Coordinated Mitigation Control for Wideband Harmonic of the Photovoltaic Grid-Connected Inverter

Yang Liu¹, Lisheng Li¹, Pengbo Shan²*, Haidong Yu¹, Shidong Zhang¹, Min Huang¹, Wenbin Liu¹, Xinhong You¹, Pengping Zhang¹, Yuanyuan Sun², Kaiqi Sun² and Yahui Li²

¹ State Grid Shandong Electric Power Research Institute, Jinan 250003, China
² School of Electrical Engineering, Shandong University, Jinan 250061, China
* Correspondence: 202220672@mail.sdu.edu.cn

Abstract: Under the current trend of power electronics in energy systems, a high percentage of renewable energy transports clean energy to the grid through grid-connected inverters. The pulse-width modulation (PWM) technique brings high-order harmonics near to the switching frequency, and LCL filters with low-pass characteristics become the common choice for grid-connected inverters. However, the low-order harmonics caused by nonideal switching characteristics are difficult to filter out, and the new resonance point introduced by the LCL filter causes a security problem for the energy systems. Firstly, the generation mechanism of the 6 k±1 order harmonic and high-frequency resonance from a PV grid-connected inverter is analyzed. Then, a virtual resistor is constructed by the active damping method to absorb the resonant component. Meanwhile, this paper also presents an adaptive modulation voltage compensation method to decrease the low-order harmonics. Finally, the actual measured data of user photovoltaic (PV) and multiple comparative simulations verify these theories. Simulation results show that the proposed coordinated control algorithm reduces the peak of the resonance point, and the rate of low-order harmonics mitigation is more than 50%. The proposed method is suitable for various operating conditions.

Keywords: photovoltaic grid-connected inverter; power quality; wideband harmonic mitigation; coordinated control

1. Introduction

With the exhaustion of traditional sources and the rapid development of power electronics technology, many distributed renewable energy sources are widely connected to the distribution system [1]. Besides improving the energy supply structure, the high proportion of power electronics also brings serious harmonic pollution to the distribution system, seriously harming its safety and stability [2]. Renewable energy connects to the grid through a grid-connected inverter, including photovoltaics and wind turbines. On the one hand, the switching frequency of power electronics varies from several hundred Hz to several tens of kHz, leading to significant high-order harmonics carried in the supply current generated by such power sources [3,4]. On the other hand, power electronic devices show the decentralization trend in the distribution network, and low-order harmonic components and the risk of parallel resonance exist simultaneously [5,6]. The continued growth of harmonic content causes problems such as resonance, distributed power off-grid, energy supply shortage, and increased equipment losses to the distribution system [7–9]. These typical power quality problems have attracted widespread attention from scholars all over the world [10–12].

The power systems’ short circuit ratio (SCR) is reduced to a certain extent due to the increasing number of distributed PVs. The system stability problems caused by harmonics in weak conditions can no longer be ignored [13–15]. LCL filters with small sizes and high-frequency attenuation capability are widely used to effectively mitigate the poor power quality of grid-connected inverters. As a high-order filter, the LCL filter has inherent
resonance points [16]. The following two categories comprise the research on resonance suppression of grid-connected inverters.

The first type is the passive suppression method. Adding impedance at the resonance frequency can prevent the resonance of the same frequency from occurring again. This method is easy to implement and can suppress resonance peaks well by incorporating passive components in the filter without any modification of the control strategy, so it is widely used in engineering practice [17]. However, passive damping changes the system’s overall amplitude and frequency characteristics and generates additional resonance points.

The second type is the active prevention method, which establishes an accurate inverter model to locate the resonance point and reduces the resonance amplitude by increasing the damping of the corresponding frequency. In the literature [18,19], we can see the development of the LCL-type grid-connected inverters’ Norton model. These researchers analyzed the influence of the system and control structures on the resonance characteristics. The literature [20] adds specific active damping based on the accurate calculation of resonance points to effectively reduce the peak resonance of grid-connected inverters. Compared with the passive approach, the active approach is more economical and has been proven to be robust in engineering. A similar method to suppress the high-order harmonics without adding any hardware changes is also used in this paper.

High-frequency resonance mitigation enhances the control system’s stability [21]. The system’s total frequency domain characteristics can be improved with the suppression of low-frequency harmonics caused by the dead zone. The suppression methods for the $6k \pm 1$ order harmonics can be divided into three categories. The first type reconstructs the modulating voltage reference to change the IGBT conduction time, thus reducing the harmonic current caused by the dead zone delay, which is also one of the most widely used harmonic suppression methods. In [22], the ripple caused by the $6k \pm 1$ order phase current harmonics to the system are analyzed. In [23], the output voltage error and the dynamics of the control system are investigated separately. The literature [24] proposed a compensation method with a square wave for steady-state application, and low-order harmonics can be reduced under most operating conditions. However, the error voltage variation under low-current operating conditions is not considered, which may cause overcompensation. In [25], the trapezoidal method is introduced to improve the adaptability of the compensation voltage model based on phase currents. The amplitude of compensation voltage becomes smaller and more effective in near zero current due to the slope change in the trapezoid waveform. The accuracy of the compensated voltage model determines the validity of such methods. Otherwise, the power quality will deteriorate due to the overcompensation voltage.

Many scholars have adopted the second method of current injection to obtain the nonideal voltage error under various operating conditions. This method achieves better suppression of current harmonics by improving the compensation voltage accuracy. In [26], a look-up table (LUT) method is proposed to enhance compensation accuracy, but this method has specific requirements for controller storage space. In [27] introduces a plan of fitting functions is introduced to construct compensating voltage commands, but universality is hard to guarantee.

In addition, some trapping algorithms, observers, and controller parameter optimization can also suppress the corresponding harmonic components [28–32]. In [33], the state space matrix explains the participation degree of the control loops, and a controller design method is proposed considering the current harmonic distortion rate. Virtual impedance is another effective filtering method, and the virtual impedance constructed in [34] effectively reduces the fifth and seventh harmonics, but such methods have high requirements for frequency component extraction.

In summary, scholars have produced extensive achievements in resonance and harmonic analysis and suppression, separately. However, the resonance point is still difficult to capture, and the dead zone or other nonideal switching states are complex and variable. Thus the suppression of high-order or low-order harmonics alone will be difficult to adapt
to the wideband properties. It also makes research which combines the two aspects remaining as a gap in large-scale promotion in engineering. Therefore, this paper proposes a resonance and dead zone compensation cooperative control strategy for LCL inverters, and its contributions are as follows:

1. Firstly, this paper derives the control transfer function of the closed-loop system and analyzes the key reason for the resonance of LCL inverters by plotting a Bode diagram. In addition, the paper explains the mechanism by which the dead zone generates low-order harmonic current by analyzing the switching state of modulation voltage.

2. Then, a high-frequency resonance mitigation strategy is proposed to improve the power quality of the PVs. Feeding the extracted capacitor current into the modulated voltage output can solve the problem of the PV resonance effectively.

3. Finally, considering the influence of parasitic capacitor charging and discharging on the dead zone voltage error under different operating conditions, an adaptive compensation strategy is proposed to suit multiple working conditions from the measured data.

The layout of this paper is organized as follows. Section 2 introduces the topology and control structure of the PV grid-connected inverter, including the analysis of resonance and harmonic generation mechanisms. Section 3 shows the active damping control strategy. Section 4 presents the measured PV data and proposes an adaptive dead zone voltage compensation strategy. Section 5 contains a study of comparative simulation experiments. Section 6 is the summary of the conclusions.

2. The Generation Mechanism of Wideband Harmonics

2.1. Topology and Control Structure

Figure 1 shows the typical topology of the PV grid-connected inverter. The DC side comprises photovoltaic panels, boost circuits, and DC bus capacitance. The maximum power point tracking (MPPT) technology ensures that the renewable sources export peak power. The grid-connected inverter usually uses PQ or DC voltage control, turning the DC energy into clean AC signals. The inverter’s output port is linked to a common coupling point (PCC) via the line impedance. Since the switching process of IGBT will cause high-frequency harmonic components, an LCL filter is needed to reduce these harmonic components due to the switching characteristics. The power network is represented by a three-phase infinity power whose valid value is 220 V.

![Figure 1. PV grid-connected system topology.](image)

Generally, the inverter controller can be designed by deriving the transfer function of the closed-loop control system, thus the precise control of PV output current can be achieved. Figure 2 shows the equivalent closed-loop control transfer function. The outer voltage control loop uses a proportional-integral (PI) controller to eliminate the static error for accurate tracking of the target bus voltage, and its output serves as the reference signal for the internal current controller. The PI controller is also used in the current loop, generating the IGBT switch signal through a sinusoidal pulse width modulation (SPWM).
The dual-loop controller transfer function can be formulated as:

\[
G_{pl}(s) = \begin{cases} 
K_{pv} + \frac{K_{iv}}{s} & \text{if } s > 0 \\
K_{pc} + \frac{K_{ic}}{s} & \text{if } s < 0 
\end{cases}
\]  

(1)

where \(K_{pv}\) and \(K_{iv}\) are the ratio and integral coefficient of the voltage loop controller, and \(K_{pc}\) and \(K_{ic}\) are the ratio and integral coefficient of the current loop controller.

2.2. Analysis of Resonance Generation Mechanism of LCL Filter

The LCL filter can effectively eliminate high harmonic components in the inverter output current, but it is not an ideal low-pass filter. The current loop usually has a very high control bandwidth, so the current can be considered as following the reference, ideally, in the analysis of LCL frequency domain characteristics. Meanwhile, assuming that the voltage outer loop parameters are reasonable and therefore the DC side voltage is stable, Figure 3 describes the equivalent function between the inverter’s output current and the voltage, where \(C\) denotes the filter capacitor, \(L_1\) and \(L_2\) represent the filter inductors on both sides of the capacitor, \(u\) is the output voltage, and \(i_g\) is the output current supplied to the grid by the inverter.

\[
G_{LCL}(s) = \frac{1}{s^3L_1L_2C + s(L_1 + L_2)}
\]  

(2)

where \(L_1\) and \(L_2\) are the filter inductances, and \(C\) is the filter capacitance.

By setting \(L_1 = 2.0\) mH, \(L_2 = 0.5\) mH, and \(C = 100\) μF, the frequency domain features of the LCL filter are shown in Figure 4. It can be seen that a resonant point exists at 1160 Hz, via which, even if the harmonic current amplitude of the corresponding frequency is small, the control stability of the current loop will be very poor due to the high gain from the LCL filter.

Compared with Equation (2) and the ideal low-pass filter transfer function, it is not hard to find that the third-order pole caused by the filter capacitor \(C\) is responsible for the LCL filter’s nonideal frequency domain characteristics. Therefore, reducing the effect of the high-order pole or constructing other closed-loop poles by changing the transfer function is an effective method for solving the resonance of the LCL filter. There are several locations in dual-loop control where additional control branches can be added. The method changing the location of the zero or pole in the characteristic equations of the control system is expressed in the next section.
Due to the influence of conductivity modulation and current tailing, a dead zone delay is usually added to IGBT signals to avoid short circuits. The inverter’s output voltage contains low-order odd harmonic components, which increase the distortion of the network connection current and directly affect the power quality. Figure 5 shows a state schematic of the A-phase IGBT turn-on and turn-off in one control cycle.

From Figure 5a,b, without consideration of IGBT conductive pressure drop and loss in the line, when \( I_a > 0 \) and \( Q_1 \) turn on, the output current in phase A passes through \( Q_1 \), midpoint voltage \( V_A = U_{dc} \). When \( Q_1 \) turns off but \( Q_2 \) has not turned on, the output current passes through the inverse parallel diode, midpoint voltage \( V_A = 0 \). Since the output current of the bridge arm does not pass through \( Q_2 \), the dead zone of \( Q_2 \) does not affect the midpoint voltage. Therefore, the error voltage amplitude of the inverter is positive during the half-cycle in which the upper bridge arm opens.

Similarly, in Figure 5c,d, if \( I_a < 0 \), the dead zone of \( Q_1 \) also does not make any difference to the grid-connected voltage. When \( I_a < 0 \) and \( Q_2 \) turns on, midpoint voltage \( V_A = -U_{dc} \).
When $Q_2$ turns off but $Q_1$ has not turned on, midpoint voltage $V_A = 0$. The error voltage amplitude of the inverter is negative during the half-cycle in which the lower bridge arm opens.

During an entire control cycle, IGBT turns on and off once, respectively. The inverter modulation voltage contains an error whose amplitude value is $U_{dc}$ and its length is $T_d$. The PV output current’s direction determines the error voltage amplitude. Therefore, the error voltage in any phase caused by the dead zone is modeled as a square wave, and its period, $T_d$, represents the time of dead zone, and $U_{dc}$ represents the DC bus voltage of the PV inverter.

![Figure 6. Error voltage in phase A.](image)

### 3. Resonance Suppression Method of LCL Filter

This section uses the capacitive current to construct a feedforward control branch. This measure redefines the LCL-type filter equivalent function. The feedforward loop increases active damping at the high-order resonant frequency. It reduces the amplitude gain of the specific resonance point without missing the control system’s dynamic characteristics and stability.

#### 3.1. Active Damping Feedforward Control Method

Due to the existence of the LCL filter, a traditional inner loop is not adequate to maintain the control system’s stability. Thus, an additional loop with the capacitor current feedforward is used to improve the ability to suppress resonance. It is difficult to quantify the influence on the subsequent control loop after integration through the PI controller. Therefore, the feedforward signal is directly added to the output signal of the modulation voltage. Figure 7 shows the active damping feedforward control method, and $K_c$ is the capacitive current feedforward gain factor.

![Figure 7. Active damping feedforward strategy.](image)
Where $G_{PWM}(s)$ is equivalent to the production of PWM gain with control and calculation delay, and its transfer function can be shown as Equation (3). Approximation of the pure delay link can be carried out by using the three-order Pade formula.

$$
\begin{align}
G_{PWM}(s) &= K_{PWM} G_{delay}(s) \\
G_{delay}(s) &= e^{-1.5T_s} = \frac{-72s^5 + 1272s^3 - 607s + 120}{72s^5 + 1272s^3 + 607s + 120}
\end{align}
$$

where $K_{PWM} = 1$ represents PWM modulation gain.

The LCL filter’s equivalent transfer function after capacitive current feedforward is shown in Figure 8.

![Figure 8. Active damping feedforward control.](image)

The transfer function of the LCL filter can be rewritten as Equation (4); compared with Equation (2), the constructed loop of capacitive current feedforward adds a second-order pole to the closed-loop characteristic equation, which changes the LCL filter’s closed-loop poles distribution.

$$
G_{LCL}'(s) = \frac{1}{s^3L_1L_2C + s^2L_2CKcG_{PWM}(s) + s(L_1 + L_2)}
$$

Assuming that the constructed new pole can be equivalent to the shunt resistance with the filter capacitor, the topological equivalent diagram is shown in Figure 9.

![Figure 9. Active damping equivalent model.](image)

The equation for the grid-connected current and the inverter’s output voltage can be constructed with Kirchhoff’s voltage law as shown in Equation (5).

$$
G_{LCL}'(s) = \frac{1}{s^3L_1L_2CR_{active} + s^2L_1L_2 + sR_{active}(L_1 + L_2)}
$$

Combining Equation (4) with Equation (5), active damping can establish the expression relationship with $K_c$ and $G_{PWM}(s)$ in Equation (6).

$$
R_{active} = \frac{L_1}{CK_c G_{PWM}(s)}
$$

The harmonics of a specific resonant frequency passes through the active shunt resistance, so the grid current quality can be improved significantly. The response characteristics of other frequencies are not affected due to virtual resistance only affecting the frequency.
segment near the resonance point. This conclusion is verified in the next section through the Bode diagram. Meanwhile, the proposed active resistance reduces the input of passive resistance, making many contributions to the economical operation of the power distribution network.

3.2. Analysis of Frequency Domain Characteristics of Active Damping Method

This paper set two group parameters of filter inductance and resistance to analyze the frequency domain characteristics of the active damping method, and these parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter 1</th>
<th>Parameter 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>2.0 mH</td>
<td>2.0 mH</td>
</tr>
<tr>
<td>$L_2$</td>
<td>0.5 mH</td>
<td>0.5 mH</td>
</tr>
<tr>
<td>$C$</td>
<td>100 µF</td>
<td>50 µF</td>
</tr>
</tbody>
</table>

Table 1. Parameters Table of LCL Filter.

The Bode diagram of the equation between output current and voltage is obtained by substituting the parameters into Equations (2) and (4). Figure 10 shows the LCL filter’s frequency characteristics from 10 Hz to 10 kHz.

![Bode diagram of LCL filter.](image1)

**Figure 10.** Bode diagram of LCL filter.
From the above diagrams, if the inductance parameter is unchanged, the capacitance parameter determines the resonance point of the PV inverter. Larger capacitance corresponds to a lower resonance frequency point. Instead, smaller capacitance brings a higher resonance frequency point. Two group experiments with different parameters show that the active resistance can adaptively reduce amplitude gain at the resonant frequency, no matter how the resonance point changes. With the $K_c$ increasing, the amplitude gain at the resonant point decreases. When the $K_c$ is massive enough, the adverse effect is that the LCL amplitude gain has a small degree of decay, but the attenuation magnitude can be neglected. Meanwhile, it has little impact on other frequency response characteristics, so the LCL filter with active resistance can be seen as an ideal low-pass filter.

4. Dead Zone Compensation Method of PV Inverter

A voltage adaptive compensation method for low-order harmonics is introduced in this section. The segmented error modeling method is used to quantify compensation values for different current operating conditions. By sampling the IGBT switching status and adding the error voltage on the modulation signal evenly, the nonideal waveform caused by the dead zone can be greatly decreased. Therefore, the harmonic current of the PV inverter can be effectively suppressed. There is no need to change any hardware and switching state.

4.1. Modeling of the Compensation Voltage

The photovoltaic inverter’s output current amplitude is affected by light, temperature, and other factors. The required modulation voltage under various current amplitudes is also different. Harmonic suppression technology must be able to adapt to a change in environment. This section analyzes the harmonic emission level and the error voltage variation under different working conditions. This paper divides the segmentation interval with the measured data and proposes a segmentation adaptive harmonic suppression method.

Figure 11 shows the actual measurement data curve of grid voltage and A-phase current waveform from a user’s PV grid-connected inverter in Taian, Shandong Province on 10 August 2022. The data recorded the distribution range of photovoltaic current for a whole day. Data acquisition is completed with the help of the NI data acquisition board. The equipment records 25,600 data points every second.

From the above figure, the photovoltaic works from 5:30 a.m. to 6:00 p.m. Its grid-connected current fluctuation range is mainly between 13 A and 41 A. Within this current range, the current trailing effect endures only for quite a short time, and the parasitic capacitor charges or discharges very quickly. The voltage error can be approximately equivalent to a square wave with a width of $T_d$. An important objective of this paper is to make the dead zone error voltage model adapt to more operating conditions especially, for
small current working conditions in bad weather. Figure 12 shows the influence of current trailing to error voltage under different current conditions.

![Diagram](image.png)

**Figure 12.** The influence of current trailing.

From the above figures, the actual nonideal voltage is no longer a fixed error if the effect of current trailing is considered. The actual dead zone under $I_{ac}$ is exactly fifty percent of the set value. The relationship between error voltage and the grid-connected current of the PV inverter is positive. A larger current amplitude makes the error voltage closer to the square wave. Instead, a smaller current amplitude makes the error voltage closer to zero. Therefore, assuming a linear relationship between the discharge speed of parasitic capacitance and the size of the grid-connected current, the error voltage can be modeled as follows:

$$
egin{align*}
U_{\text{dead}} &= [U_{dc} T_d - f(I_a)] \text{sign}(I_a) \\

f(I_a) &= \begin{cases} 
T_e U_{dc} & I_a > I_{ac} \\
\frac{T_e U_{dc}}{2T_d - K I_a} & I_a < I_{ac}
\end{cases} \\
T_e &= \frac{U_{dc}}{KI_a}
\end{align*}
$$

(7)

where $U_{\text{dead}}$ represents actual error voltage caused by the dead zone, $K$ represents slope coefficient, and $T_e$ represents the end time of the current trailing.

### 4.2. Dead Zone Compensation Method

In the fluctuation range of grid-connected current from Figure 11, the duration of the current trailing effect is almost zero, so the compensated voltage can be approximately calculated by Equation (8).

$$
U_d = T_d U_{dc}
$$

(8)

Due to the fact that the nonideal switching state is unavoidable in practical applications, a narrow pulse compensation strategy is adopted to achieve an accurate compensation result. The voltage which needs to be compensated is distributed evenly into the modulated signal of IGBT by area equivalence method. Therefore, the actual modulated voltage is added on a narrow pulse component equal to the error voltage. Figure 13 shows the schematic of modulation voltage compensation.
Figure 13. Schematic of modulation voltage compensation.

Since directly deleting the dead zone is impossible, the modulation voltage is slightly over-modulated before generating the PWM signal, which can offset the low-order harmonics caused by the error voltage to a certain extent. Therefore, the proportion of nonideal effects in the actual inverter output voltage can be reduced. Equation (9) shows the superimposed narrow pulse single in the proposed theory.

$$U_{\text{add}} = \text{sign}(I_a) \frac{T_d}{T_s} U_{\text{dc}}$$

(9)

The PWM signal is generated after the modulated session, so the over-modulated part of the voltage extends the turn-on time $T_{\text{on}}$ of IGBT. Meanwhile, the extra turn-on time offsets the unideal delay. The performance of the proposed adaptive low-order harmonic mitigation strategy in the PWM signal is shown in Figure 14.

Figure 14. Compensation voltage in PWM signal.

In this figure, $U_{\text{com}}$ represents the extra turn-on time caused by the proposed narrow pulse signal. When $I_a > 0$, $Q_1$ remains on, and the narrow pulse compensates for the error voltage generated by the upper bridge. After $Q_1$ cuts off, the narrow pulse compensates for the error voltage caused by the lower bridge. Similarly, when $I_a < 0$, it complements the process of $I_a > 0$.

However, the PV’s output current is low in cloudy weather, low temperature, or other severe conditions. In the above cases, the quality of the power generated by the PVs becomes worse, and the effect of the current trailing can no longer be ignored. The compensation for minor current working conditions is consistent with the above method.
However, unlike the preceding, the modulation voltage error can no longer be expressed in Equation (8) but should be expressed in Equation (7). Accordingly, the narrow pulse modulated voltage should also be represented in Equation (10).

\[ U_{\text{add}} = U_{\text{dead}} = \text{sign}(I_a) \frac{U_{\text{dc}}}{T_s}(T_d - \frac{K I_a}{2}) \]  

(10)

Since the slope coefficient \( K \) in the Equation (7) is unknown, many experiments with different \( K \) values must be performed to update the proper initial value. The slope coefficient accuracy can be guaranteed based on the THD results of these experiments. The harmonic current caused by the dead zone voltage is mainly \( 6k \pm 1 \) order, \( (k = 1, 2, 3, \ldots) \). The high-order component can be ignored due to the existence of an LCL filter. Therefore, only the fifth and seventh harmonic currents under ideal power supply conditions should be analyzed. The required flow diagram of parameter correction is shown in Figure 15.

**Figure 15.** Flowchart of parameter correction.

The value of \( K \) depends mainly on the type of IGBT, so different PV inverters all need the search process of \( K \) shown in the above figure. From the flowchart, the relationship between \( K \) and \( I_a \) can be established. Once the value of \( K \) is determined, there is no need to configure any extra hardware or software, such as the observers or filters. Due to the accurate initial value, the proposed narrow pulse compensation method can satisfy the low-order harmonic suppression requirements under different current output conditions. In addition, in some cases where the light is stable or the PVs are concentrated, the compensation Equation (9) can be used separately to simplify the project’s complexity.

### 5. Simulation Case Study

#### 5.1. Simulation Model and Parameters

A simulation model has been built to verify the resonance suppression and the dead zone compensation methods. The main topology of the simulation is shown in Figure 1, including a PV grid-connected inverter operating at maximum power point (MPP), LCL
filter, line impedance, and three-phase ideal supply power. Figure 2 shows the inverter control system. The PV board and line impedance parameters are shown in Table 2, and Table 3 shows the control parameters.

Table 2. Parameters of PV board.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series/Parallel groups</td>
<td>25/4</td>
</tr>
<tr>
<td>Current at MPP</td>
<td>7.35 A</td>
</tr>
<tr>
<td>Voltage at MPP</td>
<td>29 V</td>
</tr>
<tr>
<td>Temperature/Sun irradiance</td>
<td>25 °C/1000 W/m²</td>
</tr>
<tr>
<td>line impedance</td>
<td>0.1 Ω</td>
</tr>
</tbody>
</table>

Table 3. Parameters of PI controllers.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kpv</td>
<td>2</td>
</tr>
<tr>
<td>Kiv</td>
<td>100</td>
</tr>
<tr>
<td>Kpc</td>
<td>10</td>
</tr>
<tr>
<td>Kic</td>
<td>200</td>
</tr>
<tr>
<td>Ts</td>
<td>100 us</td>
</tr>
<tr>
<td>Td</td>
<td>3 us</td>
</tr>
</tbody>
</table>

5.2. Verification of Resonance Point of LCL Filter

In this section, two groups of the LCL filter parameters in Table 1 are set to verify the time domain response of dual closed-loop control of the PV inverter. Under ideal power supply conditions, the PV’s grid-connected current without capacitive current feedforward control contains a large number of resonant frequency components, and Figure 16 shows the THD analysis result of the grid-connected current.

![FFT result of Parameter 1 in Table 1.](image)

In this condition, the resonance point is 795 Hz, and the distortion current at the resonance frequency exceeds 250% of the current at the fundamental frequency. Meanwhile, there is also a small cluster of distorted current near the resonance point. Although the amplitude of current at these frequencies is lower than the current at resonance points, they also affect the power quality of the energy system. The time domain waveform in a steady state is shown in Figure 17.
As shown in this figure, the control system has lost the ability to achieve stable current tracking, and the resonant current amplitude is close to 3000 A. Obviously, the resonance point of the LCL filter greatly threatens the operation safety of the PV grid-connected inverter. The resonance frequency with another group parameter is 1160 Hz, and the FFT result is shown in Figure 18. Except for the component at the resonant frequency increasing substantially, other frequency components within the low-frequency band are also amplified to some extent. FFT results demonstrate the accuracy of the LCL filter’s resonance point, which is calculated by the closed-loop transfer function method.

These experiments show that, no matter where the LCL filter’s resonant point is, the system loses stability as long as the grid current contains resonant frequency components. In the simulation experiment, the outer loop is used in the constant voltage method, and the reference voltage is 750 V. The next section verifies the influence of the capacitive current feedforward method on resonance suppression.

Figure 17. Time domain waveform in steady state.

Figure 18. FFT result of Parameter 2 in Table 1.
5.3. Verification of Resonance Suppression Method of LCL Filter

In Figure 10, active damping constructed by the capacitive current feedforward method effectively reduces the resonant point gain of the LCL filter. Setting $K_c = 15$ and using the second group parameters in Table 1, the time domain waveform of the three-phase grid-connected current of PV is shown in Figure 19a. Under the condition that temperature and sun irradiance are set in Table 2, the maximum grid-connected current amplitude of the PV is about 45 A.

![Three phase grid-connected current](Figure 19a)

Due to the positive correlation between the modulated voltage and the inverter output current, the modulation error voltage can be considered as approximately invariant. The time domain waveform of the PV's three-phase current is shown in Figure 20a, and Figure 20b shows the FFT result. The percentage of the fifth and seventh harmonic currents are 4.243% and 3.052%, respectively. The THD of the PV's grid-connected current is over 5%. What is worse is that the lower current corresponds to even higher harmonics. This breaks the photovoltaic grid connection standard, which severely restricts the PV's connection to the distributed power system.

From Figures 19 and 20, the validity of active damping equivalent to a capacitive current feeder is verified for resonance suppression. The PV grid-connected inverters used in engineering mostly have LCL filters, so this method should be part of the general control structure of PV grid-connected inverters. In addition to resonance limiting the grid connection of new energy sources, the output current harmonic content also affects the supply power quality. Therefore, it is still necessary to verify the adaptive compensation strategy, comparing the current harmonic content before and after compensation. This part of the work is analyzed in the next section.

![FFT result of the current](Figure 19b)

The experimental results show that the resonant frequency component is greatly reduced after the capacitance current feedforward. The active shunt resistance makes the character of the LCL filter present as the ideal low-pass filter. However, the waveform still has a certain degree of distortion, especially near the zone where the grid-connected current passes zero or reaches the peak. Figure 19b shows the FFT result of the PV’s current. Obviously, the harmonic components at high frequencies are suppressed by the LCL filter, but the fifth and seventh harmonic currents caused by dead zone still exist, and harmonic amplitude decreases gradually with the increase of frequency. The fifth harmonic percentage is 2.436%, and the seventh harmonic percentage is 2.19%. Any other harmonic percentage is less than 1% of the fundamental amplitude, containing the 11th and 13th components also caused by the dead zones. The large amplitude of the current causes a
small proportion between the error voltage and the modulated voltage. Thus, the harmonic content still meets IEEE grid-connected standards.

Due to the positive correlation between the modulated voltage and the inverter output current, the modulation error voltage can be considered as approximately invariant. The time domain waveform of the PV’s three-phase current is shown in Figure 20a,b shows the FFT result. The percentage of the fifth and seventh harmonic currents are 4.243% and 3.052%, respectively. The THD of the PV’s grid-connected current is over 5%. What is worse is that the lower current corresponds to even higher harmonics. This breaks the photovoltaic grid connection standard, which severely restricts the PVs’ connection to the distributed power system.

Figure 20. The active damping experiment under the condition of 20 A.

From Figures 19 and 20, the validity of active damping equivalent to a capacitive current feeder is verified for resonance suppression. The PV grid-connected inverters used in engineering mostly have LCL filters, so this method should be part of the general control structure of PV grid-connected inverters. In addition to resonance limiting the grid connection of new energy sources, the output current harmonic content also affects the supply power quality. Therefore, it is still necessary to verify the adaptive compensation strategy, comparing the current harmonic content before and after compensation. This part of the work is analyzed in the next section.
5.4. Verification of Dead Zone Compensation Method

The harmonic content of PV output current under the two different conditions mentioned in the previous section is compared in this section. The experiment uses a three-phase ideal power supply, and the experiments verify the validity and correctness of the low-order harmonic mitigation algorithm.

After the above compensation of the low-order harmonics caused by nonideal switching, Figure 21a shows via the experimental waveform that the inverter’s output current is about 45 A. Figure 21b shows the FFT result. Compared with the data before compensation, the fifth harmonic current is reduced from 2.436% to 0.481%, and the seventh harmonic current decreases from 2.19% to 0.844%. In addition to the significant reduction of harmonic content, the sinusoidal degree of the current waveform is greatly increased after the compensation to the dead zone. There is a significant reduction in the distortion when the current is over zero, and the voltage avoids being compensated incorrectly with the precise extraction of the current sequence.

Figure 21. Experiment of the dead zone compensation.

Figure 22 shows the modulated voltage waveforms before and after the compensation. The indirect control of the inverter achieves the effect of output current by establishing an equation between the modulated and the grid side voltages. Experimental results show
that the compensated voltage accurately catches the modulation voltage polarity, so the distortion at the over-zero point is significantly reduced after compensation.

![Modulation Voltage after compensation](image)

**Figure 22.** The compared modulated voltage waveforms.

The paper also demonstrates the proposed compensation method’s effectiveness under the condition that the current is about 20 A. Figure 23 shows the FFT results, and the total current distortion rate is reduced from 5.98% to 3.46%. Among these, the fifth harmonic decreased significantly from 4.243% to 0.71%, and the proportion of the decline is more than 83%. The seventh harmonic current is also reduced from 3.052% to 1.867%. Except for the relatively high content components, the harmonics of other frequencies are each reduced to a certain extent, since the author mainly focuses on the $6k \pm 1$ order harmonics under the premise that the harmonics of other frequencies are not significantly higher. The comparative experiments show that the dead zone compensation method suits multiple conditions.

![FFT result of the current](image)

**Figure 23.** FFT result of the current.

6. Conclusions

Under the background of a power electronic distribution system, this paper conducts detailed research into wideband harmonic mitigation with PV inverters as the research object. The article first analyzes the reason for high-frequency resonance caused by the LCL filter due to its own control structure and the harmonic current generation mechanism of
the nonideal switching state. The proposed active damping control strategy for resonance suppression and the dead zone voltage compensation method for low-frequency harmonic suppression are two innovations in this paper. The capacitor current is fed forward into the current loop output reference signal, and the constructed virtual damping absorbs the resonant harmonic component. The narrow pulse compensation voltage expands the open time and thus reduce the nonideal voltage error due to the dead zone. Multiple Simulink comparative experiments verify the effectiveness and robustness of the collaboration algorithm resonance and harmonic. This new software innovation does not change any hardware or add additional controllers and can effectively suppress the wideband harmonic currents of the PVs. It provides a new choice for the power electronic energy system with a higher percentage of new energy sources. The robustness of the proposed algorithm still needs to be verified in future grids with more severe background harmonics, and suppression techniques of new harmonic components excited by background harmonics also need to be investigated.

Author Contributions: Conceptualization, Y.L. (Yang Liu), L.L. and H.Y.; methodology, Y.L. (Yang Liu) and S.Z.; software, P.S. and P.Z.; validation, M.H., W.L. and X.Y.; formal analysis, P.S.; investigation, S.Z.; resources, Y.L. (Yang Liu); data curation, P.S.; writing—original draft preparation, Y.L.; writing—review and editing, Y.S. and K.S.; visualization, Y.L. (Yahui Li). All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the science and technology project of “Research and application of power quality assessment and improvement technology for regional distribution network with large-scale distributed energy access” (Grant No. 52062622000Y).

Institutional Review Board Statement: The study did not require ethical approval.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References
11. Li, Y.; Leou, R. Harmonic Current Predictors for Wind Turbines. *Energies* 2013, 6, 1314–1328. [CrossRef]


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.