Stability Analysis and Improvement for Micro-grid Consisting of Multiple Grid-connected-converters

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1. Introduction
2. Stability analysis
3. Proposed impedance matching method
4. Experimental verification
5. Conclusion
1. Introduction

- Resonance problem is a threat to stable operation of the micro-grid consisting of multiple grid-connected-converters (MGCC) with LCL filter.

[1] Zhao Z. Key technology research of megawatt photovoltaic grid power generation. 2010 power electronic seminar of Delta Ltd.
1. Introduction

Stability problem of the micro-grid is caused by various factors.

- “LCL+ converter” shows high order unstable character\(^1\).
- Resonance among GCCs\(^2\).
- Interaction between the grid impedance and GCCs\(^2\).
- Impact of loads, especially capacitive loads.
- Nonlinear factors may be a potential problem.
- Factors not listed or still unknown……

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2. Stability analysis

- Adjust an unstable GCC system

A full state feedback control is implemented to transform the unstable, high order GCC to a stable, approximate low order system.

All the GCCs operate in the current source control mode.
For this investigation, each GCC is regulated by the classic double-loop control scheme. The “average switching model (ASM)” of single-phase equivalent representation is presented.

According to the control block diagram of the GCC, the closed-loop behaviour of it acts as a double inputs and single output system.

\[ i_g = G_c(s)i_g^* - \frac{1}{Z_c}(s)u_{PCC} \]

\[ G_c(s) = \frac{C(s)}{s^3L_1L_2C + s^2k_{ic}L_2C + s(L_1 + L_2) + C(s)} \]

\[ Z_c(s) = \frac{s^3L_1L_2C + s^2k_{ic}L_2C + s(L_1 + L_2) + C(s)}{s^2L_C + sk_{ic}C} \]
2. Stability analysis

The model of the microgrid consisting of multiple GCCs can be obtained accordingly.

It's worth noting that all the GCCs are assumed the same. The ordinary resistor-inductance loads are neglected, and the capacitive loads are lumped together with the grid impedance.

\[
Z_{\text{ext}}(s) = \frac{sL_g + R_g}{s^2L_gC_L + sR_gC_L + 1}
\]

\[
i_{g1} = H_c(s) \cdot G_c(s) i_{g1}^* - F_c(s) \cdot \frac{1}{n} \left[ G_c(s) (i_{g2}^* + \cdots + i_{gn}^*) + \frac{1}{Z_{\text{ext}}(s)} u_s \right]
\]
2. Stability analysis

Reveal the main factors on stability

After a series of derivation, the following item is considered to determine the stability.

\[ T_c(s) = \frac{Z_{ext}(s)}{(n-1)Z_{ext}(s) + Z_c(s)} \]

The stability of microgrid depends on whether \( T_c(s) \) satisfies the Nyquist stability criterion.

A micro-grid consisting of 3 GCCs (n=3); Capacitor-current feedback method is applied.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid impedance</td>
<td>Lg, Rg</td>
</tr>
<tr>
<td>Converter side inductor</td>
<td>L1</td>
</tr>
<tr>
<td>Filter capacitor</td>
<td>C</td>
</tr>
<tr>
<td>Grid side inductor</td>
<td>L2</td>
</tr>
<tr>
<td>Control case</td>
<td>[Kp kic]</td>
</tr>
</tbody>
</table>

The impact of the grid inductor, the capacitive loads, the number of GCCs and the closed-loop output impedance of GCC on system stability can be inferred.

The generation procedure of \( T_c(s) \)
2. Stability analysis

- Primary cause of resonance

- The mismatch of impedance properties between GCC and the external network in a specific frequency range introduces threat of system stability.
2. Stability analysis

- Influences of the factors

\[ T_c(s) = \frac{Z_{\text{ext}}(s)}{(n-1)Z_{\text{ext}}(s) + Z_c(s)} \]

Grid impedance increases, or GCC number increases, then the resonance is aggravated and its frequency decreases.

\[ T_c(s) = \frac{Z_{\text{ext}}(s)}{(n-1)Z_{\text{ext}}(s) + Z_c(s)} \]

Capacitive loads switch in, then the resonance is aggravated and its frequency decreases.
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3. Proposed impedance matching method

Guidance of stability improving

The mismatch of impedance properties between GCC and the external network (including grid inductor and capacitive loads) introduces threat of system stability.

Two improved routes

- Additional equipment can be installed as “stabilizer” to adjust the impedance of the external network, namely $Z_{\text{ext}}(s)$.

The impedance of GCC can be configured by some appropriate improved control methods.
3. Proposed impedance matching method

Guidance of stability improving

Harmonic oscillation is found between the grid-side current and the capacitor current.

The capacitor shunt branch performs super-low impedance at high frequency for switching harmonic. But harmonic resonance is introduced by the coupling between the capacitor shunt branch and the external network which is mainly inductive in a specific frequency range.

It seems reasonable to reconstruct the critical capacitor shunt branch to achieve impedance matching between the GCCs and the external network.
3. Proposed impedance matching method

Principle of the proposed method

In order to perform resistive impedance instead of capacitive impedance in the harmonic-frequency region, an equivalent inductor shunt branch is implemented. For the sake of robustness, an equivalent resistor shunt branch is also implemented.

Variations of the grid impedance, the GCC number and the loads are taken into consideration in the proposed method since it regulates the output impedance of the GCC based on the detected resonance frequency.

\[ f_{\text{har}} \approx \frac{1}{2\pi} \sqrt{\frac{L_m}{C_f}} \quad R_m \approx \frac{1}{2\pi f_{\text{har}} C_f} \]
3. Proposed impedance matching method

- Equivalent circuit of the proposed method

The accurate equivalent circuit of this method is illustrated, and the distinct physical meanings of the feedback parameters are demonstrated.

\[ f_{\text{har}} \approx \frac{1}{2\pi} \sqrt{\frac{L_m C_f}{m}} \quad \quad R_m \approx \frac{1}{2\pi f_{\text{har}} C_f} \]

\[ Z_c(s) = \frac{s^3 L_1 L_2 C_f + s^2 \frac{1}{R_m} L_1 L_2 + s(L_1 + L_2 + \frac{1}{L_m} L_1 L_2) + C(s)}{s^2 L_1 C_f + s \frac{L_1}{R_m} + \frac{L_1}{L_m}} \]

\[ k_1 = \frac{L_1}{R_m C_f} \quad k_2 = \frac{L_1}{L_m} \]
3. Proposed impedance matching method

Performance analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid impedance  Lg, Rg</td>
<td>1.6mH, 0.1Ω</td>
</tr>
<tr>
<td>Capacitive load       CL</td>
<td>40uF</td>
</tr>
<tr>
<td>LCL filter parameter  L1, C, L2</td>
<td>3mH, 20uF, 0.2mH</td>
</tr>
<tr>
<td>PR control parameter  Kp, Kr</td>
<td>10, 3000</td>
</tr>
<tr>
<td>Feedback parameter 1  kic</td>
<td>12</td>
</tr>
<tr>
<td>Feedback parameters 2  k1, k2</td>
<td>12, 0.91</td>
</tr>
</tbody>
</table>

The inductance-capacitance mismatch is avoided in low frequency band when the improved control method is applied.

Effect1—— The resonance point in low frequency band is eliminated.

Effect2—— The stability margin in high frequency band is also expanded.
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4. Experimental verification

Experiments are implemented on the laboratory prototype to verify the proposed method. The experimental microgrid is composed of three GCCs, and the dc link voltages of these GCCs are provided by three-phase diode rectifiers.
4. Experimental verification

Base case

In these figure, sub-graph (a) depicts the phase-A voltage of the PCC (100V/div). Sub-graph (b) shows the phase-A current of GCC1 (5A/div). The phase-A currents of GCC2 and GCC3 are shown in sub-graph (c) and (d), respectively.
4. Experimental verification

When the parallel GCCs decreases

The conventional double-loop control method

N = 2
Rg = 0.1 Ω
Lg = 1.6 mH

Compared to the base case with three GCCs, the higher frequency resonance is further drifted to around 900 Hz.

The proposed improved method

THD 5.48%, 17th 2.90%, 19th 2.45%

THD 2.83%, 17th 0.56%, 19th 1.05%
4. Experimental verification

When the grid impedance increases

Although the microgrid system remains stable, the grid current of all the GCCs and the PCC voltage are severely distorted. Compared to the base case with the original grid impedance, it is obvious that the resonance moves to the low-frequency region with the increased grid impedance.
4. Experimental verification

- When the capacitive load is switched in

![Diagram] (Diagram showing the system configuration with DG1, DG2, GCC1, GCC2, GCC3, DGn, PCC, Grid, Rg, Lg, Cl, L1, L2, Cf, N = 3, Rg = 0.1 Ω, Lg = 1.6mH, C_load=40uF)

The resonance will be aggravated, and the corresponding resonance frequency will drift to the low-frequency region significantly.

The conventional double-loop control method

THD 6.75%, 7th 4.78%

The proposed improved method

THD 3.33%, 7th 1.89%
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5. Conclusion

- By investigating the closed-loop Norton equivalent circuit model, the impedance mismatch between the GCCs and the external network in the harmonic-frequency region is found to be the primary cause of resonance phenomenon in the microgrid.

- Some critical factors associated with resonance are discovered, such as the number of the GCCs, the grid impedance and the capacitive loads.

- The proposed impedance matching control for resonance damping of multiple GCCs is proved to be effective.
Thank you!