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Adaptive Active Damping-Based Grid-side Current Harmonic Suppression Method for Totem-pole Bridgeless PFC Converter

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Outline

1 Introduction

2 Proposed Adaptive Active Damping-Based Harmonic Suppression Method

3 Experimental and Analytical Results

4 Conclusion

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1. Introduction
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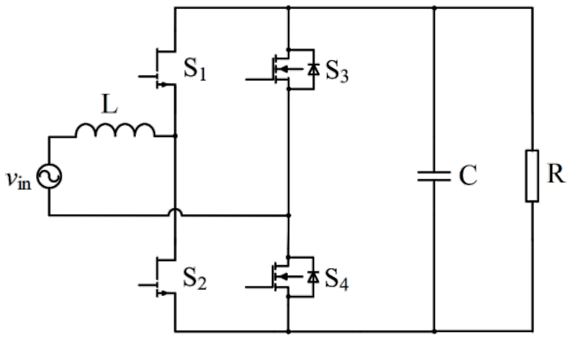
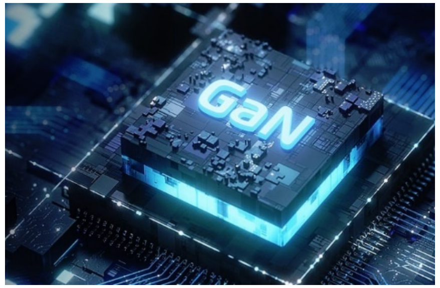
Introduction

- Features of totem pole bridgeless Boost PFC converter
  - **Advantages:**
    - Low common-mode noise, high device utilization
    - High frequency, high efficiency, high power density
  - **Disadvantages:**
    - Reverse recovery problem
- Advantages of GaN power devices
  - High electron mobility, high power density, low switching loss
  - No reverse recovery
- The control difficulty of totem pole bridgeless PFC converter



Totem pole bridgeless PFC topology



GaN devices

Power grid side current harmonic → { EMI filter considered; Adaptability to a wide load range } → design → Adaptive harmonic suppression strategy based on virtual admittance

Introduction

Harmonic suppression method of grid-side current

Harmonic suppression method of grid-side current

- **Harmonic compensation based on nonlinear control strategy**
  - PR controller
  - Complex vector PI controller
  - Repeat controller
  - Active disturbance rejection controller

  Advantages
  - ✓ Simple algorithm
  - ✓ Easy to adjust

  Disadvantages
  - ☐ Low compensation accuracy
  - ☐ Affected by load changes

- **Harmonic suppression based on active damping**
  - The forward path attaches a digital filter
  - Additional state variable feedforward/feedback

  Advantages
  - ✓ High compensation accuracy
  - ✓ Undamped loss

  Disadvantages
  - ☐ Depends on motor or inverter parameters
  - ☐ Complex algorithm

Adaptive algorithm

- ☐ Model Reference Adaptive System（MRAS）
- ☐ Extended Kalman Filter（EKF）
- ☐ Recursive least square（RLS）
- ☐ Sliding Mode Observer（SMO）
- ✓ Interpolation → High Adaptability、least resource-intensive、no instability

Adaptive algorithm	Algorithm complexity	Rate of adaptation	Robustness
MRAS	Intermediate	Quicker	High
RLS	Complexity	Fast	Low
EKF	Complexity	Quicker	Higher
SMO	More complicated	In no time	Higher
Interpolation	Easy	Fast	Higher

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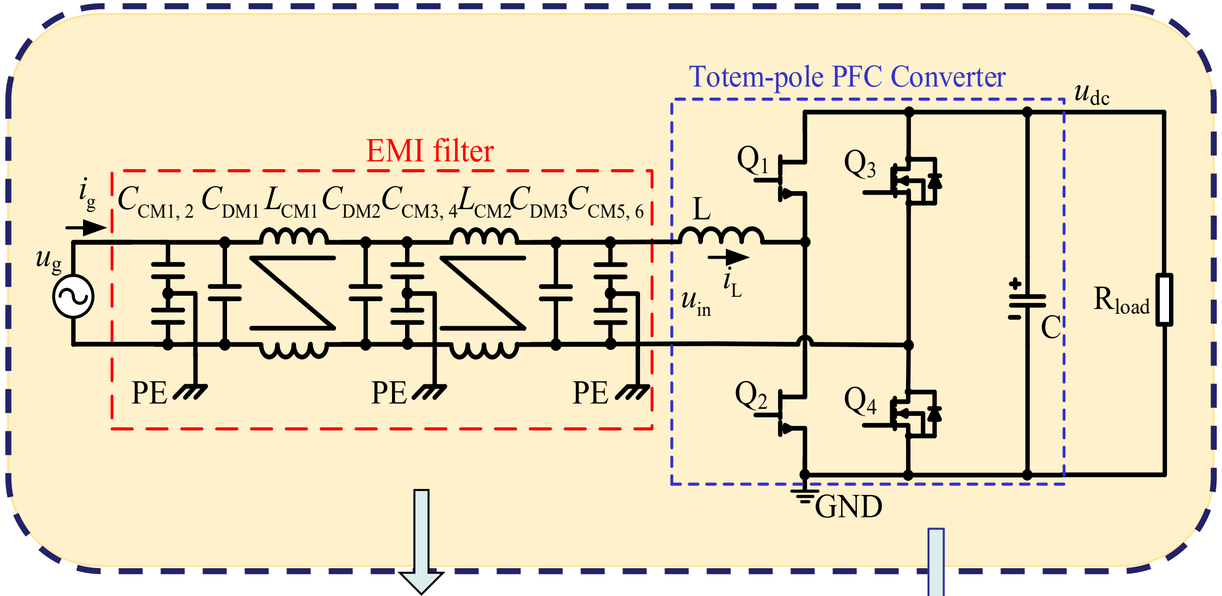
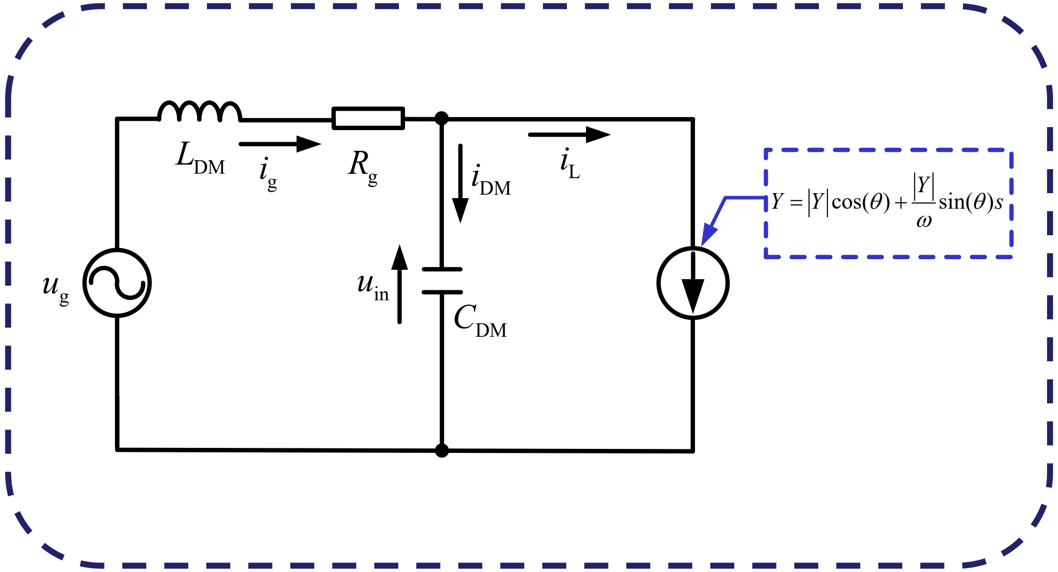
Proposed Harmonic Suppression Method

(1) Analysis of Input Impedance Characteristics of PFC Converters

- **Topology of totem pole bridgeless PFC converter**
- **System equivalent model**





Prevents high-frequency interference between the grid and the converter

It is considered as an approximate constant power load and is assumed to operate under ideal power factor conditions

Proposed Harmonic Suppression Method

(1) Analysis of Input Impedance Characteristics of PFC Converters

$$I_{\mathrm{L}}(s)=\frac{G_{\mathrm{iv}}}{1+T_{\mathrm{i}}}U_{\mathrm{in}}(s)+\frac{g_{\mathrm{in}}K_{\mathrm{ib}}G_{\mathrm{ic}}G_{\mathrm{id}}e^{-T_{\mathrm{d}}s}}{V_{\mathrm{m}}(1+T_{\mathrm{i}})}U_{\mathrm{in}}(s)-\frac{G_{\mathrm{id}}}{s(1+T_{\mathrm{i}})}$$

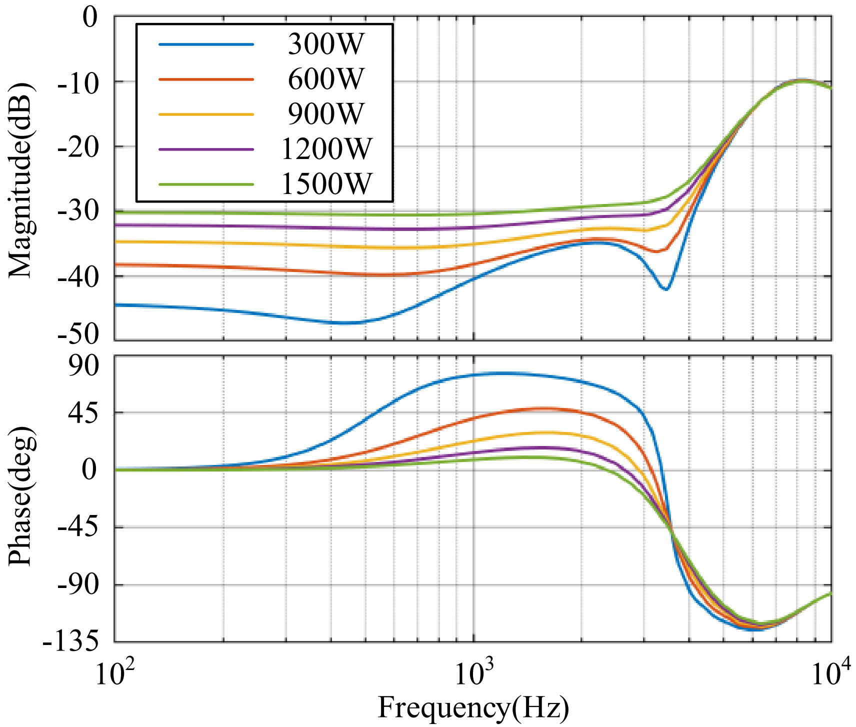
$$Y(s)=\frac{I_{\mathrm{L}}(s)}{U_{\mathrm{in}}(s)}=Y_1(s)+Y_2(s)\quad \begin{cases} Y_1(s)=\dfrac{g_{\mathrm{in}}K_{\mathrm{ib}}G_{\mathrm{ic}}G_{\mathrm{id}}e^{-T_{\mathrm{d}}s}}{V_{\mathrm{m}}(1+T_{\mathrm{i}})} \\ Y_2(s)=\dfrac{G_{\mathrm{iv}}}{1+T_{\mathrm{i}}} \end{cases}$$

$$Y_{\mathrm{va}}(\mathrm{s})=-C_{\mathrm{va}}s-\frac{V_{\mathrm{m}}}{V_{\mathrm{m}}L_{\mathrm{va}}s+U_{\mathrm{dc}}K_{\mathrm{is}}G_{\mathrm{ic}}e^{-T_{\mathrm{d}}s}}$$

Virtual admittance

when $C_{\mathrm{va}}=C_{\mathrm{DM}}$, $L_{\mathrm{va}}=L$

$$Y_{\mathrm{g}}(s)=\frac{Y(s)+Y_{\mathrm{DM}}(s)+Y_{\mathrm{va}}(s)}{[Y(s)+Y_{\mathrm{DM}}(s)+Y_{\mathrm{va}}(s)](L_{\mathrm{g}}s+R_{\mathrm{g}})+1}$$

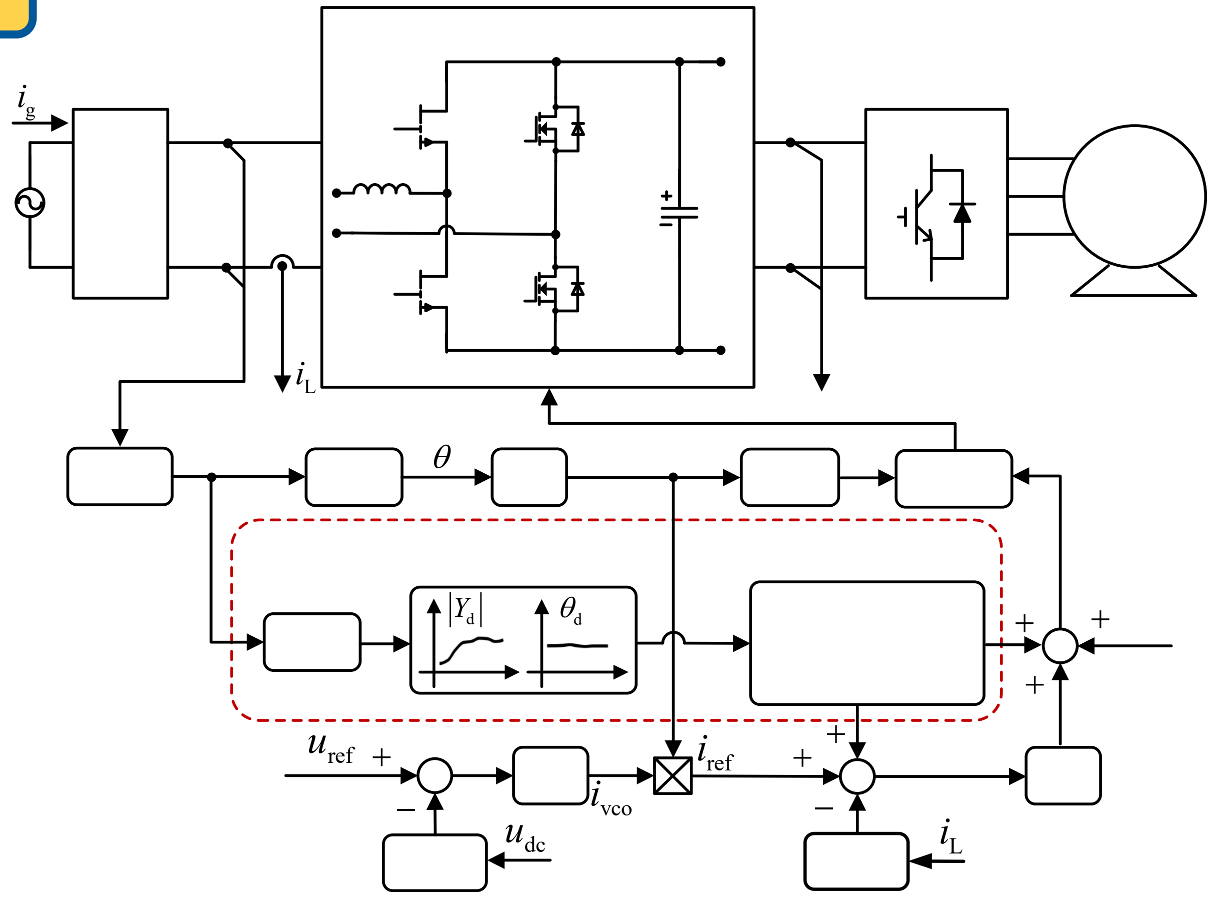


Bode diagrams of system admittance under different loads

Proposed Harmonic Suppression Method

(2) Adaptive active damping method

- Harmonic voltages are obtained using a digital filter
- The target virtual admittance current is calculated according to the virtual admittance
- The virtual admittance is assigned as reference current and modulated voltage
- Through the combination of the two, the equivalent virtual admittance current is obtained, and the active damping effect is realized

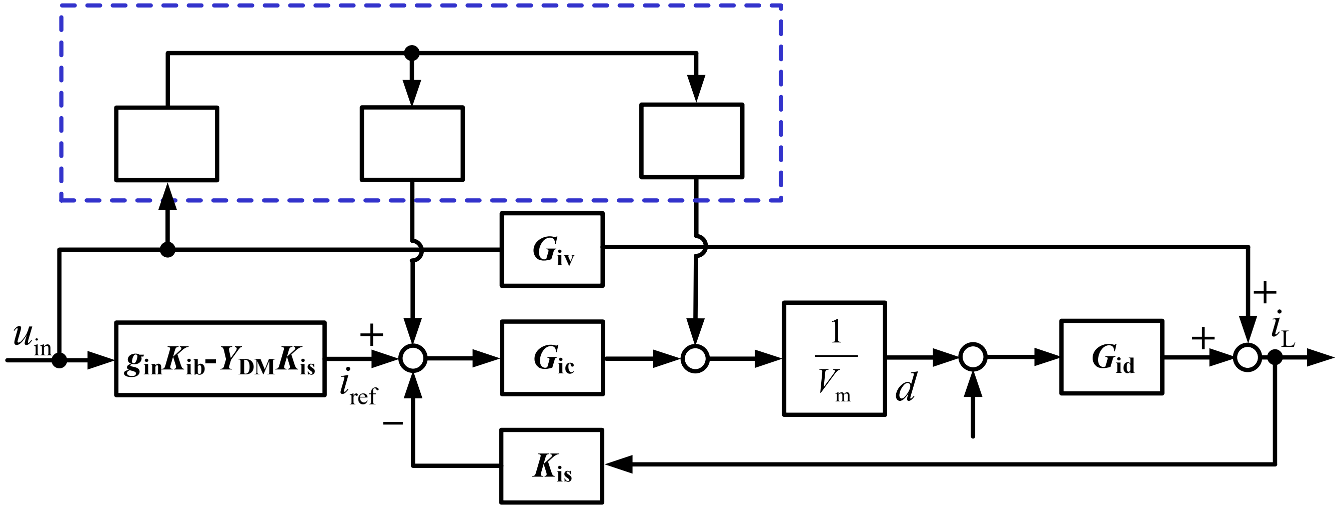


Adaptive active damping control block diagram

Proposed Harmonic Suppression Method

(2) Adaptive active damping method

- **Current loop block diagram**



$$\begin{cases} Y_{d1}(s) = \dfrac{G_{d1}G_{ic}G_{id}e^{-T_d s}}{V_m(1+T_i)} \\ Y_{d2}(s) = \dfrac{G_{d2}G_{id}}{V_m(1+T_i)} \end{cases} \quad \begin{cases} G_{d1}(s) = Y_d K_{is} \\ G_{d2}(s) = \dfrac{Y_d V_m sL}{U_{dc}} \end{cases}$$

The strategy is integrated into the average current control algorithm

The transfer function of the system at harmonic frequencies

$$Y_{g\_d}(s) = \frac{i_{g\_d}(s)}{u_{g\_d}(s)} = \frac{Y(s)+Y_{DM}(s)+Y_{va}(s)+Y_d(s)}{[Y(s)+Y_{DM}(s)+Y_{va}(s)+Y_d(s)](L_{DM}s+R_g)+1}$$

Parallel virtual admittance branch current

$$i_d = u_{in\_d}Y_d$$

Virtual admittance

$$Y_d = |Y_d|\cos\theta_d + \frac{|Y_d|}{\omega_d}\sin\theta_d s$$

Equivalent admittance from reference current and modulated voltage

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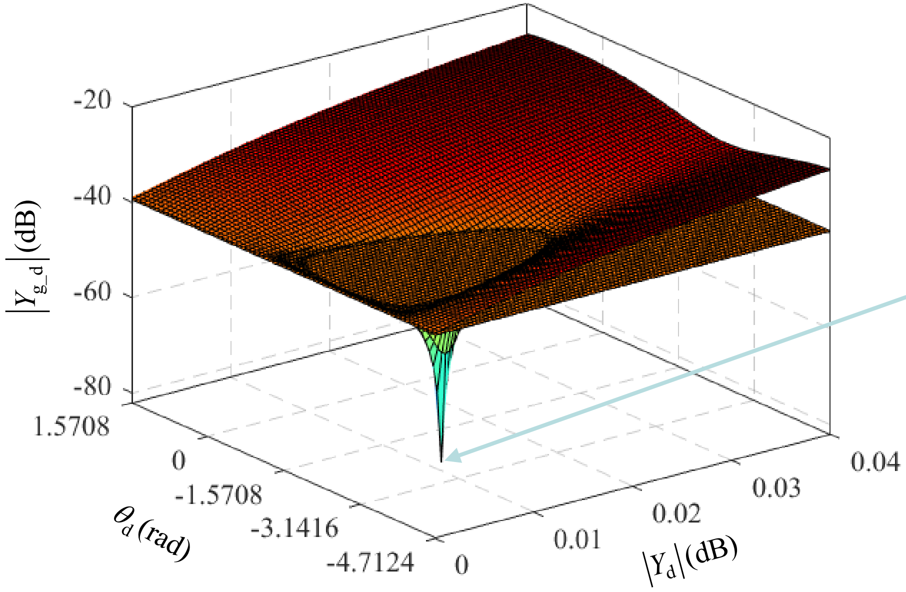
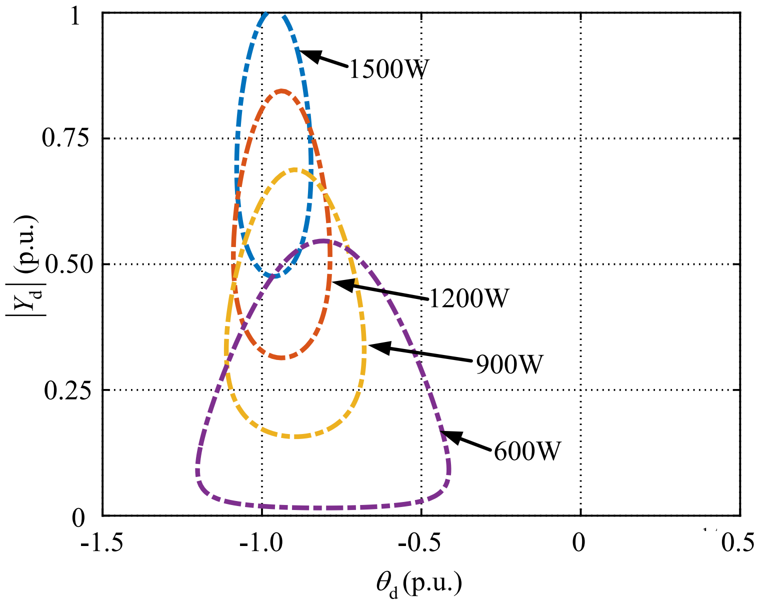
(2) Adaptive active damping method



The **lowest point** is the **optimal virtual admittance point** under the current power load



System admittance results at 900W with different virtual admittances

Optimum virtual admittance values under different power loads

(3) Hermite-based adaptive active damping realization

➢ Hermite's piecewise cubic interpolation principle

Set $\theta_d = f(P)$ be a function with a value $\theta_{di} = f(P_i)$ and a derivative value $m_i = f'(P_i)(j = 0,1,\cdots,n)$ at node $a = P_0 < P_1 < P_2 < \cdots < P_n = b$. A segmented cubic Hermite interpolation function $L_h(P)$ can be constructed to satisfy the following three conditions:

(1) $L_h \in C^1[a,b]$;

(2) $L_h(P_j) = \theta_{dj}, L_h'(P_j) = m_j, j = 0,1,\cdots n$;

(3) $L_h(P)$ is a cubic polynomial on each interval $[P_j, P_{j+1}]$.

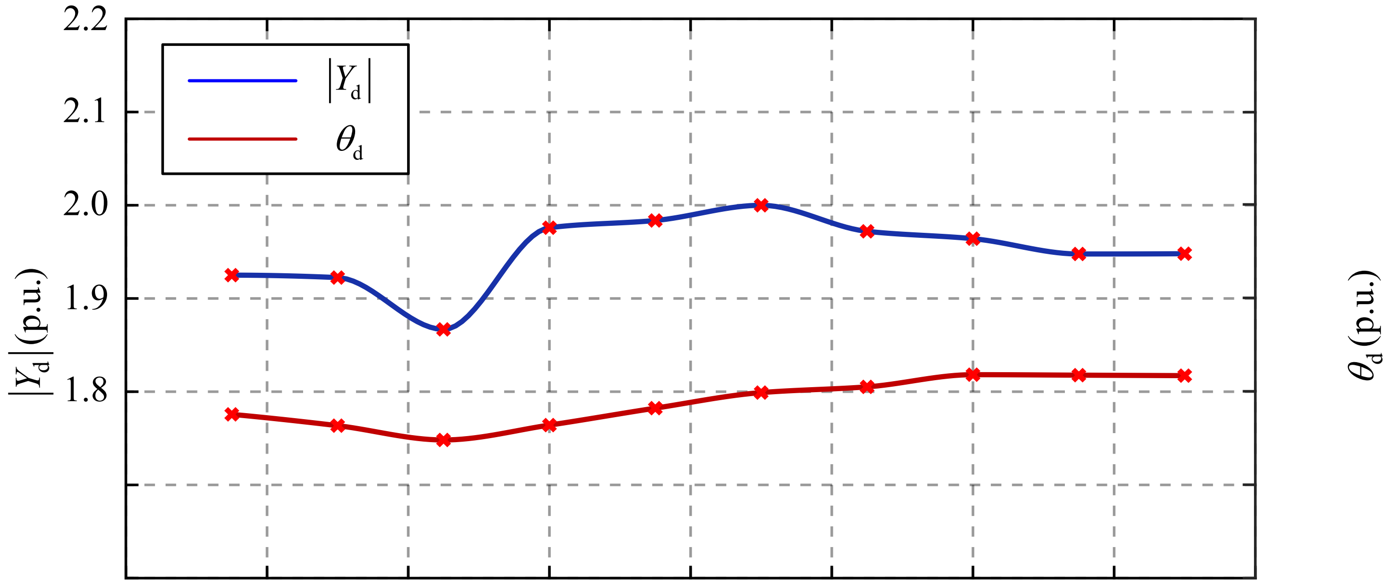
After the operation, the expression of $L_h(P)$ is written as

$$L_h(x) = \left(1 + 2\frac{x - x_j}{x_{j+1} - x_j}\right)\left(\frac{x - x_{j+1}}{x_j - x_{j+1}}\right)^2 y_j + \left(1 + 2\frac{x - x_{j+1}}{x_j - x_{j+1}}\right)\left(\frac{x - x_j}{x_{j+1} - x_j}\right)^2 y_{j+1} + (x - x_j)\left(\frac{x - x_{j+1}}{x_j - x_{j+1}}\right)^2 m_j + (x - x_{j+1})\left(\frac{x - x_j}{x_{j+1} - x_j}\right)^2 m_{j+1}$$

Advantages: Overshoot can be avoided, and the platform area can be connected more accurately

(3) Hermite-based adaptive active damping realization

➢ **Virtual admittance magnitude and phase interpolation fitting results**



Illustrating a satisfactory fitting effect for both magnitude and phase

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Experimental and Analytical Results

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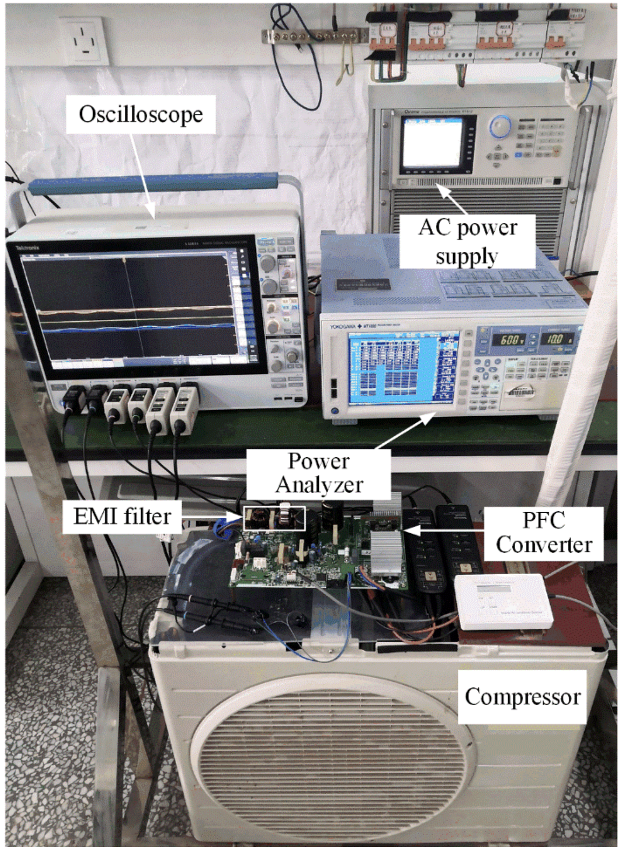


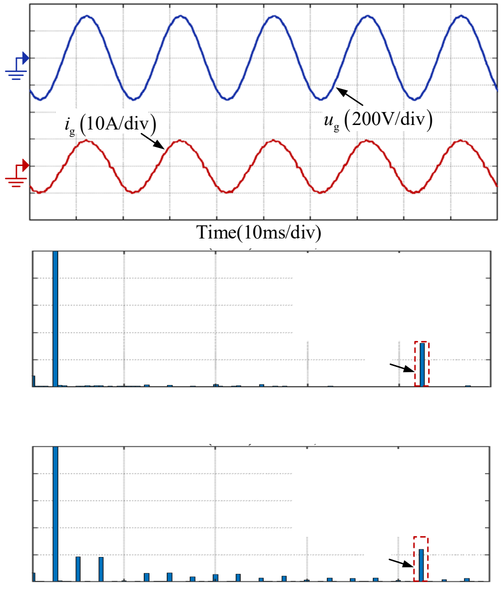
Platform of Experiment

Parameters	Value	Units
Rated power	1500	W
Switching frequency	150	kHz
Control frequency	50	kHz
Grid frequency	50	Hz
Boost inductance	500	μH
DC-link capacitance	940	μF
Differential capacitance	4	μF
Differential inductance	80	μH
Common mode capacitance	5.1	nF
Common mode inductance	4	mH

Parameters of Totem-pole Bridgeless PFC Converter

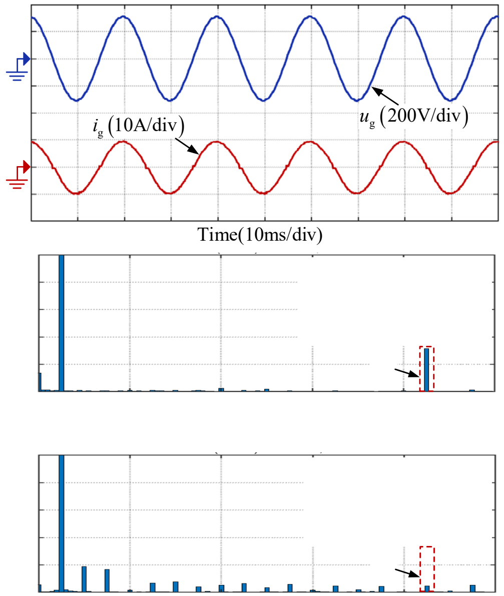
Experimental and Analytical Results

Experimental results at 1500 W



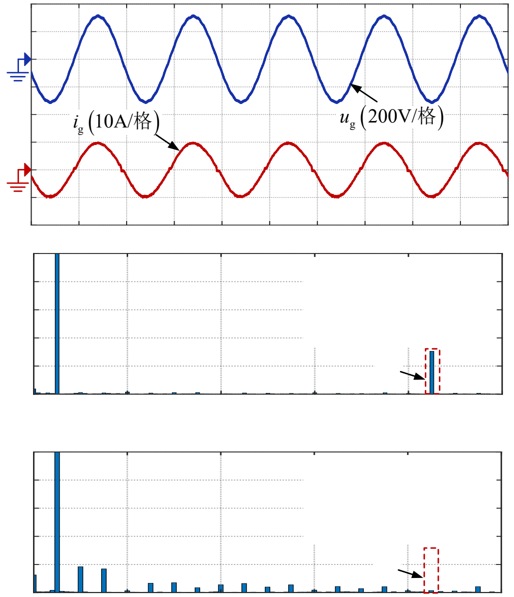
Without active damping

The current harmonic at ω_d reaches 0.4 A



With fixed active damping

The current harmonic decreases to 0.046 A



With adaptive active damping

The current harmonic further decreases to 0.014 A

The THD of the grid-side current decreases by 0.63%, indicating that **the proposed algorithm does not intro-duce significant harmonics at other frequencies**, which is conducive to further improving the per-formance of the grid-side current

Experimental and Analytical Results

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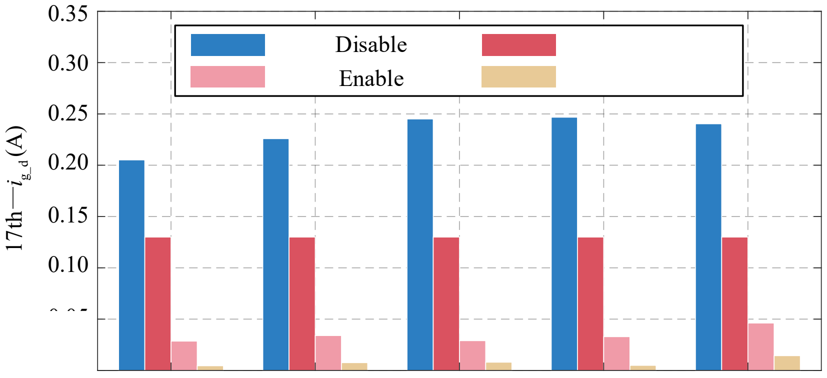
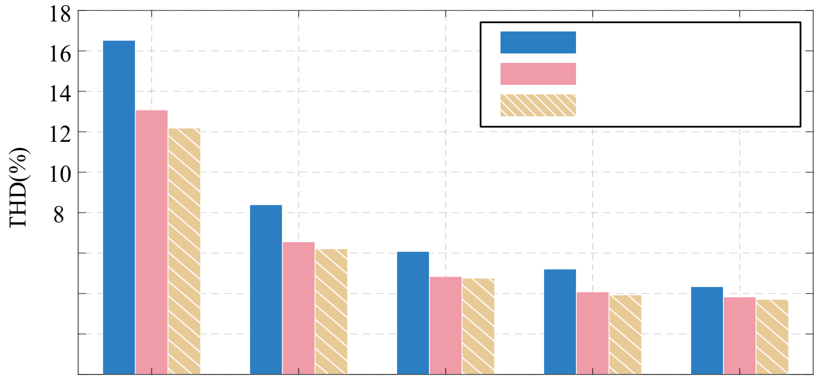
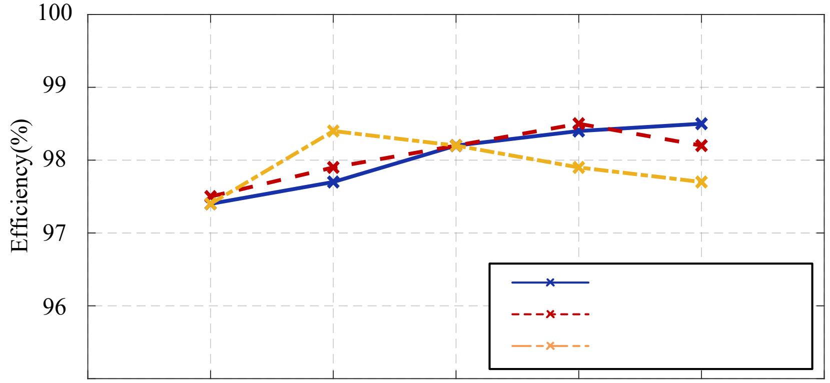
Comparison of experimental result before and after applying harmonic suppression algorithm at different load conditions



17 current harmonics



THD of the grid-side current



Efficiency

- The harmonic amplitude and THD of the 17 times of current **are reduced successively**, and the efficiency is always **maintained near 98%**
- The proposed method **is well adapted within the range of 300W-1500W**, and the suppression effect is further improved in comparison with that of the fixed virtual conductor method

Outline

Conclusion

- For the grid-side current harmonics caused by LC resonance, a grid-side current harmonic suppression method based on adaptive active damping has been proposed in this paper, which utilizes a digital filter to extract the input voltage harmonics and an interpolation method to design an adaptive virtual admittance
- The accuracy and adaptability of the damping control are improved
- Experimental results have demonstrated that the investigated current harmonic suppression method can improve the grid-side power quality over a wide load range

Thanks for your listening!