Angle Droop Design for Grid-Forming Inverters Considering Impacts of Virtual Impedance Control

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Abstract—Grid-forming inverters (GFMs) based on active power-frequency droop control and reactive power-voltage control have been developed in recent years, which can generate voltage and frequency references for isolated power systems or microgrids to improve system-wide synchronization and power-sharing capability. It is known that the control delays in GFMs may cause system harmonic instability. To eliminate this issue, virtual impedance techniques are normally adopted. This paper gives a comprehensive examination of the impacts of virtual impedance control block in GFMs on system stability. It is revealed that although Zv is effective in eliminating system harmonic stability, it may ruin system synchronization stability as a side effect. To compensate for the negative impacts caused by Zv, an active power-angle control block is added into the conventional droop control. Design criteria are also proposed accordingly to ensure system stability over the entire frequency range. Simulations and experimental testing are conducted to validate the analysis and the proposed design guidelines. It can be concluded that the Zv control-caused grid-synchronization instability issues can be eliminated with an appropriate active power-angle droop design.

Keywords—Angle droop control, grid forming inverter, harmonic instability, synchronous stability, virtual impedance control

1. INTRODUCTION

Different types of voltage-controlled converters, which are termed as grid-forming inverters (GFMs), have been developed to generate system frequency and voltage autonomously, including droop control, virtual synchronous control, virtual oscillator control, etc. [1-4]. Among them, the most well-developed grid-forming approach is the droop control, which was first proposed in the 1990s [5]. It enables multiple GFMs to share and deliver desired active and reactive power into the system through local control in a stable manner. A typical droop control includes an active power-frequency (P-f) droop and a reactive power-voltage (Q-v) droop. The general circuit diagram of the conventional droop-control based GFM is shown in Fig. 1 [3, 4, 6]. The outer power loop is to provide a well-defined voltage reference with proper amplitude and phase. Additionally, the inner voltage-current control loops are designed to regulate the output voltage, provide damping for the LC resonance, and limit the converter overcurrent. These control blocks can be implemented in either aβ or dq frames. The controllers used in this paper are implemented in aβ frame.

To study the dynamic characteristics of droop-control based GFMs and their impacts on system stability, both impedance-based Nyquist stability criterion and passivity-based stability analysis approaches have been adopted in the literature [7-10]. Generally speaking, the impacts of droop-controlled GFMs on system stability can be roughly categorized into two types: grid-synchronization stability (in the low-frequency range near fundamental frequency) and harmonic stability (in the high-frequency range about several hundred Hz to several kHz). For the analysis of system synchronization stability, the Nyquist stability criterion with a full-order complex-value-based output impedance has been used [4, 8, 9]. It has been pointed out that GFMs tend to induce sub-synchronous oscillations (SSO) under stringent grid conditions because the smaller the grid impedance is, the larger damping will be needed, which means that the smaller the p-f gain m will be allowed. Hence, to ensure stable operation of systems in the low-frequency range, the droop gains (m and n) in the outer power loop should be designed according to the grid conditions. For the analysis of system harmonic instability issues, the passivity-based stability criterion with the inverter output impedance has been used to identify the root causes. And it has been found that converter control delays will cause a non-passive region in the output impedance at high frequencies, within which the negative damping will be introduced to the current control and destabilize the system. Accordingly, passivity-based control solutions have been proposed, such as adding both virtual impedance control function Zv and the voltage feedforward control function Hv to the inner voltage-current loop as shown in Fig. 2 [7, 10]. With these two blocks Zv and Hv, the inverter passivity can be guaranteed up to Nyquist frequency. Therefore, the system harmonic instability issues caused by converter control delays can be eliminated regardless of the strength of the grid impedance.

Fig. 1. Circuit diagrams of typical droop-control based GFMs.
However, it is found in this paper that the \( Z \) block, which is initially designed for harmonic stability enhancement, might bring sub-synchronous oscillations into the system. To have a better understanding of the \( Z \) impact on system stability, fundamental mechanisms of \( Z \) control blocks are analyzed first in Section II. Based on the analysis results, an active power-angle droop control block is added to the conventional droop control loop and the design guidelines are also proposed in Section III, to eliminate the negative impacts caused by \( Z \) on grid-synchronization stability and to keep the positive impacts on harmonic stability at the same time. Simulation and experimental results are presented in Section IV to validate the effectiveness of the proposed design criteria for the active power-angle droop gain. Section V concludes the paper.

II. IMPACTS OF Z \( _\text{s} \) CONTROL ON SYSTEM STABILITY

A. Positive Impacts of Z \( _\text{s} \) on System Harmonic Stability – A Review

Passivity-oriented design is an effective stability enhancement approach and such studies have also been applied for grid forming inverters (GFMs) as in [7, 10, 11]. First, to analyze the passivity of GFMs, the single-input-single-output (SISO) output impedance model \( Z_{\text{ov}}(s) \) needs to be derived. Equation (1) shows the output impedance model \( Z_{\text{ov}}(s) \), where \( Z_{\text{ol}} \) is the open-loop output impedance, \( G_{\text{sw}}, G_{\text{in}}, \) and \( G_{\text{v}} \) are the transfer functions from converter-side voltage to inductor current, converter-side voltage to output voltage, and grid-side current to inductor current separately, \( G_{\text{ref}} \) is the current controller, \( G_{\text{v}} \) is the voltage controller, and \( G_{\text{h}} \) is the system control delay which is typically 1.5 times of the converter switching period. Note that the SISO impedance model introduced here only intends for harmonic stability analysis, and low-frequency characteristics are ignored. For more details about the model derivation, one can refer to [10].

\[
Z_{\text{ov}}(s) = \frac{Z_{\text{ol}}(1 + G_{\text{sw}}G_{\text{in}}G_{\text{v}}) + G_{\text{sw}}G_{\text{in}}G_{\text{v}}G_{\text{h}}}{1 + G_{\text{sw}}G_{\text{in}}G_{\text{v}} + G_{\text{sw}}G_{\text{in}}G_{\text{v}}G_{\text{h}}}
\]  

(1)

The Bode diagram of the impedance model \( Z_{\text{ov}}(s) \) is obtained as shown in Fig. 3. From the plot, it is seen that there is a high-frequency non-passive region (HF-NPR), i.e., phase angle exceeds the range of \([-90^\circ, 90^\circ]\), which is identified to be caused by the converter control delays. In the HF-NPR, harmonics instability issues might happen when the grid side impedance is changed.

To eliminate this HF-NPR, a linear voltage controller with virtual impedance \( Z \) and voltage decouple control \( H \), can be added in the inner voltage-current loop. With the \( Z \) and \( H \) control blocks, the original output impedance \( Z_{\text{ov}}(s) \) is modified to be \( Z_{\text{ov,c}}(s) \) as given in (2).

\[
Z_{\text{ov,c}}(s) = \frac{Z_{\text{ol}}(1 + G_{\text{sw}}G_{\text{in}}G_{\text{v}}) + G_{\text{sw}}G_{\text{in}}G_{\text{v}}G_{\text{h}}}{1 + G_{\text{sw}}G_{\text{in}}G_{\text{v}} + G_{\text{sw}}G_{\text{in}}G_{\text{v}}G_{\text{h}} - H_{\text{c}}}
\]  

(2)

Similarly, the Bode diagram of \( Z_{\text{ov,c}}(s) \) is given in Fig. 3. It is seen that the HF-NPR below Nyquist frequency can be removed with the help of the \( Z \) and \( H \) compensation blocks.

![Fig. 3. Bode diagrams of GFMs w/o and w/ passivity compensation blocks (Z and H).](image)

Note that both \( Z \) and \( H \) need to be added to achieve the passivation of the GFMs up to the Nyquist frequency. If with \( H \) only, the system stability margin could be improved, but system harmonic instability issues cannot be solved thoroughly since the inverter still has some non-passive regions. Once the grid condition changes, harmonic instability might still happen. One can see more case studies later in Section II-B.

B. Negative Impacts of Z \( _\text{s} \) on Grid-Synchronization Stability

1) Simulation investigation

To see the negative impacts of \( Z \) block on system synchronization stability, a simulation testing platform is built in MATLAB/Simulink following the circuit structure as shown in Fig. 2 with the parameters listed in Table I.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Value</th>
<th>Variables</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage RMS value ( V_g )</td>
<td>190 V</td>
<td>Fundamental frequency ( f_\text{sc} )</td>
<td>60 Hz</td>
</tr>
<tr>
<td>GFM voltage RMS value ( V_{\text{s}} )</td>
<td>190 V</td>
<td>Switching frequency ( f_\text{sw} )</td>
<td>10 kHz</td>
</tr>
<tr>
<td>LC filter capacitance ( L, C )</td>
<td>2 mH, 10 ( \mu )F</td>
<td>Power references ( P_0, Q_0 )</td>
<td>2 kW, 0 Var</td>
</tr>
<tr>
<td>Grid impedance ( L_g )</td>
<td>8 mH / 6 mH / 4 mH / 2 mH</td>
<td>Short circuit ratio SCR</td>
<td>6 / 8 / 12 / 24</td>
</tr>
<tr>
<td>Control delay ( T_c )</td>
<td>1.5 ( f_\text{sc} )</td>
<td>Current control ( G_{\text{c}} )</td>
<td>8</td>
</tr>
<tr>
<td>Voltage control ( G_{\text{v}} )</td>
<td>( 50 + \frac{0.01}{s^2 + 7.5398s + 142122} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In these cases, the grid impedance \( L_g \) range from 8 mH to 2 mH (i.e., SCR from 6 to 24) to emulate weak grid and strong grid conditions. The \( p/f \) droop gain \( m \) and \( Q/v \) droop gain \( n \) are then designed respectively based on the grid conditions using Nyquist stability criterion with assuming the converter...
control delay is ideally small enough, i.e., $T_d = 0.5T_{sw}$. This guarantees that under ideal situations, there are no high-frequency (HF) harmonics and no low-frequency (LF) SSO. Then, a larger control delay ($1.5T_{sw}$), which is also a typical and practical value in most cases, is taken into considerations.

Simulations with different control structures (CI: w/o $Z_v$ and w/o $H_v$, CII: w/o $Z_v$ and w/ $H_v$, CIII: w/ $Z_v$ and w/ $H_v$) are investigated. For example, when SCR = 8, the frequency droop gain is designed as 2% $V_d/P_0$ and the voltage droop gain is 10% $V_d/P_0$ (for simplicity, only the ratio will be given in the following text), and the simulation results show that with CI, there will be high-frequency harmonic instability issues with the harmonics component to be around 1.5 kHz as shown in Fig. 4. If there is no $Z_v$, but $H_v$ is added, that is with CII, the system is stable as shown in Fig. 5. While with CIII, high-frequency harmonics can be eliminated, but low-frequency SSO (57.6 Hz and 62.4 Hz) will be introduced into the system as shown in Fig. 6.

![Fig. 4. Simulation results of harmonic instability issues with CI when SCR = 8 ($m = 2\%$ and $n = 10\%$): (a) simulation waveforms of phase voltage and (b) FFT analysis of phase voltage.](image)

More cases under different grid conditions are summarized in Table II, where HF Harmonics refer to the unstable phenomena similar to that in Fig. 4 and LF SSO refers to instabilities similar to that in Fig. 6.

<table>
<thead>
<tr>
<th>Grid Conditions</th>
<th>CI</th>
<th>CII</th>
<th>CIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCR = 6 $m = 2%$ &amp; $n = 10%$</td>
<td>Stable</td>
<td>Stable</td>
<td>Stable</td>
</tr>
<tr>
<td>SCR = 8 $m = 2%$ &amp; $n = 10%$</td>
<td>HF Harmonics</td>
<td>Stable</td>
<td>LF SSO</td>
</tr>
<tr>
<td>SCR = 12 $m = 0.5%$ &amp; $n = 2.5%$</td>
<td>HF Harmonics</td>
<td>Stable</td>
<td>LF SSO</td>
</tr>
<tr>
<td>SCR = 24 $m = 0.2%$ &amp; $n = 1%$</td>
<td>HF Harmonics</td>
<td>HF Harmonics</td>
<td>LF SSO</td>
</tr>
</tbody>
</table>

![Fig. 6. Simulation results of SSO issues with CII when SCR = 8 ($m = 2\%$ and $n = 10\%$): (a) simulation waveforms of phase voltage and (b) FFT analysis of phase voltage.](image)

Several findings could be summarized from Table II. First, it is seen that without the passivity compensation blocks (CI: w/o $Z_v$ and w/o $H_v$), the system will have high-frequency harmonic instability issues when SCR is large (SCR = 8, 12, and 24). Second, with $H_v$ only (CII), system stability can be improved (stable under SCR = 8 or 12), but it still has harmonic instability issues when SCR = 24. Third, with both $Z_v$ and $H_v$ compensation blocks (CIII), there will be no HF harmonic issues in the system; however, LF SSO will be introduced instead. Therefore, it can be concluded that the $Z_v$ compensation block can help with system high-frequency stability, but it may negatively impact system low-frequency resonance as well.

2) Theoretical analysis

To analyze the fundamental mechanism of $Z_v$ impacts on system synchronization stability, an equivalent virtual impedance $Z_{eq}$ is obtained first by moving the $Z_v$ block to the
input side of the voltage controller $G_v$ as shown in Fig. 7, which can be expressed as in (3) with an equivalent frequency-dependent virtual resistance $R_{veq}$ and a virtual reactance $X_{veq}$. The values of the equivalent virtual impedance in this study are calculated as shown in Fig. 8. It can be seen that the equivalent $R_{veq}$ is large enough ($R_{veq} >> X_{veq}$) in both LF and HF ranges to provide enough damping for the system, but near the fundamental frequency $f_{fund}$ (shaded area in Fig. 8), the $R_{veq}$ is almost 0 which means there is no resistive damping provided for the system in this frequency range.

$$Z_{veq}(\omega) = Z_v/G_v(j\omega) = R_{veq}(\omega) + jX_{veq}(\omega)$$

Fig. 7. Equivalent virtual impedance in the control diagrams.

Then, assuming the inner voltage-current loop to be 1 since LF SSO is under investigation, the system equates to a grid-connected voltage source with $Z_{eq}$ as shown in Fig. 9. This virtual impedance $Z_{eq}$ will reduce the output voltage reference proportionally to the output current as shown in (4). Accordingly, the power flow $S$ can be calculated as (5). Based on (4) and (5), the equations about magnitude and phase angle of the reference voltage $v_{ref}'$ and output voltage $v$ are obtained as (6) and (7) [12,13].

$$V_{ref}' = V_{ref} - Z_{veq}l_q$$

Fig. 9. Equivalent virtual impedance in the entire system.

$$S = P + jQ = vZ\delta (\frac{v_{ref}' - Z_{veq}l_q}{R_{veq} + jX_{veq}})$$

Fig. 10. Small-signal model of active power loop considering virtual impedance impact.

$$\Delta v = v_{ref}' - v = \frac{R_{veq}P + X_{veq}Q}{v}$$

$$\delta_v = \delta_{ref}' - \delta = \frac{X_{veq}P - R_{veq}Q}{v'_{ref}v}$$

Assume $v_{ref}'$ and $v$ are equal to $V_s$ for simplicity, which is true for most conditions since the voltage magnitude should be limited within a narrow range. Besides, it is seen from Fig. 8 that the calculated value of $R_{veq}$ is almost 0 around $f_{fund}$. Equations (8) and (9) can then be obtained. It is found that in the $P$-$f$ control loop, the virtual impedance control $Z$ adds an equivalent power-angle droop gain $m_o$ and in the $Q$-$v$ control loop, $Z_v$ adds an equivalent voltage droop gain $n_v$. The $Q$-$v$ loop dynamics expressed in (9) can be ignored as long as $n_v$ is larger than 0 since it has little impact on system stability [9,14]. While the $Z_v$-induced $m_o$ as expressed in (8) turns out to be the culprit for the LF SSO issues in the system as analyzed below.

$$\omega \approx \omega_0 - mp_{LPF} - m_\delta(f) \frac{dP}{dt}$$

$$V_o \approx V_{ref} - nQ_{LPF} - n_\delta(f)Q$$

where, $m_\delta(f) = \frac{x_{veq}(f)}{v_o}$ and $n_\delta(f) = \frac{x_{veq}(f)}{v_o}.$

First, small-signal stability analysis on the active power loop is conducted with the linearized model derived in (10) based on the equivalent circuit as shown in Fig. 10 [12,13], where the cut-off frequency of the low-pass filter $\omega_{LPF}$ is $2\pi$ rad/s. Based on the characteristics equation of (10), it can be concluded that the $Z_v$ block does not affect the small-signal stability of the system since all the eigenvalues locate in the left half-plane (LHP).

$$(1 + m_\delta G)s^2 + \omega_{LPF}(1 + m_\delta G)s + \omega_{LPF}mg$$

where, $G = \frac{G(s + \omega_{LPF})}{(1 + m_\delta G)s^2 + \omega_{LPF}(1 + m_\delta G)s + \omega_{LPF}mg}$

$\Delta P = \frac{G(s + \omega_{LPF})}{(1 + m_\delta G)s^2 + \omega_{LPF}(1 + m_\delta G)s + \omega_{LPF}mg}\Delta \omega$
from Fig. 8, $X_{\text{veq}}$ is a negative value below $f_{\text{fund}}$ which means $m_0$ will also be negative below $f_{\text{fund}}$. Though it is difficult to quantify the damping and inertia value and to draw the phase portrait for the analysis of system stability since $m_0$ is a variable frequency-dependent value, the negative impacts can still be observed from Fig. 11, where $H_0$ and $D_0$ are the original system inertia and damping without $Z_0$, and $H$ and $D$ are the ones considering $Z_0$ impacts. Hence, it can be inferred that the system stability will be affected since a system with less damping is more likely to have LF SSO issues as shown in Table II.

$$H = \frac{1 + m_0 P_{\max}}{\omega_{\text{LPF}} m}$$

$$D = \frac{1 + m_0 P_{\max}}{m}$$

$$P_{\max} = \frac{V_o^2}{X_g}$$

Fig. 11. Impacts of $Z_0$ on system inertia and damping constant.

Finally, it can be concluded that the virtual impedance control block, which is intended to eliminate the system harmonic instability issues, might reduce the system damping near $f_{\text{fund}}$ and cause LF SSO issues in the system. Note that although the analysis method introduced here is only valid near $f_{\text{fund}}$ (30 Hz to 100 Hz) since $R_{\text{veq}}$ can only be assumed to be 0 in this region, it is already good enough for the SSO stability analysis. In addition, in the LF or HF ranges, $R_{\text{veq}}$ is large enough to provide damping for the system and can help to maintain system stability.

III. DESIGN GUIDELINES FOR MODIFIED OUTER POWER LOOP CONSIDERING $Z_0$ IMPACTS

Based on the simulation studies and theoretical analysis above, a direct solution can be proposed to eliminate the negative damping impact of $Z_0$ on active power droop control, that is adding corresponding droop compensation gains to compensate the $Z_0$ induced negative value of the equivalent angle droop gain $m_0(f)$ and voltage droop gain $n_0(f)$. Therefore, an angle droop gain $k_1$ (rad/W) is added to the active power droop loop, and a voltage droop gain $k_2$ (V/Var) is added into the reactive power droop loop as shown in Fig. 12. This modified outer power loop (i.e., conventional droop plus angle droop) is not a new topology and has been proven to be able to improve the converter power-sharing capability in [15]. But in this paper, the modified droop controls are mainly designed for the consideration of the impacts of $Z_0$, so that both LF SSO issues and harmonic instability issues can be eliminated. The design criteria for the droop gains $k_1$ and $k_2$ can be obtained as shown below.

To eliminate the low-frequency impacts caused by $Z_0$ on the swing equation, the power-angle droop gains considering both $k_1$ and $Z_0$ induced $m_0(f)$ should meet the criteria that is $m_0(f) + k_1 > 0$ (Criterion 1) to fully compensate for the negative damping impacts of $Z_0$ within the studied frequency range. Note that similar to the analysis in (10), adding $k_1$ will not introduce any right half plane poles in the system from the aspects of system small-signal stability.

Based on Criteria 1, $k_1$ should be large enough so that it would be effective for the elimination of low-frequency resonance with good system dynamics. However, $k_1$ cannot be designed to be too large either in order to keep the passivity of the GFM at high frequency. Based on the Bode plots shown in Fig. 13, when $k_1$ is small (1.8 × 10^{-5} or 3 × 10^{-5} ), the inverter output impedances stay unchanged compared with baseline impedance when $k_1 = 0$. However, if increasing $k_1$ to be 7.5 × 10^{-5}, the inverter will show an HF-NPR as the phase value indicates. Therefore, to maintain inverter passivity compensated by $Z_0$ block, $R_{\text{veq}}$ should dominate the $Z_{\text{veq}}$ characteristics at high frequencies, i.e., $R_{\text{veq}} >> X_{\text{veq}} + k_1 \times V_{\text{nom}}$ (Criterion 2), to avoid the impacts of $k_1$ on inverter passivity for system harmonic stability.

Additionally, if considering the reactive power dynamics, the sum of the $Q\cdot V$ droop gains, including original gain $n_0$, induced $n_0(f)$, and $k_2$, should be larger than 0, i.e., $n + n_0 + k_2 > 0$ (Criterion 3). As mentioned in Section II-B, active power droop is the dominant loop for system transition dynamics, therefore, $k_1$ is the key to system stability and $k_2$ is less
important. For simplicity, $k_2$ can be designed as $V_{nom} \times k_1$ first and then checked with Criterion 3.

IV. SIMULATION AND EXPERIMENTAL VALIDATIONS

A. Simulation Validation

1) System Stability Enhancement with Angle Droop

To eliminate the LF SSO of the cases studied in Table II with CIII, droop compensations are implemented at $t = 6$ s in the simulations. For SCR = 8, 12, and 24, $k_1$ is designed to be $6 \times 10^{-5}$. It can be seen from Fig. 14, by adding proper angle droop control, the LF SSO issues can all be eliminated.

2) Impacts of Different Modified Droop Gain Values on System Stability

Effects of the $k_1$ values on system performance have also been investigated under SCR = 8 as shown in Fig. 15. If $k_1$ is too small, the low-frequency resonance will not be eliminated as in Fig. 15 (a). Within the proper design range, the system will be stabilized, and a larger $k_1$ will provide better dynamics as shown in Fig. 15 (b) and Fig. 15 (c). While if $k_1$ is too large, inverter passivity will be affected and harmonic instability will happen as shown in the zoom-in view of Fig. 15 (d).

B. Experimental Validation

To further validate the effectiveness of the angle droop gain on the compensation of the negative impact of $Z_v$ on system LF stability, an experimental platform is built as shown in Fig. 16. Two converters are used to mimic the circuit connections in Fig. 2. The first converter is a grid emulator using open-loop control with grid impedance ($L_g = 3.6$ mH), and the second converter is the droop-controlled GFM with output filters ($L = 2.4$ mH and $C_f = 10$ µF). The reference powers in the test are 600 W and 0 Var. In addition, the reference output voltage and grid voltage is 50 $V_{LL, rms}$. The control parameters are the same as those in Table I.

Fig. 14. Simulation results under different cases: (a) SCR = 8, (b) SCR = 12, and (c) SCR = 24.

Fig. 15. Simulation results with different $k_1$ under SCR = 8: (a) $1.2 \times 10^{-5}$, (b) $1.8 \times 10^{-5}$, (c) $3 \times 10^{-5}$, and (d) $3 \times 10^{-4}$.

Fig. 16. Experimental setup for validation.
The impact of $Z_v$ on system stability is investigated first. From Fig. 17(a), it can be seen that if the controller is implemented with CI (i.e., no $Z_v$ and no $H_v$), there will be HF harmonic issues on the output voltage. If the controller is implemented with CIII (i.e., with $Z_v$ and with $H_v$), it is seen from the full view of Fig. 17(b) that there will be LF SSO, while there is no HF harmonics as seen from the zoom-in view of Fig. 17(b). Note that the controller implemented with CI (i.e., no $Z_v$ but with $H_v$) will not be shown here since the system is stable.

The LF SSO caused by the negative impact of $Z_v$ can be eliminated by adding active power-angle droop control as shown in Fig. 18.

V. CONCLUSIONS
This paper analyzes both the positive and negative impacts of virtual impedance control block $Z_v$ on system stability. With $Z_v$ block, the inverter can be designed to be passive at high frequency, and therefore, the HF harmonic instability issues can be eliminated for all grid conditions. However, the $Z_v$ block will also affect system LF stability by reducing the inertia and damping of the system. Therefore, to eliminate the negative impact caused by $Z_v$, an angle droop control block is added to the $P_f$ droop control, and the design criteria for the gains are proposed accordingly. Simulations and experimental results are also given to validate the effectiveness of the angle droop control in eliminating negative impacts of $Z_v$.

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