A Grid Synchronization Method for Droop Controlled Distributed Energy Resources Converters

Chia-Tse Lee, IEEE Student Member, Rui-Pei Jiang, and Po-Tai Cheng, IEEE Senior Member

Abstract—The microgrid is a very effective way of integrating various distributed generation resources into the AC power system. To provide electric power of high reliability, the converters in the microgrid often rely on autonomous droop control methods to reduce their dependency on communication, and need to operate in both the islanded mode or the grid-connected mode. In this paper, a grid synchronization method for a multi-converter distributed generation system is proposed. The proposed grid synchronization method allows multiple droop-controlled converters to adjust the frequency, phase, and amplitude of their output voltages to prepare for grid connection. The entire synchronization process can be executed with very limited communication requirement. This paper provides detailed explanation on the proposed grid synchronization method. Experimental test results are presented to validate the effectiveness of the proposed method.

Index Terms—Distributed generation systems, droop control, grid synchronization, Microgrid.

I. INTRODUCTION

In the pursuit of low carbon emissions, renewable energy resources, such as solar power, and wind power, have been widely adopted in recent years. Other alternative energy resources have also become significant research topics. Considering their generation scale and characteristics, the most effective way to utilize these alternative resources is to integrate them into a distributed generation system (DGS). The microgrid, for example, has demonstrated this concept very successfully [1], [2], [3].

The control of distributed energy resources converters (DERCs) in DGS have been explored over the years. The main approaches include the master-slave control [4], [5] and autonomous droop control [6], [7], [8], [9], [10]. In the master-slave framework, one converter in the DGS is assigned to be the master, and it operates as a voltage stiff while the other converters in this system are controlled as current sources. This master converter acts as a virtual inertia [2], and will pick up most dynamic power flows within the DGS. Therefore, this master converter must be sufficiently large in its power capacity and sufficiently fast in its control bandwidth in order to absorb all the transients in this system. A sophisticated communication network is also required to coordinate the operations of all converters. On the other hand, the droop control method allows multiple DERCs to proportionally share the transient and steady state power flow without any communication. This is a significant advantage in terms of system reliability.

Traditionally, the real power-frequency droop \( P - \omega \) control and the reactive power-voltage droop \( Q - V \) control are generally adopted in the droop controlled DGS [6], [7], [8]. The \( P - \omega \) droop control can achieve accurate real power sharing results. However, the \( Q - V \) droop control is highly dependent on the line impedances seen from the converters [9], [10]. Therefore, the \( Q - V \) droop control method has been proposed to overcome the impedance mismatch among converters and achieve better proportional sharing of reactive power [11].

To ensure the uninterrupted operation of its critical loads, the microgrid must be capable of operating in both the grid-connected mode and the islanded mode, and offer a smooth transition between these two modes. Thus the grid synchronization, which prepares islanded microgrid for grid connection, is a critical procedure of the entire operation. The grid synchronization method has been elaborately discussed for single grid-connected converter [5], [12], [13], [14]. However, it is not often explored for multi-converter oriented systems or droop controlled DGS. Droop controllers are adopted in [15], [16] during their islanded operation. However, during the grid synchronization, the droop controllers are restrained and the power flow of converters are altered from their droop control operating point in order to accommodate their synchronization design.

This paper proposes a grid synchronization method based on the frequency restoration and voltage restoration mechanism of the \( P - \omega \) and \( Q - V \) droop controls [11]. The frequency, the phase angle, and the magnitude of DERCs’ output voltages are smoothly adjusted so that the proportional sharing of active power and reactive power among DERCs, an important feature of the droop controls, are not disturbed. To maintain the autonomous nature of the droop controls, a low bandwidth communication is required only during the synchronization process. A similar synchronization design had been presented in [17] for a \( P - \omega, Q - V \) droop controlled microgrid. A center-controlled frequency and voltage restoration mechanism is required for its grid synchronization and for its islanded mode operation, thus its dependency on the communication increases. Test results are provided to illustrate the operation of the proposed grid synchronization method under low bandwidth communication.
II. CONTROLS OF DERCs

DERCs are installed in the DGS as illustrated in Fig. 1. \( R_1 + jX_1 \), \( R_2 + jX_2 \), and etc. represents the line impedances, which may vary from one to the other due to the physical distances. The bypass switch between the DGS and the utility grid may close or open depending on whether the DGS operates in the grid-connected mode or the islanded mode. The main controller detects the point-of-common-coupling (PCC) voltage of the DGS and the grid voltage and pass the information to the central console. The central console collects information from the main controller and other sources, and determines whether the DGS should operate in the grid-connected mode or in the islanded mode. Assuming the DGS is in the islanded mode, and central console decides that the system should move towards the grid-connected mode, then the central console will broadcast required information via a low bandwidth communication interface to all the autonomous controllers embedded in DERCs and commence the grid synchronization process. Details of the autonomous controller, the main controller, the center console, and their interactions are explained as follows.

A. Main controller

Fig. 2 shows the detailed control block diagram of the main controller. The main controller senses the utility grid voltages \( v_{G,abc} \) and the DGS PCC voltages \( v_{PCC,abc} \), and then calculate the utility grid frequency \( \omega_G \), the phase angle difference \( \theta_{diff} \), and the voltage magnitude difference \( V_{diff} \) between \( v_{G,abc} \) and \( v_{PCC,abc} \).

A conventional phase-locked loop (PLL) design [18] is applied to track the frequency \( \omega_G \), and the phase angle \( \theta_G \) of the utility grid voltage \( v_{G,abc} \), and \( \omega_{PCC} \) and \( \theta_{PCC} \) of the DGS PCC voltage \( v_{PCC,abc} \) respectively. Since the PLL uses synchronous reference frame (SRF) transformation as part of its computation, the SRF component \( v_{G,qd} \) and \( v_{PCC,qd} \) are readily available. Therefore \( \theta_{diff} \) and \( V_{diff} \) can be calculated as follows:

\[
\theta_{diff} = \theta_G - \theta_{PCC}
\]

\[
V_{diff} = \sqrt{v_{Gq}^2 + v_{Gd}^2} - \sqrt{v_{PCCq}^2 + v_{PCCd}^2}
\]

The information of phase angle difference (\( \theta_{diff} \)) can be detected by subtracting the phase angle \( \theta_{PCC} \) from the phase angle \( \theta_G \).

The synchronous reference frame PLL (SRF-PLL) is a very conventional PLL structure [18], [19], [20], and its operation under grid voltage harmonics and unbalance has been discussed in [19]. Therefore, in the proposed grid synchronization application, this PLL is adequate to deal with the steady-state grid disturbances. If severe disturbances, such as ground faults and phase jumps, occur in the utility grid or in the microgrid, then such situation may not be suitable for our microgrid to re-connect with the utility. The resulting distorted output of the PLL can be used as an alarm of such severe event to override the grid synchronization process.

B. Autonomous controller

The detailed control block diagram of DERC’s autonomous controller is given in Fig. 3. The autonomous controller consists of the voltage and current controller, the droop controller, and the grid synchronization controller. The voltage and current controller can track the voltage references produced by the droop controller, and it contains the outer-loop voltage PI controller and the inner-loop predictive current controller [21]. The droop controller is composed of \( P - \omega \) droop control and \( Q - \dot{V} \) droop control [11]. The \( P - \omega \) droop is expressed as

\[
\omega_x = \omega_0 x - m_x \cdot (P_{0x} - P_x)
\]

where \( m_x \) is the \( P - \omega \) droop coefficients, \( \omega_0x \) is the nominal frequency and \( P_{0x} \) is the real power set-point. \( \omega_x \) and \( P_x \) are the actual operating frequency and output real power of DERCx. To achieve the proportional real power sharing, the \( P - \omega \) droop coefficients in DERCs are set as

\[
m_1 \cdot P_{R1} = m_2 \cdot P_{R2} = \cdots = m_x \cdot P_{Rx}
\]
where $P_{Rx}$ is the rated real power capacity.

The $Q - V$ droop is expressed as

$$
V_x = V_{0x} - n_x \cdot (Q_{0x} - Q_x)
$$

$$
V_x = V_{0x} + \int \dot{V}_x \, dt
$$

where $n_x$ is the $Q - V$ droop coefficients, $V_{0x}$ and $V_{0x}$ are nominal $V$ and nominal voltage magnitude, $Q_{0x}$ is the reactive power set-point. $V_x$, $V_x$, and $Q_x$ are the actual voltage magnitude derivatives, actual voltage magnitude, and reactive power output respectively of DERCx. To accomplish the proportional reactive power sharing, the $Q - V$ droop coefficients in DERCs are set as

$$
n_1 \cdot Q_{R1} = n_2 \cdot Q_{R2} = \cdots = n_x \cdot Q_{Rx}
$$

where $Q_{Rx}$ is the rated reactive power capacity.

This paper is to address the grid synchronization issue for this multi-converter oriented and $P-\omega$, $Q-V$ droop controlled DGS, thus the grid synchronization control is implemented in the autonomous controller. The proposed grid synchronization method regulates $P_{Rx}$ and $Q_{Rx}$ of $P-\omega$ and $Q-V$ droop controller to achieve the operation of grid synchronization. The details about grid synchronization operation will be explained in the following section.

C. Central console

To minimize the transients at the instant of grid connection, the frequencies, the phase angles, and the magnitudes of $v_{PCC}$ and $v_G$ are closely matched by the proposed grid synchronization method. The central console first commences the grid synchronization process through the operation mode control. Once the synchronization is confirmed by all autonomous controllers and the main controller, the central console can decide to go for grid connection by commanding the main controller to close the bypass switch. Fig. 4 shows the flow of operation mode control signals and the sequence of the grid synchronization process.

III. Grid Synchronization Method

This paper proposes a grid synchronization method based on the existing $P-\omega$ and $Q-V$ droop controls and their restoration controls for all DERCs in the DGS. The proposed grid synchronization method adjusts DERCs’ operation frequencies and phase angles through the frequency restoration of the $P-\omega$ droop control, and DERCs’ output voltage magnitudes through the $V$ restoration of $Q-V$ droop control. As a result, the grid synchronization is accomplished in an autonomous manner, and the proportional sharing of real power and the reactive power accomplished by the droop controls can be maintained with negligible transients in the process.

A. Frequency and phase synchronization based on $P-\omega$ droop controller

Fig. 5 shows the block diagram of frequency restoration mechanism of the $P-\omega$ droop control, and how it can be utilized for the frequency and phase synchronization. While in the islanded mode, the nominal frequency ($\omega_{0x}$) and the real power set-point ($P_{0x}$) are set at $2\pi \cdot 60 \, \text{rad/sec}$ and the rated real power capacity ($P_{Rx}$) respectively as illustrated by the droop line of islanded mode in Fig. 6. The loading within the DGS forces the $P-\omega$ droop control to move its operating frequency $\omega_x$ until DERCx handles its proportional share of real power output $P_x$. As the frequency restoration is commanded by the central console, ie. $FR = 1$, the $P-\omega$ droop control is re-defined as

$$
\omega_x = \omega_0 - m_0 (P_{x,FR=1} + \Delta P_{0x} - P_x)
$$

where $P_{x,FR=1}$ represents the real power output at the moment when frequency restoration is initiated, and $\Delta P_{0x}$ comes from the phase angle synchronization control block. As in Fig. 6, this new droop line immediately restores the operating frequency $\omega_x$ to the grid frequency $\omega_G$ while the DERCx produces the same real power $P_x = P_{x,FR=1}$. 

![Control block diagram of main controller.](image-url)
For the phase angle synchronization, the phase angle difference ($\theta_{\text{diff}}$) is processed by a proportional-integral (PI) regulator, and the output $\Delta P_{0x}$ shifts the $P - \omega$ droop line horizontally in a dynamic sense. As the loading within the DGS remains unchanged, this adjustment leads to the change of operating frequency $\omega_x$ and the phase angle of DERCx’s output voltage. Eventually this PI regulator settles into the steady state when $\theta_{\text{diff}}$ becomes zero, which means $v_{\text{PCC}}$ and $v_G$ are synchronized in both their frequencies and phase angles, and DERCx operates based on Equation (3) with $\Delta P_x = 0$.

In the proposed phase angle synchronization control, $\theta_{\text{diff}}$ is first multiplied by $P_{Rx}$ before being fed into the PI regulator for the reason that the adjustment of the real power setpoints should be in proportion to their converter’s real power capacities. This ensures that the same frequency change is introduced for all the DERCx while their individual droop lines are shifted. Therefore the relative phase angle differences among all the DERCs are kept unchanged, and the proportional real power sharing in the islanded mode can also be maintained during the frequency and phase synchronization operations. Please note that all DERCs must use the same $k_{p,Psyn}$ and $k_{i,Psyn}$ gains in their phase synchronization PI regulator in order to uphold the proportional real power sharing during the process.

**B. Voltage equalization based on the $Q - \dot{V}$ droop controller**

Fig. 7 shows the $\dot{V}$ restoration and the voltage magnitude equalization control. The $\dot{V}$ restoration is an inalienable part of $Q - \dot{V}$ droop control to maintain the voltage magnitude
while accomplishing the proportional reactive power sharing in the islanded operation. The \( \dot{V} \) restoration controller adjusts the reactive power set-point \( (Q_{0x}) \) by integrating \(-V_x\), so the \( Q-V \) droop control reaches its steady state at \( \dot{V} = 0 \) to maintain a constant output voltage magnitude after \( \dot{V} \) restoration as illustrated in Fig. 8. The voltage magnitude equalization is constructed on the top of this restoration mechanism. The voltage magnitude difference \( \Delta V \) is processed by an PI regulator, the resulting \( \Delta Q_{0x} \) then shifts the reactive power droop line in a dynamic sense. As the reactive power consumption within the DGS remains unchanged, this shift leads to certain nonzero \( V_x \) and drives the DERCx output voltage magnitude towards the magnitude equalization of \( V_{diff} = 0 \), which means \( \omega_{PCC} \) and \( v_G \) are synchronized in their voltage magnitudes.

\( Q_{Rx} \) is also added before the PI regulator to ensure the same \( \dot{V} \) change is introduced for all the DERCx while their individual droop lines are shifted. The relative voltage magnitude differences among all the DERCs are thus kept unchanged, and the proportional reactive power sharing in the islanded mode can be maintained during the voltage magnitude equalization operation. Please note that all DERCs use the same \( k_{p,Qres} \), \( k_{p,Qsyn} \), and \( k_{i,Qsyn} \) in their controller in order to uphold the proportional reactive power sharing during the process.

IV. SIMULATION RESULTS

The aforementioned grid synchronization method is tested with computer simulation. A DGS composed of two DERCs as shown in Fig. 1 is investigated, and their line impedances are set as the same, \( R_1 + jX_1 = R_2 + jX_2 = 1 + j0.754 \Omega \). The parameters used in the simulation are listed in TABLE I. Fig. 9 shows the simulation results of the proposed grid synchronization with DERCs of different power capacities.

The capacity of DERC2 is two times of DERC1. The key waveforms in the main controller are shown in Fig. 9(a), and waveforms in the autonomous controller are shown in Fig. 9(b) and Fig. 9(c).

Before \( t = t_1 = 30 \, \text{sec} \), the DERCs are operated in islanded mode. A step load change from 345 W + j200 VAR to 1000 W + j200 VAR is presented at \( t = 15 \, \text{sec} \). As shown in Fig. 9(b) and Fig. 9(c), the power sharing \( P_1 = 359 \, \text{W}, \) \( P_2 = 719 \, \text{W}, \) \( Q_1 = 88 \, \text{VAR}, \) \( Q_2 = 107 \, \text{VAR} \) is achieved by \( P - \omega \) and \( Q - V \) droop control. Because of the operation of the droop controls, the operating frequencies \( \omega_1 \) and \( \omega_2 \) and the operating voltage magnitudes \( V_1 \) and \( V_2 \) are deviated from the nominal frequency and voltage magnitude. This results in the variation of \( \theta_{diff} \) and \( V_{diff} \) shown as in Fig. 9(a) when the load is changed.

This frequency difference due to the operation of droop controls can be solved with the engagement of frequency restoration at \( t = t_1 = 30 \, \text{sec} \), which is activated by issuing \( FR = 1 \) from the central console. As the frequency restoration is accomplished, \( \omega_{PCC} \) is restored to be the same as \( \omega_G \), and \( \theta_{diff} \) in Fig. 9(a) no longer varies, and the power sharing is maintained at \( P_1 = 361 \, \text{W}, \) \( P_2 = 718 \, \text{W}, \) \( Q_1 = 88 \, \text{VAR}, \) \( Q_2 = 107 \, \text{VAR} \). The voltage magnitude equalization is initiated by the command \( (VS = 1) \) issued from central console at \( t = t_2 = 40 \, \text{sec} \). The DERCs start to raise their reactive power set-points \( Q_{01} \) and \( Q_{02} \) to derive the positive \( V_1 \) and \( V_2 \) as shown in Fig. 9(c). Thus the PCC voltage magnitude increases to equalize the grid voltage magnitude, and then \( V_{diff} \) in Fig. 9(a) is reduced to zero. The output power of DERCs \( P_1 = 382 \, \text{W}, \) \( P_2 = 759 \, \text{W}, \) \( Q_1 = 94 \, \text{VAR}, \) \( Q_2 = 114 \, \text{VAR} \) are increased because of the voltage magnitude equalization. At \( t = t_3 = 50 \, \text{sec} \), the central console begins the phase angle synchronization \( (PS = 1) \). The negative real power set-points \( P_{01} \) and \( P_{02} \) are generated by the negative \( \theta_{diff} \) at this moment, and then the operating frequencies \( \omega_1 \) and \( \omega_2 \) are slowed down to match the PCC voltage phase angle with the grid voltage phase angle. As the phase angle synchronization is completed, the power sharing is still maintained at the same level as in the islanded operation, where \( P_1 = 382 \, \text{W}, \) \( P_2 = 759 \, \text{W}, \) \( Q_1 = 92 \, \text{VAR}, \) \( Q_2 = 116 \, \text{VAR} \). At \( t = t_4 = 70 \, \text{sec} \), the DERCs goes into the grid-connected mode with some transients power flows. After the DERCs operate in the grid-connected mode for 20 seconds, the central console commands the DERCs to go back to the islanded mode operation again. The grid synchronization process shown in Fig. 9 verify that the operation of \( P - \omega \), \( Q - V \) droop controlled DGS can be transferred from islanded mode to grid-connected mode without affecting the original power sharing results by the proposed grid synchronization method.

The power sharing during \( t_1 \) and \( t_4 \) are not affected because the proposed grid synchronization method takes all the DERCs’ power capacities into account. Thus the regulation of \( P_{01}, P_{02}, Q_{01}, \) and \( Q_{02} \) shown in Fig. 9(b) and Fig. 9(c) are in proportion to their DERC’s power capacities, and then \( \omega_1, \omega_2, \) \( V_1, \) and \( V_2 \) are shifted with the same variation. As a result, the relative phase angle difference \( \theta_1 - \theta_2 \) and the relative voltage magnitude difference \( V_1 - V_2 \) between DERC1 and DERC2
are maintained, thus the original proportional power sharing accomplished by the droop controls are not affected.

V. EXPERIMENTAL TEST RESULTS

The DGS test bench shown in Fig. 10 is constructed to validate the effectiveness of the proposed grid synchronization control method. Two DERCs are installed in the testbench in the same configuration as in Fig. 1. The detailed descriptions of this DGS are stated as follows.

- The system voltage is $V_{L-L} = 220$ Vrms, and the frequency is 60 Hz. The power line impedances are $R_1 + jX_1 = 1+j0.754 \Omega$ and $R_2 + jX_2 = 1+j0.754 \Omega$. A total of 1000 W and 200 VAR are made up by resistor loads and an unloaded induction machine. The bypass switch is implemented by anti-parallel connected thyristors.

- The DERCs are three-phase, hard-switched PWM converters switching at $f_{\text{switch}} = 10$ kHz. The output filter inductor is $L_f = 2$ mH, and the output filter capacitor is $C_f = 10 \mu F$. The 400Vdc bus of the DERC is supported by a DC power supply.

- The main controller and the autonomous controllers are implemented with the digital signal processor TMS320F28335 individually, and the sampling frequency is programmed at $f_{\text{sample}} = 20$ kHz. The coefficients of main controller and autonomous controllers are given in Table I.

- The communication interfaces are implemented with RS-232 to transmit and receive data among the central console, main controller, and autonomous controllers. The bandwidth of these communication units are set at approximately 152 Hz.

Fig. 11 shows the experimental test results of the proposed grid synchronization method with two DERCs of the same power capacity. Waveforms of key variables of the main controller are shown in Fig. 11(a), and those of DERC1 and DERC2 are shown in Fig. 11(b) respectively. Before $t = t_0$, DERC1 supports all the load in the DGS while DERC2 is starting up. At $t = t_0$, DERC2 engages its droop control and operate in parallel with DERC1 in the islanded mode operation. Load changes are introduced by line-starting an induction motor and connecting a resistor load bank. $P_1 = 472$ W, $P_2 = 560$ W, $Q_1 = 107$ VAR, and $Q_2 = 90$ VAR shown in Fig. 11(b) indicates that both DERCs share the loading evenly. Their $P - \omega$ and $Q - \dot{\omega}$ droop controls respond to these load changes by adjusting their operating frequencies and output voltage magnitudes, thus $\dot{V}_{\text{diff}}$ and $\theta_{\text{diff}}$ in Fig. 11(a) exhibit certain variations when the inductive load and the resistive load are added.

At $t = t_1$, the central console issues the command of frequency restoration ($FR = 1$). The operating frequencies of DERC1 and DERC2 are immediately set to the grid frequency $\omega_G$. Now $v_{PCC}$ and $v_G$ have the same frequency, thus $\theta_{\text{diff}}$ no longer varies. At the instance of the starting of frequency restoration, the power sharing is affected by the sudden change of $P_{t1}$ and $P_{t2}$. However, the power sharing is still maintained at $P_1 = 422$ W, $P_2 = 600$ W, $Q_1 = 116$ VAR, and $Q_2 = 78$ VAR.

![Fig. 9](image_url) 
Fig. 9. The responses of main controller and DERCs during grid synchronization process with the DERCs of different power capacities.
At $t = t_2$, the central console initiates the voltage equalization ($V S = 1$). The positive $V_{diff}$ in Fig. 11(a) raises the reactive power set-points $Q_{01}$ and $Q_{02}$ in DERCI and DERCI2 respectively. This leads to positive $V_1$ and $V_2$ in their $Q - V$ droop controls so their output voltage magnitude increases, and then the PCC voltage magnitude rises to match the grid voltage magnitude and complete the voltage magnitude equalization. In the meantime, the output power of DERCI2s are increased as $P_1 = 452$ W, $P_2 = 640$ W, $Q_1 = 123$ VAR, and $Q_2 = 100$ VAR as a result of the raised voltage magnitude.

At $t = t_3$, the central console starts the phase angle synchronization ($PS = 1$). The real power set-points $P_{01}$ and $P_{02}$ of DERCI1 and DERCI2 increases as a result of the positive $\theta_{diff}$ at this moment. The operating frequencies of DERCI2s go up because of their $P - \omega$ droop controls, and the phase angle of $v_{PCC}$ gradually catches up with the phase angle of $v_G$ and reduce $\theta_{diff}$ to zero. As the grid synchronization completes, the power sharing of DERCI2s is maintained at $P_1 = 496$ W, $P_2 = 610$ W, $Q_1 = 121$ VAR, and $Q_2 = 95$ VAR.

At $t = t_4$, the central console confirms that the grid synchronization is accomplished, $v_{PCC}$ and $v_G$ are matched in their frequencies, phase angles, and magnitude. So the command of grid-connection is issued to the main controller. The bypass switch is closed and the DGS enters the grid connection mode smoothly with little transients. The system operates in the grid connection mode for nearly one minute. At $t = t_5$, the central console commands the DGS to go back into the isolated mode.

As shown in Fig. 11(b), the grid synchronization process between $t_1$ and $t_4$ does not affect the power sharing accomplished by the droop controls in the isolated operation. This outcome shows that the proposed grid synchronization method effectively preserve the relative phase angle difference and voltage magnitude difference between DERCI1 and DERCI2 while adjusting their operation frequencies and output voltage magnitudes.

Test results in Fig. 11(b) shows errors in the sharing of real power and reactive power. The finite resolution of the phase angle look up table ($2\pi \times 10^{-3}$ rad) with respect to the droop slope ($m_1, m_2$) can be one potential cause. The VAR consumption of the filter capacitor must be removed from the reactive power calculation before the $Q - V$ controller. However, it is estimated based on the capacitor name plate value, thus the reactive power calculation may have certain errors. The unbalance within the testbench, which comes from the filter inductors, filter capacitors, and the three-phase line chokes which emulate the power line impedance, may also contribute to the power sharing errors.

Note that DERCI2s’ real power output $P_1$, $P_2$, and reactive power output $Q_1$, $Q_2$ show certain deviations in the grid-connected mode as shown in Fig. 11(b). A power flow control [17] at PCC can be implemented in the central console to adjust the droop control set-points of autonomous controllers to mitigate such problems.

Fig. 12 compares the line-to-line voltages of the utility grid, PCC, DERCI1, and DERCI2 at various instances. After the frequency restoration is accomplished, $v_{G,ab}$ and $v_{PCC,ab}$ have the same frequency, and $v_{G,ab}$ leads ahead of $v_{PCC,ab}$ by $85.8^\circ$. The voltage magnitude difference between $|v_{G,ab}| = 212.6$ Vrms and $|v_{PCC,ab}| = 206.7$ Vrms is also obvious. After the voltage magnitude equalization is completed, The magnitude difference is effectively eliminated and these voltage magnitudes become $|v_{G,ab}| = 214.0$ Vrms and $|v_{PCC,ab}| = 215.0$ Vrms. By commencing the phase angle synchronization, the phase angle difference driven down

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**TABLE I**

| RELATED PARAMETERS OF MAIN CONTROLLER AND AUTONOMOUS CONTROLLERS IN THE SIMULATION AND THE EXPERIMENTAL TEST |

<table>
<thead>
<tr>
<th>Section IV</th>
<th>Section V</th>
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<tbody>
<tr>
<td>$P - \omega$ droop control</td>
<td>$m_1 = 2 \cdot m_2 = -18.85 \times 10^{-6}$ rad/Vsec $m_1 = m_2 = -18.85 \times 10^{-6}$ rad/Vsec</td>
</tr>
<tr>
<td>Rated real power capacity</td>
<td>$P_{R1} = P_{R2} = 2.0$ kW $P_{R1} = P_{R2} = 1.0$ kW</td>
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<tr>
<td>$Q = V$ droop control</td>
<td>$n_1 = 2 \cdot n_2 = -8.0 \times 10^{-3}$ V/VARsec $n_1 = n_2 = 2.0 \times 10^{-3}$ V/VARsec</td>
</tr>
<tr>
<td>Rated reactive power capacity</td>
<td>$2 \cdot Q_{R1} = Q_{R2} = 2.0$ kVAR $Q_{R1} = Q_{R2} = 1.0$ kVAR</td>
</tr>
<tr>
<td>V. restoration</td>
<td>$k_{P,PSYN} = 0.025$ V$^{-1}$</td>
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<tr>
<td>Phase angle synchronization</td>
<td>$k_{P,PSYN} = 20.0$ rad$^{-1}$, $k_{Q,PSYN} = 15.0$ rad$^{-1}$sec$^{-1}$</td>
</tr>
<tr>
<td>Voltage magnitude equalization</td>
<td>$k_{P,PSYN} = 1.0$ sec/V, $k_{Q,PSYN} = 1.0$ V$^{-1}$</td>
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<tr>
<td>Synchronous voltage PI controller</td>
<td>$k_{Vp} = 0.04$ A/V, $k_{Vv} = 6.0$ A/V/sec</td>
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<td>Predictive current controller</td>
<td>$k_{L2} = 30.0$ V/A</td>
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to zero. At this point, $v_{G,ab}$ and $v_{\text{PCC},ab}$ have the same frequency, the same phase angle, and the same magnitude, so their waveforms are closely matched. Finally the bypass switch is closed and the DGS becomes grid-connected.

The proposed method achieves the grid synchronization by transmitting the PCC information from the main controller to the central console, and then to the autonomous controllers through the RS-232 communication links. Fig. 13 shows the grid synchronization test results of the proposed method under slow communication with equivalent bandwidth of 91 Hz and 65 Hz. Test results show that the proposed method can accomplish the grid synchronization operation even with the low-bandwidth communication.

Fig. 11. Experimental test results of grid synchronization process as the rated power capacities of DERCs are the same.

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<thead>
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<th>2 DERCs are connected</th>
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<th>Bypass switch is closed</th>
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<tbody>
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<td>$t_0$</td>
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<td>$t_0$</td>
<td>$t_1$</td>
<td>$t_2$</td>
<td>$t_3$</td>
</tr>
</tbody>
</table>

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VI. CONCLUSION

The proposed method maintains the phase angles relationship and voltage magnitude relationship among DERCs during the synchronization process, therefore the proportional power sharing accomplished in the islanded operation mode can be maintained. Laboratory test results show the frequency, the phase angle and the magnitude of the PCC voltage are matched to those of the grid voltage without disturbing the real and reactive power output of DERCs, and then the DGS moves into the grid-connected mode smoothly. The proposed method is built upon the foundation of the $P - \omega$ and $Q - \dot{V}$ droop controls of the autonomous controller within each DERC. The central console only transmits the frequency, phase angle and voltage magnitude. Based on these information, the autonomous controller fine-tunes the droop control set-point, and manipulates the output voltage of its DERC. This architecture uphold the autonomous nature of the DGS by constraining the
role of the central console in the synchronization process. Thus the proposed method can operate with the very low bandwidth communication.

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**REFERENCES**


**Fig. 12.** The variations of line-to-line voltage of the utility grid, PCC, DERC1, and DERC2 during the grid synchronization process. ($V_{G,ab}$, $V_{PCC,ab}$, $V_{DERC1,ab}$, $V_{DERC2,ab}$) X-axis: 10ms/div, Y-axis: 200V/div.
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