Fast Reactive Power Sharing, Circulating Current and Resonance Suppression for Parallel Inverters Using Resistive-Capacitive Output Impedance

Yandong Chen, Member, IEEE, Josep M. Guerrero, Fellow, IEEE, Zhiyong Chen, Leming Zhou, and An Luo, Senior Member, IEEE

Abstract—In this paper, an inverter using resistive-capacitive output impedance (RC-type inverter) is proposed not only to provide fast reactive power sharing to support microgrid voltage, and but also to reduce circulating currents and damp high-frequency resonances among inverters. Introducing the RC virtual impedance loop, the inverter provides fast transient response. Based on the RC-type inverter modeling, the comparative frequency-domain analysis of equivalent output impedances are discussed, and the impact of the virtual complex impedance over the circulating currents and high-frequency resonances among parallel inverters are quantitatively analyzed. The control parameters are systematically selected, and effect of virtual complex impedance on the inverter output voltage is depicted. The RC-type inverter can reduce circulating currents and damp resonances due to different equivalent output impedances of inverter, and line impedances. Simulation and experimental results verify the effectiveness of proposed method.

Index Terms—Microgrid, parallel-connected inverters, resistive-capacitive virtual impedance, reactive power sharing, circulating current, resonance

I. INTRODUCTION

NOWADAYS more renewable energy, distributed generation (DG), energy storage systems (ESS), and local loads are conjugated and integrated in microgrids via power-electronics interfaced equipment [1-4]. Multi-inverters operating in parallel are commonly used in islanded microgrids [4-6]. However, the issues of circulating current and power sharing among multiple parallel inverters directly threat the operational security of the microgrid [7]. Therefore, how to effectively reduce the circulating current and to accurately share power among multi-parallel inverters becomes an important issue to be addressed [7-10].

In order to achieve ‘plug and play’ functionality of the DG units integrated into the microgrid, the conventional droop control method was proposed to solve the power sharing problem [11-15]. Power droop control theory can be applied to multi-parallel inverter systems without relying on communications [16-17]. This decentralized control method is realized by adjusting the frequency and amplitude of output voltage of inverter in the function of active and reactive powers delivered by the inverter, respectively. Nevertheless, the output impedance of parallel inverters in low-voltage microgrids is usually deliberately designed to be inductive [5,6,11], which causes the power sharing and circulating currents even worse due to the fact that the output impedance and the line impedance among inverters are not equal [9]. Therefore, a number of improved droop control methods such as adaptive droop control [18-23] are proposed to enhance the accuracy of power sharing. The virtual impedance was introduced to the feedback path of the output current to modify the amplitude-frequency characteristic of inverter output impedance [11-13, 24-27]. By using different virtual impedance nature, the parallel inverter can present different behaviors: resistive (R-type inverter), inductive (L-type inverter), or resistive and inductive (RL-type inverter), which satisfy different needs [24-30].

In contrast to synchronous generators, inverter dynamics presents low inertia behavior [31]. With the increasing use of nonlinear loads and resistive-inductive motor loads integrated into the distribution network or microgrid, the demand of active and reactive power from the consumers will drastically increase, which leads to voltage fluctuations or sags at the point of common coupling (PCC) [32,33]. To solve this problem, high-capacity static var compensators (STATCOM) can be connected to the PCC to reduce the voltage fluctuations or sags. However, the required time to calculate the reactive power by the STATCOM reduces its compensating effectiveness. STATCOMs in microgrid are usually centralized, installed in a fix location, commonly far away from local loads [34], so that the capacity of the STATCOM will increase with the raise of the required reactive current. In addition, an increasing amount of STATCOMs connected to PCC leads microgrid dynamics to be more complex. On the other hand, passive filters cannot realize fast continuous dynamic compensation. Consequently, all these methods either make the voltage fluctuations worse, or reduce the reliability of parallel system.

Manuscript received October 13, 2014; revised March 11, 2015 and May 26, 2015; accepted October 9, 2015. This work was supported by the National Natural Science Foundation of China under Grant 51577056 and Grant 51237003, by the Fundamental Research Funds for the Central Universities, and in part by the International Cooperation Program of China under Grant 51237003, by the Fundamental Research Funds for the Central Universities, and in part by the International Cooperation Program of China under Grant 51237003.
Alternatively, parallel inverters could provide extra reactive power to support the voltage of the PCC during transient voltage sags. Since most parallel inverters in microgrids are installed near the local loads, the equivalent output impedance of these inverters could be redesigned to be capacitive (C-type inverters), similar to an STATCOM, which may have the ability to provide fast reactive power and to achieve low-voltage ride through performance [35]. Hence, C-type inverters may meet grid microgrid demands and improve the PCC voltage without adding any external components, rather than slightly modify the control of the existing inverters. However, C-type inverter may cause resonance between inverter output impedances and line impedances in high-order harmonic frequency range [36-40]. Taking a two parallel inverter system for example, there are two resonant frequencies (modes) and one inverse-resonance frequency. With the growth quantity of inverters, the equivalent series impedances of the grid will increase and leads to a resonant frequency migrating to lower frequency range [38]. Therefore, it is an effective way to modify the parallel resonant frequency by improving the power sharing control method among the parallel inverters. By using the inverter output current and the PCC voltage as feed-forward terms, the virtual impedance at the fundamental and selected harmonic frequencies is proposed to regulate the equivalent inverter impedance, which may realize a better reactive and harmonic power sharing [39, 40]. However, the resonant conditions are related to inverter’s power stage, control strategy and number of parallel inverters.

In this paper, a fast reactive power control method for parallel inverters using resistive-capacitive (RC) output impedance is proposed. The paper is organized as follows. Section II presents the droop characteristics of five types of inverters and the RC-type inverter. Section III shows the proposed control architecture based on three cascaded control loops. Section IV presents the impacts of the virtual complex impedance over the fundamental and selected harmonic frequencies circulating currents among inverters, effect of virtual complex impedance on the inverter output voltage, and the selection of the main control parameters. Simulation and experimental results are illustrated and discussed in Section V. Conclusions are given in Section VI.

II. MODELING OF RESISTIVE-CAPACITIVE INVERTERS

A. Output power characteristics of inverter with five different types of virtual impedance

The simplified diagram of two parallel inverters which consist of two voltage sources, the total equivalent impedances, and a common load is shown in Fig. 1. The total equivalent impedance includes the equivalent inverter output impedance $Z_{oi}$ ($i=1, 2$) and the line impedance $Z_{linei}$. $E_i$ is the amplitude of inverter output voltage $e_i$ with no-load at the fundamental frequency, and $\delta_i$ is the phase error between $e_i$ and the load voltage $u_{oi}$ at the fundamental frequency.

![Fig. 1. Simplified diagram of two parallel inverters.](image)

By considering only the influence of the line impedance, $u_{oi}$ is the terminal output voltage, and the output active and reactive power of the inverter can be expressed respectively as [17, 21, 40, 41].

$$\begin{align*}
P_i &= (E_iU_i \cos \delta_i - U_i^2) \cos \phi_i + E_iU_i \sin \delta_i \sin \phi_i \\
Q_i &= (E_iU_i \cos \delta_i - U_i^2) \sin \phi_i - E_iU_i \sin \delta_i \cos \phi_i
\end{align*}$$

(1)

where $\phi_i$ is the impedance angle of total equivalent impedance, the line impedance is presented as $Z_{linei} = R_{linei} + jX_{linei}$ and the equivalent inverter output impedance is $Z_{oi} = R_{oi} + jX_{oi}$. As a result, active power and reactive power are both associated with the amplitude and phase of the inverter output voltage, $\phi_i$ [17, 41].

By adding different virtual impedance loops into the feedback path of the output current, it can make the equivalent inverter output impedance has different impedance angles. In case of low-voltage networks, the total equivalent impedance angle $\phi_i$ is mainly dominated by the equivalent inverter output impedance angle since $R_{linei}$ far larger than $X_{linei}$ ($R_{linei} >> X_{linei}$) [42]. Next, power equations and droop equations of five types of inverters by embedding different virtual impedance are shown in Table I, where $\omega_i'$ is the reference value of angular frequency at no-load condition, $E'$ is the reference value of output voltage amplitude at no-load condition, and $m_i$ and $n_i$ are the droop coefficients of frequency and voltage respectively. Notice that $\delta = \omega - \omega_i$, thus frequency droop is used here instead of phase droop since the initial phase of each inverter is unknown. This is because the inverters do not know the initial phase value of the other units; however, the initial frequency at no load can easily be fixed as $\omega_i$. In fact, it is necessary to compensate the difference between the crystal clock generators [11].

**Table 1: Power Transfer Expressions and Droop Equations**

<table>
<thead>
<tr>
<th>Impedance angle</th>
<th>Power equations</th>
<th>Droop equations</th>
</tr>
</thead>
</table>
| $\phi = 90^\circ$ (L-type) | \begin{align*}
P_i &= \frac{E_iU_i \sin \delta_i}{X_{oi} + X_{line}} \\
Q_i &= \frac{E_iU_i \cos \delta_i - U_i^2}{X_{oi} + X_{line}}
\end{align*} | $\omega_i = \omega_i' - n_iP_i$ | $E_i = E' - m_iQ_i$
| $0^\circ < \phi < 90^\circ$ (RL-type) | \begin{align*}
P_i &= \frac{E_iU_i \cos (\phi - \delta_i) - U_i^2 \cos \phi_i}{Z_{oi} + Z_{line}} \\
Q_i &= \frac{E_iU_i \sin (\phi - \delta_i) - U_i^2 \sin \phi_i}{Z_{oi} + Z_{line}}
\end{align*} | $\omega_i = \omega_i' - n_iP_i + m_iQ_i$ | $E_i = E' - n_iP_i - m_iQ_i$ |
and current droop controller. Firstly, the value of angular frequency 
the line current
and virtual impedance loop. It includes outer power
circulating current characteristic
RC\text{-}j<90°
Assuming that the switching period \(T_s\) is very small, the average value in the period of \(T_s\) can be replaced by its instantaneous value. From Fig. 2, \(u_{inv}\) can be expressed as
\[
L_x C_o \frac{d^2 u_{inv}}{dt^2} + R_o C_o \frac{du_{inv}}{dt} + u_{inv} + L_x \frac{di_o}{dt} + R_l i_o = u_{inv}
\]
(2)
Assuming that \(G(s)\) is the equivalent gain of the voltage control loop, \(u_o\) can be expressed as
\[
u_o = u_{inv} - Z_v(s)i_o = G(s)u_{inv} - Z_v(s)i_o
\]
(3)
where, \(Z_v(s)\) is the equivalent inverter output impedance.
To modify the equivalent inverter output impedance, the virtual complex impedance \(Z_v(s)\), which contains resistive and capacitive components, is introduced into the output current feedback path, and \(Z_v(s)\) is defined as
\[
Z_v(s) = R_p + \frac{1}{sC_v}
\]
(4)
where \(R_p\) is the virtual resistive part and \(C_v\) the virtual
capacitive part. The block diagram of the voltage control loop with the virtual impedance is showed in Fig. 3.
![Fig. 3. Block diagram of the voltage control with virtual impedance loop.](image-url)
current sharing can be achieved by considering equal RC virtual impedances or, in case of different power ratings, inversely proportional to their power ratings.

![Fig. 4 Equivalent circuit of the two RC-type inverters sharing a common load.](image)

### III. PROPOSED CONTROL ARCHITECTURE

The proposed power sharing control strategy of RC-type inverter mainly includes power droop control, virtual impedance feedback control, and voltage and current dual-loop control.

#### A. Power droop control strategy

The block diagram of power droop controller is shown in Fig. 5. To achieve inverter output active and reactive power, the orthogonal two-phase voltage vectors are implemented, and virtual instantaneous active power \( P \) and reactive power \( Q \) are calculated. The average active power \( P \) is obtained through a low-pass filter to \( p \), where \( \omega_p \) is the cut-off frequency of low-pass filter. The average reactive power \( Q \) is obtained through a band-pass filter to \( q \), where \( \omega \) is constant.

![Fig. 5 Block diagram of power droop controller.](image)

The droop coefficients \( m \) and \( n \) are determined by considering the fluctuation range of frequency and voltage in the parallel system. The output reference voltage of inverter \( u_i^* \) is expressed as

\[
u_i^* = \sqrt{2}E \sin(\omega t + \phi)
\]

When a new inverter is going to be connected to the parallel system, \( \phi \) is used to keep the phase of inverter output voltage as same as the phase of PCC voltage, and \( \omega \) does not disable until connecting operation is successfully finished.

#### B. Voltage and current dual-loop control

Voltage and current dual-loop control method based on the virtual complex impedance is shown in Fig. 6. The proportional-integral-derivative (PID) controller is adopted to enforce the outer voltage loop to accurately track the inverter output voltage. The proportional controller is used as inner current loop which uses to track the current \( i_C \) flowing through the output filter capacitor \( C_v \). Dual-loop control method can further reduce the influence of output voltage fluctuation, where \( k_m \) is the proportional gain of current loop, and \( k_{	ext{inj}} \) is the equivalent gain of inverter.

To avoid the noise produced by the derivative term, the differential of the filter capacitor voltage \( u_C \) is replaced by the following expression [11]:

\[
du_C/dt = i_C/C_v
\]

![Fig. 6 Block diagram of voltage and current control based on virtual complex impedance.](image)

The voltage feed-forward coefficient of the outer voltage loop is \( k_u = 1 \), and \( k = k_p/C_v \). Without considering the inner current loop dynamics, \( u_o \) can be expressed as

\[
u_o = u_p + k_p (u_p - u_o) + k_i \int (u_p - u_o) dt + k_D \frac{du_p}{dt} (u_p - u_o)
\]

where \( k_p, k_i, k_D \) are the proportional, integral, and differential coefficients of the PID controller, respectively.

### IV. IMPACT ANALYSIS OF EQUIVALENT OUTPUT IMPEDANCE OVER THE CIRCULATING CURRENT

#### A. Comparative analysis of equivalent output impedance characteristics

Without using virtual impedance, according to Fig. 5, we can obtain the following expression:

\[
u_o = \frac{k_p \omega^2 + (1+k_p)s + k_i}{L_s C_v \omega^2 + (R C_v + k_p) \omega + (1+k_p)s + k_i} u_p
\]

Combining (3) and (11), we can obtain the following transfer functions:

\[
G(s) = \frac{k_p \omega^2 + (1+k_p)s + k_i}{L_s C_v \omega^2 + (R C_v + k_p) \omega + (1+k_p)s + k_i}
\]

\[
Z_o(s) = \frac{L_s \omega^2 + k_i}{L_s C_v \omega^2 + (R C_v + k_p) \omega + (1+k_p)s + k_i}
\]

If the virtual impedance \( Z_o(s) \) is applied to voltage control, the equivalent output impedance \( Z_{eq}(s) \) of the parallel inverters, by combining (6) and (12), can be expressed as

\[
Z_{eq}(s) = \frac{A_1(s) + A_2(s) + A_3(s)}{B_1(s) + B_2(s) + B_3(s)}
\]

where

\[
A_1(s) = k_p \omega^2 + L_s, \quad A_2(s) = (1+k_p) \frac{R_{\text{f}} + R_k + k_D}{C_v}, \quad A_3(s) = k_i \frac{R_{\text{f}} + (1+k_p)}{C_v}, \quad B_1(s) = L_s, \quad B_2(s) = R_{o} C_v, \quad B_3(s) = R_{o} C_v + k_D, \quad B_4(s) = 1+k_p, \quad B_5(s) = k_D.
\]

To analyze the impact of the equivalent output impedance, the system simulation parameters are given in Table II.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_p )</td>
<td>2.5</td>
</tr>
<tr>
<td>( k_i )</td>
<td>0.18</td>
</tr>
<tr>
<td>( k_D )</td>
<td>0.00015</td>
</tr>
<tr>
<td>( L_{\text{f}} )</td>
<td>0.01Ω</td>
</tr>
<tr>
<td>( R_{\text{f}} )</td>
<td>3.8 mH</td>
</tr>
<tr>
<td>( R_0 )</td>
<td>0.8 Ω</td>
</tr>
<tr>
<td>( C_v )</td>
<td>1800 μF</td>
</tr>
</tbody>
</table>

A comparative analysis of the amplitude-frequency characteristics of \( Z_o(s), Z_{eq}(s), \) and \( Z_{\text{inj}}(s) \) is conducted. The
amplitude-frequency characteristic of output voltage control transfer function \(G(s)\) is shown in Fig. 7, where the voltage gain is close to 1, and voltage phase is approximately to 0 within a wide low-frequency band.

![Fig. 7. Bode diagrams of the voltage control transfer function \(G(s)\).](image)

The comparative results of the amplitude-frequency characteristics of \(Z_i(s)\), \(Z'_i(s)\), and \(Z_o(s)\) are shown in Fig. 8. Without virtual impedance, the equivalent output impedance \(Z_o(s)\) is inductive at the fundamental frequency and its amplitude is small within low-frequency band. On the other hand, if RC-type virtual impedance \(Z_i(s)\) is included, the equivalent output impedance \(Z'_o(s)\) is resistive-capacitive, and its amplitude and phase are approximately as same as \(Z_o(s)\). Therefore, \(Z_i(s)\) drastically changes the output impedance characteristics.

![Fig. 8. Bode diagrams of the different impedance.](image)

**B. Analysis of the virtual capacitive component impact on the circulating current**

Assuming that \(i_{o1}\) and \(i_{o2}\) are the output line currents of two inverters respectively, and fundamental and harmonic circulating currents are defined as \(i_{circ} = (i_{o1} - i_{o2}) / 2\), where \(h\) is the selected harmonic order between 1st and 50th. The two line impedances are intentionally unbalanced as: \(Z_{line1} = 0.036 + j0.012\) and \(Z_{line2} = 0.079 + j0.032\), respectively. In order to analyze the influence of virtual impedance parameters \(R_p\) and \(C_v\) on the fundamental and harmonic circulating currents, and also to determine the proper control parameters, we firstly suppose that \(R_p = 0\), and the amplitude of each order harmonic voltage is 10V. The relationship among the amplitude of \(i_{circ}\), \(C_v\), and \(h\) in two parallel inverters system is depicted in Fig. 9, where the value of \(C_v\) increases from 0µF to 4000µF and the order of harmonic voltage ranges from the 1st to the 20th component.

![Fig. 9. Diagram of the circulating currents of parallel system with \(C_v\) changing \((R_p = 0)\).](image)

Obviously, when decreasing the value of \(C_v\), there is a series resonance or quasi-resonance peak of circulating current that occurs at each specific value of \(C_v\). In other words, there is a quasi-resonance bandwidth, and the resonance amplitude of specific order harmonic current is decided by the frequency deviation of system resonance frequency. The smaller the frequency deviation, the larger the circulating current is. When the value of \(C_v\) is becoming extremely smaller, the amplitude of equivalent output impedance tends to be infinite, which blocks the inverter delivering current to the load. As a result, \(C_v\) should not be chosen as an extreme small value. Therefore, the relationship among the amplitude of \(i_{circ}\), \(C_v\) and \(h\) when \(R_p = 1.2\Omega\) is depicted in Fig. 10. Obviously, the virtual impedance component \(R_p\) has the ability to damp resonance and to attenuate the circulating current, which is significantly reduced at a low-frequency bandwidth.

![Fig. 10. Diagram of the circulating currents of parallel system with \(C_v\) changing \((R_p = 1.2)\).](image)

In terms of circulating current reduction, \(C_v\) has to satisfy the condition that its value should be larger than the corresponding value causing maximum resonance peak. Accordingly, the relationship among the amplitude of \(i_{circ}\), \(C_v\), and \(h\) in the condition of \(R_p = 0\) is depicted in Fig. 11, where the value of \(C_v\) ranges from 420µF to 460µF. This value range of \(C_v\) is inside the neighborhood of the upper boundary of the value of \(C_v\), this causing maximum resonance peak. It can be seen from Fig. 11 that the peak of resonance
circulating currents is located nearby the fundamental frequency, with $C_v = 437\mu F$. So that $C_v > 450\mu F$ is a reasonable choice range.

With $R_D = 0$ and $C_v$ changing from 45μF to 10mF, the amplitude-frequency characteristics of the equivalent output impedance $Z_v'(s)$ are shown in Fig. 12. $Z_v'(s)$ presents inductive behavior in fundamental and the second harmonic frequencies when $C_v$ is selected to be an excessively large value. However, $Z_v'(s)$ presents capacitive behavior when $C_v$ is selected a small value, its impedance amplitude is so large that limits the output power of inverters. In order to maintain the inverter output power providing to the loads, the voltage level of dc link of inverter has to be boost up, which is undesirable method. Considering the condition of $C_v < 1/\omega^2L_v$, the reasonable choice range of $C_v$ is $C_v < 2.2mF$. Therefore, $C_v = 1.8mF$ is recommended.

**A. Effect of virtual resistive component on circulating current**

To confirm the acceptable choice range of $R_D$, the relationship between the amplitude of $i_{oh}$, $R_D$ and $h$ for $C_v = 450\mu F$ is depicted in Fig. 13, where the value of $R_D$ ranges from $0\Omega$ to $4\Omega$. Obviously, with the increase of $R_D$ value, circulating currents greatly decrease. Obviously, the fundamental circulating current decreases from 30A to 3A, approximately. That is to say, the decrease of fundamental circulating current amplitude is up to 90%. Especially, when $R_D$ changes from 0.5$\Omega$ to 1.2$\Omega$, the amplitude voltage drop is more evident.

With $C_v = 1.8mF$, and $R_D$ selecting 0, 0.1$\Omega$, 0.5$\Omega$, 1.2$\Omega$, and 4$\Omega$, respectively, the amplitude-frequency characteristics of the equivalent output impedance $Z_v'(s)$ are shown in Fig. 14.

From Fig. 14, it can be seen that $Z_v'(s)$ varies greatly along with the frequency when $R_D$ takes a very small value. Within the low-frequency range, the amplitude of $Z_v'(s)$ tends to a relatively constant value along with the increasing value of $R_D$. In these circumstances, $Z_v'(s)$ is only determined by $R_D$. This means that the accuracy of power sharing and the reduction of circulating current are greatly improved. However, the value of $R_D$ should not be too large, otherwise it will deviate too much inverter output voltage regulation. Consequently, $R_D = 0.8$ was chosen in this paper.

**B. Effect of virtual complex impedance on the inverter output voltage**

When introducing an additional current feedback path to emulate a virtual complex impedance into the feed-forward path of the voltage-control loop, the amplitude-frequency characteristic of equivalent output impedance of an inverter is modified. Nevertheless, the virtual complex impedance may change the amplitude and phase of inverter output voltage depending on the output current.

By taking into account a single inverter, by combining (3) and (6), we can obtain the following expression:
\[
\begin{align*}
\frac{u_{o1} = G_1(s)u_{i1} - Z_{o1}(s)}{Z_{o1}(s) + Z_{\text{line}}(s) + Z_d(s)} & \\
\frac{u_{o2} = G_2(s)u_{i2} - Z_{o2}(s)}{Z_{o2}(s) + Z_{\text{line}}(s) + Z_d(s)}
\end{align*}
\]

(14)

\[
\frac{u'_{o1} = G_1(s)u'_{i1} - Z'_{o1}(s)}{Z'_{o1}(s) + Z'_{\text{line}}(s) + Z_d(s)} = \frac{G_1(s)u_{i1}}{Z_{o1}(s) + Z_{\text{line}}(s) + Z_d(s)}
\]

(15)

To analyze the impact of the equivalent output impedance, assuming \( u'_{i1} = u_{i1} \), we can obtain the gain functions of inverter output voltage \( G_{o1}(s) \):

\[
G_{o1}(s) = \frac{u'_{o1}}{u_{i1}} = \frac{Z_{o1}(s) + Z_{\text{line}}(s) + Z_d(s)}{Z_{o1}(s) + Z_{\text{line}}(s) + Z_d(s)}
\]

Since \( Z'_{o1}(s) = Z_{o1}(s) \) within the low-frequency band, assuming \( Z_{o1}(s) = R_L + sL \), we can obtain the following gain function in the low-voltage microgrid:

\[
G_{o1}(s) = \frac{R_L + sL + R_{\text{line}} + Z_{o1}(s)}{R_L + sL + R_{\text{line}} + Z_{o1}(s)}
\]

(16)

\[
= \frac{M_1 s^2 + M_2 s^3 + M_3 s^4 + M_4 s^5 + M_5 s^6}{N_1 s^2 + N_2 s^3 + N_3 s^4 + N_4 s^5 + N_5 s^6 + N_6 s^7 + N_7}
\]

where \( N_1 = M_2 s^2 + M_3 s^3 + M_4 s^4 + M_5 s^5 + M_6 s^6 \), \( N_2 = N_3 s^3 + N_4 s^4 + N_5 s^5 + N_6 s^6 + N_7 \), \( N_3 = N_4 s^4 + N_5 s^5 + N_6 s^6 + N_7 s^7 \), \( N_4 = N_5 s^5 + N_6 s^6 + N_7 s^7 \), \( N_5 = N_6 s^6 + N_7 s^7 \), \( N_6 = N_7 s^7 \), \( N_7 = 1 \), \( M_1 = M_2 s^2 + M_3 s^3 + M_4 s^4 + M_5 s^5 + M_6 s^6 \), \( M_2 = N_1 s^2 + N_2 s^3 + N_3 s^4 + N_4 s^5 + N_5 s^6 + N_6 s^7 + N_7 \), \( M_3 = N_3 s^4 + N_4 s^5 + N_5 s^6 + N_6 s^7 + N_7 s^8 \), \( M_4 = N_5 s^6 + N_6 s^7 + N_7 s^8 \), \( M_5 = N_7 s^9 \).

The system simulation parameters are given in Table III, and the local load is resistive-inductive \( Z_L = 24 \Omega \text{ and } L = 36 \text{ mH} \). The amplitude attenuation and phase lag characteristic of 1\textsuperscript{st} inverter \( (t = 1) \) output voltage are shown in Fig. 15.

![Fig. 15. Bode diagrams of the gain \( G_{o1}(s) \) of single inverter output voltage.](image)

In a clear contrast to the traditional L-type inverter, the RC-type inverter can provide fast dynamic reactive power. When inductive load is connected to be supplied by the parallel system, the RC-type inverter has the ability to improve the dynamic response time of capacitive reactive power. The response time of RC-type inverter reduces 5 ms than L-type inverter, and to reduce the circulating current, which also improves the accuracy of power sharing.

![Fig. 16. Simulation results of output voltage and circulating current under different parallel system with inductive loads. (a) L-type inverter. (b) RC-type inverter.](image)

V. SIMULATION AND EXPERIMENTAL RESULTS

In this Section, the proposed power sharing method is verified via simulations and experimental results.

A. Simulation results

A simulation model of two parallel inverters is built by using Psim6.0 software. The rated power of the two inverters is 2.2kVA for both and the same switching frequency fixed at 19.2 kHz. The filter parameters and line impedances were intentionally different, and the specific system parameters are shown in Table III. In the simulations, the first inverter runs independently at \( t = 0s \). At \( t = 0.05s \), the second inverter is connected to system. And at \( t = 0.15s \), the first one shuts down, while the second one keeps running. The local loads are resistive-inductive with its initial impedance \( Z_L = 24 + j11.35 \Omega \), also its apparent power of 1.8kVA, and inductive-reactive power of 760Var. Comparative simulation waveforms between two L-type parallel inverters and two RC-type parallel inverters are depicted in Figs. 16 and 17 respectively.

<table>
<thead>
<tr>
<th>Table III System parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>( k_r )</td>
</tr>
<tr>
<td>( E )</td>
</tr>
<tr>
<td>( \omega_0 )</td>
</tr>
<tr>
<td>( m )</td>
</tr>
<tr>
<td>( n )</td>
</tr>
</tbody>
</table>

![Table III System parameters](image)
inverter, the virtual resistance component increases the
current resonance in low-system with
Fig. 19(a), (b), and (c) respectively. Obviously, parallel inverters operating to supply inductive loads current and power under different parallel system with inductive loads changing. (a) L-type inverter. (b) RC-type inverter.

With the same simulation process, inductive reactive power of the resistive-inductive loads suddenly increased 90%. As shown in Fig. 18(a), there has a transient overshoot and oscillation with gradually recovering in L-type inverters parallel system. On the contrary, Fig. 18(b) shows that RC-type inverters can provide more quickly and stably the reactive power to the local loads, and the recovering time is much shorter.

Fig. 18. Simulation results of loads current and power under different parallel system with inductive loads changing. (a) L-type inverter. (b) RC-type inverter.

Simulation waveforms of L-type, C-type, and RC-type parallel inverters operating to supply nonlinear rectifier loads are depicted in Fig. 19(a), (b), and (c) respectively. Obviously, parallel system consisting L-type or C-type inverters occurs series resonance in low-frequency range, and its circulating current is large. In the parallel system consisting of RC-type inverter, the virtual resistance component increases the damping of the parallel system to attenuate the resonance between the equivalent inverter output impedance and line impedance at the high-order harmonic frequency bandwidth, which is caused by pure capacitive output impedance of C-type inverter. The virtual resistance component has the ability to effectively attenuate the harmonic circulating current and to realize the harmonic power sharing.

Fig. 19. Simulation results of the different type parallel inverters with nonlinear rectifier loads. (a) L-type inverter. (b) C-type inverter. (c) RC-type inverter.

To verify the influence of virtual impedance capacitive component $C_v$ on the circulating currents, we firstly set $R_d = 0$, and the amplitude of 17th harmonic voltage is about 1V. Simulation waveforms of $i_{ph}, i_{o1}, $ and $i_{o2}$ with the different parameter $C_v$ in two parallel inverters system are depicted in Fig. 20, where the value of $C_v$ are selected 310µF, 430µF, and 1800µF respectively. As shown from Fig. 20, the circulating current of parallel inverters $i_{ph}$ is close to the peak value when $C_v = 310µF$, and $C_v = 1800µF$ is a proper value. To verify the influence of virtual resistive component $R_d$ on the fundamental and harmonic circulating currents, we set $C_v = 1800µF$. Simulation waveforms of $i_{ph}, i_{o1}, $ and $i_{o2}$ with the different parameter $R_d$ in two parallel inverters system are depicted in Fig. 21, where the value of $R_d$ are selected 0.1Ω, 0.8Ω, and 1.2Ω respectively. Obviously, with $R_d$ increasing, the fundamental and harmonic circulating currents greatly decrease, and resonance is suppressed significantly at a low-frequency bandwidth.
two inverters rated power at 2.2kVA is built including full-bridge inverter, local loads, DSP control system, and etc. Note that the experimental parameters are same as the simulation parameters shown in Tables II and III. For the experimental results, the hardware configuration is shown in Table IV. The digital high-speed oscilloscope DPO3032 is used to measure the voltage and current, etc. The initial local loads are resistive-inductive with an apparent power of 1.8kVA, inductive-reactive power 760Var.

![Parallel system with two single-phase inverters.](image)

**TABLE IV Hardware Configuration**

<table>
<thead>
<tr>
<th>Devices Name</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intelligent power module (IPM)</td>
<td>PM50BSLA060</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>TMS320F2812</td>
</tr>
<tr>
<td>A/D converter chip</td>
<td>AD88556</td>
</tr>
<tr>
<td>AC voltage sensor</td>
<td>KD3518</td>
</tr>
<tr>
<td>Hall Current sensor</td>
<td>LA25-NP</td>
</tr>
<tr>
<td>DC storage capacitor</td>
<td>1000uF/450V</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>19.2 kHz</td>
</tr>
<tr>
<td>Dead time</td>
<td>2.0 μs</td>
</tr>
</tbody>
</table>

The comparative testing results of L-type parallel system and RC-type parallel system are depicted in Fig. 23(a) and (b) respectively when the first inverter shuts down suddenly, and the second inverter is connected to parallel system. Compared with the L-type inverter and R-type inverter, the RC-type inverter can provide fast dynamic reactive power for the local resistive-inductive loads to support the PCC voltage quickly.

![Comparative results of output currents and reactive powers under the different type inverters parallel system with 2nd inverter connected.](image)

**B. Experimental results**

As shown in Fig. 22, the prototype of a parallel system of

![Fig. 21. Simulation results of output inverter currents and circulating currents of parallel system with \( R_D \) changing (\( C_V = 1800μF \)). (a) \( R_D = 0.1Ω \). (b) \( R_D = 0.8Ω \). (c) \( R_D = 1.4Ω \).](image)
local loads changes suddenly including the inductive reactive power increased to twice and inductive reactive power reduced to a half. As shown in Fig. 24(a), L-type inverters parallel system has a transient overshoot and oscillation. On the contrary, Fig. 24(b) shows that RC-type inverters can provide reactive power more quickly and stably to the local loads, and support the PCC voltage stability.

Fig. 24. Comparative results of inverters reactive powers under the different type inverters parallel system with loads inductive reactive power changing suddenly. (a) L-type inverters parallel system. (b) RC-type inverters parallel system.

The comparative results of PCC voltage in the different parallel system are depicted in Fig. 25(a) and (b) respectively. With the same testing process, the loads inductive reactive power increase 20%. As shown in Fig. 25(a), the voltage of PCC has an obvious transient from voltage sag to gradually recovering (in one fundamental frequency cycle) in L-type inverters parallel system using conventional droop control. On the contrary, Fig. 25(b) shows that by using RC-type inverters, the voltage of PCC is more stable and the recovering time is much shorter than L-type inverters during the transient of voltage sags.

Fig. 25. Comparative results of the PCC voltages under the different type inverters parallel system. (a) L-type inverters system. (b) RC-type inverters system.

To verify the influence of virtual impedance capacitive component \( C_V \) and resistive component \( R_D \) on the circulating currents, Comparative results of the currents \( i_{o1} \), \( i_{o2} \), and \( i_{o} \) with the different parameters \( C_V \) and \( R_D \) in two parallel inverters system are depicted in Fig. 26. Obviously, the fundamental and harmonic circulating currents greatly decrease, and the resonance is suppressed significantly at a low-frequency bandwidth with \( R_D = 0.8 \), \( C_V = 1800 \mu F \).

Fig. 26. Comparative results of the output inverter currents and circuiting currents under the different control parameters in the RC-type inverters parallel system. (a) \( R_D = 0 \), \( C_V = 430 \mu F \). (b) \( R_D = 0 \), \( C_V = 1800 \mu F \). (c) \( R_D = 0.8 \), \( C_V = 1800 \mu F \).

Comparative results of circulating currents of the different parallel system are depicted in Fig. 27, where the THDs of PCC voltage is both 3.5%. Obviously, the harmonic voltage aggravates fundamental circulating current, and the output current appears distorted. Compared to the L-type inverter, the RC-type inverter effectively attenuates the fundamental and harmonic circulating currents by adding virtual complex impedance. In the steady-state, the RMS of circulating currents attenuates from 2.8A of L-type inverters to 0.99A of RC-type inverters. This means that the decreasing amplitude of circulating current is about 65%.

Fig. 27. Comparative results of circulating currents of different parallel inverters under the same background harmonic voltage. (a) L-type inverter. (b) RC-type inverter.

When the resistive-inductive loads suddenly reduce to a half, the experimental waveforms of the 1st and 2nd inverters’ output currents are depicted for C-type inverter and RC-type inverter in Fig. 28. In case of C-type inverter, the two inverters’ currents apparently contain a lot of ripples due to high-frequency quasi-resonance, which is significantly increased after the transient. On the contrary, for RC-type inverter, the virtual impedance component \( R_D \) can damp resonance and reduce the circulating current between RC-type inverter, and the high-frequency ripple is drastically decreased.
The comparative results of C-type and RC-type parallel inverters with nonlinear rectifier loads are depicted in Figs. 29(a) and (b) respectively. Obviously, parallel system consisting C-type inverters occurs series resonance in low-frequency range, and its circulating current is large. In the parallel system consisting of RC-type inverter, the virtual resistance component increases the damping of the parallel system to attenuate the resonance between the equivalent inverter output impedance and line impedance at the high-order harmonic frequency bandwidth, which is caused by pure capacitive output impedance of C-type inverter.

VI. CONCLUSIONS

The paper proposes an inverter using resistive-capacitive output impedance (RC-type inverter) and its power sharing method, which has the ability to provide fast reactive power to support the PCC voltage, reduce the circulating current, and damp high-frequency resonances among inverters. The multi-loop control method of power sharing in RC-type inverter includes the outer power droop loop, virtual impedance loop, and inner voltage loop. Introducing the RC virtual impedance loop, the inverter provides fast transient response. Based on the RC-type inverter modeling, the comparative frequency-domain analysis of equivalent output impedances are discussed, and the impact of the virtual complex impedance over the circulating currents and high-frequency resonances among parallel inverters are quantitatively analyzed. The control parameters are systematically selected, and effect of virtual complex impedance on the inverter output voltage is depicted. The RC-type inverter can reduce circulating currents and damp resonances due to different equivalent output impedances of inverter and line impedances. Simulation and experimental results verify the validity and effectiveness of proposed method.

REFERENCES

Yandong Chen (S’13–M’14) was born in Hunan, China, in 1979. He received the B.S. and M.S. degrees in instrument science and technology from Hunan University, Changsha, China, in 2003 and 2006, respectively, and the Ph.D. degree in electrical engineering from Hunan University, Changsha, China, in 2014. He has been an Assistant Professor with the National Electric Power Conversion and Control Engineering Technology Research Center, Hunan University, Changsha. His research interests include power electronics for microgrid, distributed generation, power quality, and energy storage. Dr. Chen is a recipient of the 2014 National Technological Invention Awards of China, and the 2014 WOPO-SIPO Award for Chinese Outstanding Patented Invention. He is a member of IEEE Power Electronics Society.

Josep M. Guerrero (S’01–M’04–SM’08–FM’15) received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, in 1997, 2000 and 2003, respectively. Since 2011, he has been a Full Professor with the Department of Energy Technology, Aalborg University, Denmark, where he is responsible for the Microgrid Research Program. From 2012 he is a guest Professor at the Chinese Academy of Science and the Nanjing University of Aeronautics and Astronautics; from 2014 he is chair Professor in Shandong University; and from 2015 he is a distinguished guest Professor in Hunan University. His research interests is oriented to different microgrid aspects, including power electronics, distributed energy-storage systems, hierarchical and cooperative control, energy management systems, and optimization of microgrids and islanded microgrids. Prof. Guerrero is an Associate Editor for the IEEE TRANSACTIONS ON POWER ELECTRONICS, the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, and the IEEE Industrial Electronics Magazine, and an Editor for the IEEE TRANSACTIONS ON SMART GRID and IEEE TRANSACTIONS ON ENERGY CONVERSION. He has been Guest Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS Special Issues: Power Electronics for Wind Energy Conversion and Power Electronics for Microgrids; the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS Special Sections: Uninterruptible Power Supplies systems, Renewable Energy Systems, Distributed Generation and Microgrids, and Industrial Applications and Implementation Issues of the Kalman Filter; and the IEEE TRANSACTIONS ON SMART GRID Special Issue on Smart DC Distribution Systems. He was the chair of the Renewable Energy Systems Technical Committee of the IEEE Industrial Electronics Society. In 2014 and 2015 he was awarded by Thomson Reuters as Highly Cited Researcher, and in 2015 he was elevated as IEEE Fellow for his contributions on “distributed power systems and microgrids.”
Dr. Shuai is a recipient of the 2010 National Scientific and Technological Awards of China, the 2012 Hunan Technological Invention Awards of China, the 2007 Scientific and Technological Awards from the National Mechanical Industry Association of China.

Zhiyong Chen was born in Hunan, China, in 1985. He received the B.S. degree in automation from Xiangtan University, Xiangtan, China, in 2007, and received the M.S. degree in power electronics and power drives in 2010. He is currently pursuing the Ph.D. degree in electrical engineering at Hunan University, Changsha, China. From 2010 to 2012, he was employed as an electrical and market manager in XEMC New Energy Co., Ltd., Xiangtan. His research interests include power electronics of microgrid, distributed generation.

Leming Zhou was born in Hunan, China, in 1989. He received the B.S. degree in electrical engineering from Hunan University, Changsha, China, in 2011. He is currently pursuing the Ph.D. degree in electrical engineering at Hunan University, Changsha, China. His research interests include power electronics for microgrid, distributed generation and power quality.

An Luo (SM’09) was born in Changsha, China, in 1957. He received the B.S. and M.S. degrees in industrial automation from Hunan University, Changsha, in 1982 and 1986, respectively, and the Ph.D. degree in fluid power transmission and control from Zhejiang University, Hangzhou, China, in 1993. Between 1996 and 2002, he was a Professor with Central South University. Since 2003, he has been a Professor with the College of Electrical and Information Engineering, Hunan University. He has published over 300 articles. His research interests include distributed generation system, and power quality control. Prof. Luo is a senior member of IEEE Power Electronics Society.