be written as the following:

\[
x_1 = -k_1 x_1 + k_3 x_2 - k_3 uG,
\]

\[
x_2 = -k_1 x_1 + k_x x_1,
\]

\[
x_3 = k_d \frac{d}{dt} u_{\text{Control}} - k_3 x_2 - k_3 x_1,
\]

where

\[ x_1 = \xi_1, \quad x_2 = \xi_2, \quad x_3 = \xi_3, \]

By substituting

\[
\begin{align*}
\dot{x}_1 &= x_1, \\
\dot{x}_2 &= -k_1 x_1 + k_3 x_2 - k_3 uG, \\
\dot{x}_3 &= (k_3 - k_3) x_1 - k_3 x_2 + k_3 x_1 + k_3 uG - k_3 uG,
\end{align*}
\]

into (8), the system can be presented in the cascade integral form:

\[
\begin{align*}
\dot{x}_1 &= x_1, \\
\dot{x}_2 &= x_2 - k_1 x_1 + k_3 x_2 - k_3 uG, \\
\dot{x}_3 &= f(x_1, x_2, x_3, uG) + b_h u_{\text{Control}},
\end{align*}
\]

where \( x_1, x_2, \) and \( x_3 \) are state variables of the cascade integral form, \( b_h = k_3 k_d u_{\text{Control}} \) and the known system dynamic \( f \) is

\[
\dot{x}_1 = x_1, \\
\dot{x}_2 = x_2 - k_1 x_1 + k_3 x_2 - k_3 uG, \\
\dot{x}_3 = f(x_1, x_2, x_3, uG) + b_h u_{\text{Control}},
\]

\[
\begin{align*}
\dot{x}_1 &= x_1, \\
\dot{x}_2 &= x_2 - k_1 x_1 + k_3 x_2 - k_3 uG, \\
\dot{x}_3 &= f(x_1, x_2, x_3, uG) + b_h u_{\text{Control}},
\end{align*}
\]

\[
f(x_1, x_2, x_3, uG) = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3,
\]

\[
\dot{x}_1 = \dot{x}_2 = \dot{x}_3 = 0.
\]

There is an inevitable unknown disturbance in the system, noted as \( d_w \), which includes modelling error, measuring error, grid impedance variations etc. The real system equation should be written as (12), instead of (10)

\[
\begin{align*}
\dot{x}_1 &= \dot{x}_2, \\
\dot{x}_2 &= \dot{x}_3, \\
\dot{x}_3 &= f(x_1, x_2, x_3, uG) + b_h u_{\text{Control}} + d_w.
\end{align*}
\]

Taking the external disturbance in (12) as the extended state variable, and denoting the overall disturbance as

\[
\dot{d}_{\text{Overall}} = [f(x_1, x_2, x_3, uG) + d_w] / b_h.
\]

The linear form ESO used for this cascade integral plant can be expressed as follows:

\[
\begin{align*}
\dot{e}_1 &= \xi_1 - \dot{\xi}_1, \\
\dot{z}_1 &= \xi_2 - \dot{\xi}_2, \\
\dot{z}_2 &= \xi_3 - \dot{\xi}_3, \\
\dot{z}_3 &= f(z_1, z_2, z_3, uG) + \xi_3 + b_h u_{\text{Control}} - b_x e, \\
\dot{z}_4 &= -b_x e, \\
\dot{d}_{\text{Overall}} &= [f(x_1, x_2, x_3, uG) + z_3] / b_x,
\end{align*}
\]

where \( \dot{d}_{\text{Overall}} \) is the estimation of the overall disturbance for ADRC. In (14), the known dynamic \( f \) is used. Alternatively, all presenting \( f \) can also be removed from this equation, resulting in ESO without dynamic \( f \). The differences are discussed in Section 4.

### 3.4 ESO parameter selection and estimation error

Denoting the estimation error as \( e_i = \xi_i - \dot{\xi}_i, \) \( e_2 = \xi_2 - \dot{\xi}_2, \) \( e_3 = \xi_3 - \dot{\xi}_3, \) \( e_4 = \xi_4 - \dot{\xi}_4, \) the equation of estimation error can be derived as

\[
\begin{align*}
\dot{e}_1 &= \xi_1 - \dot{\xi}_1, \\
\dot{e}_2 &= \xi_2 - \dot{\xi}_2, \\
\dot{e}_3 &= \xi_3 - \dot{\xi}_3, \\
\dot{e}_4 &= \alpha_4 e_1 + \alpha_5 e_2 + \alpha_6 e_3 + \alpha_7 e_4, \\
\dot{z}_4 &= -b_x e_4.
\end{align*}
\]

The coefficients can be chosen by assigning all observer eigenvalues as \( \alpha \), referring to [32]. Specifically, for this application

\[
\begin{align*}
b_1 &= 4\alpha_1 + \alpha, \\
b_2 &= 6\alpha_2 + \alpha + b_3\alpha, \\
b_3 &= 4\alpha_3 + \alpha + b_4\alpha, \\
b_4 &= \alpha_4.
\end{align*}
\]
According to (15) and (16), the transfer function between disturbance estimation error $e_i$ and external disturbance $d_w$ can be derived as

$$
\frac{e_i(s)}{d_w(s)} = \frac{s^4 + 4\omega_0^2 s^2 + 6\omega_0^4 s^2 + 4\omega_0^6 s}{(s + \omega_0)^2}.
$$

The $\omega_0$ can be optimised according to the desired bandwidth of the observer. With $\omega_0$ increasing, the bode diagram of the error transfer function change as shown in Fig. 3a. It can be seen that overall disturbance estimation error is very small in the low-frequency region. With $\omega_0$ increasing, observer bandwidth increases and lead to more accurate estimates. However, in practice, the bandwidth is limited by noises and the fixed sampling rate.

### 3.5 Feedback control law with disturbance compensation and control error analysis

With a linear control law, the virtual control value $u^\prime$ can be obtained as follows:

$$
\begin{align*}
  u^\prime &= \beta_1 e^\prime + \beta_2 e^\prime + \beta_3 e^\prime, \\
  e^\prime &= \bar{z}_l - \bar{z}_o, \\
  e^\prime &= \bar{z}_l - \bar{z}_o, \\
  e^\prime &= \bar{z}_l - \bar{z}_o.
\end{align*}
$$

(18)

where $\beta_1$, $\beta_2$, $\beta_3$ are feedback proportional coefficients that should be tuned to improve the performance of the closed-loop system. Applying Laplace transform to (18), it leads to:

$$
\mathcal{D}(u^\prime) = (\beta_1 s^2 + \beta_2 s + \beta_3)\mathcal{D}(e^\prime) - \beta_1 \mathcal{D}(\bar{z}_l) - \beta_2 \mathcal{D}(\bar{z}_o) - \beta_3 \mathcal{D}(\bar{z}_o).
$$

(19)

The resonance and grid voltage induced distortion are disturbances in $\mathcal{D}(\text{Overall})$, the disturbance can be compensated by removing it from the calculated $u^\prime$, as follows:

$$
\mathcal{D}(\text{Control}) = u^\prime - \hat{\mathcal{D}}(\text{Overall}).
$$

(20)

Substituting (20) into ESO (14), the relation between $u^\prime$ and the output state variable can be derived as follows:

$$
\begin{align*}
  e &= \bar{z}_l - \bar{x}_l, \\
  \bar{z}_l &= \bar{z}_o - b e, \\
  \bar{z}_o &= \bar{z}_o - b e, \\
  \bar{z}_o &= \bar{b}_o u^\prime - b e.
\end{align*}
$$

(21)

The s-domain description of (21) is as follows:

$$
\begin{align*}
  \bar{z}_l(s) &= \bar{z}_l(s) + b[\bar{z}_o(s) - x_l(s)], \\
  \bar{z}_o(s) &= \bar{s}[\bar{z}_l(s) + b\bar{z}_o(s) - x_l(s)] + b[\bar{z}_o(s) - x_l(s)], \\
  \bar{z}_o(s) &= \bar{s}^2[\bar{z}_l(s) + b\bar{z}_o(s) - x_l(s)].
\end{align*}
$$

(22)

Combining (19) and (22), the output state variable $\bar{x}_l$ can be expressed with current reference $\bar{u}_o$ and state estimation error $e_i$ in the s-domain as follows:

$$
\begin{align*}
  \text{Den}(s)\bar{x}_l(s) &= g(s)\bar{u}_o(s) + g(s)e_i(s), \\
  \text{Den}(s) &= [s^4 + (\beta_3 + \beta_2 + \beta_1)s + \beta_1][s^4 + (\beta_3 + \beta_2 + \beta_1)s + \beta_1], \\
  g(s) &= b[s^2 + \beta_2 s + \beta_3] - [s^3 + (\beta_3 + \beta_2 + \beta_1)s + \beta_1][s^3 + (\beta_3 + \beta_2 + \beta_1)s + \beta_1].
\end{align*}
$$

(23)

When the state estimation error $e_i$ converges to zero, the transfer function between $\bar{u}_o$ and $\bar{x}_l$ is simplified as follows:

$$
\frac{\bar{x}_l(s)}{\bar{u}_o(s)} = \frac{b(s^2 + \beta_2 s + \beta_3)}{s^4 + (\beta_3 + \beta_2 + \beta_1)s + \beta_1}.
$$

(24)

Similar to ESO parameter tuning, the control parameters can be adjusted through ‘bandwidth-parameterisation’. All poles of (24) can be assigned to $\omega_k$. Thus, controller parameters $\beta_1$, $\beta_2$, $\beta_3$ can be expressed as functions of $\omega_k$ in the following form:

$$
\begin{align*}
  \beta_1 &= \frac{\omega_k^3}{b_0}, \\
  \beta_2 &= \frac{3\omega_k^2}{b_0}, \\
  \beta_3 &= \frac{3\omega_k}{b_0}.
\end{align*}
$$

(25)

Substituting (25) into (24), the transfer function between $\bar{u}_o$ and $\bar{x}_l$ can be derived as follows:

$$
\frac{\bar{x}_l(s)}{\bar{u}_o(s)} = \frac{3\omega_k s^2 + 3\omega_k^2 s + \omega_k^3}{s^4 + 3\omega_k s^3 + 3\omega_k^2 s + \omega_k^3}.
$$

(26)

With the increasing of $\omega_k$, the error transfer relation changes as in Fig. 3b.

Fig. 3b shows that the grid injection current trace the reference well when the angular frequency is much less than $\omega_k$. With $\omega_k$ increasing, the closed loop system bandwidth becomes larger, which lead to smaller amplitude error and phase error. However, the bandwidth is also limited by measurement noise and fixed control and sampling rate.

### 4 Experimental results

#### 4.1 Experimental setup

The experiment platform is shown in Fig. 4. The grid is emulated by a programmable AC voltage source (Chroma 61511). The AC source is able to output sine-wave and can be configured as an amplifier to generate voltage output proportional to real grid measurement. The control scheme is implemented in DSP.
TMS320F28069 with 20 kHz switching and sampling frequency. As the AC power supply is designed for supplying power not sinking power, the experiment is carried out in 1/8 scale of 220 V grid to avoid the risk of permanent damage by injecting current. Two inductance sets in mH and μH levels are used. The test parameters are shown in Table 1. The control parameters are listed in Table 2.

4.2 Large inductance results

Large inductance tests are performed for \( L_I \) (5.16 mH) and \( L_G \) (4.14 mH) with grid voltage THD about 4.55%. Figs. 5a and 5b show the experiment results when the reference current amplitude steps from 1 to 6 A, for the conventional and proposed control strategy, respectively. From the zoomed dynamic view in the left bottom corner of each figure, it can be seen conventional active damping with a full grid voltage feedforward strategy has obvious transient oscillations lasting for about one period after the step change. The proposed ADRC strategy does not have such problems and gives a better transient performance.

In the steady-state waveforms when grid current reference amplitude is 1 A. For conventional strategy, the amplitude of fundamental current is 1.11 A and the THD of current is 7.53%. For the proposed control strategy, the amplitude of the fundamental current is 1.059 A and the THD of current is 7.21%.

In steady-state waveforms with 6 A grid current reference amplitude, the amplitude of fundamental current is 6.279 A and the THD of current is 2.81% for the conventional strategy, and the amplitude of fundamental current is 6.076 A and the THD of current is 1.40% for the proposed strategy.

For comparing the effect of current harmonic suppression performance in the wide operating range, the analysis results of THD from 1 to 6 A are presented in Fig. 5c. It can be seen that the current contains less harmonic distortion using the proposed strategy in the whole amplitude variation range under the influence of the grid voltage distortion.

4.3 Small inductance results

Experimental tests are also carried out for small inductance parameters with \( L_I \) (801 μH) and \( L_G \) (359 μH) for the two methods with sinusoidal grid voltage.

The obtained waveforms with different current references are given in Figs. 6a and 6b. It can be seen that for both methods the current phase errors are not obvious. However, the conventional method suffers from obvious distortion at low-current amplitude and oscillations at large current amplitude.

Figs. 6c and 6d give the analysis for THD and phase error between grid voltage and current.
The THD, phase and amplitude are given in Figs. 7c and d. During the full parameter variation range, the control is always stable, and the THD is within 5%, phase errors are within 10°, and the amplitude error are within ±10%. With parameter increases, both phase error and current amplitude decrease. The THD decreases and then increases, because the current starts to have oscillations for too large \( L_G \) values.

4.5 ADRC performance with and without known dynamic \( f \) in the algorithm

In this study, we have used the known dynamic \( f \) in the ADRC algorithm as expressed in (6) and (14). In theory, both ADRC with \( f \) and without \( f \) are able to compensate for the overall disturbance and thus should have similar results. However, during experimental tests, it is found that the performance of ADRC without \( f \) is not as good as ADRC with \( f \). One possible reason is that the known dynamic \( f \) represents a large part of the overall disturbance. When \( f \) is not included in the observer, the ESO requires higher bandwidth to observe the overall disturbance containing the dynamic \( f \). On the other hand, when the observer bandwidth is higher, the noise can be amplified and can also affect the overall disturbance observation. Thus, during our experimental tests, there was a ‘turning point’ maximum observer bandwidth limited by the noise. After exceeding this value, the current starts to oscillate.

To validate whether noise plays the role and to exceed this limit, we have tried to reduce the sampling noise without introducing delay. This is carried out by reducing the common mode noise during chopping transients by such a way: \( i_G \) sampling includes switching induced common mode noise as \( i_G + n_{CM} \); in order to get clean signal of \( i_G \), we have sampled the other two signals as \( i_1 + n_{CM} \) and \( i_2 + n_{CM} \), then \( i_G \) is calculated as \( (i_1 + n_{CM}) - (i_2 + n_{CM}) \), which gets \( i_G \) and eliminates the common mode noise.

Although this approach of eliminating common mode noise is not so accurate due to cable length and distributed parameters, the stable observation bandwidth limit still can be improved by 24%. The waveforms before and after increasing bandwidth for ADRC without \( f \) is given in Fig. 8.

In Fig. 8, it can be seen that with the increase of bandwidth, the phase error has been reduced by 57.2%, signifying the higher disturbance rejection ability. The THD is almost at the same level. The results indicate that the measurement noise is one limit for improving bandwidth in ADRC control, when the noise can be reduced, the ADRC without known dynamic \( f \) can get a better disturbance rejection ability and approaches a similar disturbance rejection ability as ADRC with known dynamic \( f \). In other words, when using known dynamic \( f \) in ADRC algorithm, the required bandwidth can be reduced, offering more tolerance to measurement noise.

5 Conclusion

In this study, a current control strategy was proposed based on linear ADRC for a grid-connected inverter with an LCL filter to enhance power quality. The proposed strategy handles two issues of active damping and grid voltage-induced distortion through the concept of overall disturbance rejection. The proposed strategy is compared with the conventional strategy of using two separate algorithms of PID dual-loop active damping and full grid voltage feedforward compensation. The proposed strategy is able to realise active damping and suppression of grid voltage-induced current distortion at the same time in the same control structure with fewer sensors. Moreover, the proposed strategy is able to give better performance in both dynamic and steady state. The proposed ADRC controller has only two parameters to tune for ‘fast’ or ‘slow’, which makes it easy for implementation.

For ADRC control, both large and small inductance tests are carried out, it can be seen that ADRC have a better disturbance rejection ability, reflected by current phase error and distortion. For 40–500% parameter variation tests, although the waveforms are affected, the control is stable. It is revealed that for ADRC with known dynamic \( f \) in the ADRC algorithm, the required bandwidth method, which is able to significantly reduce the power factor, especially at low-current amplitude.

It can be seen that for small inductance tests, the proposed ADRC control gives stable THD performance around 4%, even for low-current amplitude. No matter with or without grid voltage feedforward compensation, the PID controllers resulted THD is relatively large at the low-current level and get smaller when the current increases. Not until 6 A output, the THD for the conventional strategy is smaller than that of ADRC. For the phase error, ADRC is slightly larger than the conventional strategy, which is almost at the same level in the aspect of unit power factor operation. ADRC demonstrated a better distortion suppression ability over most of the full operating range.

4.4 Parameter variation tests

The used ADRC parameter variation test is carried out for variation of \( L_G \). The parameter variation for ADRC is performed for a large inductance set. The parameters variation ranging about 40–500% of the real value in ADRC algorithm is performed for 5 A amplitude. Two waveforms at 40 and 500% variations are given in Figs. 7a and b. It can be seen the current amplitude, phase and waveform change with parameter variation.
can be reduced, offering more tolerance to measurement noise. Linear ADRC control can be adopted for grid-connected inverters, whose disturbance rejection ability can handle resonance and grid voltage induced distortion, offering higher current quality especially for low-current operation, which is able to provide high-power quality for distributed renewable generations in the full operating range.

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7 References