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Oscillation Suppression Method by Two Notch Filters for Parallel Inverters under Weak Grid Conditions

Ling Yang 1, Yandong Chen 1,*, Hongliang Wang 1, An Luo 1 and Kunshan Huai 2

1 College of Electrical and Information Engineering, Hunan University, Changsha 410082, China; yangling_1992@163.com (L.Y.); liangliang-930@163.com (H.W.); an_luo@126.com (A.L.)

2 Guangzhou Power Supply Co., Ltd., Guangzhou 510620, China; huaikunshan@126.com

* Correspondence: yandong.chen@hnu.edu.cn; Tel.: +86-151-1626-8089

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Abstract: With plenty of parallel inverters connected to a weak grid at the point of common coupling (PCC), the impedance coupling interactions between the inverters and the grid are enhanced, which may cause high-frequency harmonic oscillation and further aggravate the system instability. In this paper, a basic technique for inverter output impedance is proposed to suppress the oscillation, showing that the inverter output impedance should be designed relatively high at the harmonic oscillation frequency, while relatively low at other frequencies. On the basis of the proposed technique, two virtual impedances are added to be in parallel and in series with the original inverter output impedance, respectively. Thus, an oscillation suppression method by two notch filters is proposed to realize the virtual impedances and increase the whole system damping. The implementation forms of the virtual impedances are presented by the proposed PCC voltage feedforward and grid-side inductor current feedback with two notch filters. Finally, simulation and experimental results are provided to verify the validity of the proposed control method.

Keywords: weak grid; parallel inverters; oscillation suppression; notch filter; impedance reshaping

1. Introduction

With the increasing energy crisis and environmental problems, renewable energy generation, mostly in power plants or microgrids, have grown rapidly [1–3]. Due to the distributed locations of renewable energy generators, multiple transformers and long transmission lines are utilized to connect the systems to the public grid [4]. Thus, the public grid exhibits the feature of a weak grid in which grid impedance cannot be ignored [5].

Especially, in a large-scale power plant or microgrid, renewable energies are mostly connected to the grid via parallel inverters [6,7]. By this way, the power plant or microgrid can easily expand the output power capacity, and it is also convenient to connect plenty of renewable energies into the grid [8]. Under weak grid conditions, the impedance coupling interactions between the inverters and the grid are enhanced further due to grid impedance [9]. If control parameters and device selection of all inverters are the same, the grid impedance seen by each inverter will become n times of the real grid impedance [10]. Therefore, these interactions may cause oscillation if inverters are improperly designed or controlled.

There are two methods to analyze the system’s stability. The first is the eigenvalue-based analysis [11], which is usually utilized to evaluate the system’s stability. The eigenvalue-based stability analysis studies the eigenvalues of a system’s state space model matrix, which requires the physical features and control parameters in the system [12]. The second one is the impedance-based stability criteria [13,14], which is well built to adjudicate the system stability. The system will be stable if two requirements are satisfied [15]. The first requirement is that the grid-connected inverter is stable in
the public grid, and the other is that the product of grid impedance and inverter output admittance satisfies the Nyquist criterion. The industrial and academia community have widely accepted the theory of impedance-based stability analysis [15,16].

Some strategies were proposed to suppress the oscillation, which can be divided into two cases. One is to introduce additional hardware equipment to the PCC [17], the other is to reshape the inverter output impedance [18–23]. Adding additional equipment was adopted to stabilize the paralleled multi-inverter system, in which structures and control parameters of the inverters are unknown. Reference [17] installed an active damper at the PCC to suppress the oscillation. However, extra cost may exist owing to the demand of additional circuitry [24].

Different impedance reshaping methods need to be adopted to suppress the oscillation. The existing impedance reshaping methods mainly include: capacitance-current-feedback methods [18,19], capacitance-voltage-feedback methods [20,21], and virtual resistor methods [22,23]. In Reference [18], the real-time computational method was proposed to decrease the computational delay, which can simplify the design and enhance the performance. However, if the grid voltage has much harmonics, it will make the duty cycle of the inverters change sharply. Similar to the capacitance-current-feedback methods, useful active damping was induced by the derivative feedback of the capacitance voltage [20,21]. However, the capacitance-voltage-feedback methods should handle the challenge of grid voltage variation. In References [22,23], the virtual resistor methods made the inverter output impedance show high impedance at all frequencies, which can suppress the oscillation. However, due to the high impedance characteristics of the inverters at the fundamental frequency, the methods will cause the change of the fundamental current, and then influence the tracking precision of the grid-connected power. Therefore, the fundamental impedance and high-frequency harmonic impedance of inverters are separately considered. The fundamental impedance should be designed as the low impedance, which does not affect the grid-connected power tracking. However, the high-frequency harmonic impedance is designed as the high impedance to suppress the oscillation.

In this paper, the oscillation suppression method by two notch filters is proposed to increase the whole system damping. This paper is organized as follows. Section 2 analyzes the oscillation mechanism of a paralleled multi-inverter system. Section 3 presents the demand for the inverter output impedance for the purpose of oscillation suppression, and the method of adding the virtual impedances to meet the demand is proposed, which introduces two notch filters to the PCC voltage feedforward and grid-side inductor current feedback. Section 4 compares and analyzes the system’s stability in two cases. Sections 5 and 6 provide the simulation and experimental results to verify the validity of the proposed control method. Finally, Section 7 gives the conclusion.

2. Oscillation Mechanism of Paralleled Multi-Inverter System

2.1. System Description

The structure of a paralleled multi-inverter system is shown in Figure 1. The left and right side are the inverter subsystem and the grid subsystem. \( j = 1, 2, \ldots, n \). \( U_{dc} \) is the DC voltage. \( u_{\text{inv}j}, u_{\text{C}1j} \), and \( u_{\text{PCC}} \) are the inverter output voltage, filter capacitor voltage, and PCC voltage. \( u_g \) is the grid voltage. \( Z_g \) is the grid impedance. Inductor-capacitor-inductor-type (LCL-type) filter is constituted by the inverter-side inductor \( L_{1j} \), grid-side inductor \( L_{2j} \), and filter capacitor \( C_{1j} \). \( R_{L1j} \) and \( R_{L2j} \) are parasitic resistances of \( L_{1j} \) and \( L_{2j} \). \( i_{L1j} \) is the inverter-side inductor current. \( i_{C1j} \) is the filter capacitor current. \( i_{oj} \) is the grid-side inductor current. \( i_g \) is the grid-connected current.
2.2. Oscillation Mechanism

In the grid-connected mode, single inverter is equivalent to the current source \( i_j \) in parallel with equivalent admittance \( Y_j \), which is the Norton equivalent circuit [23]. The grid is equivalent to the grid voltage \( u_g \) in series with grid impedance \( Z_g \). From the PCC, the Norton equivalent circuit of paralleled multi-inverter system is shown in Figure 2a. From Figure 2a, the circuit relationship about \( u_{PCC} \) is shown in Equation (1) by the nodal analysis method.

\[
(Y_1 + Y_2 + \cdots + Y_n)u_{PCC} + u_{PCC} / Z_g = (i_1 + i_2 + \cdots + i_n) + u_g / Z_g
\]

where \( i_j \) is the current source of a single inverter, and \( Y_j \) is the equivalent admittance of a single inverter.

![Paralleled multi-inverter system](Figure 1)

**Figure 1.** Structure of paralleled multi-inverter system.

(a) Norton equivalent circuit; (b) Output admittance model; (c) Parallel oscillation; (d) Series oscillation.

**Figure 2.** Output admittance model and oscillation mechanism of paralleled multi-inverter system.

(a) Norton equivalent circuit; (b) Output admittance model; (c) Parallel oscillation; (d) Series oscillation.
From Equation (1), the output admittance model of paralleled multi-inverter system satisfies the Equation (2), as depicted in Figure 2b.

\[
\sum_{j=1}^{n} Y_j + \frac{u_{PCC}}{Z_g} = \sum_{j=1}^{n} \frac{i_j}{Y_j} + \frac{u_g}{Z_g}
\]

The frequency of harmonic current \(i_{hj}\) is caused by the system nonlinear factor. If it is equal to or close to the parallel resonance frequency of impedance network, it will cause the parallel oscillation, as shown in Figure 2c. The frequency of harmonic voltage \(u_{gh}\) is caused by the grid distortion. If it is equal to or close to the series resonance frequency of impedance network, it will result in the series oscillation, as shown in Figure 2d.

From Figure 2b, the grid-connected current \(i_g\) can be derived as

\[
i_g = \left(\sum_{j=1}^{n} i_j - \sum_{j=1}^{n} Y_j \cdot \frac{1}{1 + Z_g \cdot \sum_{j=1}^{n} Y_j}\right)
\]

where the product of grid impedance and inverter output admittance is defined as the impedance ratio \(K\), which can be expressed as

\[
K = Z_g \cdot \sum_{j=1}^{n} Y_j
\]

From Equation (3), it can be assumed that the grid voltage is stable in the absence of the inverter, and the inverter will be stable if the grid impedance is zero. Nevertheless, when the grid impedance is not negligible, the system will be stable only if the impedance ratio \(K\) satisfies the Nyquist criterion in Reference [12]. In other words, the system will be stable, only if the Nyquist curve of the impedance ratio does not surround \((-1, j0)\).

Thus, there are impedance coupling interactions between the inverters and the grid, which will aggravate the harmonic distortion of grid-connected current, lead to the oscillation in paralleled multi-inverter system, and even cause the system to be unstable.

3. Oscillation Suppression Method by Two Notch Filters for Parallel Inverters

3.1. Demand for the Inverter Output Impedance

To suppress the oscillation, the inverter output impedance should be designed relatively high at the harmonic oscillation frequency while relatively low at other frequencies. For this purpose, the virtual impedances are added to be connected with the original output impedance, as shown in Figure 3. Figure 3a–c presents parallel, series, and parallel-series virtual impedances, respectively. The above three forms can reach the same performance for oscillation suppression. For the first and second forms, it is relatively complicated to introduce one virtual impedance to realize that the inverter output impedance shows high at the harmonic oscillation frequency while relatively low at other frequencies. However, the third form with two virtual impedances is relatively easy to achieve this purpose. Thus, the third form is mainly discussed in this paper.
In Figure 3, \( Z_{oj} \) is the self-impedance when the parallel-series virtual impedances are not added. The equivalent impedance \( Z_i (Z_i = 1/Y_i) \) is formed by \( Z_{oj} \) in parallel with \( Z_{pj} \), and then in series with \( Z_{pj} \).

The grid equivalent impedance \( Z_{eqj} \) consists of the virtual impedance \( Z_{pj} \) and the grid impedance \( Z_g \) connected in series. \( i_{f/h1} \), \( i_{f/h2} \), \( i_{f/h3j} \), and \( i_{g} \) are total fundamental/high-frequency harmonic current, fundamental/high-frequency harmonic current of \( Z_{nj} \) branch, fundamental/high-frequency harmonic current of \( Z_{pj} \) branch, and fundamental/high-frequency harmonic current of \( Z_{sj} \), respectively. \( i_{f/hj} = i_{f/h1} + i_{f/h2} + i_{f/h3j} \). The total fundamental frequency current \( i_j \) and the total high-frequency harmonic current \( i_{f/hj} \) are determined by the shunt circuit, consisting of the self-impedance \( Z_{pj} \), parallel virtual impedance \( Z_{pj} \), and grid equivalent impedance \( Z_{sj} \). From the PCC, the Norton equivalent circuit of Figure 3c is refined into the forms of Figure 3d.

On the basis of the proposed basic technique, the parallel virtual impedance \( Z_{pj} \) should be designed to show low impedance at the harmonic oscillation frequency. By doing so, most high-frequency harmonic current will flow into the parallel virtual impedance \( Z_{pj} \) branch; it effectively suppresses the oscillation of paralleled multi-inverter system. In the meantime, to improve the power quality of grid-connected current, the series virtual impedance \( Z_{sj} \) should be designed to display low impedance at the fundamental frequency. This way, most fundamental frequency current flows into the grid branch with relatively low impedance.

3.2. Oscillation Suppression Method

The parallel-series virtual impedances in Figure 4 can be realized by introducing two notch filters. In Figure 4, two virtual impedances are added in parallel and series with inverter output impedance, respectively. \( G_i \) is the grid-connected current loop proportional resonant (PR) controller, \( G_{PWM} \) is the equivalent gain of the inverter, \( Z_{L1j} = sL_{1j} + R_{L1j}, \ Z_{C1j} = 1/sC_{1j}, \ Z_{L2j} = sL_{2j} + R_{L2j} \).

The parallel virtual impedance \( Z_{pj} \) and series virtual impedance \( Z_{sj} \) can be expressed as

\[
\begin{align*}
Z_{pj} &= r_1/G_N \\
Z_{sj} &= r_2G_N
\end{align*}
\]

(5)

where \( r_1 \) and \( r_2 \) are the proportional coefficient and \( G_N \) is the notch filter.

The grid-connected current loop PR controller \( G_i \) can be expressed as

\[
G_i = k_p + \frac{2k_{i1}\omega c_s}{s^2 + 2\omega c_s + \omega_o^2}
\]

(6)
where \( k_p \) is the proportional coefficient of quasi-proportional resonant controller, \( k_{11} \) is the resonance gain of quasi proportional resonance controller, \( \omega_c \) is the cut-off angular frequency, and \( \omega_o \) is the fundamental angular frequency.

The effects of dead-time of switching devices in paralleled multi-inverter system are regarded as a disturbance, which have a constant amplitude and an alternative direction depending on the inverter-side inductor current \( i_{L1j} \) [25]. It is notable that the disturbance can be seen as the controlled current source \( i_{dj} \) in Norton equivalent circuit, which can be presented as

\[
i_{dj} = \frac{U_{ej}}{Z_p/A + Z_{sj}/B} \text{sign}(i_{L1j})
\]

where \( A = Z_{L1j}Z_{L2j} + Z_{C1j}/(G_{j\text{PWM}} + Z_{L1j} + Z_{L2j}) \) and \( B = Z_{L1j}/Z_{C1j} + (Z_{L1j} + Z_{C1j})(Z_{L2j} + Z_p) \).

According to Reference [25], \( U_{ej} \) in Equation (7) can be expressed as

\[
U_{ej} = 2(U_{dcj} + U_{Ddj} - U_{Tj}) \frac{t_{dj} + t_{onj} - t_{offj}}{T_{sj}} - U_{Dj} - U_{Tj}
\]

where \( U_{Tj} \) and \( U_{Dj} \) are the on-state voltage drop of switching devices and diodes, \( T_{sj}, t_{dj}, t_{onj} \) and \( t_{offj} \) are switching period, dead-time, turn-on time, and turn-off time of switching devices.

Meanwhile, \( \text{sign}(i_{L1j}) \) in Equation (7) can be expressed as

\[
\text{sign}(i_{L1j}) = \begin{cases} 
1 & i_{L1j} > 0 \\
-1 & i_{L1j} < 0 
\end{cases}
\]

From Figure 4, the closed-loop transfer function of the system can be expressed as

\[
i_{oj} = G_{j}i_{\text{refj}} + i_{dj} - Y_{j}u_{\text{PCC}} = \frac{G_{j}i_{\text{refj}} + i_{dj} - Z_{L1j}/Z_{C1j} + (Z_{L1j} + Z_{C1j})(Z_{L2j} + Z_p)}{Z_p/A + Z_{sj}/B}u_{\text{PCC}}
\]

where \( i_{\text{refj}} \) is the reference current of single inverter, \( G_{j} \) is the current source equivalent coefficient of single inverter, and \( Y_{j} \) is the equivalent admittance of single inverter.

Figure 4. Equivalent control block diagram of oscillation suppression method by two notch filters for parallel inverters.

According to Equation (10), the refined equivalent output impedance model is shown in Figure 5. The current source \( i_j \) is equivalent to the current source \( i_{L1j} \) in parallel with the current source \( i_{dj} \). Two virtual impedances are added to be in parallel and in series with the original inverter output impedance, respectively. Thus, Figure 5 is equivalent to the refinement of Figure 3d, which can achieve the proposed approach.
where $i_{\text{refm}}, G_m, i_{\text{dm}}, Z_{1\text{m}}, Z_{\text{C1m}}, Z_{\text{L2m}}, Z_{\text{pm}},$ and $Z_{\text{sm}}$ are the variables of the $m$-th inverter. Substitute Equation (1) into Equation (11), and Equation (11) can be rewritten as

$$i_{\text{om}} = G_{\text{selim}}i_{\text{refm}} + \sum_{j=1,j\neq m}^{n} G_{\text{paralm,}j}i_{\text{refj}} - G_{\text{serim}}u_{\text{g}} + i_{\text{dm}}$$

$$= (G_m - \frac{Z_gY_m}{1 + Z_g\sum_{j=1}^{n} Y_j})i_{\text{refm}} + \sum_{j=1,j\neq m}^{n} \left( -\frac{Z_gY_m}{1 + Z_g\sum_{j=1}^{n} Y_j} \right)G_ji_{\text{refj}} - \frac{Y_m}{1 + Z_g\sum_{j=1}^{n} Y_j}u_{\text{g}} + i_{\text{dm}}$$

(12)

where $G_{\text{selim}}$ is the transfer relationship between the grid-side inductance current $i_{\text{om}}$ of the $m$-th inverter and reference current $i_{\text{refm}}$ of the $m$-th inverter; $G_{\text{paralm,}j}$ is the transfer relationship between the grid-side inductance current $i_{\text{om}}$ of the $m$-th inverter and reference current $i_{\text{refj}}$ of the $j$-th inverter, and $G_{\text{serim}}$ is the transfer relationship between grid-side inductance current $i_{\text{om}}$ of the $m$-th inverter and grid voltage $u_{\text{g}}$.

When a similar analysis method is adopted to other inverters, the system can be expressed using a closed-loop transfer function matrix with reference currents, grid voltage and controlled current sources as inputs and grid-side inductor currents as outputs

$$
\begin{bmatrix}
i_{\text{om}}
i_{\text{refm}}
i_{\text{ref1}}
i_{\text{ref2}}
\end{bmatrix}
= 
\begin{bmatrix}
G_{\text{selim}} & G_{\text{paral1,} 2} & \cdots & G_{\text{paral1,} n} \\
G_{\text{paral2,} 1} & G_{\text{sel2}} & \cdots & G_{\text{paral2,} n} \\
\vdots & \vdots & \ddots & \vdots \\
G_{\text{paraln,} 1} & G_{\text{paraln,} 2} & \cdots & G_{\text{selim}}
\end{bmatrix}
\begin{bmatrix}
i_{\text{om}}
i_{\text{ref1}}
i_{\text{ref2}}
i_{\text{refm}}
\end{bmatrix}
- 
\begin{bmatrix}
G_{\text{ser1}} & G_{\text{ser2}} & \cdots & G_{\text{serim}}
\end{bmatrix}
\begin{bmatrix}
u_{\text{g}}
i_{\text{dm}}
\end{bmatrix}
$$

(13)

It is obvious that the strong coupling between the inverters and the grid may exist and introduce harmonic oscillation currents under weak grid condition.

According to Figure 4, Figure 6 gives the control block diagram of the oscillation suppression method by two notch filters for parallel inverters. The first notch filter is introduced into the feedforward path of PCC voltage and the second notch filter is introduced into the feedback path of the grid-side inductor current. The feedback path of the grid-side inductor current with the notch filter is equivalent to a virtual impedance in series with inverter output impedance, which can effectively improve the power quality of the grid-connected current. The feedforward path of PCC voltage with the notch filter equals to a virtual impedance in parallel with inverter output impedance. This can effectively restrain the parallel inverters’ harmonic current from flowing into the grid and avoid the oscillation phenomenon. $H_{ij}$ is the feedback coefficient of the grid-side inductor current, and $H_{ij}$ is the feedforward coefficient of PCC voltage.
Figure 6. Control block diagram of the oscillation suppression method by two notch filters for parallel inverters.

From Figure 6, the equivalent closed-loop transfer function of the system can be expressed as

\[ i_{oj} = G_{eq}i_{refj} + i_d - Y_{eq}u_{PCC} = \frac{G_i G_{PWM} Z_{C1j} Z_{pj}}{C + D + E} i_{refj} + i_d - \frac{Z_{L1j} + Z_{C1j} + H_2 G_{PWM} Z_{C1j}}{C + D + E} u_{PCC} \]  \( (14) \)

where \( G_{eq} \) is the equivalent coefficient of the current source after the single inverter transformation, \( Y_{eq} \) is the inverter equivalent admittance after the single inverter transformation, \( C = Z_{L1j} Z_{L2j} \), \( D = (1 + H_1 j) G_i G_{PWM} Z_{C1j} \), and \( E = Z_{C1j} (Z_{L1j} + Z_{L2j}) \).

In order to achieve the same purpose of Figures 4 and 6, the equivalent coefficient of the current source and the inverter equivalent admittance in Equation (10) are equal to those in Equation (14). Thus, it can be expressed as

\[
\begin{align*}
    \frac{G_i G_{PWM} Z_{C1j} Z_{pj}}{Z_{pj} A + Z_{pj} B} &= \frac{G_i G_{PWM} Z_{C1j}}{Z_{pj} A + Z_{pj} B} \\
    \frac{Z_{L1j} Z_{C1j} + (Z_{L1j} + Z_{C1j}) (Z_{pj} + Z_{pj})}{Z_{pj} A + Z_{pj} B} &= \frac{Z_{L1j} Z_{C1j} + H_2 G_{PWM} Z_{C1j}}{C + D + E}
\end{align*}
\]  \( (15) \)

From Equation (15), the feedback coefficient of the grid-side inductor current \( H_{ij} \) and the feedforward coefficient of PCC voltage \( H_{2j} \) can be expressed as

\[
\begin{align*}
    H_{ij} &= \frac{G_i G_{PWM} Z_{C1j} + (Z_{L1j} + Z_{C1j}) (Z_{pj} + Z_{pj})}{Z_{pj} A + Z_{pj} B} \\
    H_{2j} &= \frac{Z_{L1j} Z_{C1j} + H_2 G_{PWM} Z_{C1j}}{Z_{pj} A + Z_{pj} B}
\end{align*}
\]  \( (16) \)

At the specific frequency, the amplitude of the notch filter is greatly attenuated while the amplitude at other frequencies is almost non-destructive. The notch filter \( G_N \) can be expressed as

\[ G_N = \frac{(\frac{s}{2\pi f_o})^2 + 1}{(\frac{s}{2\pi f_o})^2 + \frac{s}{2\pi f_o} + 1} \]  \( (17) \)

where \( f_o \) is the fundamental frequency and \( Q \) is the quality factor of the notch filter.

The analysis diagrams of the notch filter with \( Q = 0.25, 0.5, \) and \( 1 \) are shown in Figure 7. From Figure 7a, the larger \( Q \) is, the better the notch characteristic of the notch filter, but the worse the frequency adaptability. From Figure 7b, when \( Q = 0.25 \), the characteristic equation has two unequal real poles on the negative real axis of the s plane, which is over-damping. When \( Q = 0.5 \), the characteristic equation has two equal real poles on the negative real axis of the s plane, which is critical-damping. When \( Q = 1 \), the characteristic equation has the conjugate complex poles on the left half plane, which is under-damping. From Figure 7c, the tuning time of notch filter with \( Q = 0.5 \) is better than \( Q = 0.25, 1 \). Therefore, considering the notch characteristics and dynamics comprehensively, the \( Q \) value was selected to be 0.5.
virtual impedance $Z$ effectively suppresses the oscillation of the paralleled multi-inverter system. At the high frequency, the parallel virtual impedance $Z_p$ flows into the parallel virtual impedance $Z_{pj}$ and the series virtual impedance $Z_s$ displays a high impedance, so that the high-frequency harmonic current flows into the parallel virtual impedance $Z_{pj}$ branch.

The Bode diagrams of parallel virtual impedance $Z_{pj}$ and series virtual impedance $Z_{sj}$ are shown in Figure 8. The Bode diagrams of the inverter self-impedance $Z_{oj}$, parallel virtual impedance $Z_{pj}$, grid equivalent impedance $Z_{sgj}$, and grid impedance $Z_g$ are shown in Figure 9. Combined with Figure 5, the grid equivalent impedance $Z_{sgj}$ is much lower than the self-impedance $Z_{oj}$ and the parallel virtual impedance $Z_{pj}$ at the fundamental frequency, thus most fundamental frequency current flows into the grid branch with relatively low impedance, which improves the power quality of grid-connected current. At the high frequency, the parallel virtual impedance $Z_{pj}$ is much lower than the self-impedance $Z_{oj}$ and grid equivalent impedance $Z_{sgj}$, thus most high-frequency harmonic current flows into the parallel virtual impedance $Z_{pj}$ branch with relatively low impedance, and it effectively suppresses the oscillation of the paralleled multi-inverter system.

**Figure 7.** Analysis diagrams of notch filter with $Q = 0.25, 0.5, 1$. (a) The Bode diagram of notch filter; (b) Pole-zero plot of notch filter; (c) Unit step dynamic responses of notch filter.

**Figure 8.** The Bode diagrams of parallel virtual impedance $Z_{pj}$ and series virtual impedance $Z_{sj}$. 

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4. Contrast Analysis of System Stability under Weak Grid Condition

In order to compare and analyze the system stability, different conditions of adding parallel-series virtual impedances are shown in Table 1. Parallel virtual impedance $Z_{pj} = r_1$ and series virtual impedance $Z_{sj} = r_2$, abbreviated as case I. Parallel virtual impedance $Z_{pj} = r_1/G_N$ and series virtual impedance $Z_{sj} = r_2 G_N$, abbreviated as case II (proposed control method).

<table>
<thead>
<tr>
<th>Number</th>
<th>Parallel Virtual Impedance $Z_{pj}$</th>
<th>Series Virtual Impedance $Z_{sj}$</th>
<th>Control Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$r_1$</td>
<td>$r_2$</td>
<td>case I</td>
</tr>
<tr>
<td>II</td>
<td>$r_1/G_N$</td>
<td>$r_2 G_N$</td>
<td>case II</td>
</tr>
</tbody>
</table>

To verify that the system satisfies the precondition of using the Nyquist criterion, the open-loop Bode diagrams and closed-loop pole-zero diagrams of the equivalent coefficient of current source $G_{j, eq}$ for single inverter in different cases are shown in Figure 10. From Figure 10a,b, it can be seen that the gain margin (GM) and the phase margin (PM) are greater than 0, no right half-plane pole exists, and the single-inverter system is in a stable state. Therefore, the system satisfies the precondition of using the Nyquist criterion. The stability condition of the paralleled multi-inverter system is that the Nyquist curve of the impedance ratio does not surround $(-1, j0)$.

**Figure 9.** The Bode diagrams of the inverter self-impedance $Z_{oj}$, parallel virtual impedance $Z_{pj}$, grid equivalent impedance $Z_{agj}$, and grid impedance $Z_g$.

**Figure 10.** The open-loop Bode diagrams and closed-loop pole-zero diagrams of the equivalent coefficient of current source $G_{j, eq}$ for single inverter in different cases. (a) Case I; (b) Case II.
Figure 11 shows the Nyquist diagrams of impedance ratio $K$ for the paralleled multi-inverter system. From Figure 11a, when the number of inverters is 2, 3, 4, 5, and 6, respectively, the Nyquist curve does not surround ($-1, j0$) in case I, and the system is in a stable state. However, when the number of inverters is 7, 8, 9, 10, and 11, respectively, the Nyquist curves all surround ($-1, j0$), and the system is in an unstable state. However, from Figure 11b, regardless of the number of inverters, the Nyquist curves would never wrap around ($-1, j0$) in case II, and the system is in a stable state. Therefore, compared with case I, the proposed oscillation suppression method by two notch filters can effectively restrain parallel inverters’ harmonic current from flowing into the grid, and avoid the oscillation phenomenon.

Figure 11. Nyquist diagrams of impedance ratio $K$ for the paralleled multi-inverter system. (a) Case I; (b) Case II.
To verify the correctness of theoretical analysis, the simulation model of a paralleled multi-inverter system was built based on Figure 1. Several cases including two and seven inverters were simulated by PSIM (Powersim Inc., Rockville, MD, USA) simulation. The system parameters are shown in Table 2.

When two inverters were connected to a weak grid in case I and case II, the root mean square (RMS) value of the reference grid-side inductor current \(i_{\text{refm}}\) for each grid-connected inverter increased from 18.75 A to 37.5 A at 0.405 s. Therefore, the RMS of the reference grid-connected current \(i_{\text{gref}}\) increased from 37.5 A to 75 A for the two parallel inverters. Simulation results of the grid-connected current with two parallel inverters are shown in Table 3.

### Table 2. System parameters.

<table>
<thead>
<tr>
<th>Parameter/Unit</th>
<th>Value</th>
<th>Parameter/Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC voltage (U_{\text{dc}}/\text{V})</td>
<td>720</td>
<td>Switching frequency (f_s/\text{kHz})</td>
<td>10</td>
</tr>
<tr>
<td>Grid phase voltage (U_g/\text{V})</td>
<td>220</td>
<td>Proportional coefficient (k_p)</td>
<td>2.1</td>
</tr>
<tr>
<td>Amplitude of triangular carrier (U_{\text{tri}}/\text{V})</td>
<td>1</td>
<td>Resonance gain (k_1)</td>
<td>175</td>
</tr>
<tr>
<td>Inverter-side inductor (L_1/\text{mH})</td>
<td>2.2</td>
<td>Cut-off angular frequency (\omega_c/\text{rad/s})</td>
<td>6.28</td>
</tr>
<tr>
<td>Parasitic resistance of (L_1 R_1/\Omega)</td>
<td>0.002</td>
<td>Fundamental angular frequency (\omega_{01}/\text{rad/s})</td>
<td>314</td>
</tr>
<tr>
<td>Filter capacitor (C_1/\mu\text{F})</td>
<td>10</td>
<td>Fundamental frequency (f_0/\text{Hz})</td>
<td>50</td>
</tr>
<tr>
<td>Grid-side inductor (L_2/\text{mH})</td>
<td>0.8</td>
<td>Quality factor (Q)</td>
<td>0.5</td>
</tr>
<tr>
<td>Parasitic resistance of (L_2 R_2/\Omega)</td>
<td>0.001</td>
<td>Proportional coefficient (r_1)</td>
<td>5</td>
</tr>
<tr>
<td>Grid inductor (L_g/\text{mH})</td>
<td>2</td>
<td>Proportional coefficient (r_2)</td>
<td>15</td>
</tr>
</tbody>
</table>

### Table 3. Simulation results of grid-connected current with two parallel inverters. THD: total harmonic distortion.

<table>
<thead>
<tr>
<th>Number</th>
<th>Case</th>
<th>Before Reference Current Transient</th>
<th>After Reference Current Transient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>THD</td>
<td>Resonance Point and Resonance Peak</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
<td>6.07%</td>
<td>25th harmonic 1.77 A</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>3.27%</td>
<td>39th harmonic 0.88 A</td>
</tr>
</tbody>
</table>

In case I, the transient simulation waveforms of PCC voltage \(u_{\text{PCC}}\) and grid-connected current \(i_g\) are depicted in Figure 12a,b. It can be seen that the distortion rate of PCC voltage \(u_{\text{PCC}}\) is 1.57%. The grid-connected current \(i_g\) and corresponding spectrum from 0.30 s to 0.36 s are shown in Figure 12c,d, which describes the situation before the reference current surges. The distortion rate of grid-connected current \(i_g\) is 6.07%, the resonance point is near the 25th harmonic (1250 Hz), and the resonance peak is 1.77 A. The grid-connected current \(i_g\) and corresponding spectrum after the reference current suddenly increases are shown in Figure 12e,f. The distortion rate of grid-connected current \(i_g\) decreases to 3.16%, the resonance point is still near the 25th harmonic (1250 Hz), and the resonance peak value is 1.81 A. At this time, the major high-frequency harmonics of the grid-connected current are 25th harmonics.

In case II, the transient simulation waveforms of PCC voltage \(u_{\text{PCC}}\) and the grid-connected current \(i_g\) are depicted in Figure 13a,b. From Figure 13a, the distortion rate of PCC voltage \(u_{\text{PCC}}\) is 0.82%. The grid-connected current \(i_g\) and corresponding spectrum before the reference current surges are shown in Figure 13c,d. The distortion rate of the grid-connected current \(i_g\) is 3.27%, the resonance point is near the 39th harmonic (1950 Hz), and the resonance peak is 0.88 A. The grid-connected current \(i_g\) and corresponding spectrum after the reference current suddenly increases are shown in Figure 13e,f. The distortion rate of the grid-connected current \(i_g\) decreases to 1.51%, the resonance point is still near the 39th harmonic (1950 Hz), and the resonance peak value is 0.79 A. Meanwhile, the power quality of the grid-connected current can be significantly improved, and the resonance phenomenon has obviously decreased.
When seven inverters are connected to a weak grid in cases I and II, the RMS of reference grid-side inductor current $i_{\text{refm}}$ for each grid-connected inverter is 10.71 A. Therefore, the RMS of the reference grid-connected current $i_{\text{gref}}$ is 75 A for seven parallel inverters. The simulation waveforms and spectrograms of PCC voltage $u_{\text{PCC}}$ and the grid-connected current $i_g$ are shown in Figures 14 and 15. The simulation results of the grid-connected current with seven parallel inverters are shown in Table 4. In case I, the system is in an unstable state. The resonance phenomenon is obvious. The reason is that the high-frequency harmonic current frequency is equal to or close to the parallel resonance frequency of self-impedance, resulting in a parallel resonance or quasi-resonance of the impedance network. The grid-connected current is still severely polluted by the impedance coupling interactions between the inverters and the grid. In case II, the distortion rate of the grid-connected current $i_g$ is 3.38%, the resonance point is near the 39th harmonic (1950 Hz), and the resonance peak is 1.51 A. Due to the sufficient resistive damping introduced to the impedance network, the system can operate stably. Therefore, case II can effectively improve the power quality of the grid-connected current and suppress the oscillation of the paralleled multi-inverter system.

Figure 12. Simulation waveforms of point of common coupling (PCC) voltage $u_{\text{PCC}}$ and grid-connected current $i_g$ in case I during reference current transient (two parallel inverters). (a) PCC voltage $u_{\text{PCC}}$; (b) grid-connected current $i_g$; (c) grid-connected current $i_g$ (before); (d) spectrogram of grid-connected current $i_g$ (before); (e) grid-connected current $i_g$ (after); (f) spectrogram of grid-connected current $i_g$ (after).
Figure 13. Simulation waveforms of PCC voltage $u_{\text{PCC}}$ and the grid-connected current $i_g$ in case II during reference current transient (two parallel inverters). (a) PCC voltage $u_{\text{PCC}}$; (b) grid-connected current $i_g$; (c) grid-connected current $i_g$ (before); (d) spectrogram of grid-connected current $i_g$ (before); (e) grid-connected current $i_g$ (after); (f) spectrogram of grid-connected current $i_g$ (after).

Table 4. Simulation results of grid-connected current with seven parallel inverters.

<table>
<thead>
<tr>
<th>Number</th>
<th>Case</th>
<th>THD</th>
<th>Resonance Point and Resonance Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>I</td>
<td>(unstable)</td>
<td>(unstable)</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>3.38%</td>
<td>39th harmonic 1.51 A</td>
</tr>
</tbody>
</table>

Figure 14. Simulation waveforms of PCC voltage $u_{\text{PCC}}$ and the grid-connected current $i_g$ in case I (seven parallel inverters). (a) PCC voltage $u_{\text{PCC}}$; (b) grid-connected current $i_g$. 


When the model was running, the OP5700 sent the analog signals (voltages and currents) to the real controllers through the I/O ports, which could be observed on the oscilloscope. The measurement information during the simulation were converted into analog signals through the I/O ports, which interacted in real time during the simulation process to ensure the normal operation of the system. The data interacted in real time during the simulation process to ensure the normal operation of the system. After data processing, the real controllers transmitted the digital control signals (pulses) to OP5700 through the I/O ports in real time. The data interacted in real time during the simulation process to ensure the normal operation of the system. The measurement information during the simulation were converted into analog signals through the I/O ports, which interacted in real time during the simulation process to ensure the normal operation of the system. After data processing, the real controllers transmitted the digital control signals (pulses) to OP5700 through the I/O ports in real time. The data interacted in real time during the simulation process to ensure the normal operation of the system. The measurement information during the simulation were converted into analog signals through the I/O ports, which could be observed on the oscilloscope.

6. Experimental Verification

To verify the validity of simulation analysis, a hardware-in-the-loop experimental platform based on a real controller TMS320F2812 digital signal processor (DSP) (Texas Instruments, Inc, Dallas, TX, USA) and a real-time laboratory (RT-LAB) (Opal-RT Technologies, Montreal, QC, Canada) was built [26], as shown in Figure 16a. The system parameters are shown in Table 2. The hardware-in-the-loop experimental platform mainly includes an RT-LAB simulator OP5700 (Opal-RT Technologies, Montreal, QC, Canada), real controllers of grid-connected inverters, a host computer as a real-time control interface, and an oscilloscope, as shown in Figure 16b. The main circuit model of the system was established in the host computer, which was loaded to the OP5700. When the model was running, the OP5700 sent the analog signals (voltages and currents) to the real controllers through the input/output (I/O) ports in real time. After data processing, the real controllers transmitted the digital control signals (pulses) to OP5700 through the I/O ports in real time. The data interacted in real time during the simulation process to ensure the normal operation of the system. The measurement information during the simulation were converted into analog signals through the I/O ports, which could be observed on the oscilloscope.

Figure 15. Simulation waveforms of PCC voltage $u_{PCC}$ and the grid-connected current $i_g$ in case II (seven parallel inverters). (a) PCC voltage $u_{PCC}$; (b) grid-connected current $i_g$; (c) spectrogram of grid-connected current $i_g$.

Figure 16. Experimental platform for paralleled multi-inverter system based on hardware-in-loop simulation. (a) Whole; (b) Structure.
When two inverters operated in parallel, as in case I and case II, the RMS values of reference for the grid-side inductor current $i_{refm}$ for each grid-connected inverter increased from 18.75 A to 37.5 A at 0.405 s. Therefore, the RMS of reference grid-connected current $i_{gref}$ increased from 37.5 A to 75 A for two parallel inverters. The transient experimental waveforms and spectrograms in case I and case II are depicted in Figures 17 and 18. Experimental results of the grid-connected current with two parallel inverters are shown in Table 5. Before the reference current surged in Figure 17b, the distortion rate of the grid-connected current $i_g$ was 7.01%, the resonance point was near the 25th harmonic (1250 Hz), and the resonance peak was 2.66 A. After the reference current suddenly increased in Figure 17c, the distortion rate of the grid-connected current $i_g$ decreased to 4.22%, the resonance point was still near the 25th harmonic (1250 Hz), and the resonance peak value was 2.89 A. Thus, the grid-connected current apparently contained high-frequency ripples, and it is obvious that the major harmonics are 25th harmonics.

Before the reference current surged in Figure 18b, the distortion rate of the grid-connected current $i_g$ was 4.82%, the resonance point was near the 39th harmonic (1950 Hz), and the resonance peak was 2.06 A. After the reference current suddenly increased in Figure 18c, the distortion rate of grid-connected current $i_g$ decreased to 2.79%, the resonance point was still near the 39th harmonic (1950 Hz), and the resonance peak value was 2.04 A. Meanwhile, the power quality of grid-connected current can be significantly improved, and the resonance phenomenon has obviously decreased. Therefore, the distortion rate was smaller after the reference current surge in the same case. Moreover, before and after the reference current surged, the distortion rate in case II was less than case I.

Table 5. Experimental results of the grid-connected current with two parallel inverters.

<table>
<thead>
<tr>
<th>Number</th>
<th>Case</th>
<th>Before Reference Current Transient</th>
<th>After Reference Current Transient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>THD</td>
<td>Resonance Point and Resonance Peak</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
<td>7.01%</td>
<td>25th harmonic 2.66 A</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>4.82%</td>
<td>39th harmonic 2.06 A</td>
</tr>
</tbody>
</table>

Figure 17. Experimental waveforms of PCC voltage $u_{PCC}$ and grid-connected current $i_g$ in case I during reference current transient (two parallel inverters). (a) PCC voltage $u_{PCC}$ and grid-connected current $i_g$; (b) grid-connected current $i_g$ and spectrogram (before); (c) grid-connected current $i_g$ and spectrogram (after).
When seven inverters operate in parallel in cases I and case II, the RMS of the reference grid-side inductor current $i_{\text{refm}}$ for each grid-connected inverter was 10.71 A. Therefore, the RMS of the reference grid-connected current $i_{\text{gref}}$ was 75 A for the seven parallel inverters. The experimental waveforms and spectrograms in cases I and case II are shown in Figures 19 and 20. The experimental results of the grid-connected current with the seven parallel inverters are shown in Table 6. As can be seen in Figure 19, the system is in an unstable state. The resonance phenomenon is obvious. The reason is that the high-frequency harmonic current frequency is equal to or close to the parallel resonance frequency of self-impedance, resulting in a parallel resonance or quasi-resonance of the impedance network. The grid-connected current is still severely polluted by the impedance coupling interactions between the inverters and the grid. From Figure 20, it can be seen that the distortion rate of the grid-connected current $i_g$ is 4.36%, the resonance point is near the 39th harmonic (1950 Hz), and the resonance peak is 2.99 A. Due to the sufficient resistive damping introduced to the impedance network, the system can operate stably. Therefore, case II can effectively improve the power quality of the grid-connected current and suppress the oscillation of the paralleled multi-inverter system.

Table 6. Experimental results of the grid-connected current with seven parallel inverters.

<table>
<thead>
<tr>
<th>Number</th>
<th>Case</th>
<th>THD</th>
<th>Resonance Point and Resonance Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>I</td>
<td>(unstable)</td>
<td>(unstable)</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>4.36%</td>
<td>39th harmonic 2.99 A</td>
</tr>
</tbody>
</table>
In this paper, the oscillation suppression method by two notch filters is proposed to realize the virtual impedances and increase the whole system damping. The implementation form of the virtual impedances is presented by the proposed PCC voltage feedforward and grid-side inductor current feedback with two notch filters. The feedforward path of PCC voltage with the notch filter equals to a virtual impedance in parallel with inverter output impedance, which is designed to show low impedance at the harmonic oscillation frequency. By doing so, most high-frequency harmonic current will flow into the parallel virtual impedance branch, and it effectively suppresses the oscillation. Meanwhile, the feedback path of the grid-side inductor current with the notch filter is equivalent to a virtual impedance in series with inverter output impedance, which is designed to display low impedance at the fundamental frequency. This way, most of the fundamental frequency current flows into the grid branch with relatively low impedance. In addition, it improves the power quality of the grid-connected current. Finally, simulation and experimental results are provided to verify the validity of proposed control method.

Author Contributions: L.Y. and Y.C. provided the original idea for this paper. L.Y., H.W., A.L. and K.H. organized the manuscript and attended the discussions when analysis and verification were carried out. All the authors gave comments and suggestions on the writing and descriptions of the manuscript.

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