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

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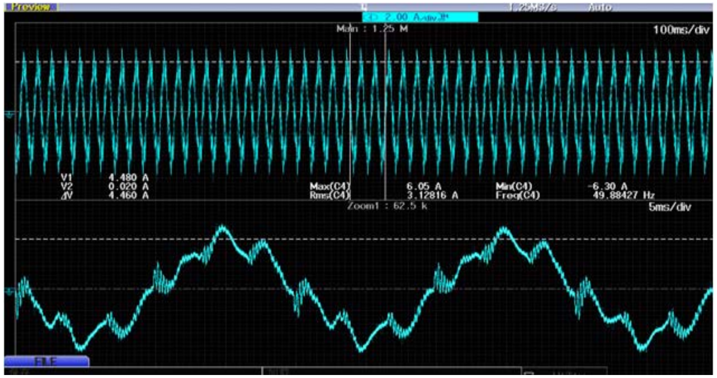
1. Introduction

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

[1]



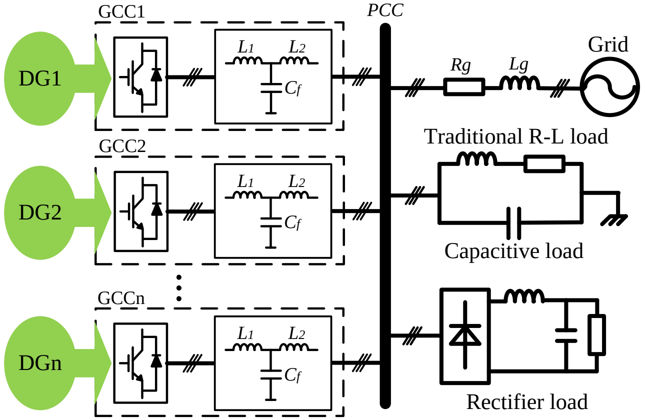
[2]

[1] Zhao Z. Key technology research of megawatt photovoltaic grid power generation. 2010 power electronic seminar of Delta Ltd.
[2] Growatt Ltd. Investigation of the key technology about inverters in distributed photovoltaic power station. 2013.

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……



[1] Xue M, Zhang Y, Kang Y, et al. Full feedforward of grid voltage for discrete state feedback controlled grid-connected inverter with LCL filter[J]. Power Electronics, IEEE Transactions on, 2012, 27(10): 4234-4247.
[2] He J, Li Y W, Bosnjak D, et al. Investigation and active damping of multiple resonances in a parallel-inverter-based microgrid[J]. Power Electronics, IEEE Transactions on, 2013, 28(1): 234-246.

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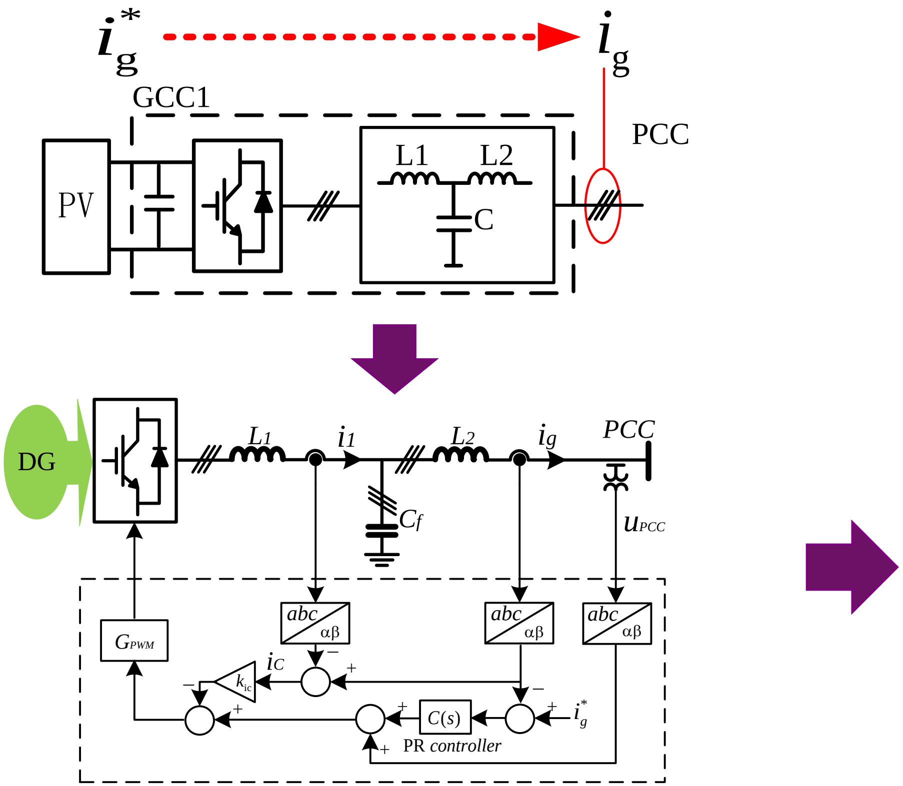
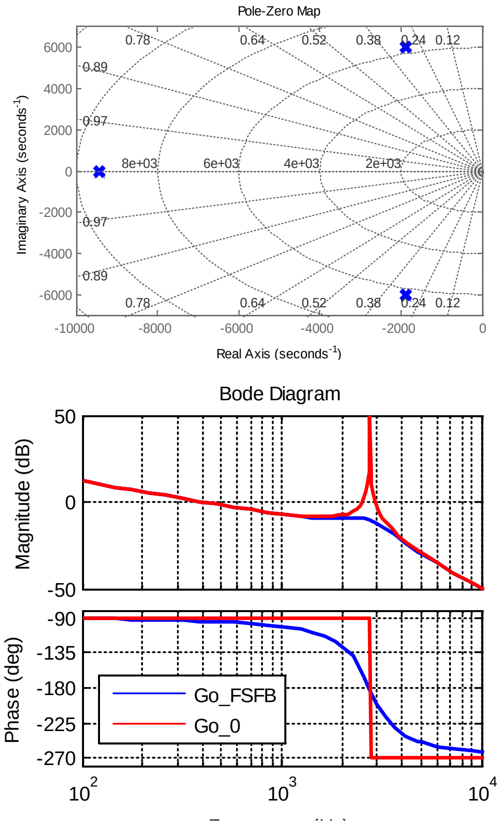
2. Stability analysis

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.

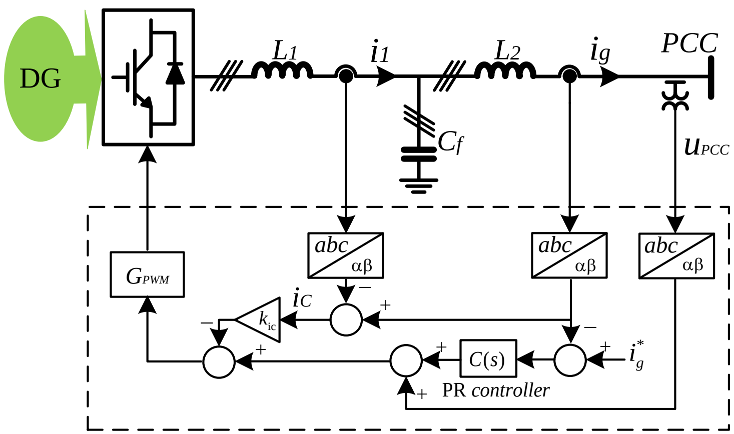
All the GCCs operate in the **current source** control mode.

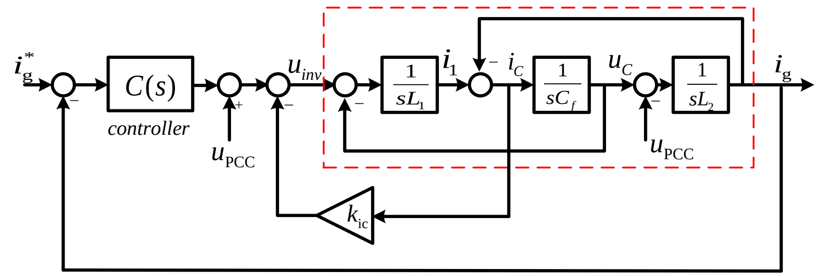




2. Stability analysis

- 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.



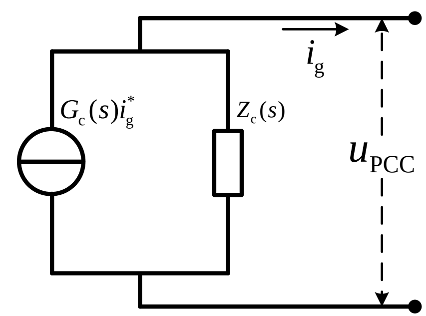


According to the control block diagram of the GCC, the closed-loop behaviour of it acts as a double inputs and single output system.

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

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

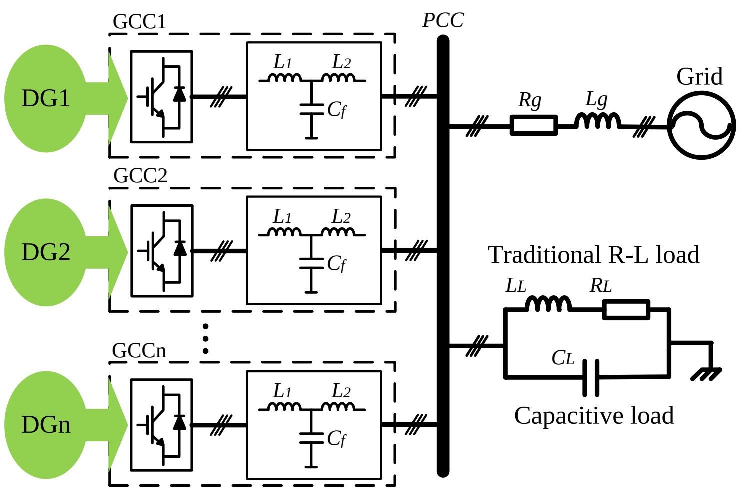
$$Z_c(s) = \frac{s^3L_1L_2C + s^2k_{ic}L_2C + s(L_1+L_2) + C(s)}{s^2L_1C + sk_{ic}C}$$

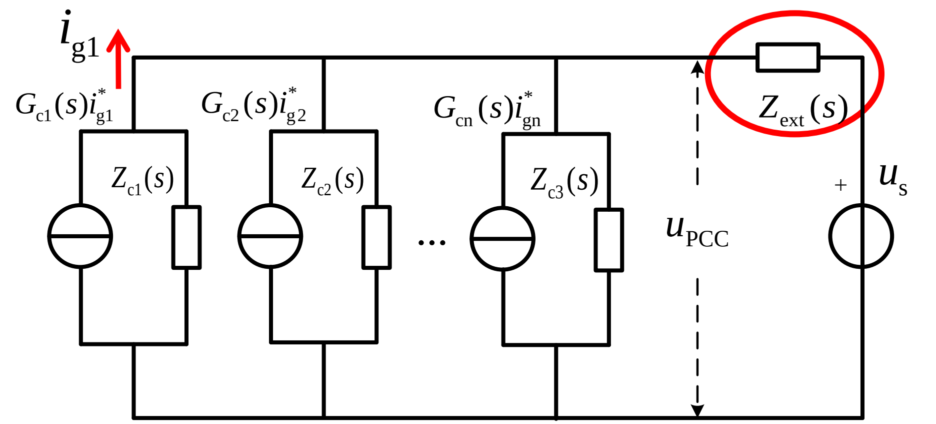


2. Stability analysis

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

$$Z_{\text{ext}}(s) = \frac{sL_g + R_g}{s^2 L_g C_L + sR_g C_L + 1}$$





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.

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

2. Stability analysis

Reveal the main factors on stability

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

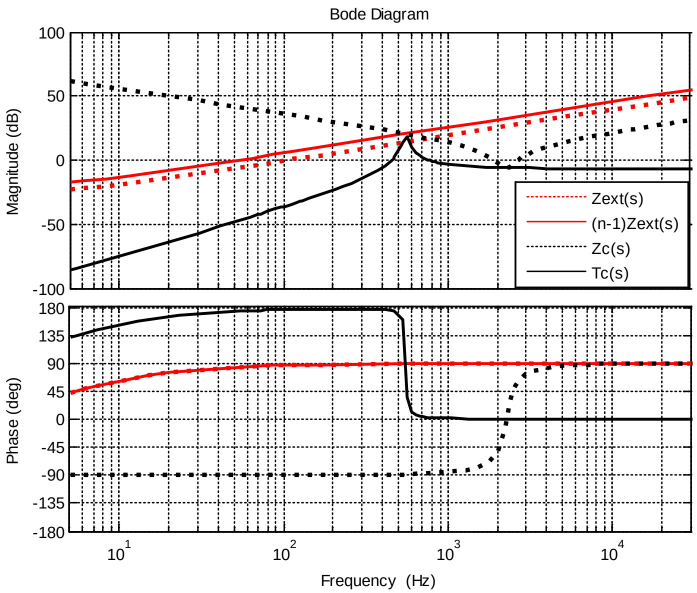
$$T_c(s) = \frac{Z_{ext}(s)}{(n-1)Z_{ext}(s) + Z_c(s)}$$

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.

Parameters		Values
Grid impedance	Lg, Rg	1.6mH, 0.1Ω
Converter side inductor	L1	3mH
Filter capacitor	C	20uF
Grid side inductor	L2	0.2mH
Control case	[Kp kic]	[10 12]

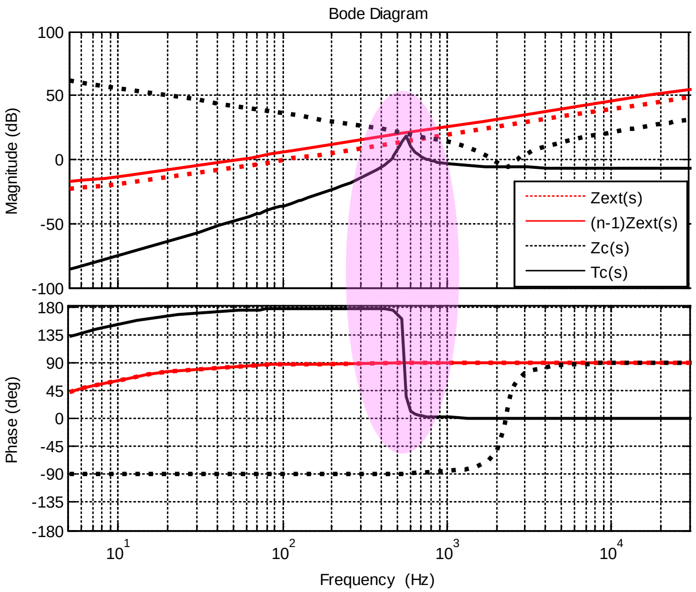
The impact of the grid inductor , the capacitive loads , the number of GCCs and the closed-loop output impedance of GCC on system stability can be inferred.

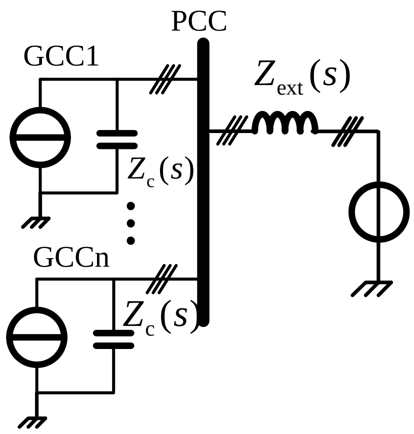


The **generation procedure** of $T_c(s)$

2. Stability analysis

Primary cause of resonance

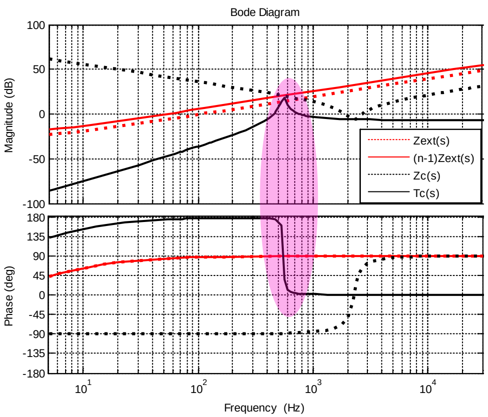




- The mismatch of impedance properties between GCC and the external network in a specific frequency range introduces threat of system stability.

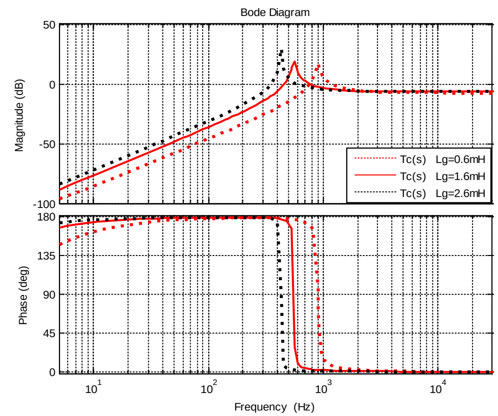
2. Stability analysis

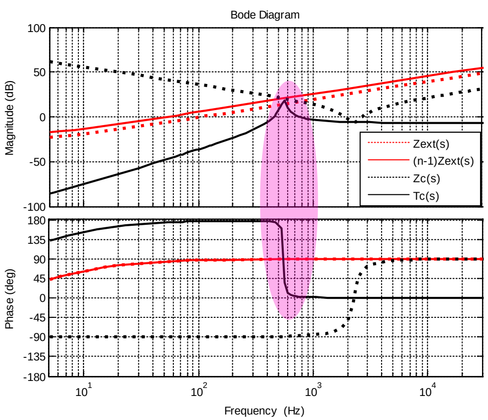
Influences of the factors



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

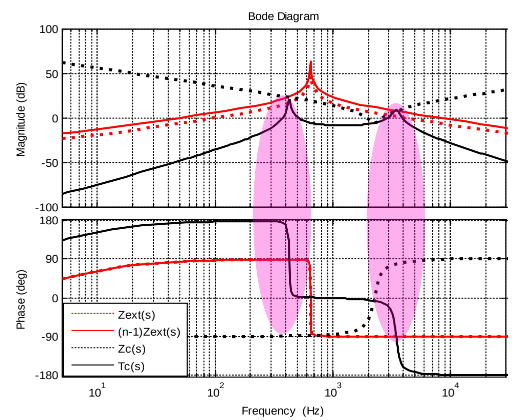
Grid impedance increases, or GCC number increases, then the resonance is aggravated and its frequency decreases.





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

Capacitive loads switch in, then the resonance is aggravated and its frequency decreases.



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3. Proposed impedance matching method

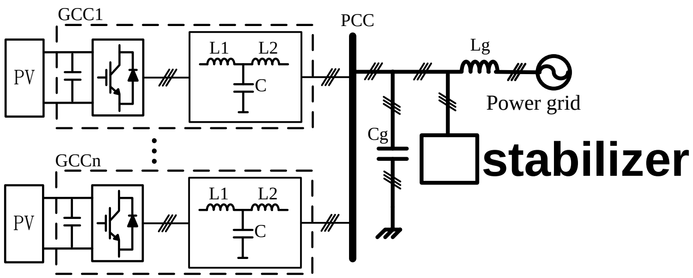
Guidance of stability improving

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 $Z_{\text{ext}}(s)$.

costly



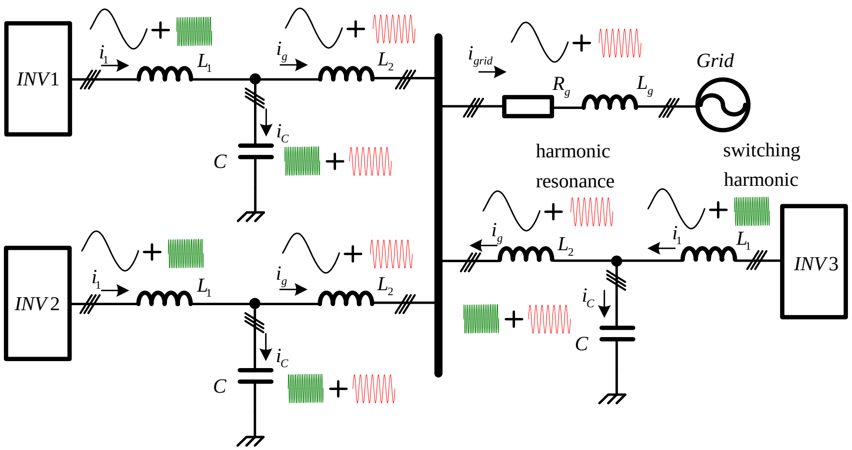
- The impedance of GCC can be configured by some appropriate improved control methods.

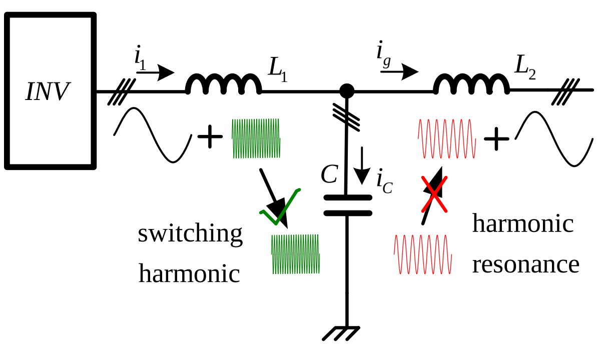
economical

3. Proposed impedance matching method

Guidance of stability improving

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



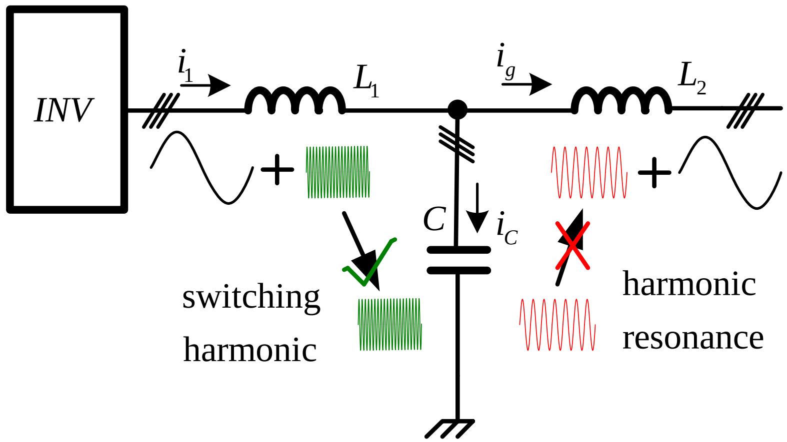


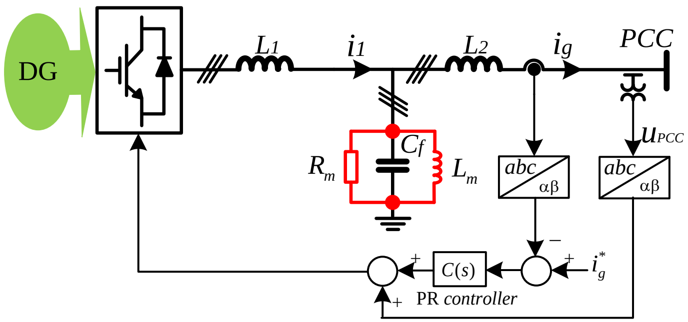
The capacitor shunt branch performs super-low impedance at high frequency for switching harmonic. But harmonic resonance is introduced by the coupling between the capacitor shunt branch and the external network which is mainly inductive in a specific frequency range.

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





$$f_{\mathrm{har}} \approx \frac{1}{2\pi\sqrt{L_{\mathrm{m}} C_f}} \qquad R_{\mathrm{m}} \approx \frac{1}{2\pi f_{\mathrm{har}} C_f}$$

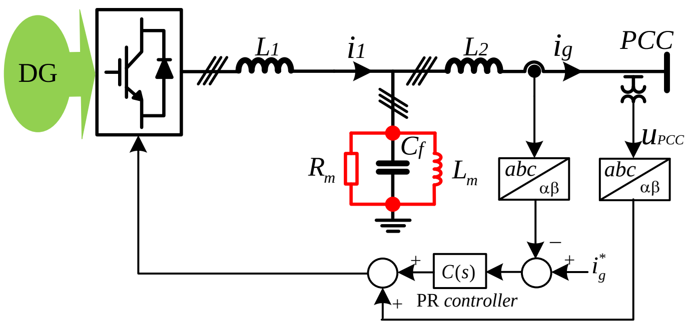
In order to perform resistive impedance instead of capacitive impedance in the harmonic-frequency region, an equivalent inductor shunt branch is implemented. For the sake of robustness, an equivalent resistor shunt branch is also implemented.

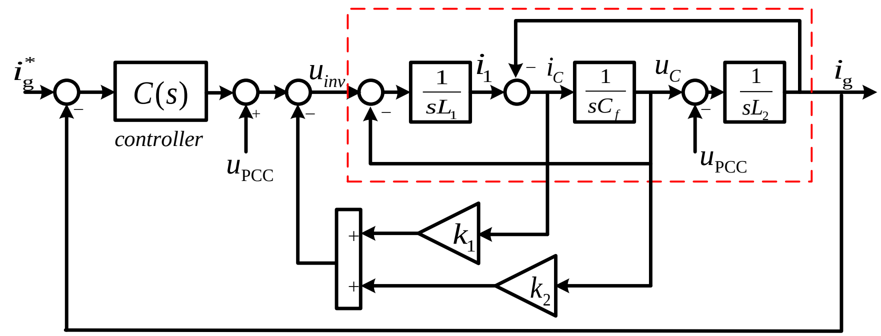
Variations of the grid impedance, the GCC number and the loads are taken into consideration in the proposed method since it regulates the output impedance of the GCC based on the detected resonance frequency.

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.





$$f_{\mathrm{har}} \approx \frac{1}{2\pi}\sqrt{L_{\mathrm{m}}C_f} \qquad R_{\mathrm{m}} \approx \frac{1}{2\pi f_{\mathrm{har}} C_f}$$

$$k_1 = \frac{L_1}{R_{\mathrm{m}}C_f} \qquad k_2 = \frac{L_1}{L_{\mathrm{m}}}$$

$$Z_{\mathrm{c}}(s) = \frac{s^3 L_1 L_2 C_f + s^2 \frac{1}{R_{\mathrm{m}}} L_1 L_2 + s(L_1 + L_2 + \frac{1}{L_{\mathrm{m}}} L_1 L_2) + C(s)}{s^2 L_1 C_f + s\frac{L_1}{R_{\mathrm{m}}} + \frac{L_1}{L_{\mathrm{m}}}}$$

$$Z_{\mathrm{c}}(s) = \frac{s^3 L_1 L_2 C + s^2 k_1 L_2 C + s(L_1 + L_2 + k_2 L_2) + C(s)}{s^2 L_1 C + s k_1 C + k_2}$$

3. Proposed impedance matching method

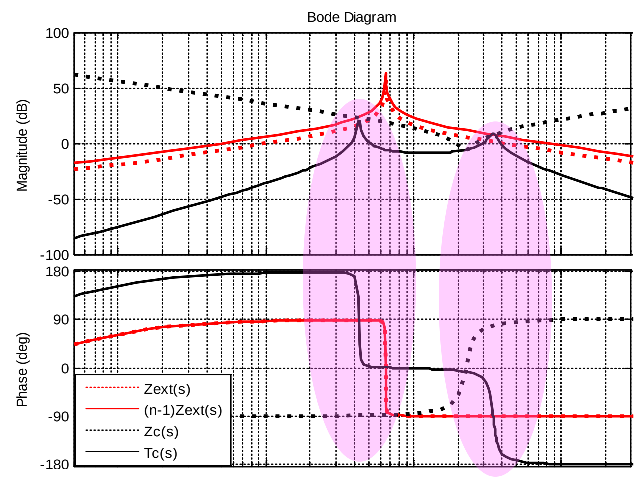
■ Performance analysis

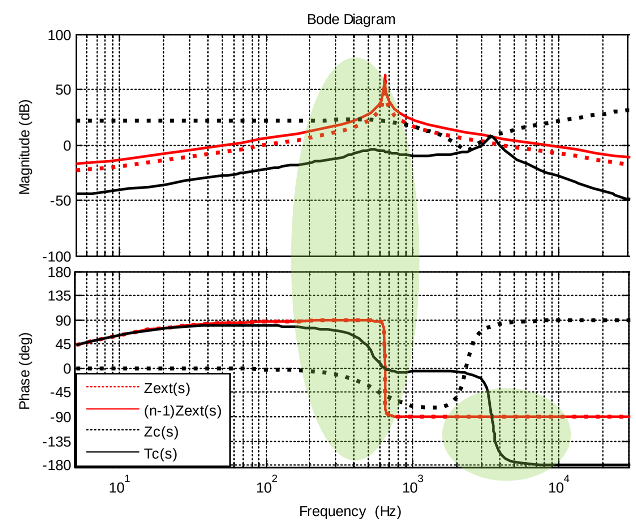
Parameters		Values
Grid impedance	Lg, Rg	1.6mH, 0.1Ω
Capacitive load	CL	40uF
LCL filter parameter	L1, C, L2	3mH, 20uF, 0.2mH
PR control parameter	Kp, Kr	10, 3000
Feedback parameter 1	kic	12
Feedback parameters 2	k1, k2	12, 0.91

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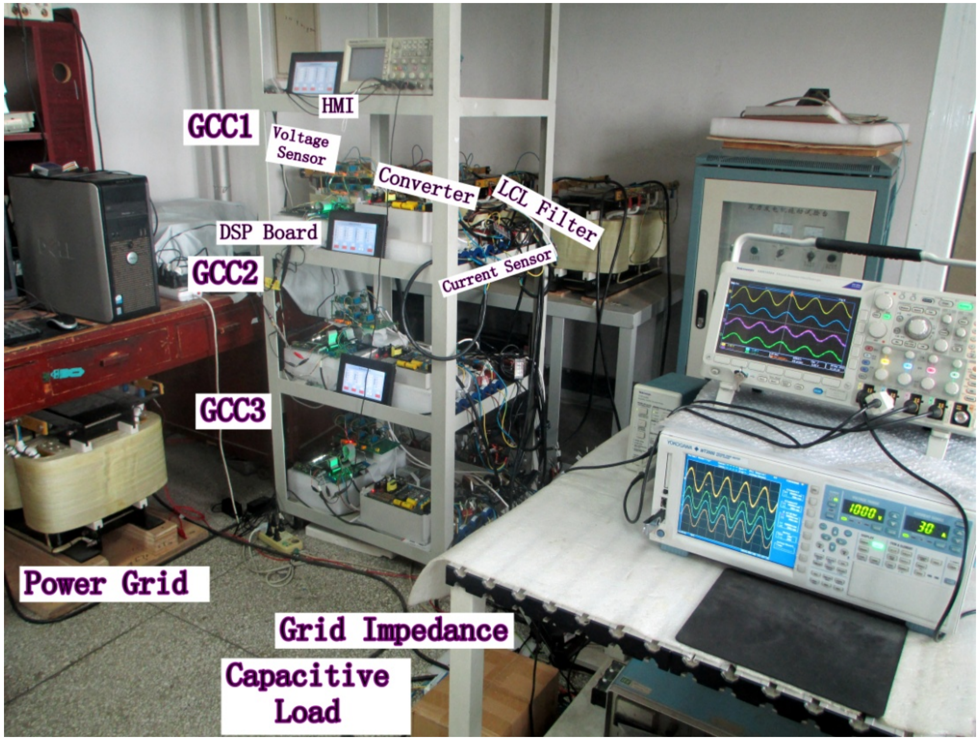
- 2. Stability analysis
- 3. Proposed impedance matching method
- 4. Experimental verification
- 5. Conclusion

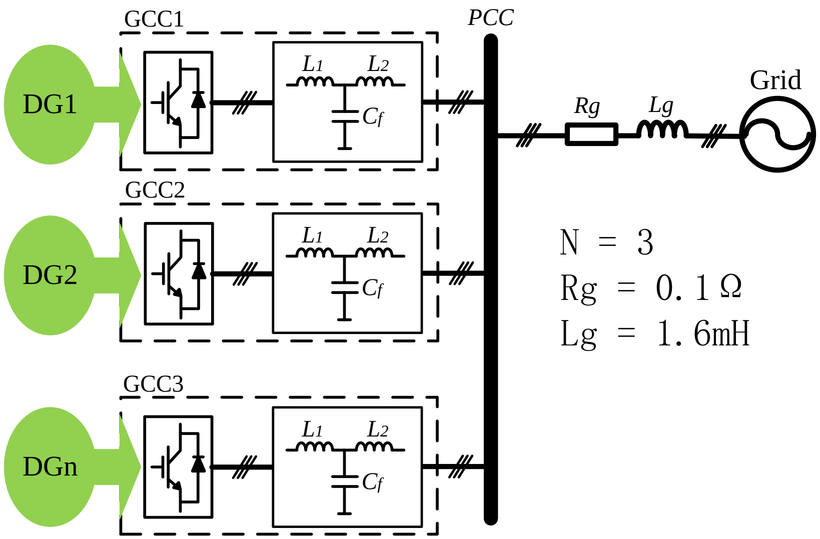
4. Experimental verification

■ 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.



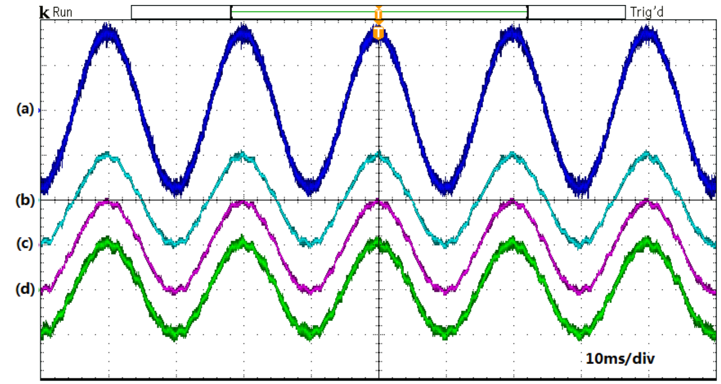
4. Experimental verification

■ Base case



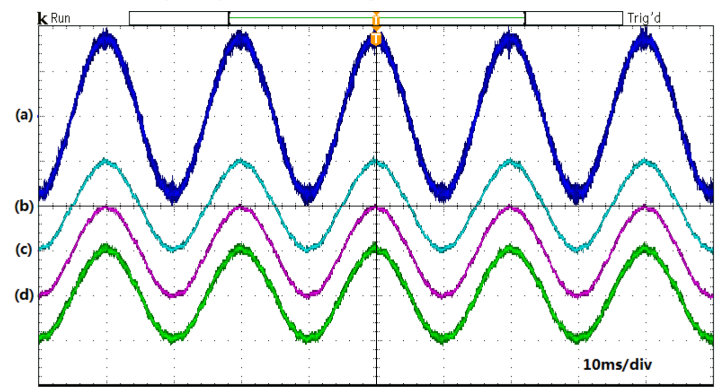
In these figure, sub-graph (a) depicts the phase-A voltage of the PCC (100V/div). Sub-graph (b) shows the phase-A current of GCC1 (5A/div). The phase-A currents of GCC2 and GCC3 are shown in sub-graph (c) and (d), respectively.

The conventional double-loop control method



THD 5.28%, 11^{th} 2.05%, 13^{th} 3.17%

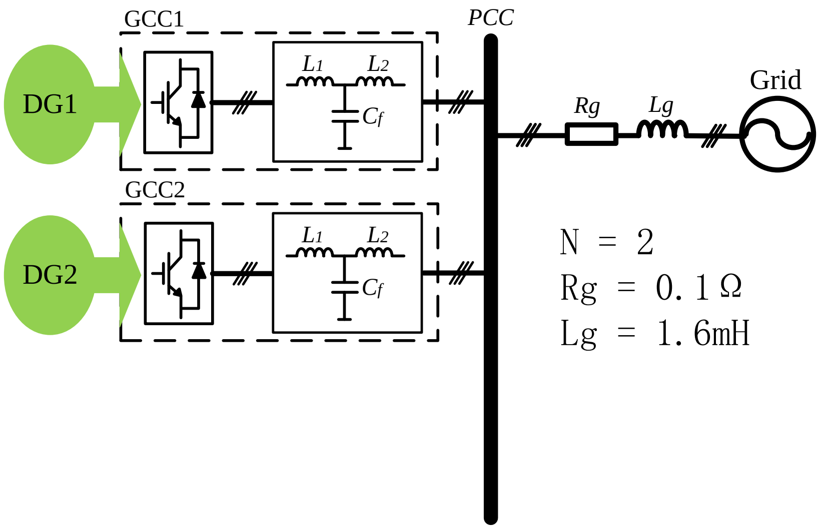
The proposed improved method



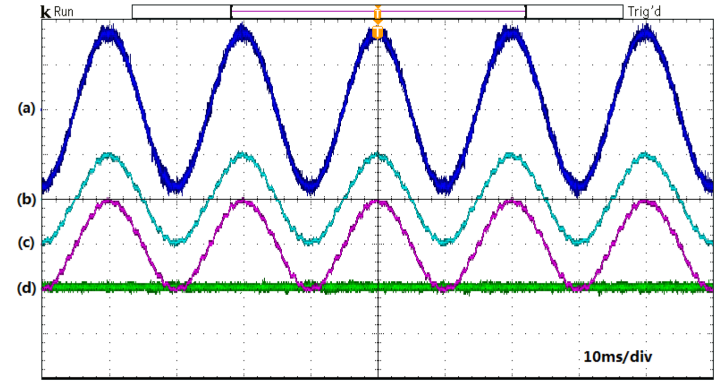
THD 3.20%, 11^{th} 0.82%, 13^{th} 1.21%

4. Experimental verification

- When the parallel GCCs decreases

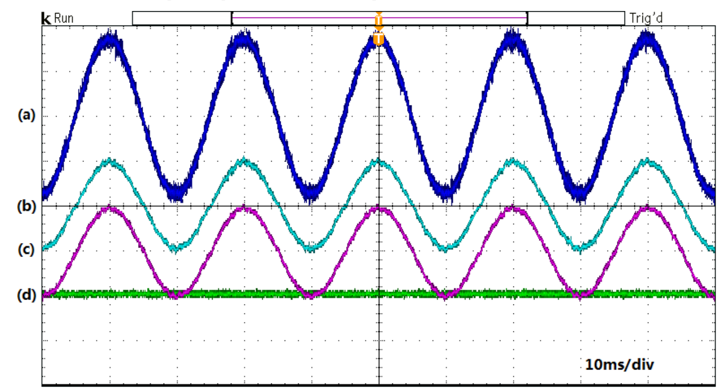


The conventional double-loop control method



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

The proposed improved method

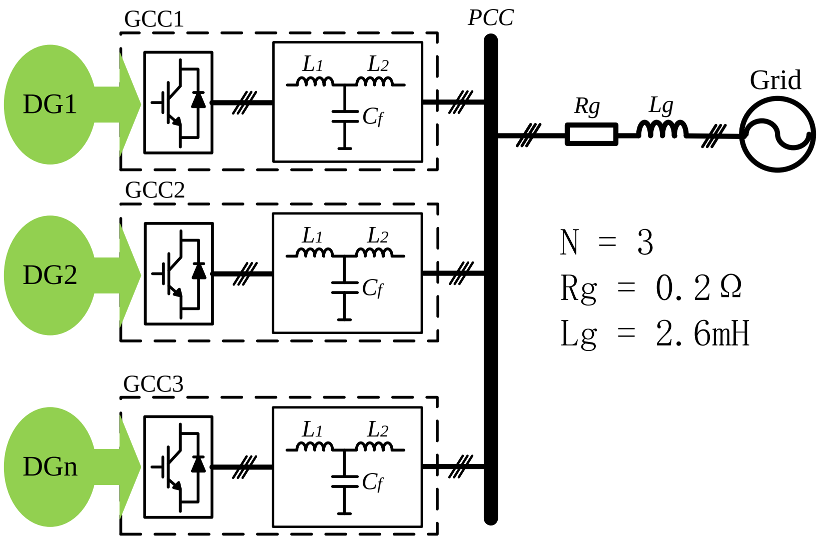


THD 2.83%, 17th 0.56%, 19th 1.05%

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

4. Experimental verification

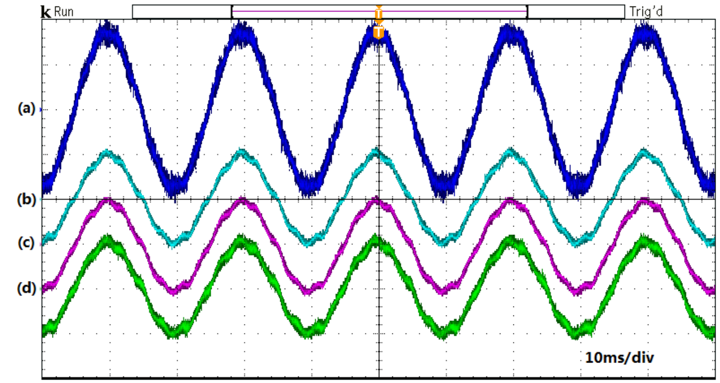
- When the grid impedance increases



N = 3
Rg = 0.2 Ω
Lg = 2.6mH

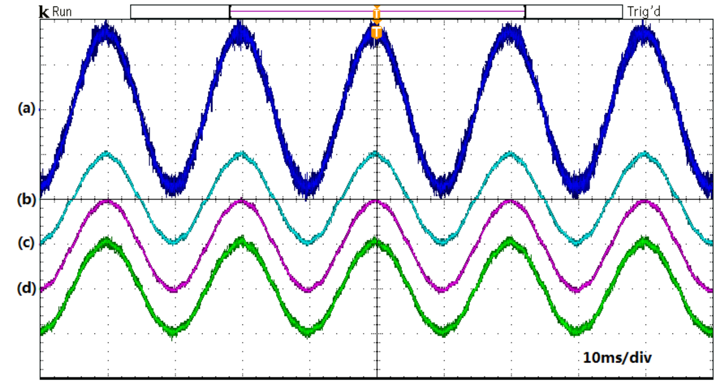
Although the microgrid system remains stable, the grid current of all the GCCs and the PCC voltage are severely distorted.
Compared to the base case with the original grid impedance, it is obvious that the resonance moves to the low-frequency region with the increased grid impedance.

The conventional double-loop control method



THD 5.62%, 7th 4.39%

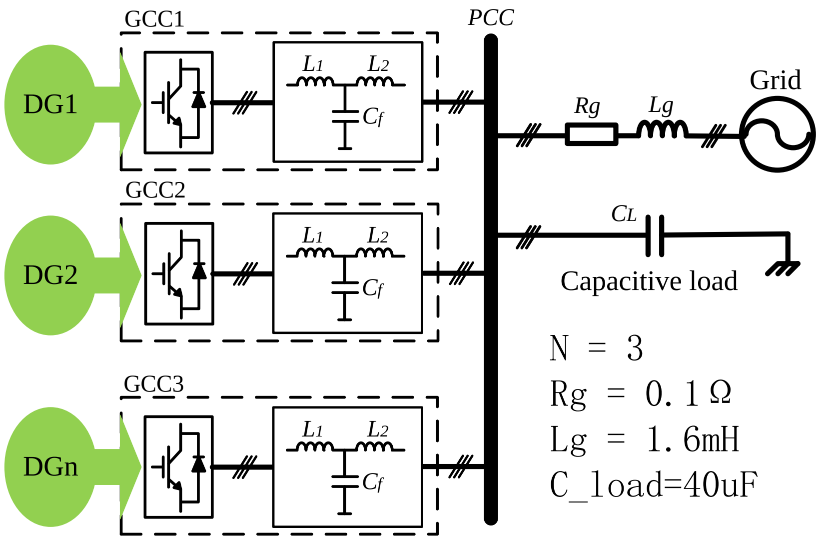
The proposed improved method



THD 3.12%, 7th 1.24%

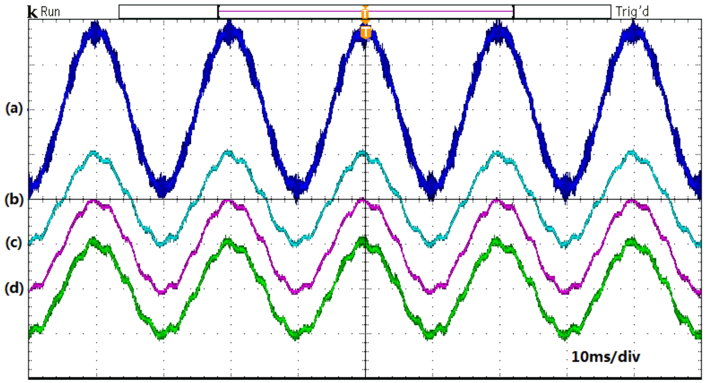
4. Experimental verification

- When the capacitive load is switched in



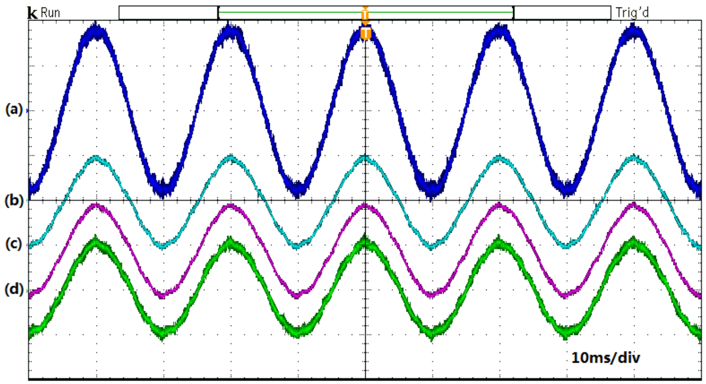
The resonance will be aggravated, and the corresponding resonance frequency will drift to the low-frequency region significantly.

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 !