Steady-State Stability Analysis of Synchronization Loops in Weak-Grid-Connected Microgrid

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Abstract. The Microgrid (MG) is a flexible system composed of paralleled inverters. When the MG runs in grid-connected mode, the first step is to synchronize with the grid stably. However, the weak grid may interact with the synchronization loops and result in instability issues, where the steady-state instability of the MG coming from the loss of equilibrium points remains to be studied. Concretely, the synchronization loop of each inverter determines the equilibrium point. While, when the paralleled inverters work together, interactions among synchronization loops complicate the steady-state analysis. To recognize the synchronization mechanism and steady-state stability of the MG, a kind of hybrid quasi-static models of synchronization loops in the MG is developed in this paper. Studies show that the stable grid-injected currents of current-controlled inverters (CCIs) in a MG are greatly increased, while the allowed grid-injected power of the voltage-controlled inverter (VCI) are decreased obviously and it is closely dependent on the operating currents of the CCIs. Therefore, it is essential to recognize the operating points of each inverter in a MG considering the steady-state stability. Finally, the simulations are carried out to verify the analysis.

Keywords. Microgrid; Steady-state stability; Synchronization loops; Hybrid quasi-static models

1. Introduction

The Microgrid (MG) is a local grid, whose power mostly comes from the renewable energy generation plants and the storage units[1]. Usually, the MG should be able to connect and disconnect with the grid flexibly to fully utilize its advantages, which are achieved by the interface inverters[2,3]. Commonly, the storage units are connected with the voltage-controlled inverters (VCIs) to provide voltage and frequency support of the standalone MG[4]; the renewable energy generation plants are linked with the current-controlled inverters (CCIs) to achieve the maximus power tracking[5]. When the MG works in grid-connected model, corresponding voltage and frequency of the MG are supported by the power grid, so both of the VCIs and CCIs track the grid synchronization signals to exchange power with the grid[6]. Therefore, the stable synchronization is the first step of the MG to gain connection with the power grid. While, interactions of the mixed synchronization loops and the grid challenge the synchronization stability of the MG, especially in weak grid[7].

With regards to the synchronization stability in weak grid, most attentions are paid on the phased locked loops (PLLs) applied in CCIs[8-10]. According to the existing researches, the PLL-related synchronization stability can be divided into three types: the small-signal stability, the transient stability and the steady-state stability[11,12]. It has been widely recognized from the impedance models that the
PLL functions as a negative resistance within its control bandwidth[8], and it is the negative resistance that can easily interact with the large grid impedance and triggers the small-signal stability[7]. As for the transient stability, it happens under large disturbances and grid fault situations[9,11], which can be attenuated by increasing the damping ratio of the PLL. In[9], the transient stability of the PLL was studied by means of the phase portrait approach, and it concluded that the first-order PLL could always guarantee the transient stability of CCIIs when equilibrium operation points existed. However, the accessible equilibrium points are the prerequisites to carry out the small-signal and transient stability. If the equilibrium points are lost, which means the generated power exceeds the power transfer capability of the synchronization loops, the steady-state instability could occur[2]. Ref.[10] firstly proposed a quasi-static model to analyze the steady-state stability of the PLL. Comparatively, corresponding researches on the steady-state stability are rare, especially for the VCI and paralleled inverters. The accessible currents or powers given to the synchronization loops remain to be studied.

Therefore, this paper takes the weak-grid-connected MG, composed of the PLL-based CCI and the virtual synchronous generator (VSG) based VCI, as the object to study the steady-state stability. Representatively, hybrid quasi-static models of synchronization loops in the MG are firstly developed to analyze the synchronization mechanism. Additionally, the steady-state analysis is studied by the quasi-static models, which reveals the factors that would lead to the loss of equilibrium points.

2. Hybrid Quasi-Static Models of the MG

2.1. System Introduction of the Studied MG

As the inverters in a MG are usually selected from the same manufacturer, they are equipped with the same parameters and power ratings as for one kind of the generation units. Thus, the studied MG in this paper is simplified as a PLL-based CCI working in parallel with a VSG-based VCI, whose grid-connected equivalent circuit is shown in Figure 1. Where the CCI is equivalent to a current source in parallel with its output impedance $Z_c$, the VCI is equivalent to a voltage source $v_e$ in series with its output impedance $Z_e$ and virtual impedance $Z_a$, the grid is represented by the Thévenin’s circuit consisting of the grid voltage $v_g$ and grid line impedance $Z_{g}$. Further, $i_c = I_c e^{j	heta_c}$, where $I_c$ and $\theta_c$ denote the amplitude and phase of grid-connected currents of the CCI, respectively; $v_e = E_v e^{j\theta_v}$, where $E_v$ is the output voltage amplitude of the reactive power control loop of the VSG, $\theta_v$ is the out phase of active power control loop of the VSG; $v_g = V_g e^{j\theta_v}$, where $V_g$ and $\theta_v$ represent the amplitude and phase of grid voltage, respectively. The CCI, VCI and the grid are connected at the point of common coupling (PCC), whose voltage is described as $v_p = V_p e^{j\theta_p}$, where $V_p$ and $\theta_p$ represent its amplitude and phase.

![Figure 1. Equivalent circuit model of the studied grid-connected MG.](image)

From Figure 1, $v_p$ can be calculated as:

$$v_p = \frac{\left[ Z_v(\omega_f) \right] Z_{i_c}(\alpha_f) v_g}{\left[ Z_v(\omega_f) + Z_{g}(\alpha_f) \right]} + \frac{\left[ Z_i(\alpha_f) \right] Z_{g}(\alpha_f) i_c}{\left[ Z_{g}(\alpha_f) + Z_{z}(\alpha_f) \right]}$$ (1)

where $Z_{z} = Z_{g} + Z_{r}$, denoting the total output impedance of the VCI. $\omega_c$ and $\omega_v$ represent the output angular frequency of the PLL and VSG, respectively. $\omega_f$ is the grid angular frequency. ‘||’ represents the parallel operation.

Assume the inner current control loop of the CCI and the inner cascaded voltage-current control loops of the VCI are designed to be able to track their reference signals well. Therefore, their dynamics can be neglected in the steady-state analysis and we can approximately derive that:

$$Z_z = \alpha_z; Z_c = 0$$ (2)
Substitute (2) into (1), \( v_p \) can be simplified as:

\[
v_p = \frac{Z_s(\omega_r) v_g}{Z_s(\omega_r) + Z_r(\omega_r)} + \frac{Z_s(\omega_e)c_e}{Z_s(\omega_r) + Z_r(\omega_r)}
\]

(3)

Define that:

\[
\begin{align*}
K_e e^{j\omega_r} &= \frac{Z_s(\omega_r)}{Z_s(\omega_r) + Z_r(\omega_r)}; K_c e^{j\omega_e} &= \frac{Z_s(\omega_e)}{Z_s(\omega_r) + Z_r(\omega_r)}
\end{align*}
\]

(4)

The PCC voltage \( v_p \) can be written as:

\[
v_p = K_e V_g e^{j(\theta_+\theta_p)} + K_c E e^{j(\theta_+\theta_p)} + K I e^{j(\theta_+\theta_p)}
\]

(5)

The grid synchronization of the CCI and the VSG is achieved by the PLL and the VSG, respectively. Both the PLL and VSG obtain the synchronization signals from the PCC voltage. According to the quasi-static model of the PLL of a single CCI proposed in [10], in the following, we will further develop the unified hybrid quasi-static models of the PLL and VSG by analysis of \( v_p \). At the same time, their synchronization mechanisms are analyzed.

2.2. The Hybrid Quasi-Static Model of the PLL

Based on the derived \( v_p \) in (5), the structure of the PLL in the studied MG can be modified as shown in Figure 2, where \( \omega_N \) is given angular frequency and it satisfies \( \omega_N=\omega_g \) in grid-connected mode; \( H_{PLL} \) represents the PLL controller. The \( q \)-axis voltage \( v_{gq} \) derived from the \( abc \)-to-\( dq \) transformation with \( \theta_c \) is the signal that flows into the PLL control loop. It can be clearly seen that the grid connection information of the VCI is introduced to the PLL via the PCC voltage. Based on the recognitions from the Figure 2, the hybrid quasi-static model of the PLL can be obtained as Figure 3. As presented in Figure 3, there exist three loops: ① the grid-synchronization loop; ② the PLL self-synchronization loop; ③ the interactive synchronization loop resulted from the paralleled VCI. The PLL achieves synchronization with the grid by adjusting its output phase \( \theta_c \) to make the error signal \( \Delta=v_{eq} \) to be zero. That means \( \theta_c=\theta_g \) and the CCI are running with unity power factor. In the ideal grid \( (Z_e=0) \), \( v_p=v_{eq} \), the PLL is not influenced by the self-synchronization loop and the interactive synchronization loop, it satisfies \( \theta_c=\theta_g \). While in the weak grid, each subsystem show close couplings via the grid impedance, which would influence the running range of grid-connected current \( I_e \).

2.3. The Hybrid Quasi-Static Model of the VSG

Firstly, it is assumed that the phase difference between \( e \) and \( v_p \) is \( \delta \), and the added virtual impedance is pure inductive to decouple the active power and reactive power better, which are written as \( \delta=\theta_+-\theta_c \) and \( Z=\omega_N L_e \). Then the average values of the instantaneous active and reactive powers at PCC can be expressed as[13]:

\[
\begin{align*}
P_e &= 1.5 \frac{E V_e \sin \delta}{\omega_e L_e}, \quad Q_e = 1.5 \frac{E V_e \cos \delta - V_p^2}{\omega_e L_e}
\end{align*}
\]

(6)
Considering the active power and reactive power is approximately decoupled, it can be concluded that $\delta_c$ and $E_r$ can be regulated separately by the active power and reactive power, respectively. That is to say, the VSG realizes the synchronization via the active power control. Here dynamics of the reactive power are neglected and we assume $E_r=V_r$. Refer to the PLL synchronization structure, we can develop the synchronization loop of the VSG as presented in Figure 4, where $J$ is the virtual inertia coefficient, $D_p$ is the damping coefficient, $P_N$ is the given active power. The $q$-axis voltage $v_{dq}$ derived from the $abc$-to-$dq$ transformation with $\theta_c$ is the signal that flows into the VSG active power control loop. Corresponding hybrid quasi-static model of the VSG is depicted as Figure 5. Similarly, the VSG also contains three synchronization loops: ① the grid-synchronization loop; ② the VSG self-synchronization loop; ③ the interactive synchronization loop resulted from the paralleled CCI. Differently, the VSG synchronizes with the grid by controlling its output phase $\theta_c$ to make the error signal $\Delta=\Delta F=P_N-P_c$ to be zero. Therefore, $v_{dq}$ is not zero and $\theta_c$ is not equal to $\theta_p$. That also verifies the VSG realizes the power transfer by the phase difference $\delta_c$. In the ideal grid $(Z_L=0)$, the VSG is not influenced by the self-synchronization loop and the interactive synchronization loop, it satisfies $1.5E_r \sin(\theta_c-\theta_p)/(\omega_s L_v)=P_N$. However, in the weak grid, the grid-connected currents $I_c$ of the CCI would influence the equilibrium point of the VSG.

3. Steady-State Stability Analysis of the MG
In the steady state, it is valid that $\omega_c=\omega_r=\omega_p=\omega_N$. Additionally, to fully utilize the inertia and damping features, the control bandwidth of the VSG is generally designed to be much smaller than that of the PLL. Therefore, we can make the reasonable assumption that control dynamics of the PLL and the VSG are decoupled. Based on this assumption, $\theta_c$ can be regarded as invariable in Figure 3 and $\theta_c$ is variable to the synchronization process of the VSG.

Parameters in (4) can be calculated as:

$$
K_g = \frac{\omega_c L_v}{\sqrt{\omega_N (L_v + L_c)^2 + R^2_g}} \quad \phi_g = \frac{\pi}{2} - \arctan \left( \frac{\omega_N (L_v + L_c)}{R_g} \right)
$$

$$
K_r = \frac{(\omega_c L_v)^2 + R^2_g}{\sqrt{\omega_N (L_r + L_e)^2 + R^2_g}} \quad \phi_r = \arctan \left( \frac{\omega_N L_v}{R_g} \right) - \arctan \left( \frac{\omega_N (L_v + L_c)}{R_g} \right)
$$

$$
K_e = \sqrt{\frac{(\omega_c L_v)^2 + (\omega_N L_e)^2}{\omega_N (L_v + L_e)^2 + R^2_e} + \frac{(\omega_c L_v)^2}{\omega_N (L_r + L_v)^2 + R^2_r}} \quad \phi_e = -\arctan \left( \frac{R_e}{\omega_N L_v} \right) - \arctan \left( \frac{\omega_N (L_r + L_v)}{R_g} \right)
$$

$$
\phi_c = \frac{\pi}{2} - \arctan \left( \frac{R_g}{\omega_N L_v} \right)
$$

Figure 4. The developed synchronization loop of the VSG in the studied MG.

Figure 5. The hybrid quasi-static model of the VSG in the studied MG.
Furthermore, we can derive that:

\[ K_v \sin(-\varphi_v) = \frac{\omega_0 L_v R_v}{\left[\omega_0 (L_r + L_g)\right]^2 + R_v^2} \left[ \omega_0 L_r \left( (\omega_0 L_g)^2 + R_v^2 \right) \right] \]

\[ K_v \sin \varphi_v = \frac{\omega_0 L_r R_v}{\left[\omega_0 (L_r + L_g)\right]^2 + R_v^2} \left[ \omega_0^2 L_r (L_r + L_g) + R_v^2 \right] \] \( (8) \)

In the weak grid, compared with the large grid inductance \( L_g \), the grid resistance \( R_v \) can be neglected, then the parameters in (4) are simplified as follows:

\[ K_e = \frac{L_r}{L_r + L_g}, \quad \varphi_e = 0 \]

\[ K_r = \frac{L_g}{L_r + L_g}, \quad \varphi_r = 0 \]

\[ K_r = \frac{\omega_0 L_r L_g}{L_r + L_g}, \quad \varphi_r = \frac{\pi}{2} \] \( (9) \)

3.1. The Steady-State Stability Analysis of the CCI

It can be drawn from Figure 3 that when the PLL reaches to the steady state, the following relationships can be deduced:

\[ I_v K_v \sin \varphi_v = -V_v K_v \sin(\theta_e + \varphi_e - \theta_r) \]

\[ -E_v K_v \sin(\theta_e + \varphi_e - \theta_r) \leq V_v K_v + E_v K_v \]

(10)

To ensure the equilibrium point and steady-state stability, the given active power current of the CCI should satisfy:

\[ I_v \leq \frac{K_v}{K_v} \leq \frac{K_v}{K_v} = I_v \]

(11)

When \( R_v = 0 \), (11) is written as (12), which demonstrates \( I_v \) could be reduced by the larger \( X_e \), the larger \( L_r \) and the grid voltage sag. Therefore, the weak grid is also bad for the steady-state stability.

\[ I_v \leq \frac{V_v}{X_e} + \frac{V_v}{\omega_0 L_r} = I_v \]

(12)

While, for the single grid-connected CCI, considering \( R_v \) or not, the limitation of the given active power current is [10]:

\[ I_v \leq \frac{V_v}{X_g} = I_v \]

(13)

Compare (12) with (13), it can be concluded that the paralleled VCI greatly improves the maximum value of the grid-connected currents of the CCI. That means the steady-state stability of the CCI can be enhanced by the paralleled VCI in a MG. Furthermore, define \( N_e = I_{v_{\text{max}}} / I_{v_{\text{max}}} \), the relationship of the \( N_e \) and \( Z_g \) is depicted in Figure 6, which shows that the increased grid resistance can decrease the maximum stable steady-state value of \( I_v \) in a MG.
Figure. 6. Plots of $N_c$ vs. $Z_g$

3.2. The Steady-State Stability Analysis of the VCI

For the VSG, because of its slow response speed compared with the PLL, it should withstand the worst effect of the CCI. Thus, the active power reference of the VCI should satisfy:

$$P_N = \left[ E_c K_v \sin(-\varphi_v) + V_g K_g \sin(\theta_v - \theta_g - \varphi_g) + I_c K_v \sin(\theta_v - \theta_g - \varphi_g) \right] \frac{1.5E_v}{\omega_N L_v} \leq \frac{1.5E_v}{\omega_N L_v} \left[ I_c K_v + E_c K_v \sin(-\varphi_v) - I_c K_v \right] = P_{N_{\text{max}}}. \quad (14)$$

When $R_g = 0$, (14) is written as (15). Based on the developed quasi-static model of the VSG, the given active power limitation of the single grid-connected VCI can be deduced as (16). By comparison of (15) and (16), we can draw the conclusion that the paralleled CCI would largely limit the maximum grid-injected active power of the VCI. Additionally, the adverse effect of the CCI would be enlarged with its increased grid-injected current. Therefore, the active power current reference of the CCI and the active power reference of the VCI must have a reasonable balance to ensure the steady-state stability of the MG.

$$P_N^i \leq \frac{1.5E_v (V_g - I_c X_g)}{\omega_N (L_v + L_g)} = P_{N_{\text{max}}}^i \quad (15)$$

$$P_N^o \leq \frac{1.5E_v V_g}{\omega_N (L_v + L_g)} = P_{N_{\text{max}}}^o \quad (16)$$

Furthermore, define $N_v = P_{N_{\text{max}}}/P_{N_{\text{max}}}^1$, the relationship of the $N_v$ and $Z_g$ is depicted as Figure 7, which shows that the suitable grid resistance is conductive to widen the range of the equilibrium point of the VCI in a MG.

Figure. 7. Plots of $N_v$ vs. $Z_g$

The above steady-state analysis indicates that when the CCI and VCI run together in a MG, their steady-state stability status could change compared to the single grid-connected inverter system. As for the CCI, its steady-state stability would be greatly enhanced via the VCI support; while, the steady-state stability of the VCI would be heavily deteriorated by the CCI, especially for a MG with the large
penetration of the CCI. Additionally, the weak grid with large inductance may result in steady-state instabilities both to the CCI and VCI.

4. Simulations Verification
To verify the above steady-state stability analysis, the studied MG is built in the Plecs. The MG is connected with a weak grid with \( V_g = 155 \text{V}, \omega_g = 314 \text{rad/s}, L_g = 14 \text{mH} \) or \( 20 \text{mH}, R_g = 0 \Omega \) or \( 1 \Omega \). Additionally, set \( L_c = 4 \text{mH} \), other parameters are shown in Table I. Four simulation cases are carried out: Case I, the CCI and VCI are separately connected to the grid with \( L_c = 14 \text{mH} \) and \( R_g = 0 \Omega \); Case II, the CCI and VCI are parallel connected to the grid with \( L_c = 14 \text{mH} \) and \( R_g = 0 \Omega \); Case III, the CCI and VCI are parallel connected to the grid with \( L_c = 14 \text{mH} \) and \( R_g = 1 \Omega \); Case IV, the CCI and VCI are parallel connected to the grid with \( L_c = 20 \text{mH} \) and \( R_g = 0 \Omega \).

| Parameters of the CCI | Values |
|-----------------------|--------|
| DC-Bus voltage: \( V_{dc}/\text{V} \) | 400 |
| LCL filter: \( L_1/\text{mH} \) | 2.8 |
| LCL filter: \( L_2/\text{mH} \) | 1.4 |
| LCL filter: \( C_1/\mu \text{F} \) | 9.4 |
| Damping resistance of the LCL filter: \( R_1/\Omega \) | 5 |
| PLL controller: \( H_{\text{pll}}(s) = K_p + K_i/s \) | \( H_{\text{pll}}(s) = 1 + 5/s \) |
| Current Controller: \( ri(s) = K_{pi} + K_{ri}s(s^2 + \omega_1^2)^{-1} \) | \( H_{ri}(s) = 10 + 5000s(s^2 + \omega_1^2)^{-1} \) |
| Given active current: \( I_a/\text{A} \) | variable |
| Given reactive current: \( I_d/\text{A} \) | 0 |
| J/kg*\text{m}^2 | 0.03 |
| \( D_\phi \) | 5 |
| Reactive power droop coefficient: \( K_q \) | 0.001 |
| Voltage Controller: \( r_v(s) = K_{pv} + K_{rv}s(s^2 + \omega_1^2)^{-1} \) | \( H_{rv}(s) = 0.5 + 1000s(s^2 + \omega_1^2)^{-1} \) |
| Current Controller: \( H_{rv}(s) = K_{pv} + K_{rv}s(s^2 + \omega_1^2)^{-1} \) | \( H_{rv}(s) = 8 + 1000s(s^2 + \omega_1^2)^{-1} \) |
| Given active power: \( P_N/\text{kW} \) | variable |
| Given reactive power: \( Q_N/\text{kvar} \) | 0 |

4.1. Case I
As for the single grid-connected CCI, according to (13), the maximum current reference \( I_{c_{max}} \) is calculated to be 35.4A. If the given current exceeds 35.4A, the steady-state instability would be triggered because of the loss of the equilibrium point. Figure 8 depicts the output voltage and current waveforms of the CCI equipped with different given current values. It shows the steady-state instability is aroused when \( I_c \) steps from 34A to 35A, which could verify the theoretical value.

If the VCI is connected to the grid alone, based on (16), we can derive that \( P_{N_{max}} = 6.4 \text{kW} \), which denotes the given active power of the VSG should be within 6.4kW to ensure the accessible equilibrium point. As presented in Figure 9, the steady-state instability exactly occurs when \( P_N = 6.5 \text{kW} \).
4.2. Case II

When the CCI and VCI works together in a grid-connected MG, it can be calculated from (12) that $I_{c1\text{max}}=159.2\text{A}$ regardless of the running power of the VCI. While, seen from (15) the maximum power transfer capability of the VCI is dependent on the running current of the CCI. If $I_c=20\text{A}$, $P_{V1\text{max}}=2.8\text{kW}$; if $I_c=40\text{A}$, $P_{V1\text{max}}<0\text{kW}$. Corresponding time-domain simulation results are shown in the following Figure 10 and Figure 11.

In Figure 10, the given active power of the VCI keeps constant as 2kW, the given current of the CCI is increased from 20A to 40A at 4s. It can be seen that when $I_c=20\text{A}$, $P_N=2\text{kW}<2.8\text{kW}$, both the CCI and VCI have stable outputs; while, when $I_c=40\text{A}$, $P_N=2\text{kW}>0\text{kW}$, the CCI can output stable currents, but the output power of the VCI is unstable and the PCC voltages also turn to be unstable because of the VCI.

In Figure 11, the given current of the CCI keeps constant as 20A, the given active power of the VCI is increased from 2kW to 3kW at about 3.27s. The simulation results also indicate that if the reference
signals of each inverter in a MG exceed the upper limit of the steady-state stability, the power transfer between the inverter and the grid would be failed.

4.3. Case III
If a resistance is introduced to the grid with \( R_e=1 \Omega \), based on (11) and (14), if \( I_e=20A \), corresponding upper limits of the CCI and VCI can be calculated as \( I_{\text{max}}=158.5A \) and \( P_{\text{Nmax}}=3.8kW \). As shown in Figure 12, when \( P_N \) is increased from 2kW to 3kW, the CCI and VCI can run stably. Only when \( P_N \) is further increased to 4kW, the VCI loses the equilibrium point and cannot ensure the steady-state instability. Compared with Figure 11, the steady-state instability of the 3kW-VCI is attenuated by the suitable grid resistance.

![Output waveforms of the CCI](image1)

![Output waveforms of the VCI](image2)

**Figure. 12.** Output simulation waveforms of the CCI and VCI in a MG when \( I_e \) keeps constant with 20A and \( P_N \) changes from 2kW to 3kW to 4kW

4.4. Case IV
If \( L_g \) is increased from 14mH to 20mH, it can be calculated from (12) that \( I_{\text{c max}}=148A \). Additionally, if \( I_e=20A \), \( P_{\text{N max}}=904.6W \) much smaller than 2.8kW in case II. Figure 13 depict the simulations results of the MG when \( I_e \) keeps constant with 20A and \( P_N \) varies from 500W to 800W to 1kW. It confirms the increased grid inductance requires the smaller \( P_N \) within 904.6kW to ensure the existence of the equilibrium points of the MG. Otherwise, the steady-state instability could be triggered as shown in Figure 13(b). Additionally, the PCC voltages are also unstable as seen from Figure 13(a).

**Figure. 13.** Output simulation waveforms of the CCI and VCI in a MG when \( I_e \) keeps constant with 20A and \( P_N \) changes from 2kW to 3kW to 4kW

5. Conclusions
In this paper, the steady-state stability related to the equilibrium points is studied based on a CCI- and VCI-based hybrid MG. Specially, the hybrid quasi-static models of synchronization loops of the MG are developed to analyze the synchronization mechanism and further steady-state stability. It can be concluded that the allowed running currents of the CCI can be greatly improved by the paralleled VCI, but the allowed power to be transferred by the VCI may be greatly decreased by the paralleled CCI. Comparatively, the VCI in a MG determines more on the system steady-state stability. Say concretely, the equilibrium point of the VCI is closely dependent on the running currents of the CCI, thus the given active power of the VCI should be reasonably considered according to the deduced limitation in this
paper. Moreover, the weak grid featuring with large grid inductance could deteriorate the steady-state stability of the MG. Researches in this paper not only contribute to understand the synchronization mechanisms, but also help to clearly recognize the equilibrium points in a grid-connected system with paralleled inverters to guarantee the steady-state stability.

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