Modeling and Advanced Control of a Dual Active Bridge DC/DC Converter

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ZJU-Hangzhou Global Scientific and Technological Innovation Center

Contents

- DAB modeling methods, quantitatively compare the following models:
  - Reduced order model
  - Generalized average model
  - Discrete-time model

- DAB control, quantitatively compare the following control methods:
  - Conventional feedback control
  - Feedforward plus feedback control
  - Virtual direct power control
  - Disturbance observed based control
  - Feedforward current control
  - Predictive current control
  - Model predictive control

- Practical control issues of DAB
  - Phase drift
  - Steady state magnetizing flux bias
  - Transient magnetizing flux bias

Zhejiang University (ZJU)

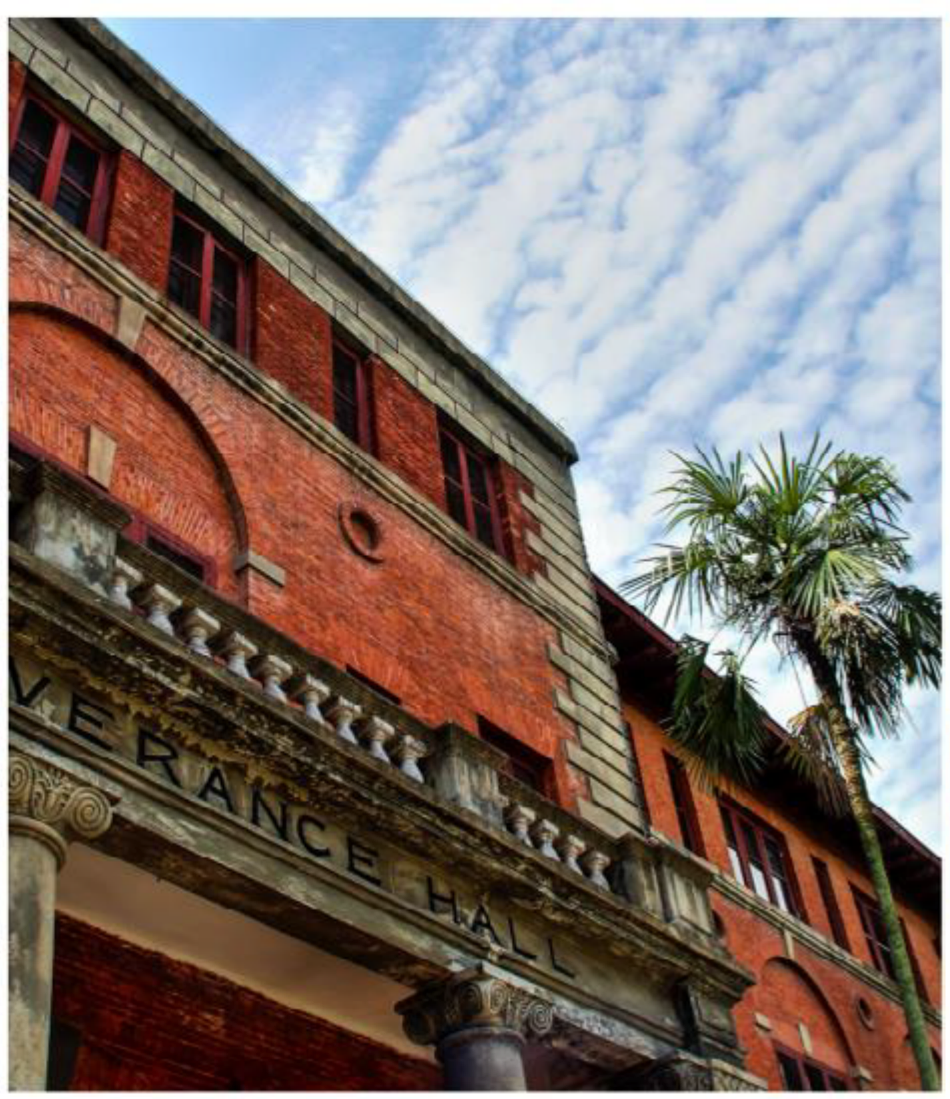
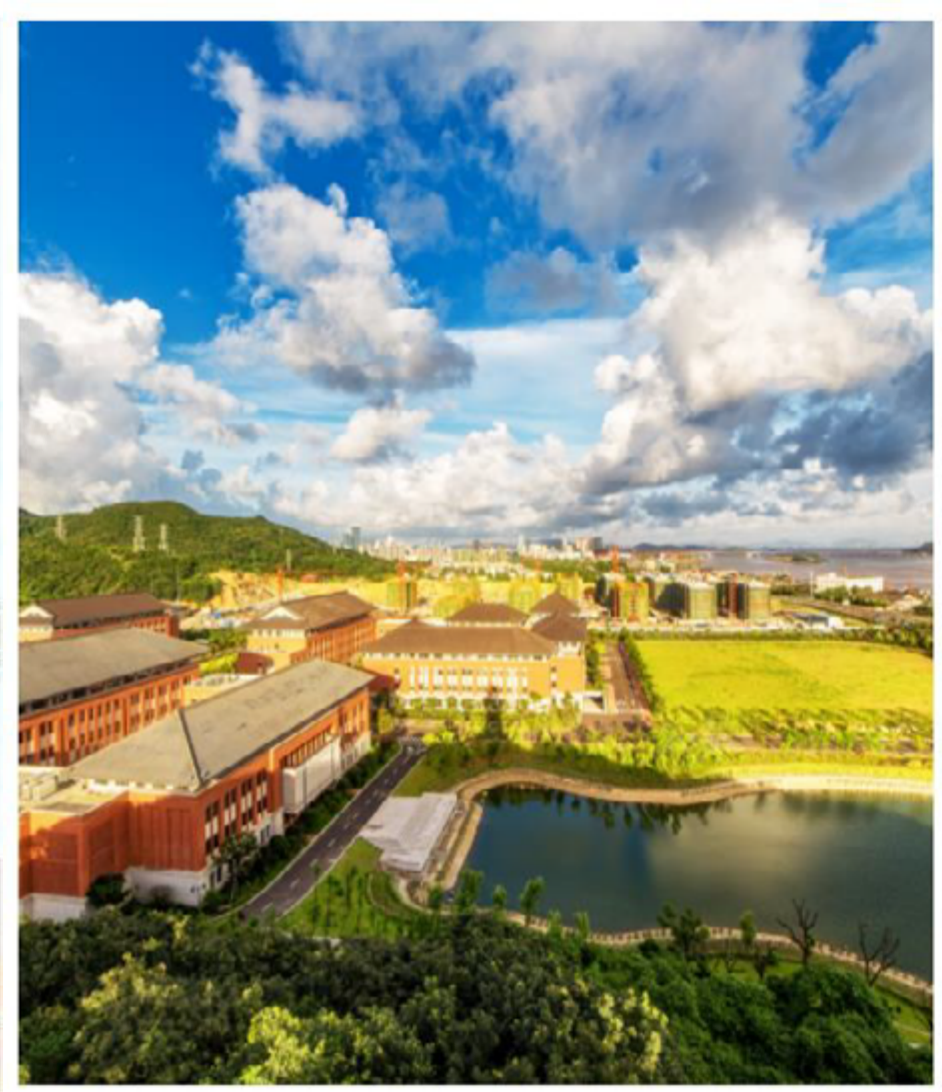
- In Hangzhou, host city of G20 Summit 2016 and the 2022 Asian Games
- Founded 1897
- 37 Colleges and Schools
- Full-time faculty: 3,741
- Students 54,641
  - Undergraduate: 25,425
  - Graduate: 29,216
  - International students: 7,074

International Rankings	Regional Rankings	National Rankings
#54	**#6**	**#3**
QS World University Rankings >	Asia University Rankings >	Best Chinese Universities Ranking >
QS, 2020	QS, 2020	ShanghaiRanking Consultancy, 2018

7 campus at Zhejiang University






DC Microgrid

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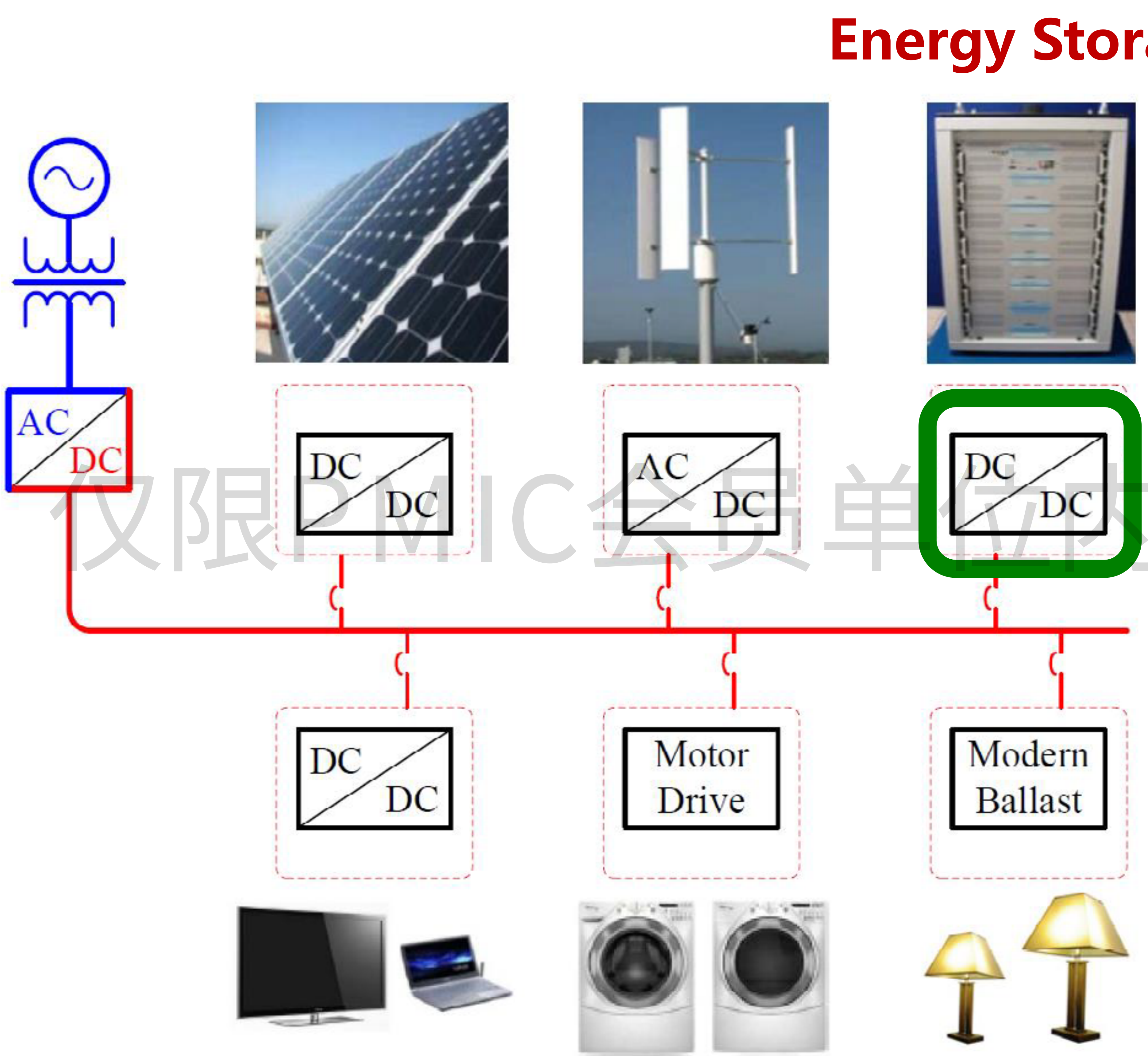

Compared with AC, a DC grid has:

- **Higher efficiency**
- **Better power capacity**
- **Better controllability**

[1] T. Dragičević. et. al , "DC Microgrids—Part I: A Review of Control Strategies and Stabilization Techniques," in *IEEE Transactions on Power Electronics*, 2016.

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DC Smart Grid

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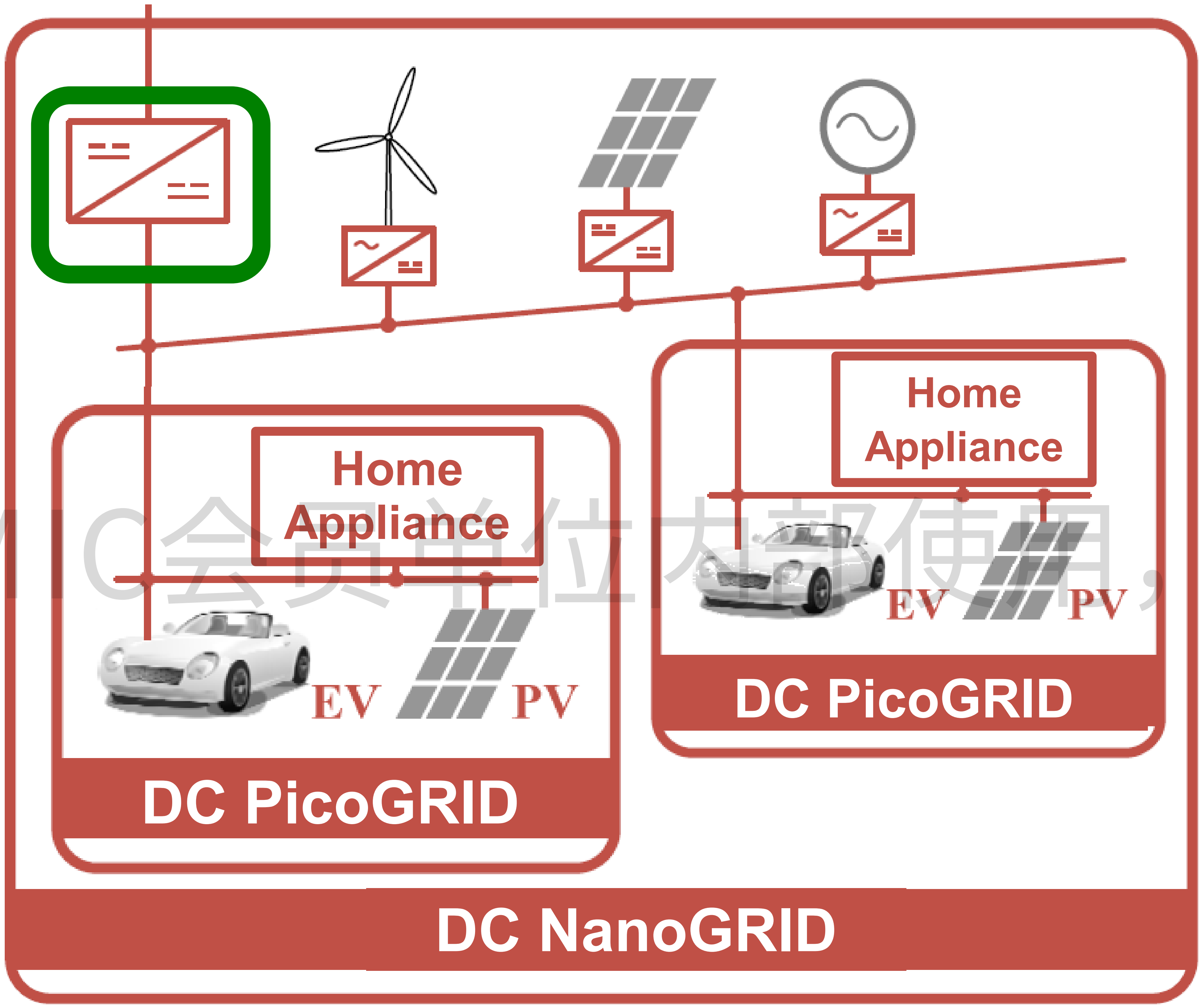
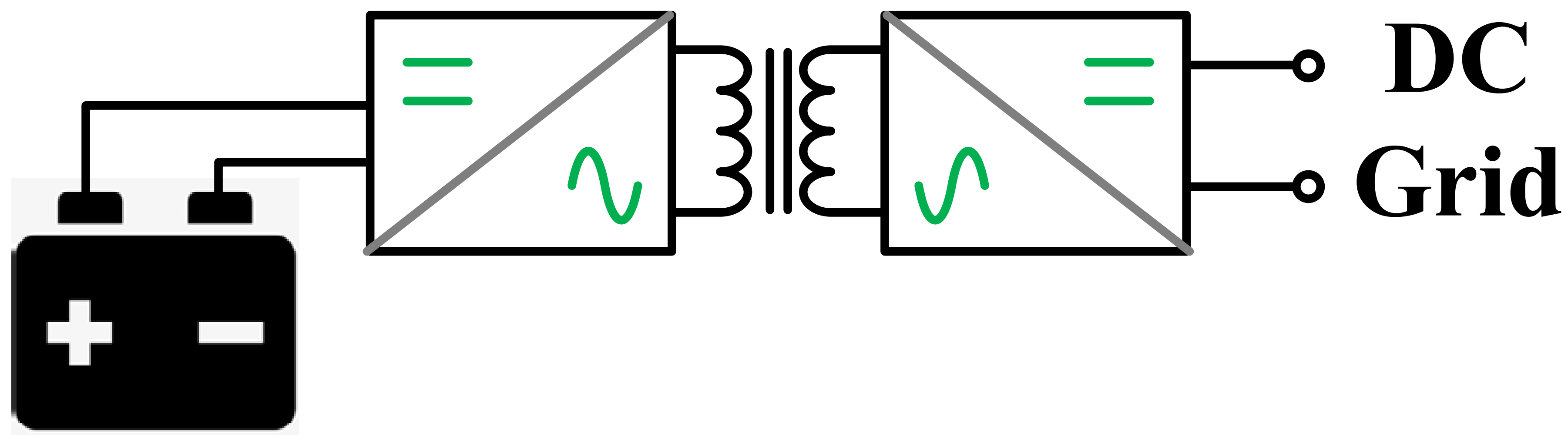
DC Transformer



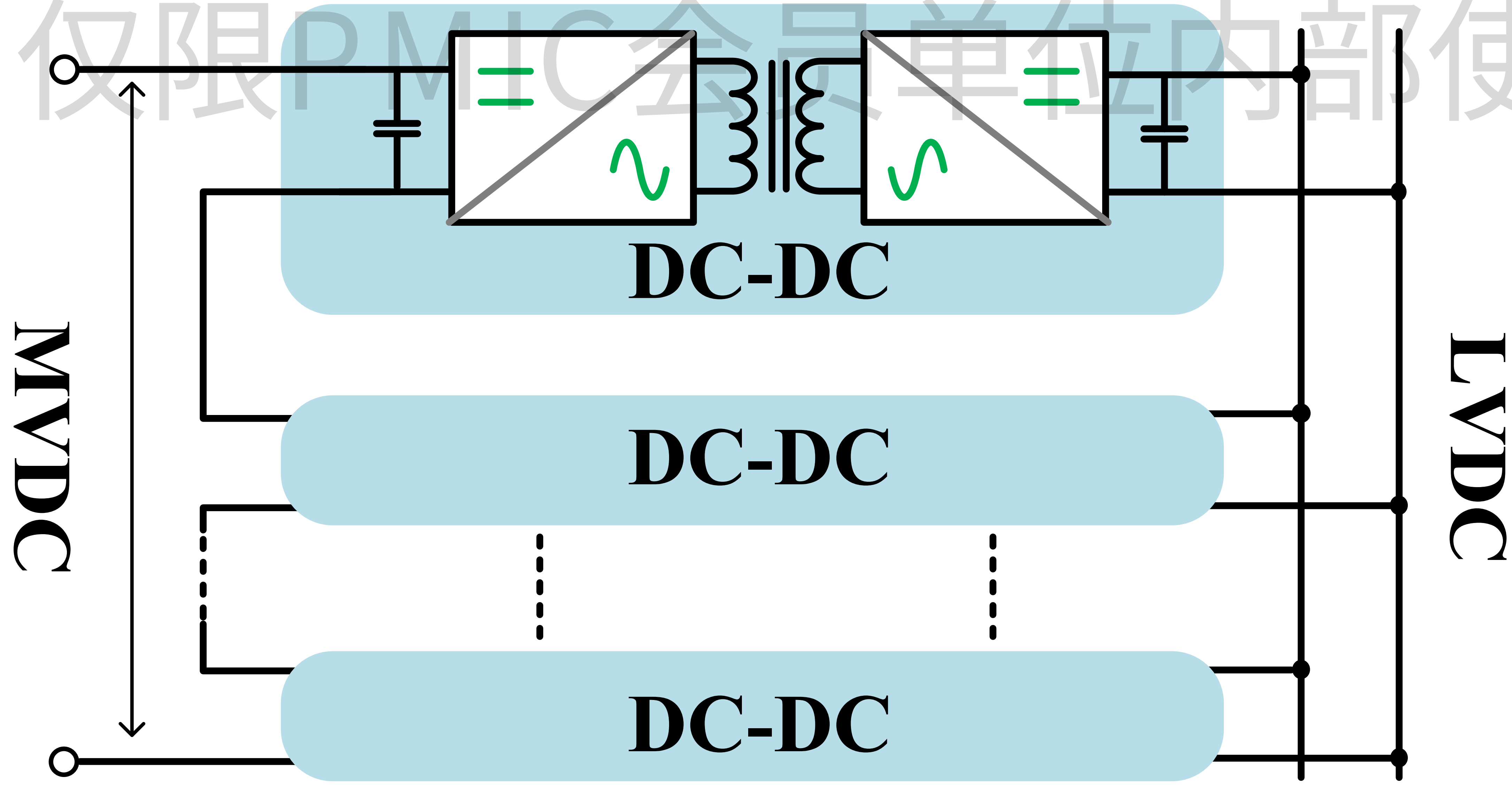
[1] Yunjie Gu, “Distributed Peer-to-Peer Control for Renewable Power Generation DC Microgrid”, Zhejiang University, PhD thesis, 2015

[2] D. Boroyevich, I. Cvetković, D. Dong, R. Burgos, F. Wang and F. Lee, "Future electronic power distribution systems a contemplative view," 2010 12th International Conference on Optimization of Electrical and Electronic Equipment, Basov, 2010, pp.

Isolated bidirectional DC–DC



Interface of Energy storage



Building Blocks of DC Transformer

Isolated bidirectional DC–DC

Dual flyback

Dual Cuk

Dual push-pull

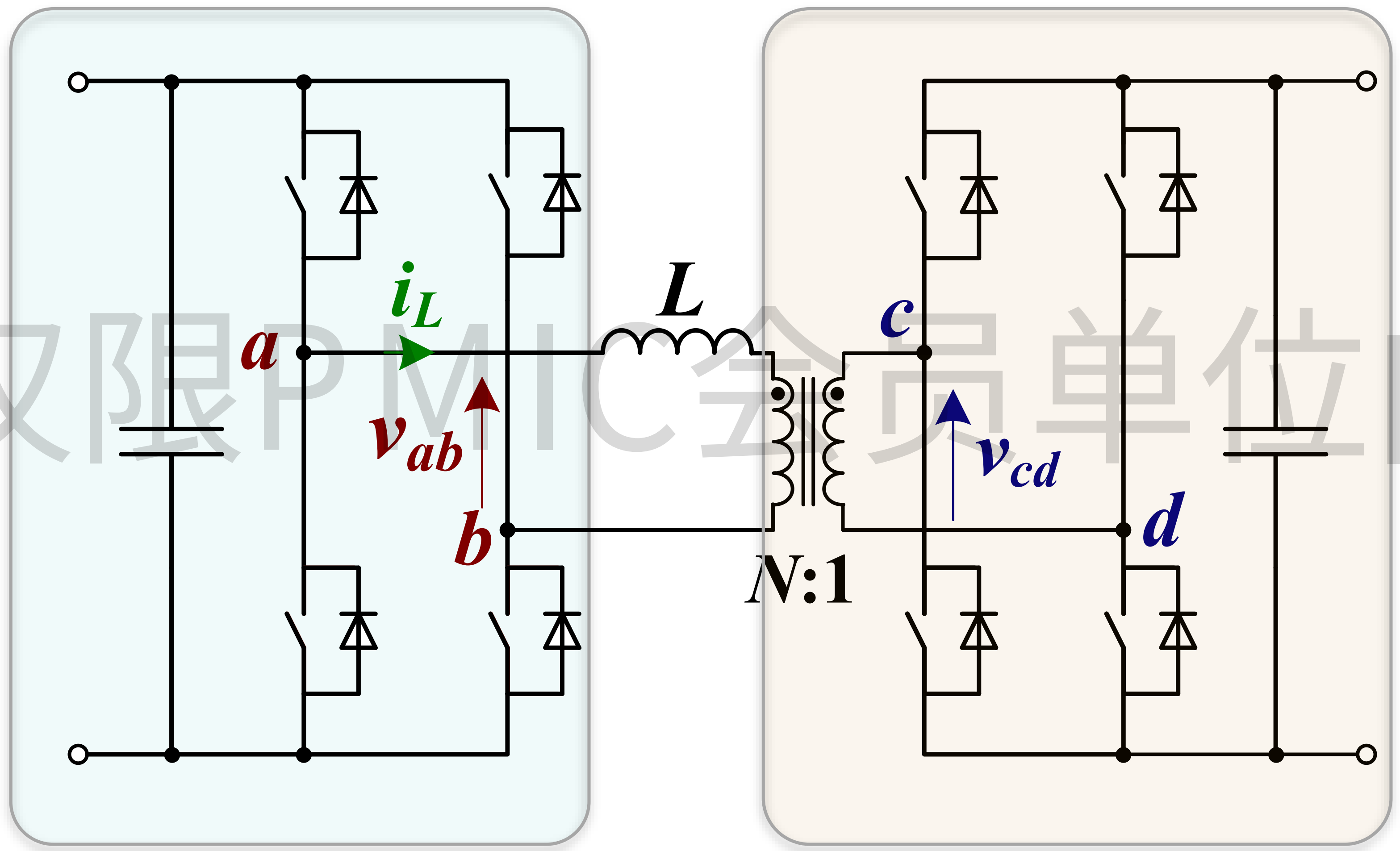
Bidirectional Resonant Converter

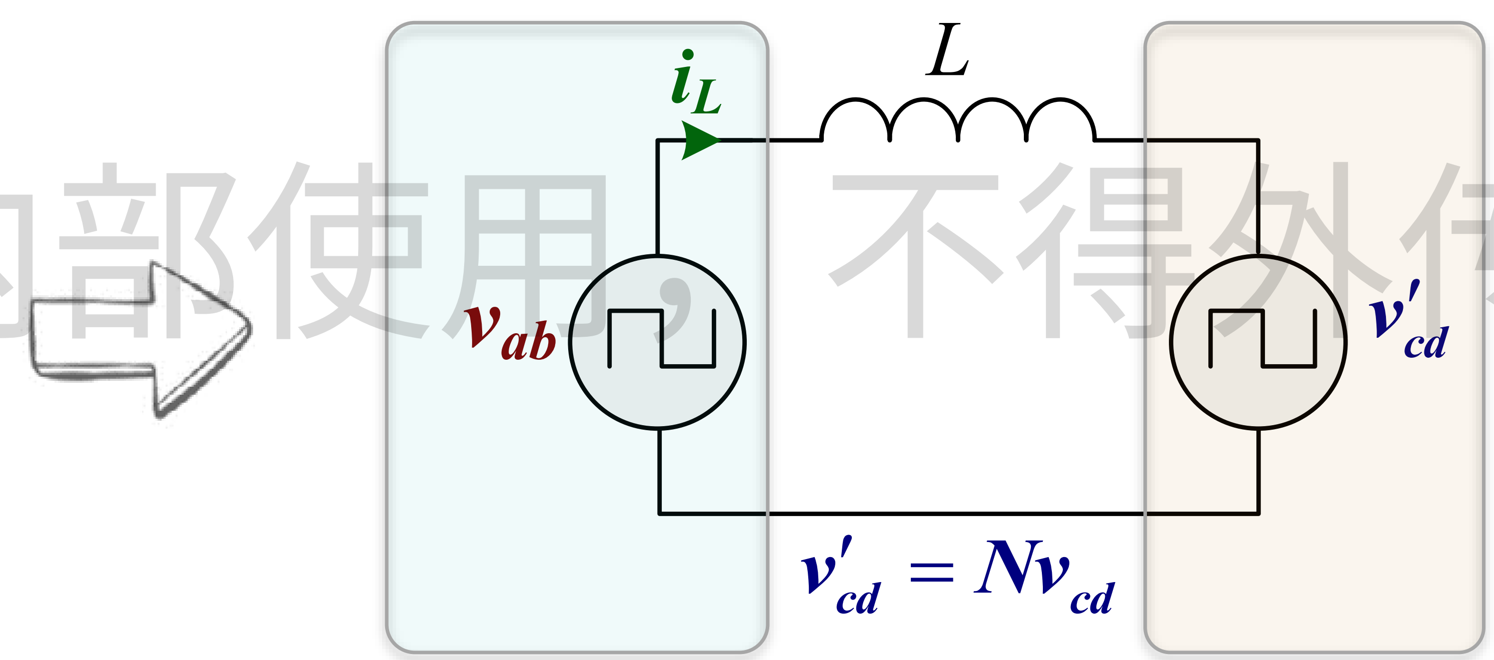
Dual Active Bridge (DAB)

- Simple
- Auto-adjust bidirectional power flow
- Wide voltage conversion range
- Zero voltage switching (ZVS) capability

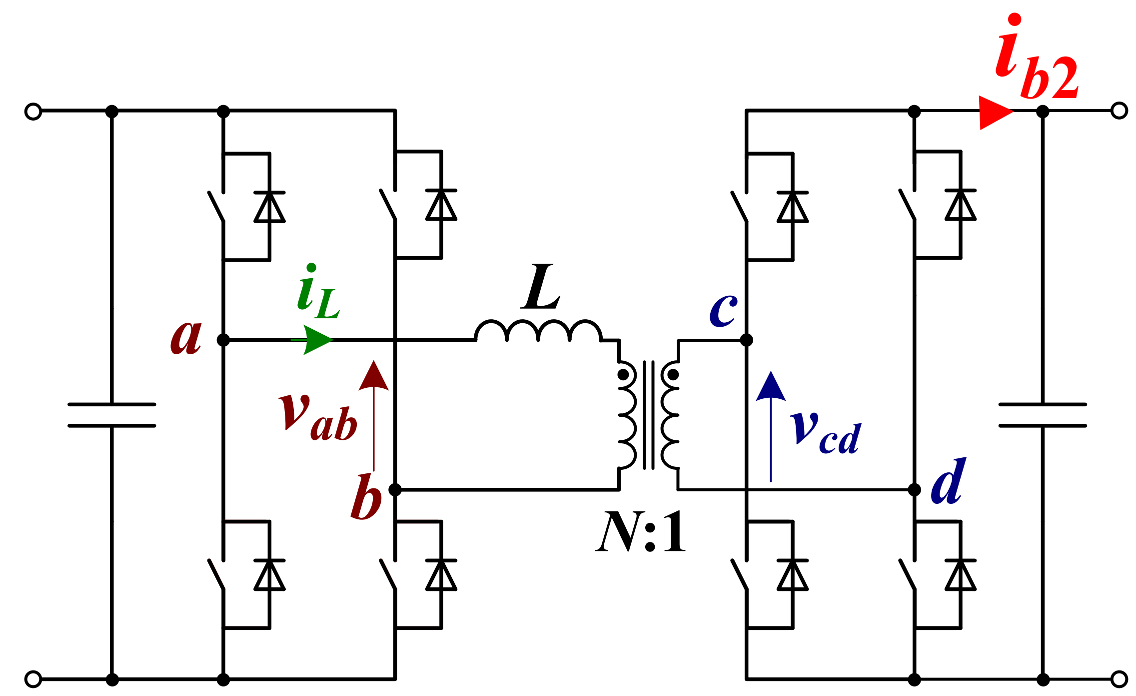
Dual Active Bridge

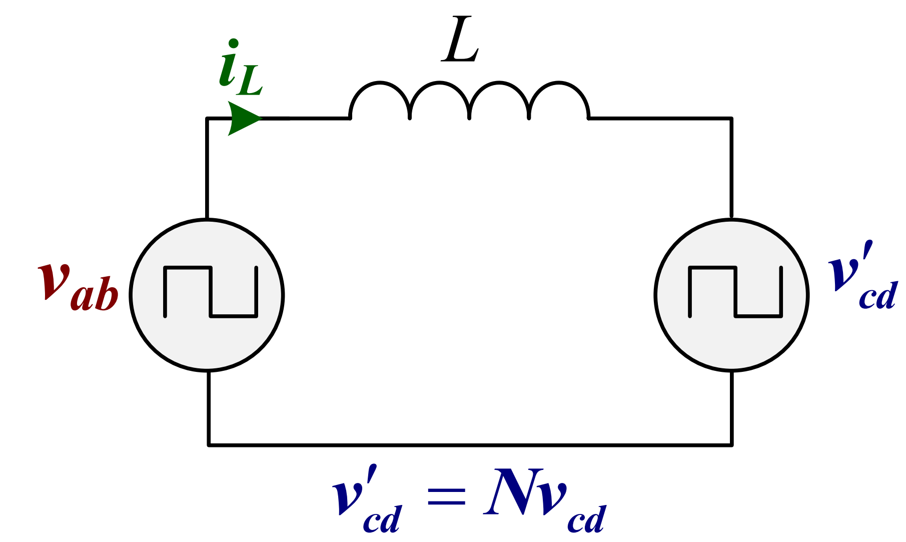
- **Simple structure**

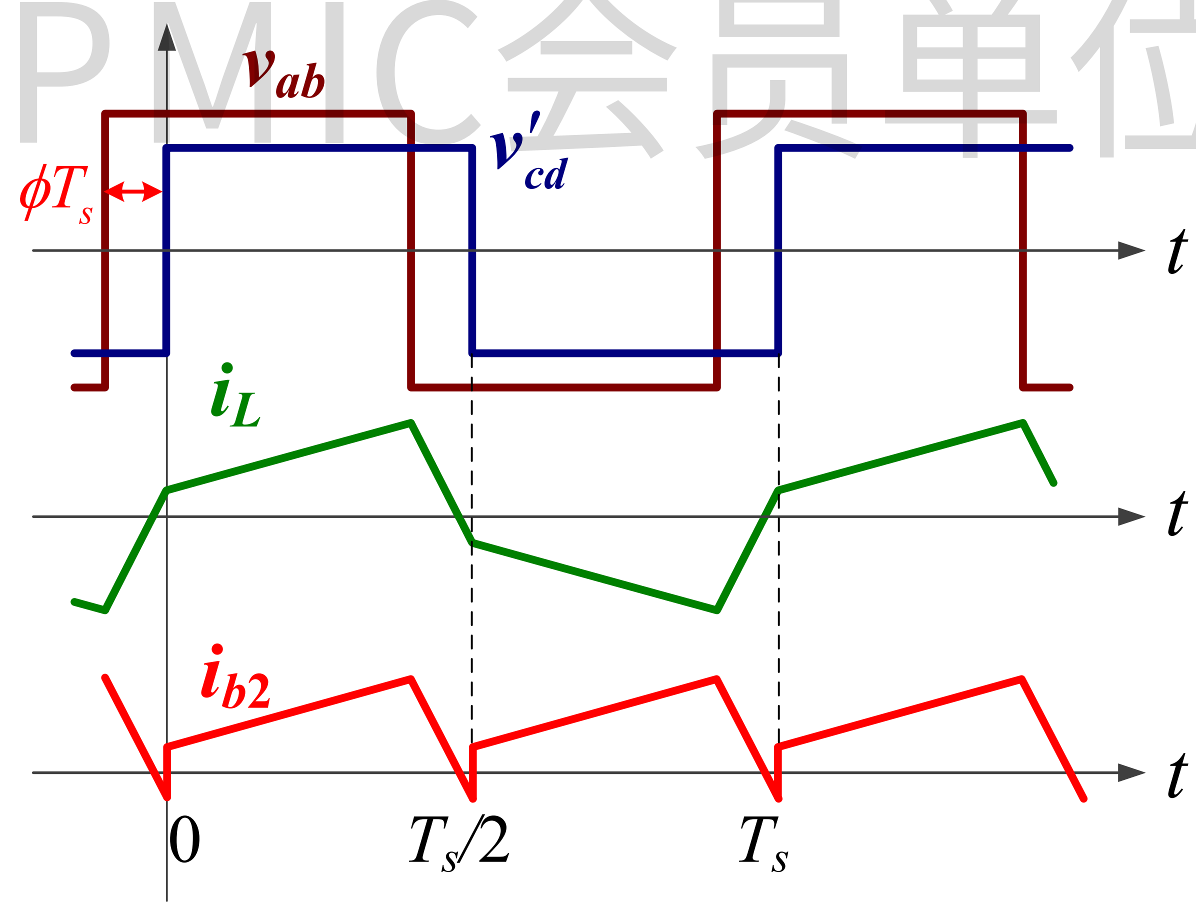


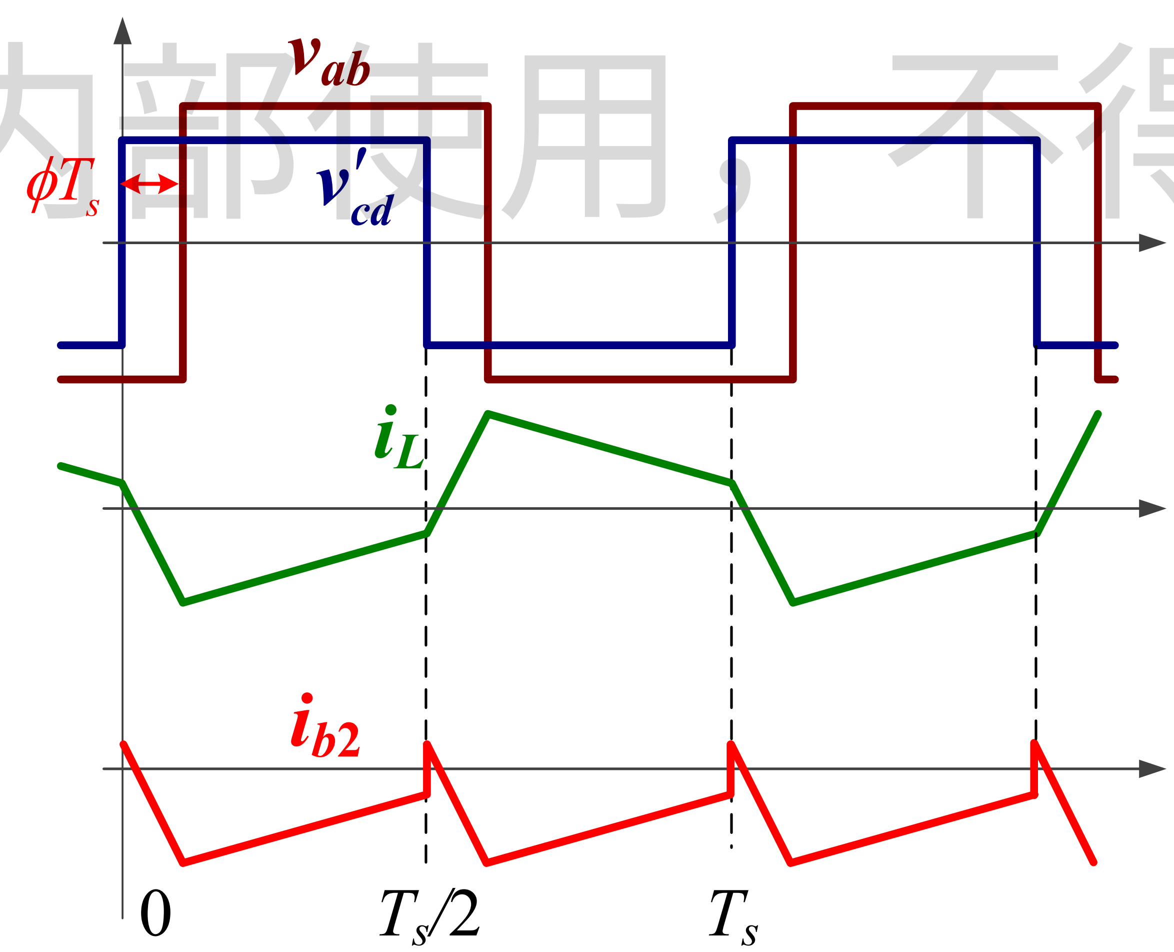


[1] R. Doncker, et. al. “A three-phase soft-switched high power density dc/dc converter for high power applications,” in Conference Record of the 1988 IEEE Industry Applications Society Annual Meeting, Oct 1988







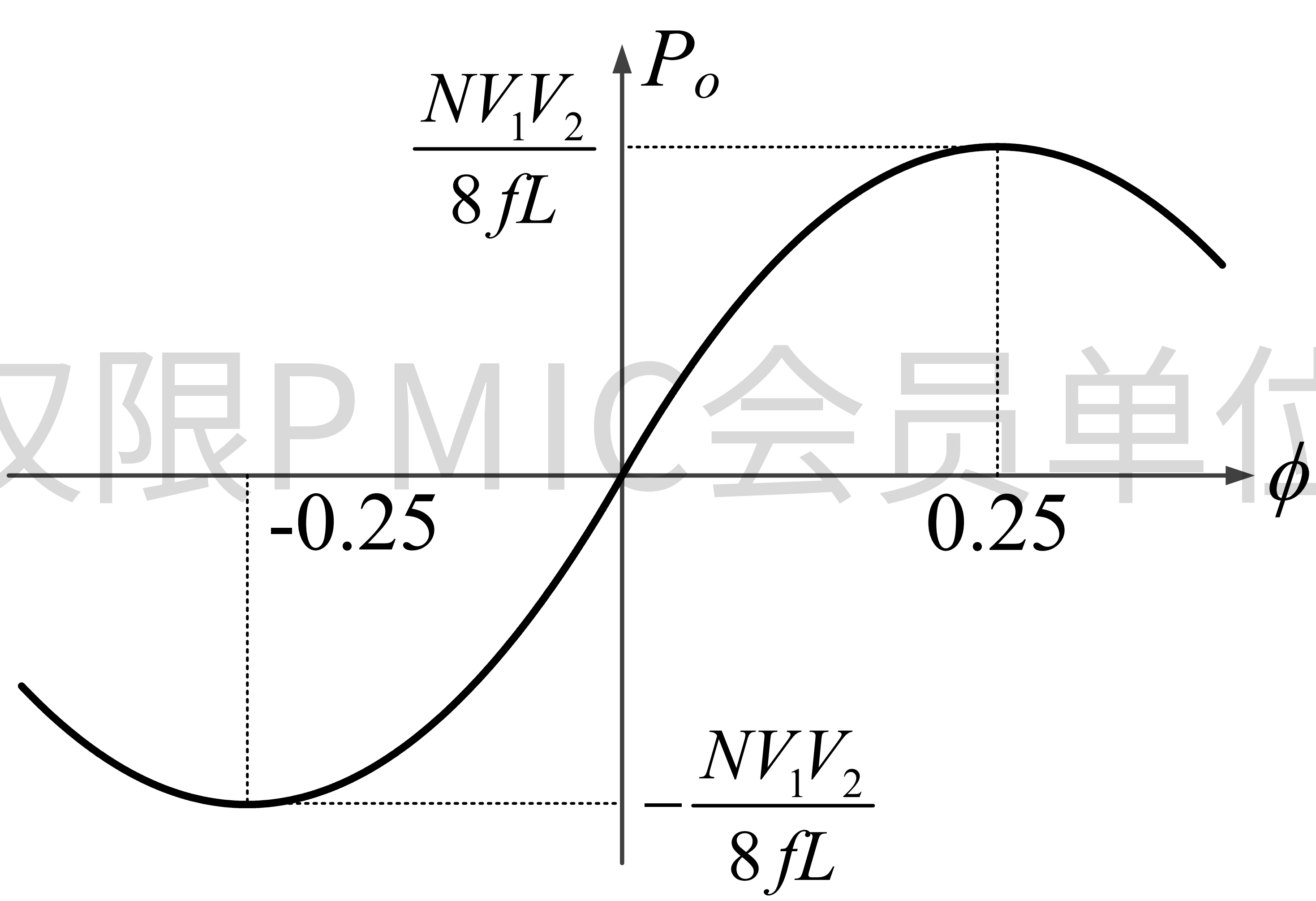


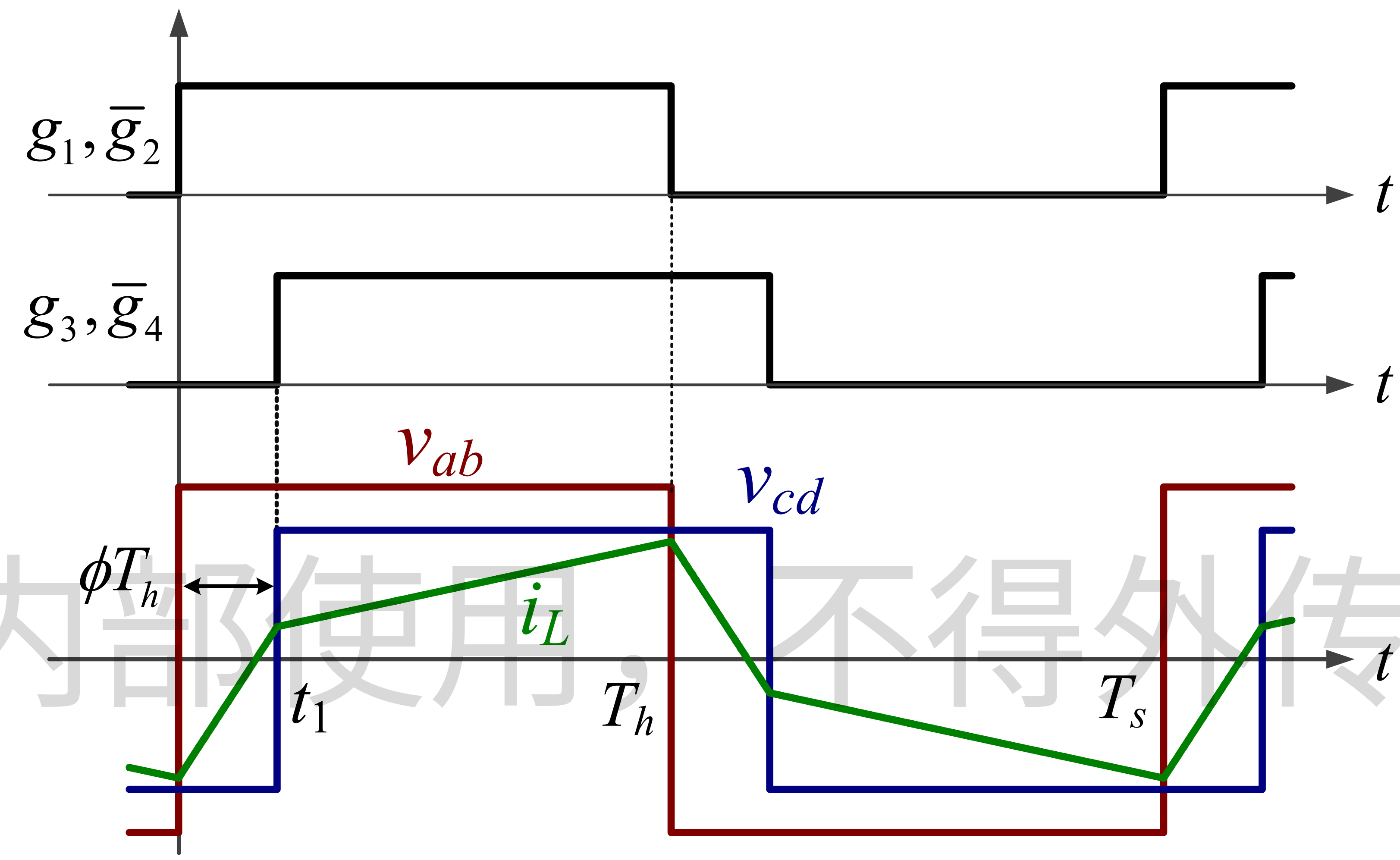
$\phi > 0$, Positive power flow

$\phi < 0$, Negative power flow

DAB output power

$$P_o = \frac{N v_1 v_2 \phi (1 - 2|\phi|)}{f_s L}$$





DAB waveforms using SPS modulation

- **Output voltage can be regulated by adjusting ϕ**
  - **Under any voltage range**
  - **Bidirectional**

Contents

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Power Converter Modeling

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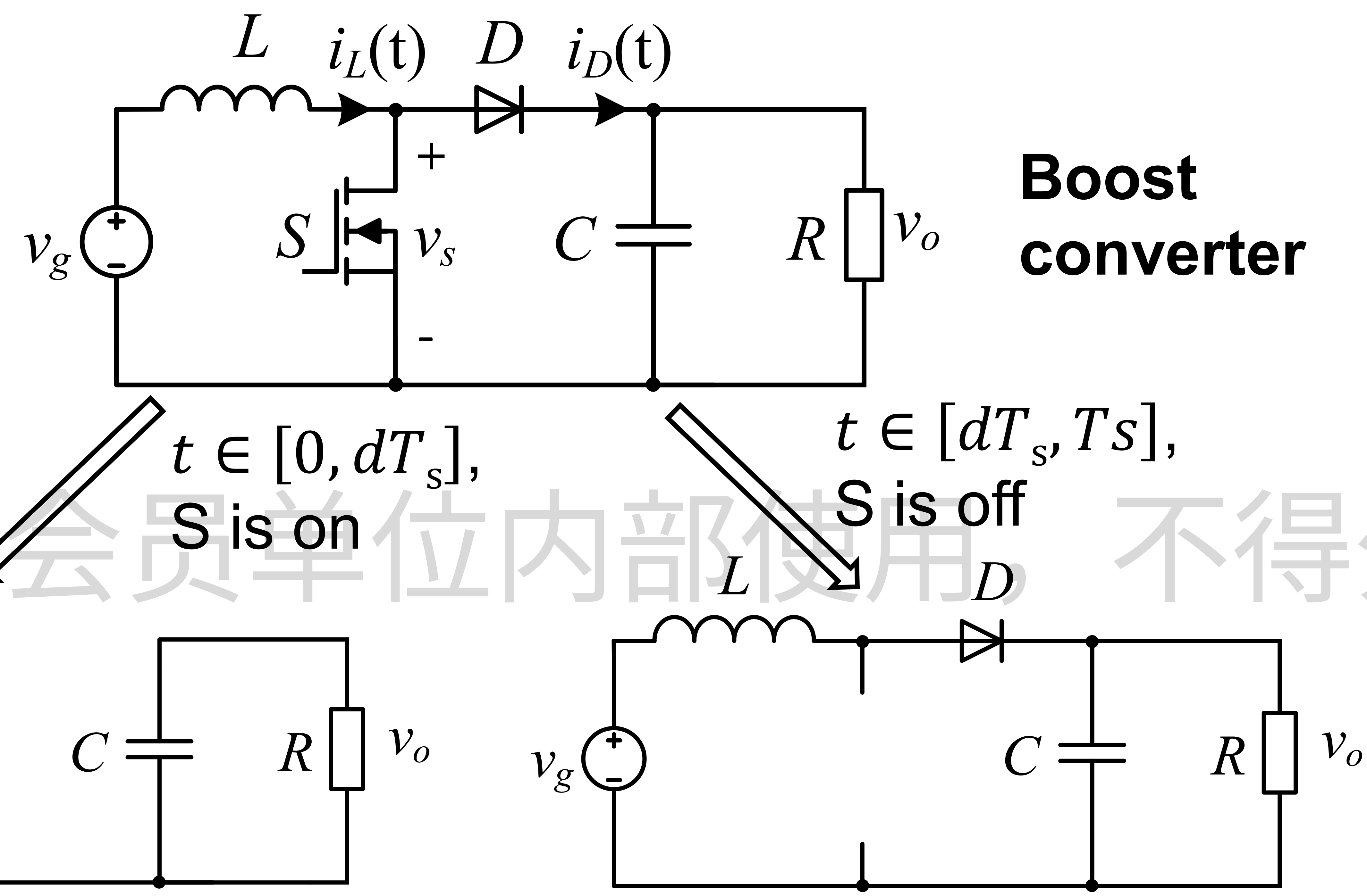
- Modeling = Representation of a physical phenomena by mathematical means.
- A power converter model can be useful to design the controller and to analyze the stability.
- Model dominant behavior of system, ignore other insignificant but complicated phenomena.
  - Simplified model yields physical insight, allowing engineer to design system to operate in specified manner.

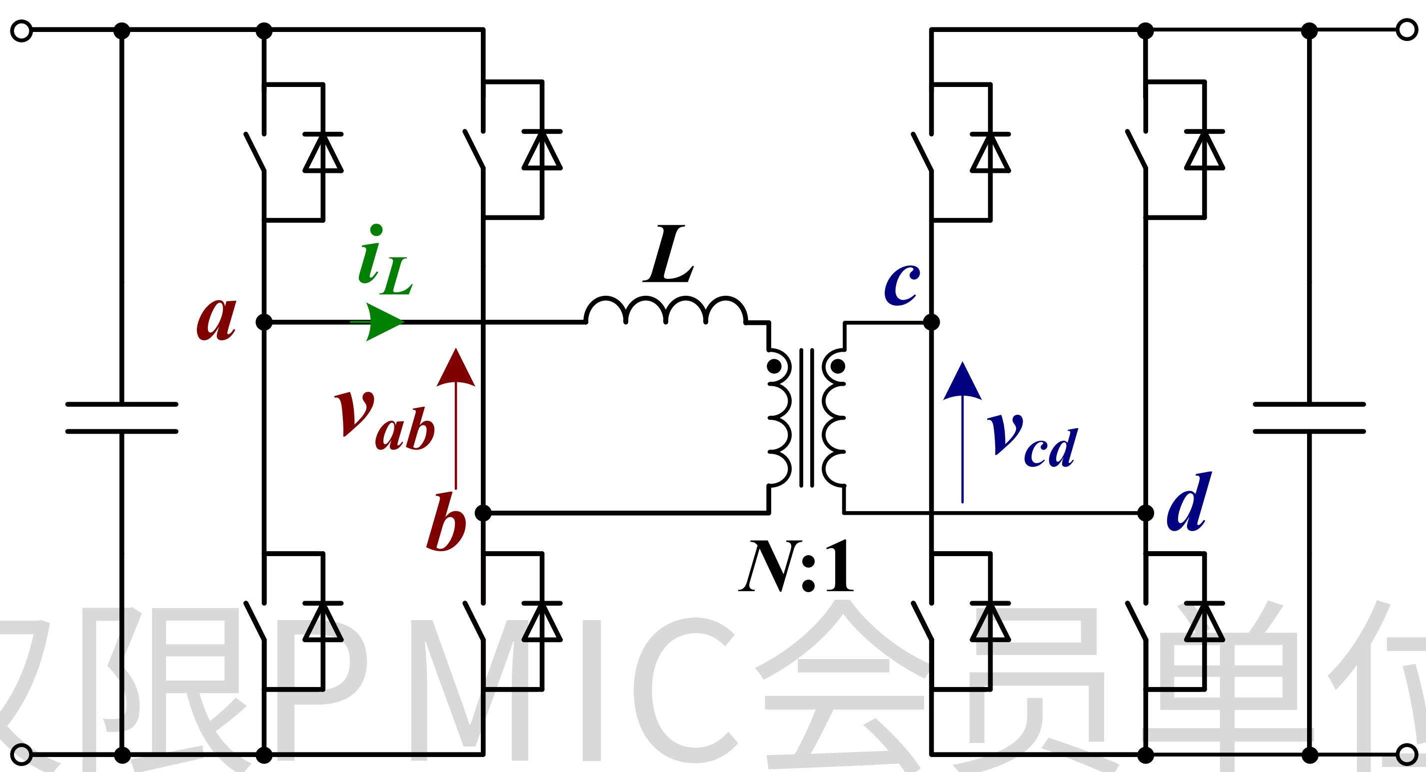
Reference: Erickson R W, Maksimovic D. **Fundamentals of power electronics**[M]. Springer Science & Business Media, 2007.

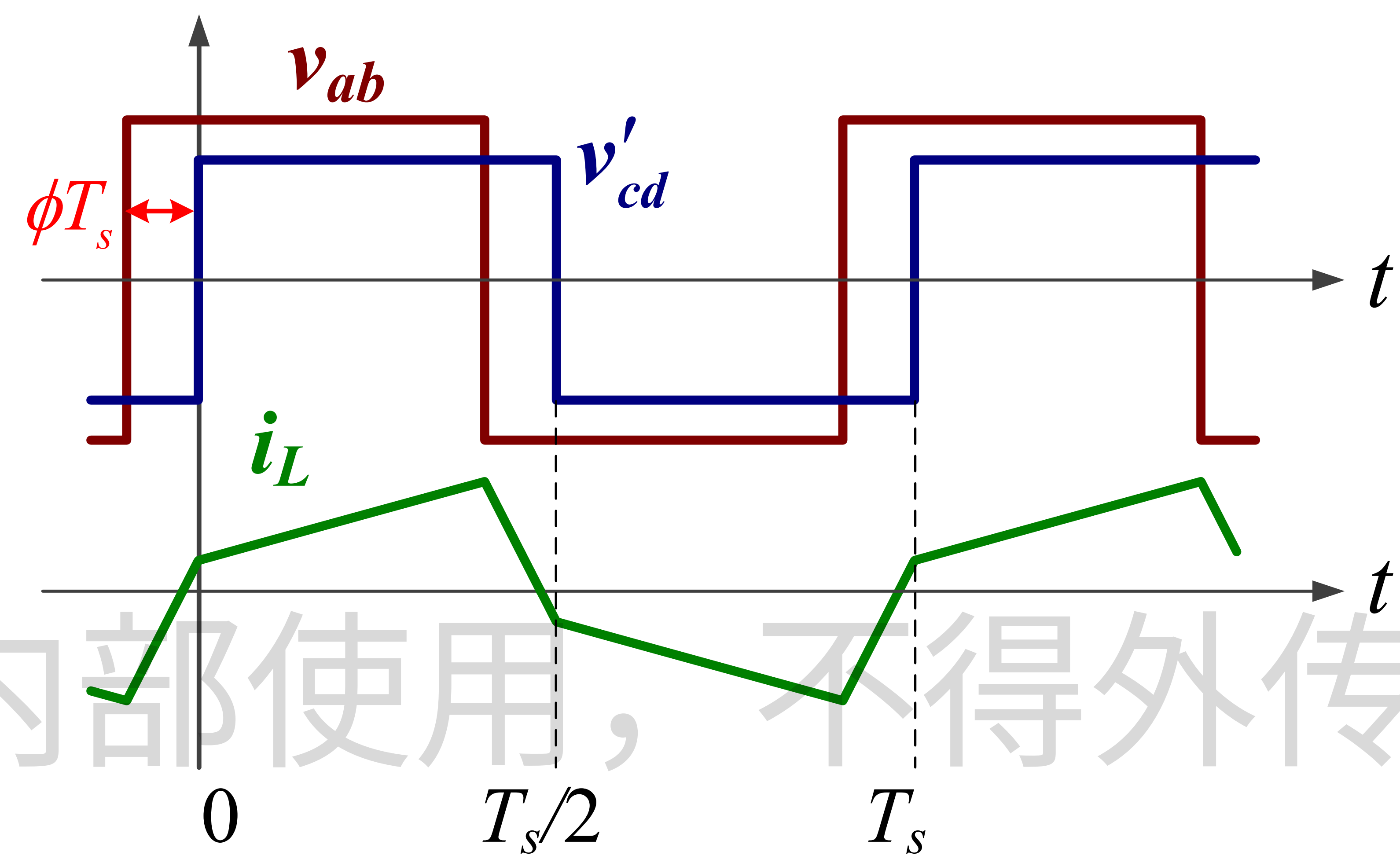
Modeling of conventional converters



$$\mathbf{X} = \begin{bmatrix} i_L \\ v_o \end{bmatrix} \qquad \dot{\mathbf{X}} = \mathbf{A}_1\mathbf{X} + \mathbf{B}_1\mathbf{U} \qquad \dot{\mathbf{X}} = \mathbf{A}_2\mathbf{X} + \mathbf{B}_2\mathbf{U}$$

Switching cycle average: $\dot{\mathbf{X}} = \mathbf{A}\mathbf{X} + \mathbf{B}\mathbf{U}$ **where** $\begin{cases} \mathbf{A} = \mathbf{A}_1 d + \mathbf{A}_2(1-d) \\ \mathbf{B} = \mathbf{B}_1 d + \mathbf{B}_2(1-d) \end{cases}$



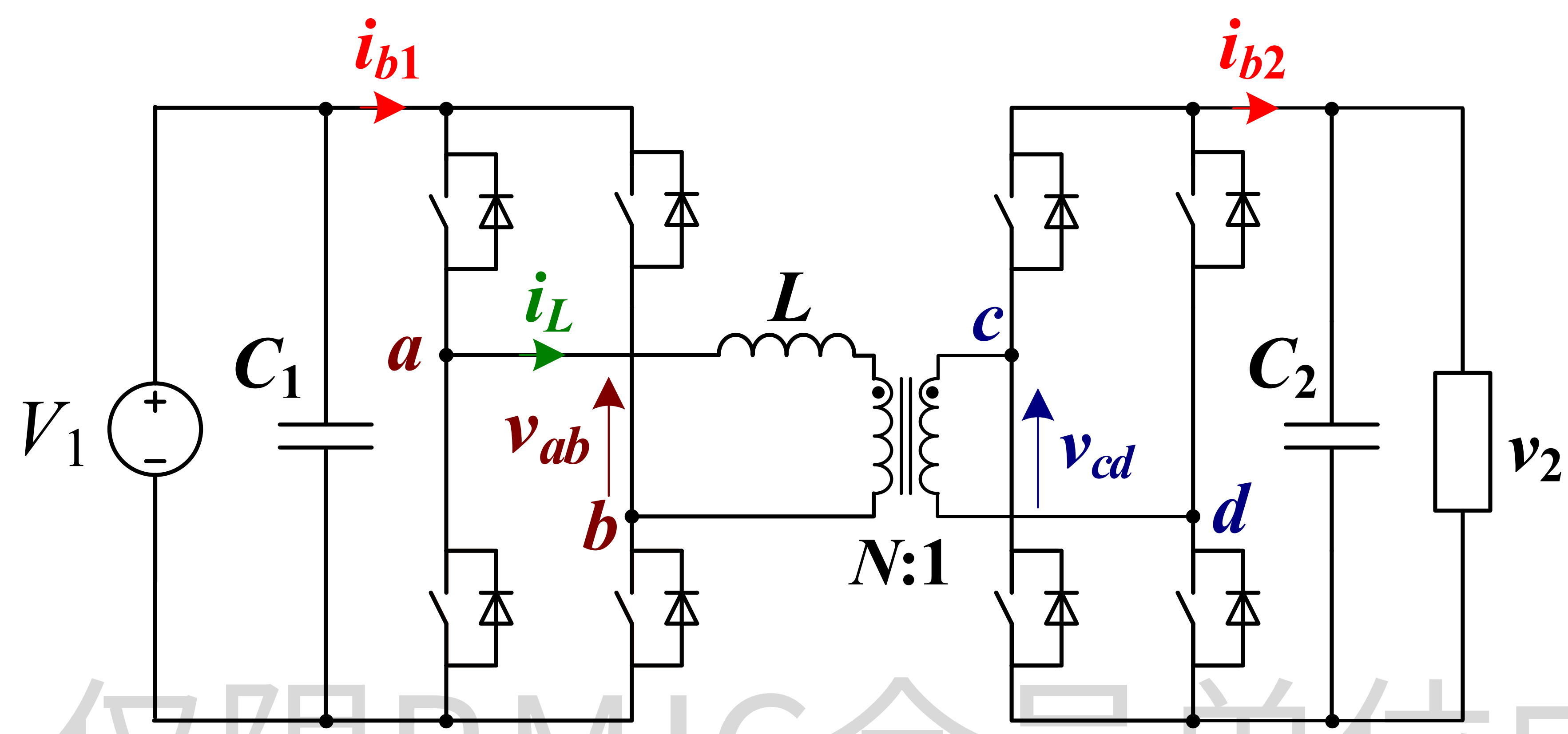


- i_L is purely ac with a averaging value 0, switching cycle average cannot be used directly.

Modeling of A DAB

- **Reduced order model**
- **Generalized average model**
- **Discrete-time model**

Reduced order model

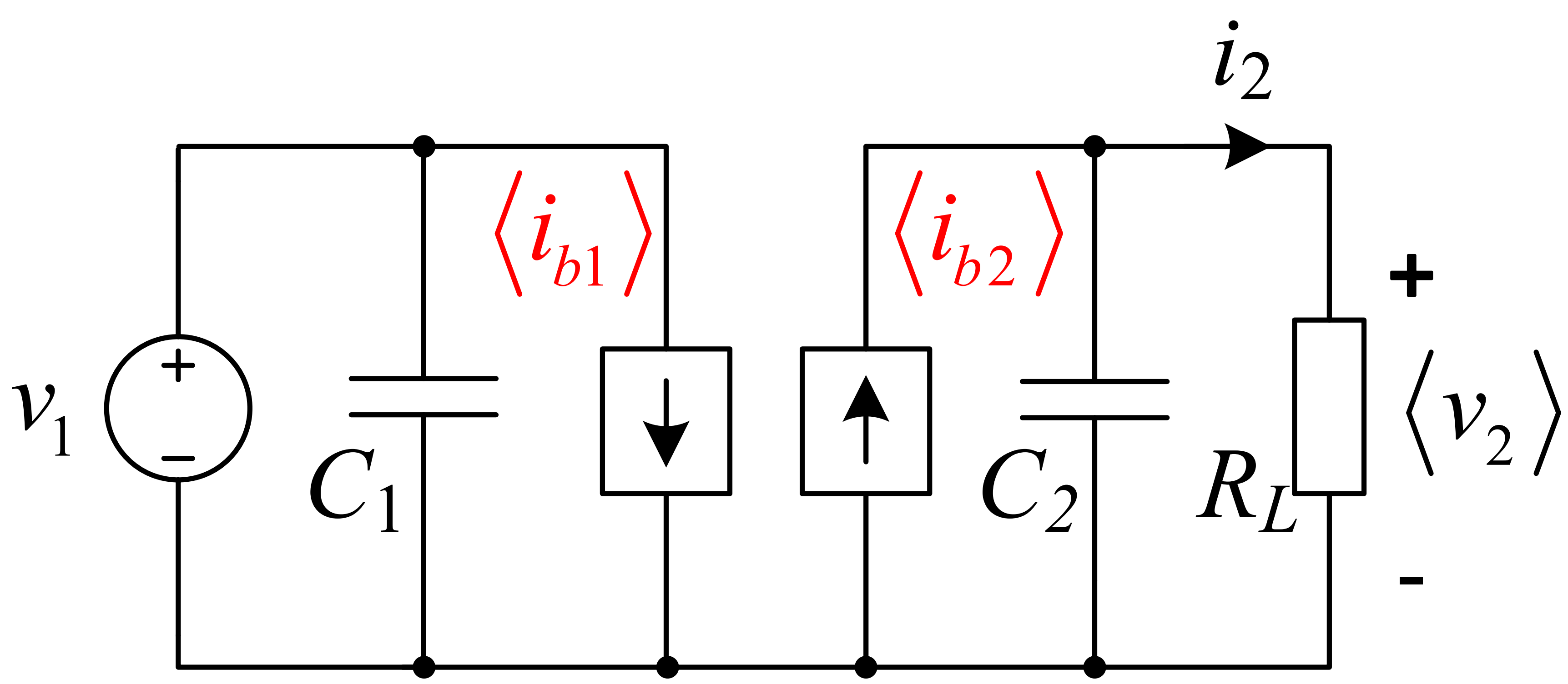


$$P_o = \frac{N v_1 v_2 \phi(1-2|\phi|)}{f_s L}$$

$$= v_2 \langle i_{b2} \rangle$$

Average value of i_{b2}

Ignore the dynamics of $\boldsymbol{i_L}$



$$\Rightarrow \langle i_{b2} \rangle = \frac{N v_1 \phi(1-2\phi)}{f_s L}$$

Reduced order model

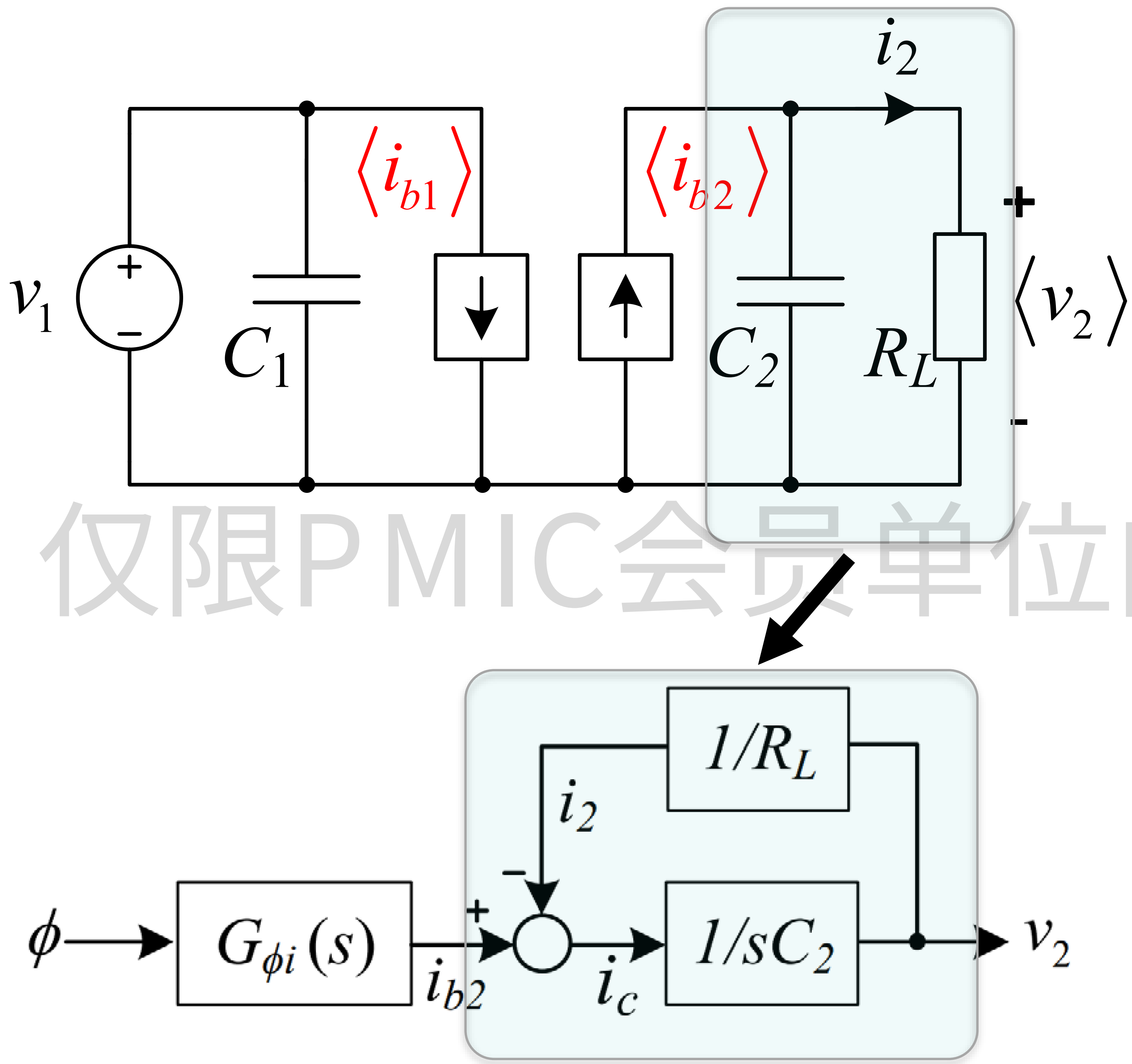


Diagram of the reduced order model

$$\langle i_{b2} \rangle = \frac{N v_1 \phi (1-2\phi)}{f_s L}$$

Introducing perturbation

$$\Rightarrow G_{i\phi}(s) = \frac{\hat{i}_{b2}}{\hat{\phi}} = \frac{N V_1 (1-4\Phi)}{f_s L}$$

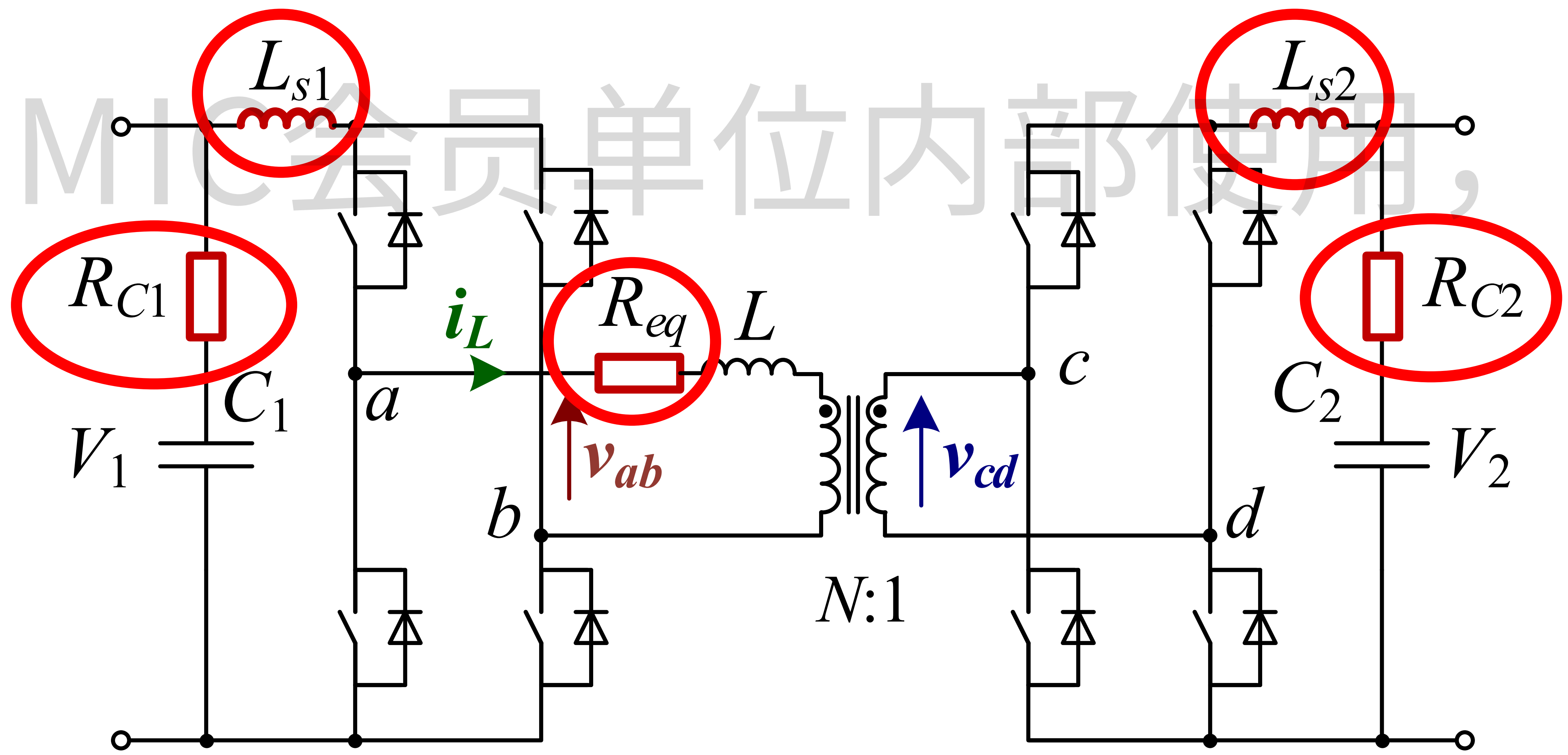
Transfer function

$$G_{v\phi}(s) = \frac{\hat{v}_2}{\hat{\phi}} = \frac{N V_1 (1-4\Phi)}{f_s L} \frac{R_L}{R_L C_2 s + 1}$$

First order system

Improved reduced order model

- **Improve the accuracy of reduced order model by considering the parasitic parameters.**
- **Resultant model is much more complex.**



[1] K. Zhang, Z. Shan, and J. Jatskevich, “Large- and small-signal average-value modeling of dual-active-bridge dc-dc converter considering power losses,” IEEE Transactions on Power Electronics, vol. 32, no. 3, pp. 1964–1974, March 2017.

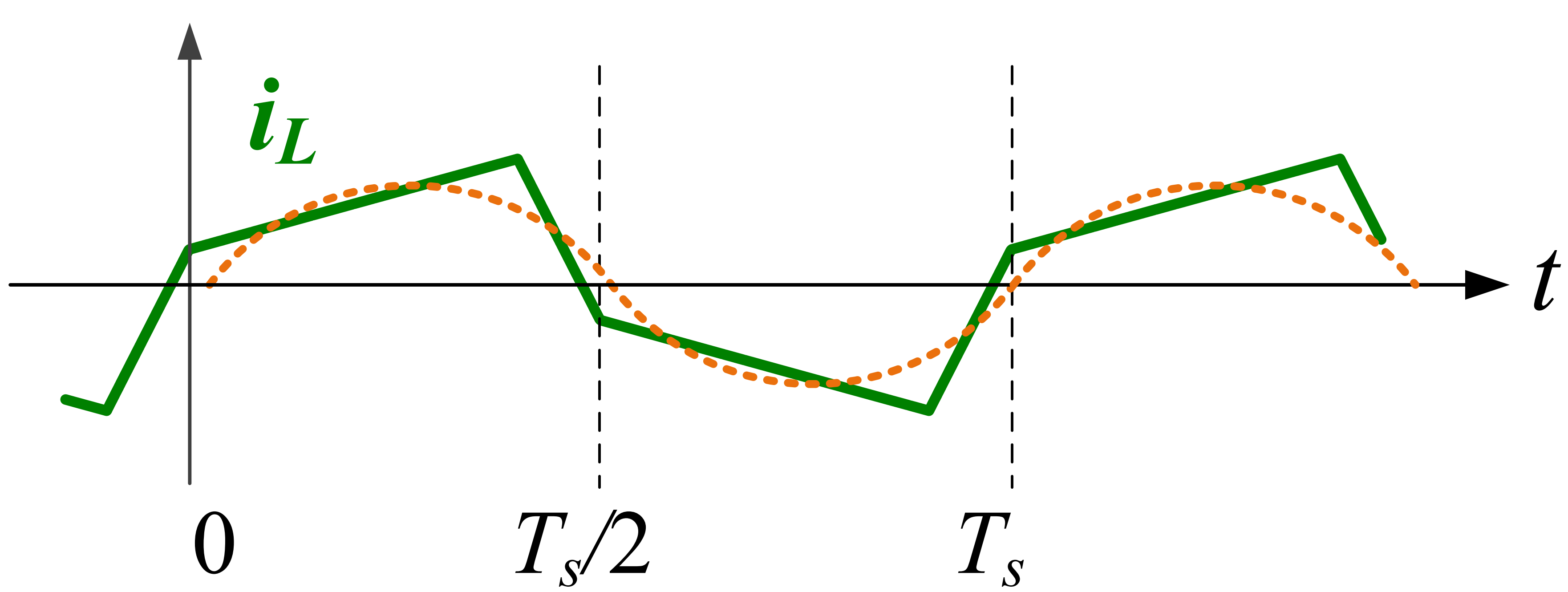
Generalized average model

- **$x(\tau)$ can be represented using its Fourier series**

$$x(\tau)=\sum_{-\infty}^{\infty}\langle x\rangle_k(t)e^{jk\omega_s\tau}=\cdots+\langle x\rangle_{-1}(t)e^{-j\omega_s\tau}+\langle x\rangle_0+\langle x\rangle_1(t)e^{j\omega_s\tau}+\cdots$$

where $\langle x\rangle_k$ is the *k*th coefficient

- **Conventional state-space averaging only considers the dc term $\langle x\rangle_0$, generalized averaging can include more terms.**
- **For the inductor current i_L in DAB, $k=\pm1$ the fundamental component can be considered.**



Generalized average model

Generalized average, small signal model

$$\begin{cases} d\mathbf{x}/dt = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{U} \\ \mathbf{y} = \mathbf{C}\mathbf{x} \end{cases}$$

where

$$\mathbf{x} = \begin{bmatrix} \hat{v}_{2(0)} & \hat{i}_{LR(1)} & \hat{i}_{LI(1)} \end{bmatrix}^T$$

$$\mathbf{y} = \begin{bmatrix} \hat{v}_{2(0)} \end{bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} -\frac{2}{R_L C_2} & -\frac{8N\sin(2\pi\Phi)}{\pi C_2} & \frac{-8N\cos(2\pi\Phi)}{\pi C_2} \\ \frac{4N\sin(2\pi\Phi)}{\pi L} & -\frac{2R_{eq}}{L} & 2\omega_s \\ \frac{4N\cos(2\pi\Phi)}{\pi L} & -2\omega_s & -\frac{2R_{eq}}{L} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \frac{8}{C_2}\left(I_{LI(1)}\sin(2\pi\Phi) - I_{LR(1)}\cos(2\pi\Phi)\right) \\ \frac{4V_{2(0)}}{L}\sin(2\pi\Phi) \\ -\frac{4V_{2(0)}}{L}\sin(2\pi\Phi) \end{bmatrix}$$

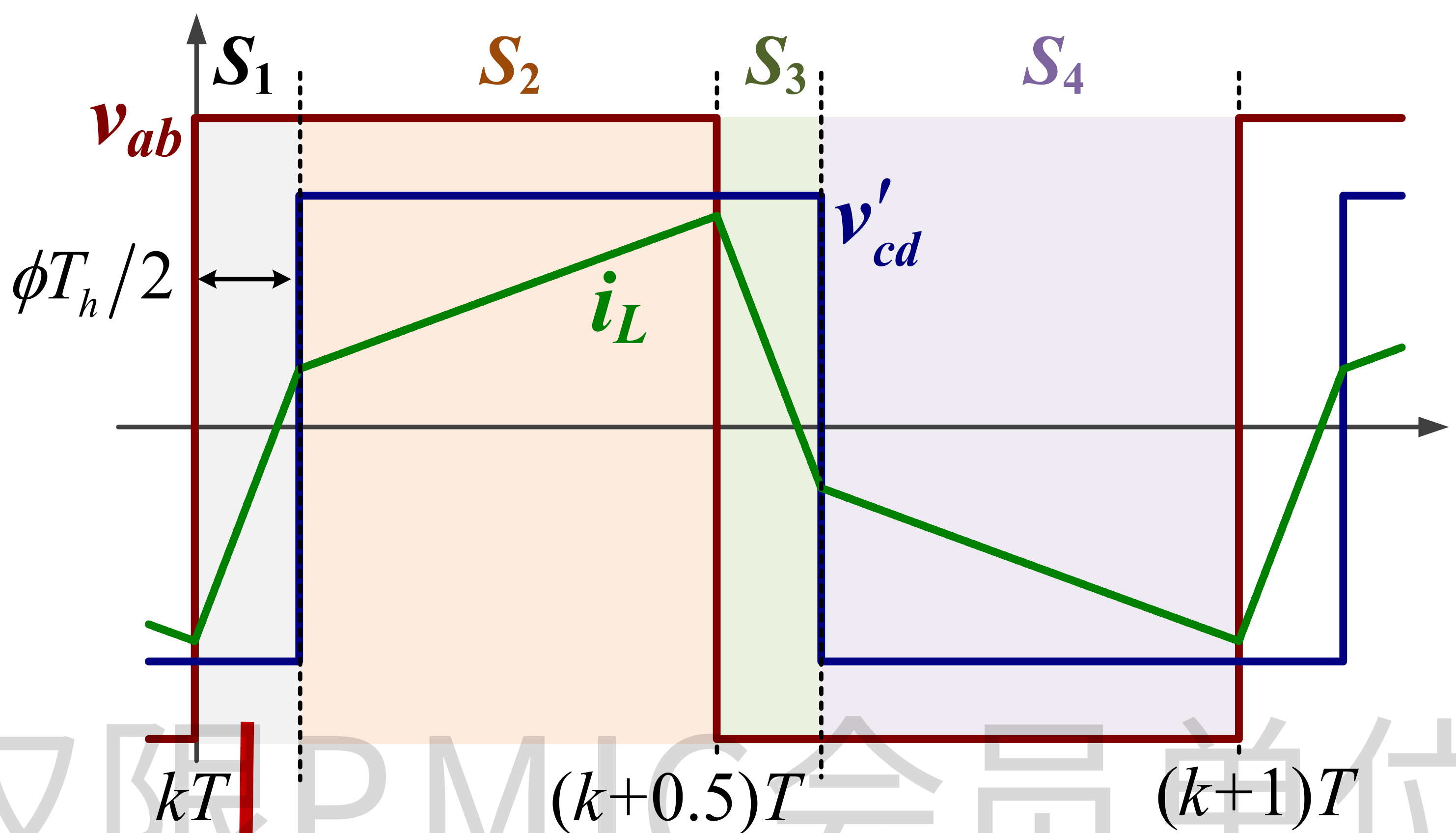
$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^T$$

Transfer function

$$G_{v\phi}(s) = C(sI - A)^{-1}B$$

[1] H. Qin and J. W. Kimball, "Generalized average modeling of dual active bridge dc-dc converter," IEEE Transactions on Power Electronics, vol. 27, no. 4, pp. 2078–2084, April 2012.

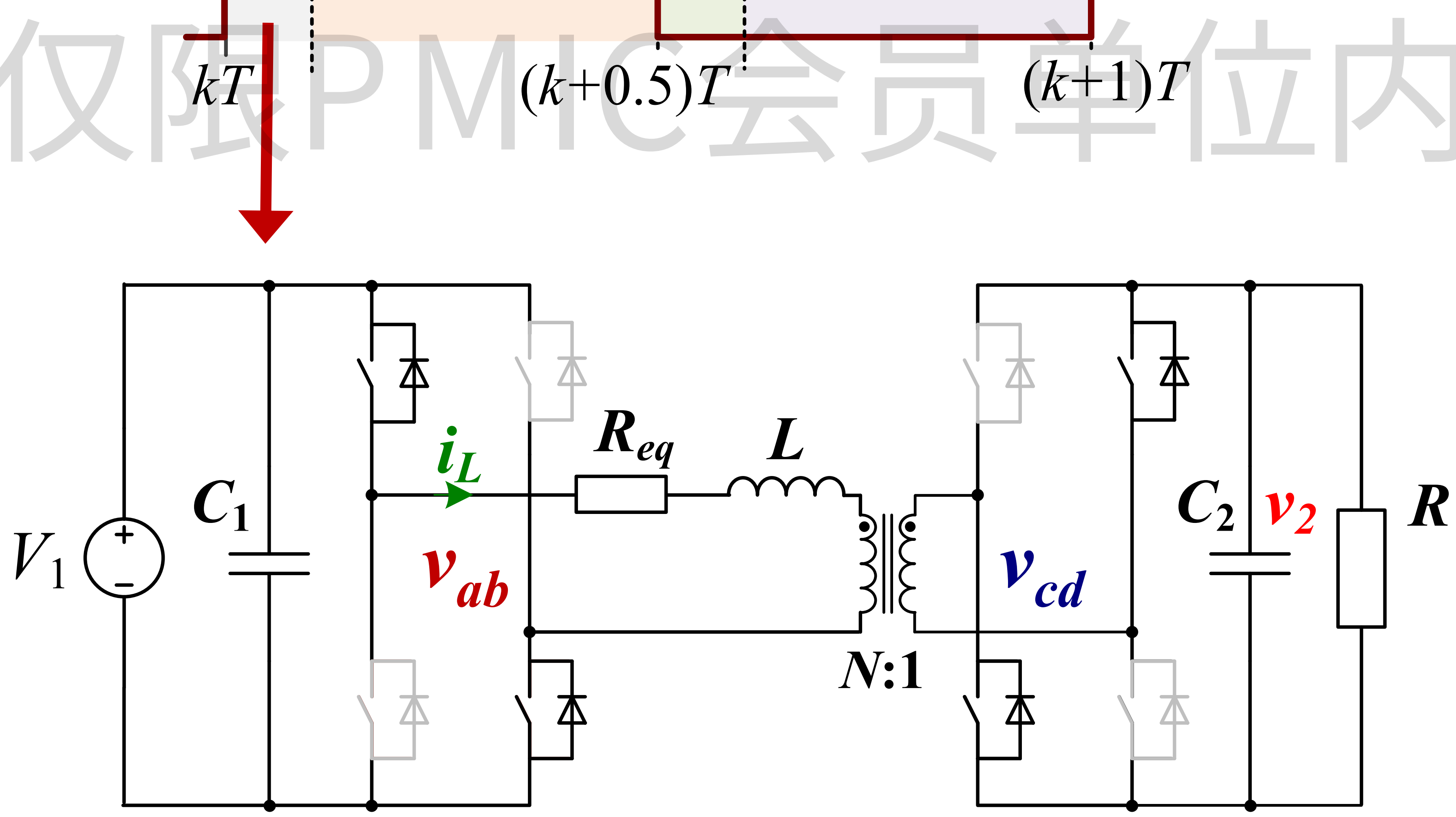
Discrete–time model



$$\begin{cases} L\dfrac{di_L}{dt} = -i_L R_{eq} + Nv_2 + V_1 \\ C_2\dfrac{dv_2}{dt} = -Ni_L - \dfrac{v_2}{R} \end{cases}$$

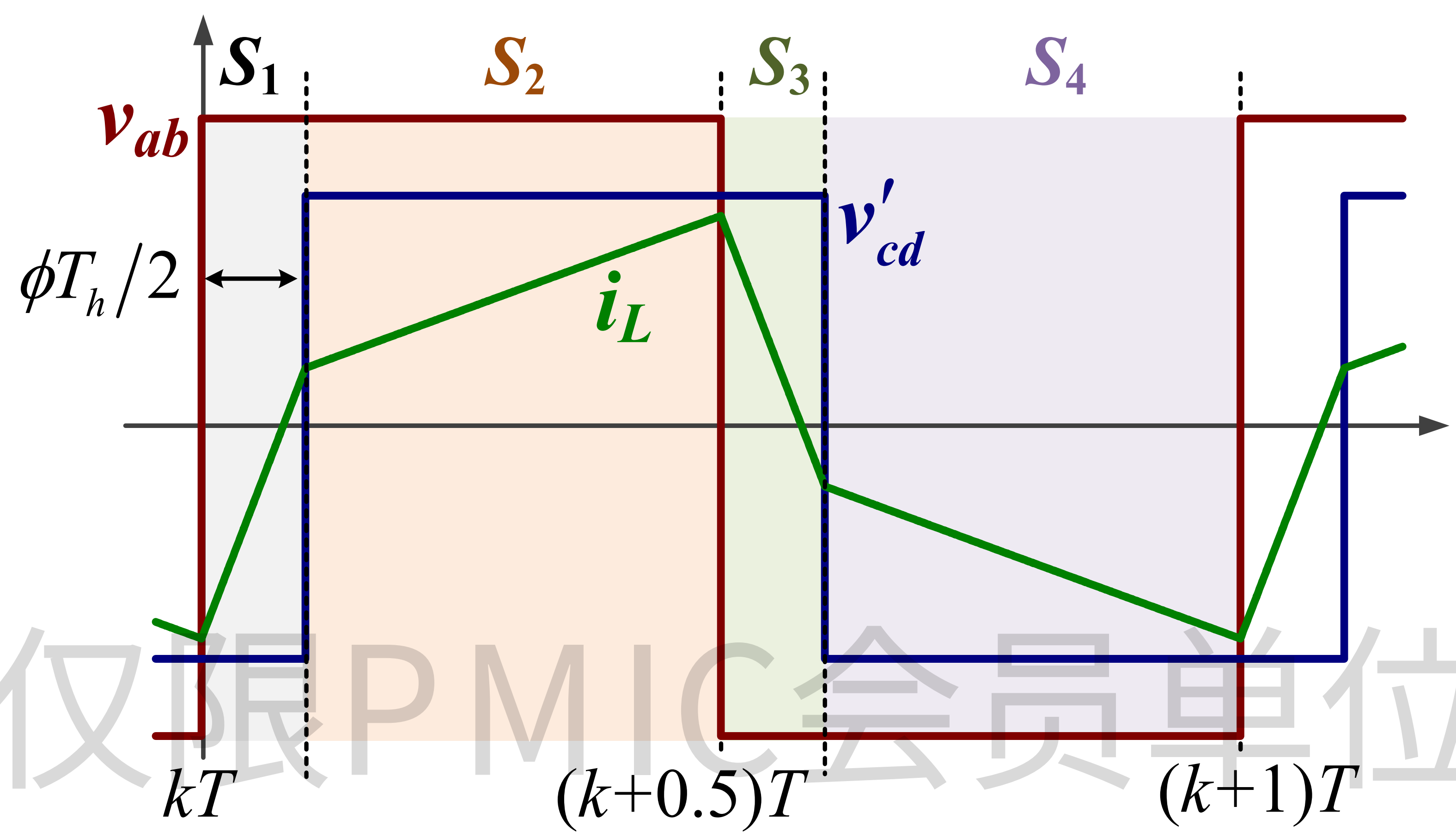
Let $\mathbf{x} = [i_L, v_2]^T$

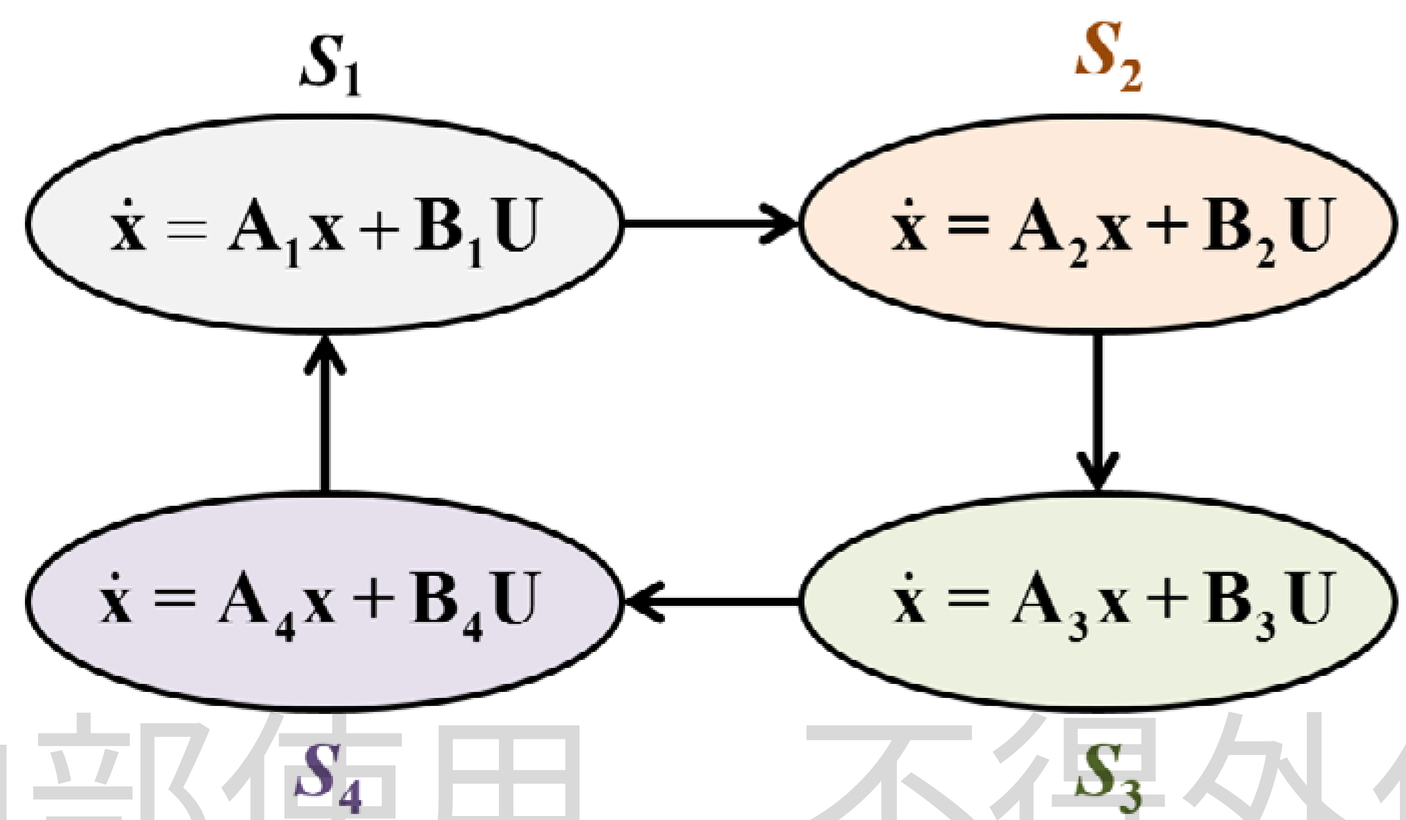
$$\dot{\mathbf{x}} = \mathbf{A}_1\mathbf{x} + \mathbf{B}_1\mathbf{U}$$



[1] L. Shi et. al, “Bilinear discrete-time modeling and stability analysis of the digitally controlled dual active bridge converter,” IEEE Transactions on Power Electronics, Nov 2017.

Discrete–time model





State space equation of each state

$$\mathbf{x}[k+1] = \mathbf{F}\mathbf{x}[k] + \mathbf{G}\mathbf{U}[k]$$

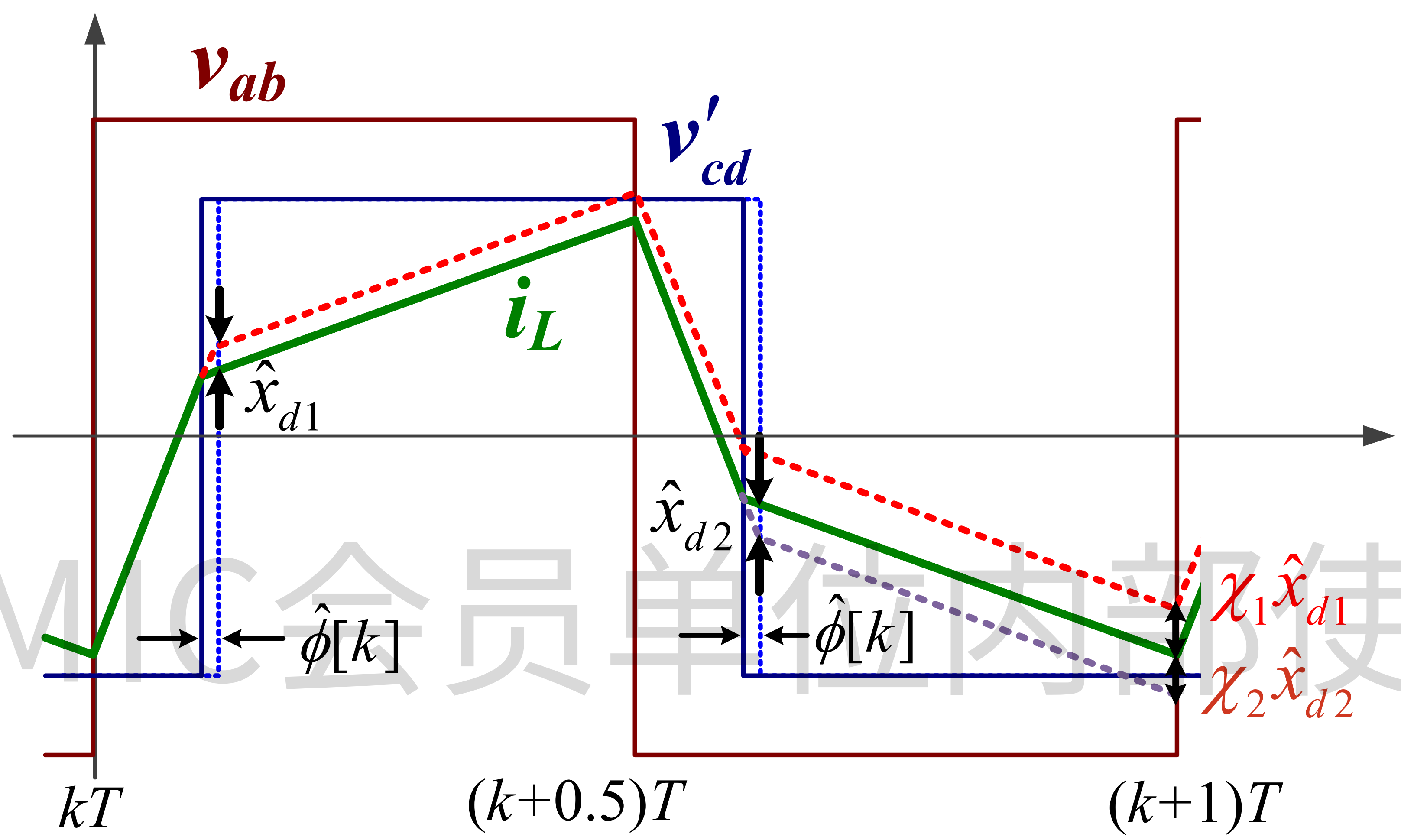
$$\mathbf{F} = e^{\mathbf{A}_4 t_{n4}} \cdot e^{\mathbf{A}_3 t_{n3}} \cdot e^{\mathbf{A}_2 t_{n2}} \cdot e^{\mathbf{A}_1 t_{n1}}$$

$$\mathbf{G} = e^{\mathbf{A}_4 t_{n4}} \cdot e^{\mathbf{A}_3 t_{n3}} \cdot e^{\mathbf{A}_2 t_{n2}} \psi_1 + e^{\mathbf{A}_4 t_{n4}} \cdot e^{\mathbf{A}_3 t_{n3}} \cdot \psi_2 + e^{\mathbf{A}_4 t_{n4}} \cdot \psi_3 + \psi_4$$

[1] L. Shi et. al, “Bilinear discrete-time modeling and stability analysis of the digitally controlled dual active bridge converter,” IEEE Transactions on Power Electronics, Nov 2017.

Discrete–time model

- Introduce a phase perturbation to get the small signal model



- Then the corresponding small-signal model can be derived:

$$\hat{\mathbf{x}}[k+1] = \mathbf{F}\hat{\mathbf{x}}[k] + \mathbf{G}\hat{\phi}[k]$$

- Convert the state-space to transfer function

$$G_{v\phi}(z) = \mathbf{C}(z\mathbf{I} - \mathbf{F})^{-1}\mathbf{G}$$

[1]D. Costinett, R. Zane, and D. Maksimovi´ c, “Discrete-time small-signal modeling of a 1 mhz efficiency-optimized dual active bridge converter with varying load,” in 2012 IEEE 13th Workshop on Control and Modeling for Power Electronics (COMPEL), June 2012, pp. 1–7.

Comparison of modeling methods

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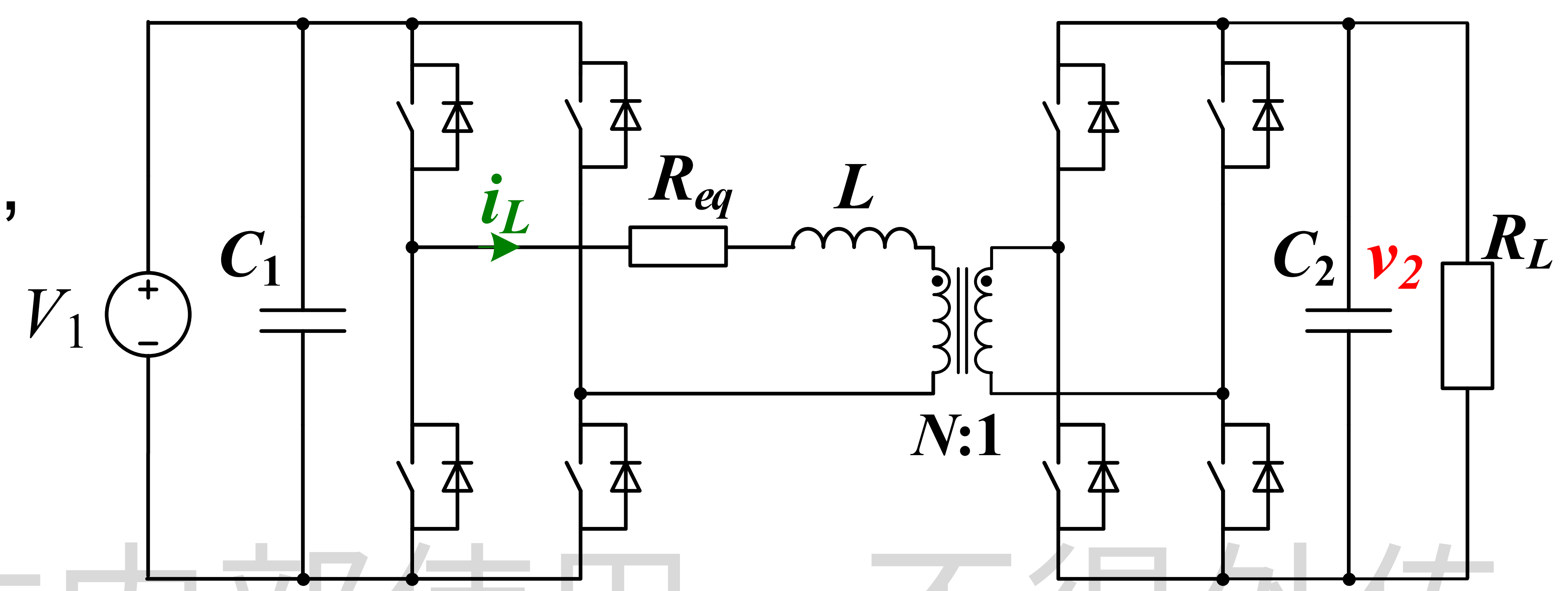
- Reduced order model [1], [2]
- Improved reduced order model [3],
- Generalized average model [4]
- Discrete-time model [5], [6]



Parameters used for model comparison

N	Transformer turns ratio	2:1
f	Switching frequency	20kHz
L	Inductor	70μH
R_{eq}	Equivalent resistance	0.25Ω
C_2	DC Capacitor 2	1mF
R_L	Load resistor	4Ω
T_d	Dead time	200ns

[1] A. R. Alonso, *et. al.* , "An overall study of a dual active bridge for bidirectional dc/dc conversion," in 2010 IEEE Energy Conversion Congress and Exposition
[2] H. Bai, *et. al.* , "The dynamic model and hybrid phase-shift control of a dual-active-bridge converter," in 2008 34th Annual Conference of IEEE Industrial Electronics,
[3] K. Zhang, *et. al.* , "Large- and small-signal average-value modeling of dual-active-bridge dc-dc converter considering power losses," IEEE Transactions on Power Electronics
[4] H. Qin *et. al.* , "Generalized average modeling of dual active bridge dc-dc converter," IEEE Transactions on Power Electronics
[5] D. Costinett, *et. al.* , "Discrete-time small-signal modeling of a 1 mhz efficiency-optimized dual active bridge converter with varying load," in 2012 IEEE 13th Workshop on Control and Modeling for Power Electronics (COMPEL)
[6] L. Shi, *et. al.* , "Bilinear discrete-time modeling and stability analysis of the digitally controlled dual active bridge converter," IEEE Transactions on Power Electronics

Modeling comparison – Large signal

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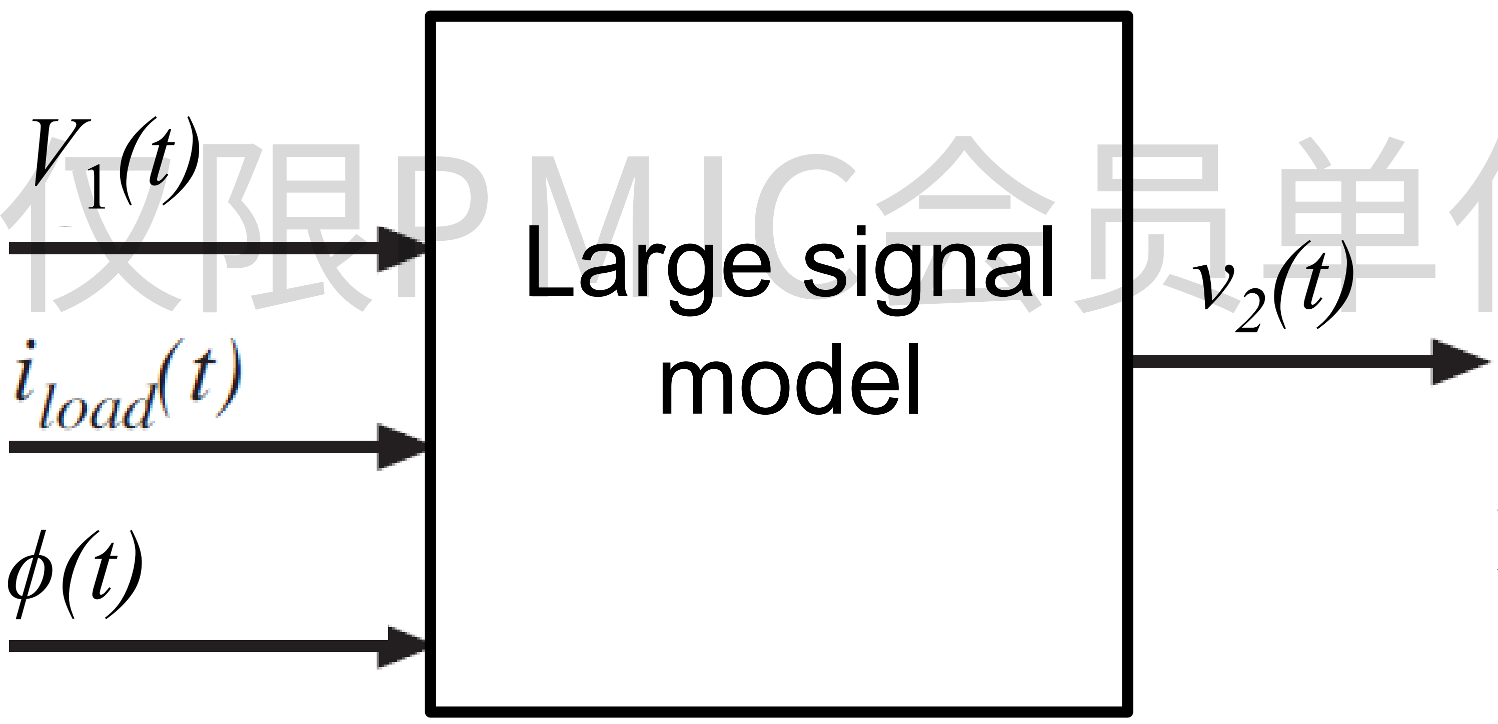
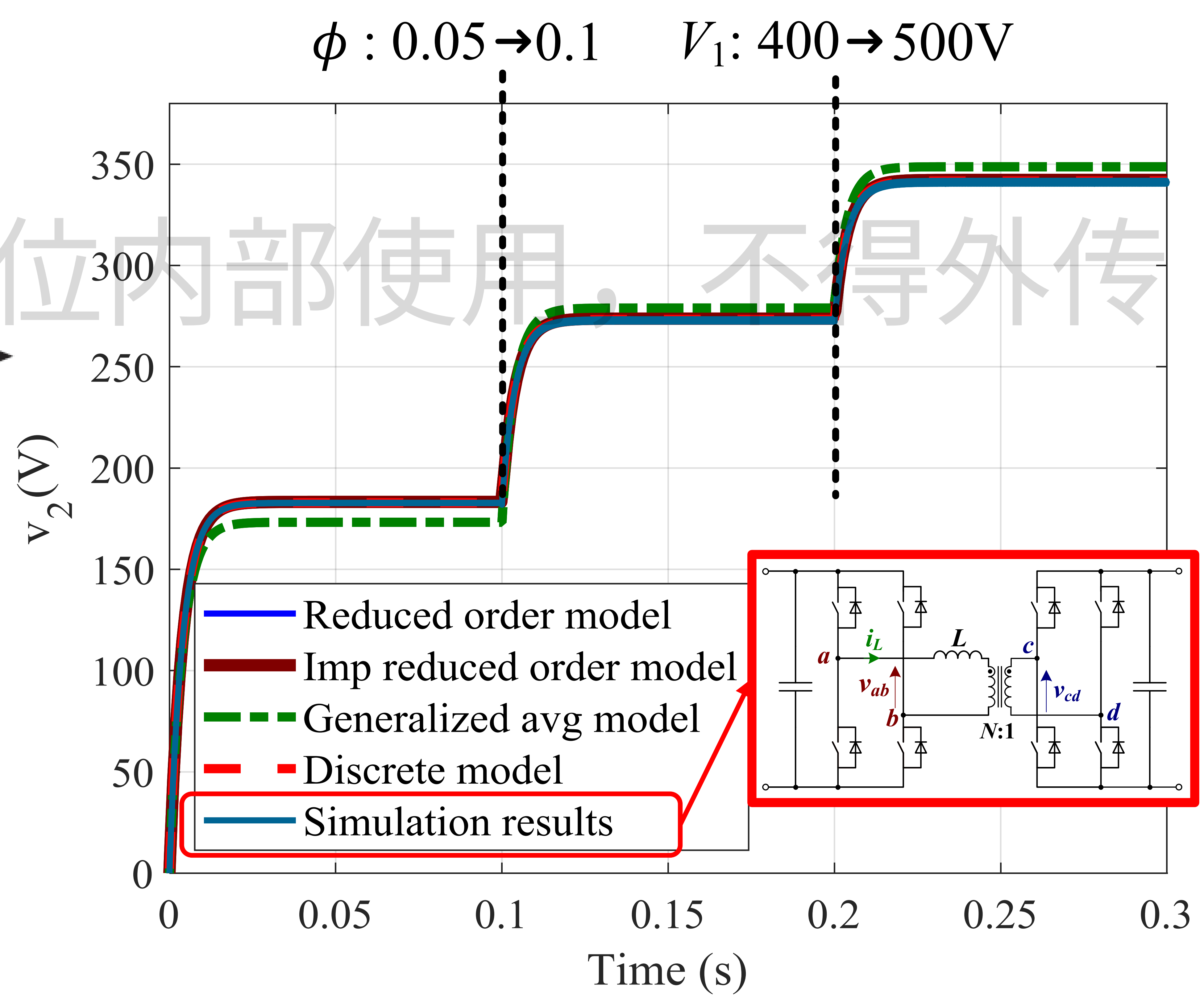
- The output of each model is compared with output of the DAB switching circuit.
- Generalized avg model has some steady state error.

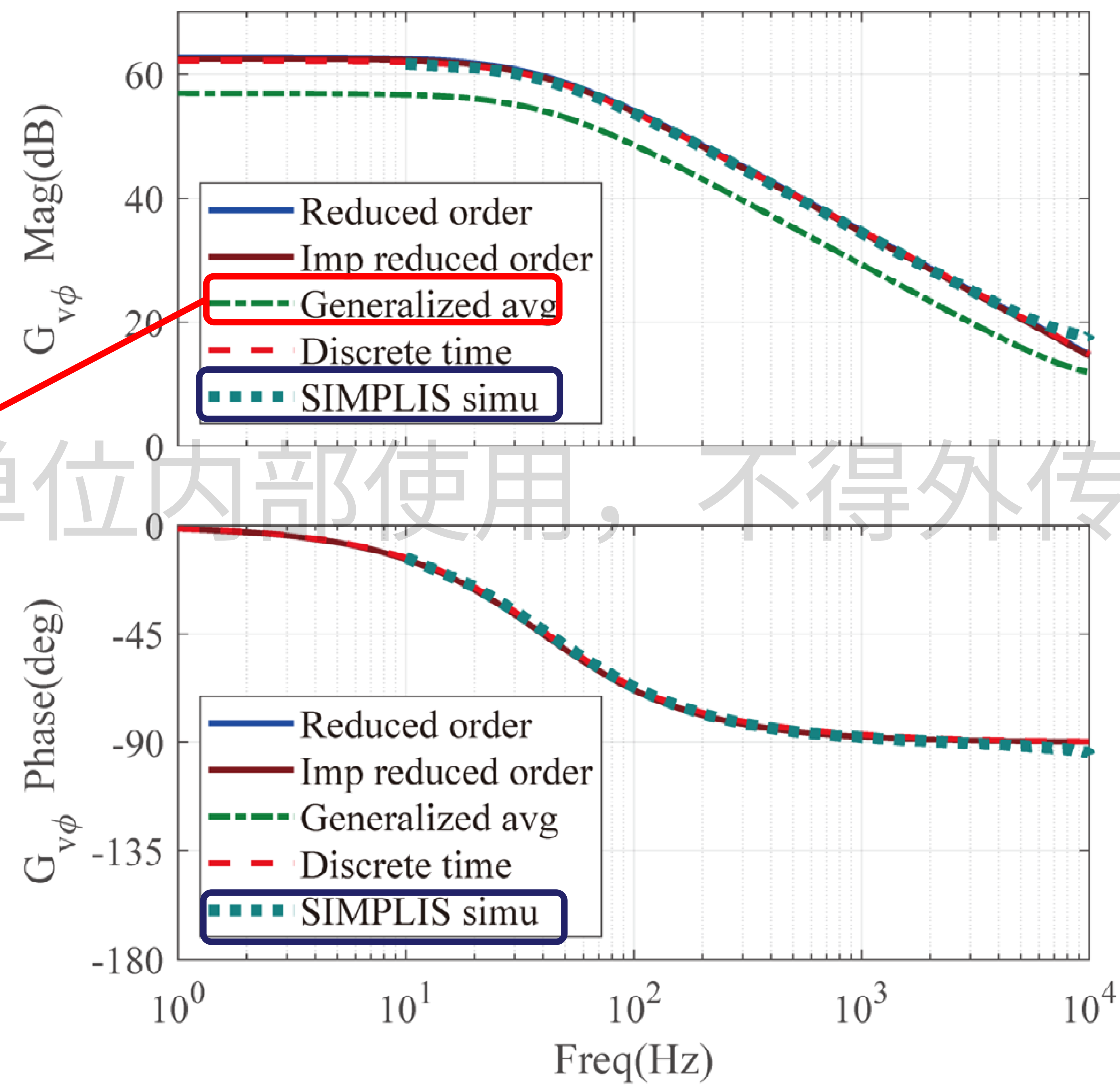




Modeling comparison – bode plots

- **Small signal models are compared with SIMPLIS simulation results.**

Have a magnitude error because the third and higher order components of i_L are ignored.



Comparison of bode plot of small signal models $G_{v\phi}$ (from ϕ to v_2).

Comparison of modeling methods

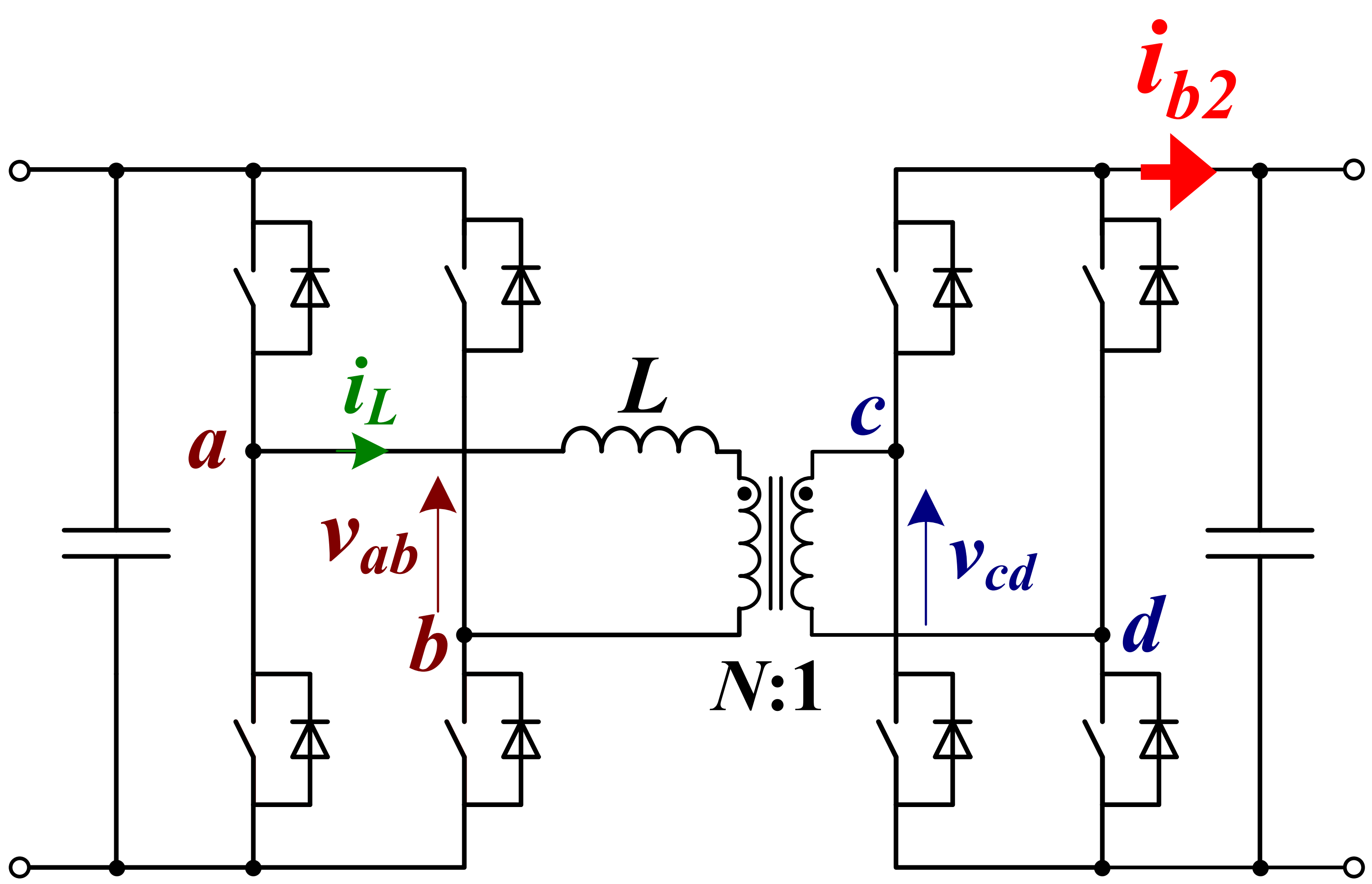
- Reduced order model has best overall performance and is recommended in normal applications.

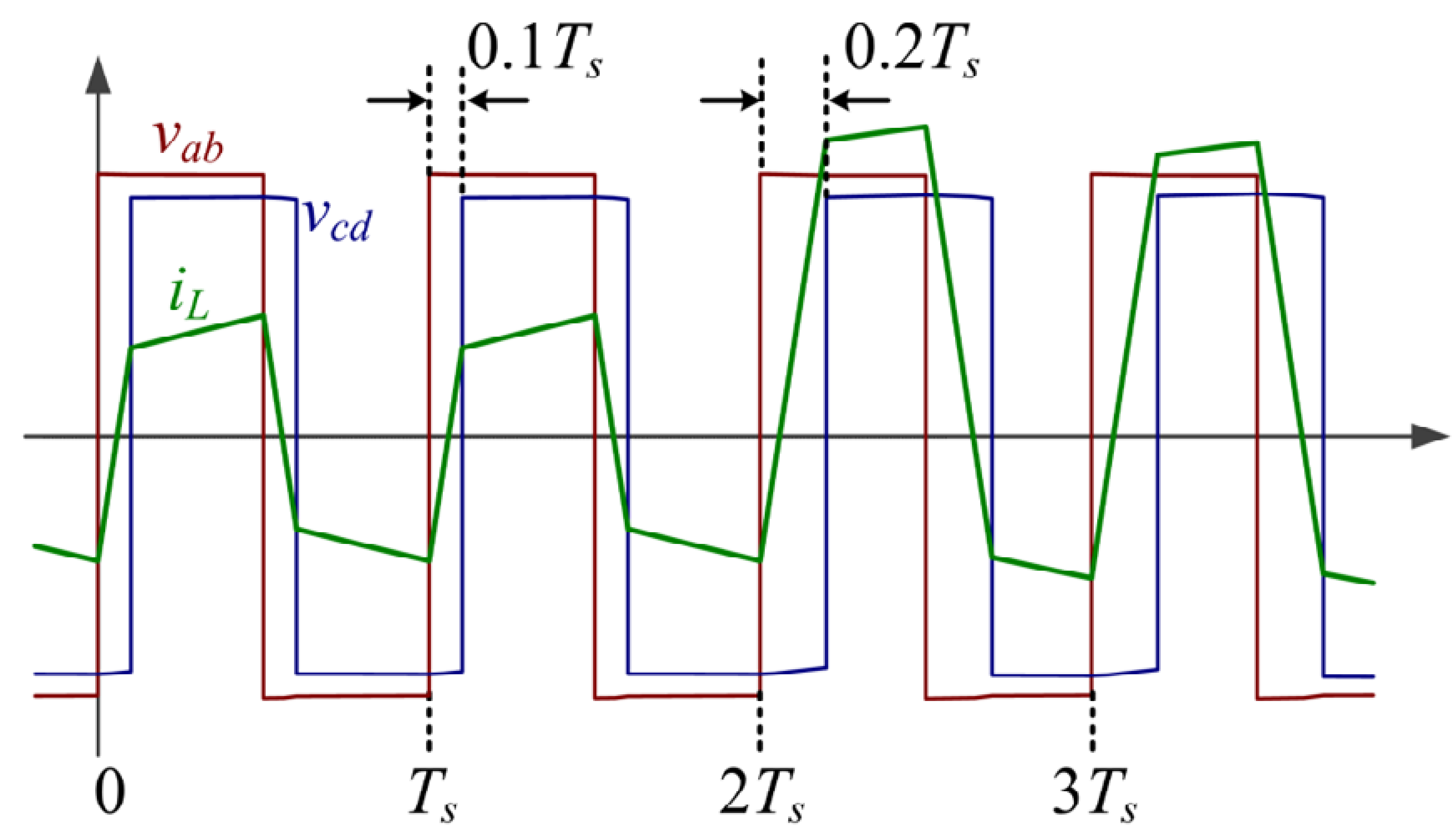
Modeling methods	**Model complexity**	**Large signal**	**Bode plot**
Reduced order	Low	++++	++++
Imp reduced order	Medium	++++	++++
Generalized average	Medium	++	++
Discrete time	High	++++	++++

Note: + = **Poor**; ++ = **Average**; +++ = **Good**; ++++ = **Excellent**

Discussion of reduced order model

- Reduced order model has the best overall performance.
- Reduced order is of a first order system
- Why does the dynamics of inductor ***L*** disappear?
  - v_{ab} and v_{cd} are square voltages at switching frequency f_s
  - **The integral of two sine functions with different frequency is 0.**
  - **The low frequency component of i_L is "filtered"** by the two square voltages.
  - **The output current i_{b2} only has dc and f_s component**.





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  - **Model predictive control**

- Practical control issues of DAB
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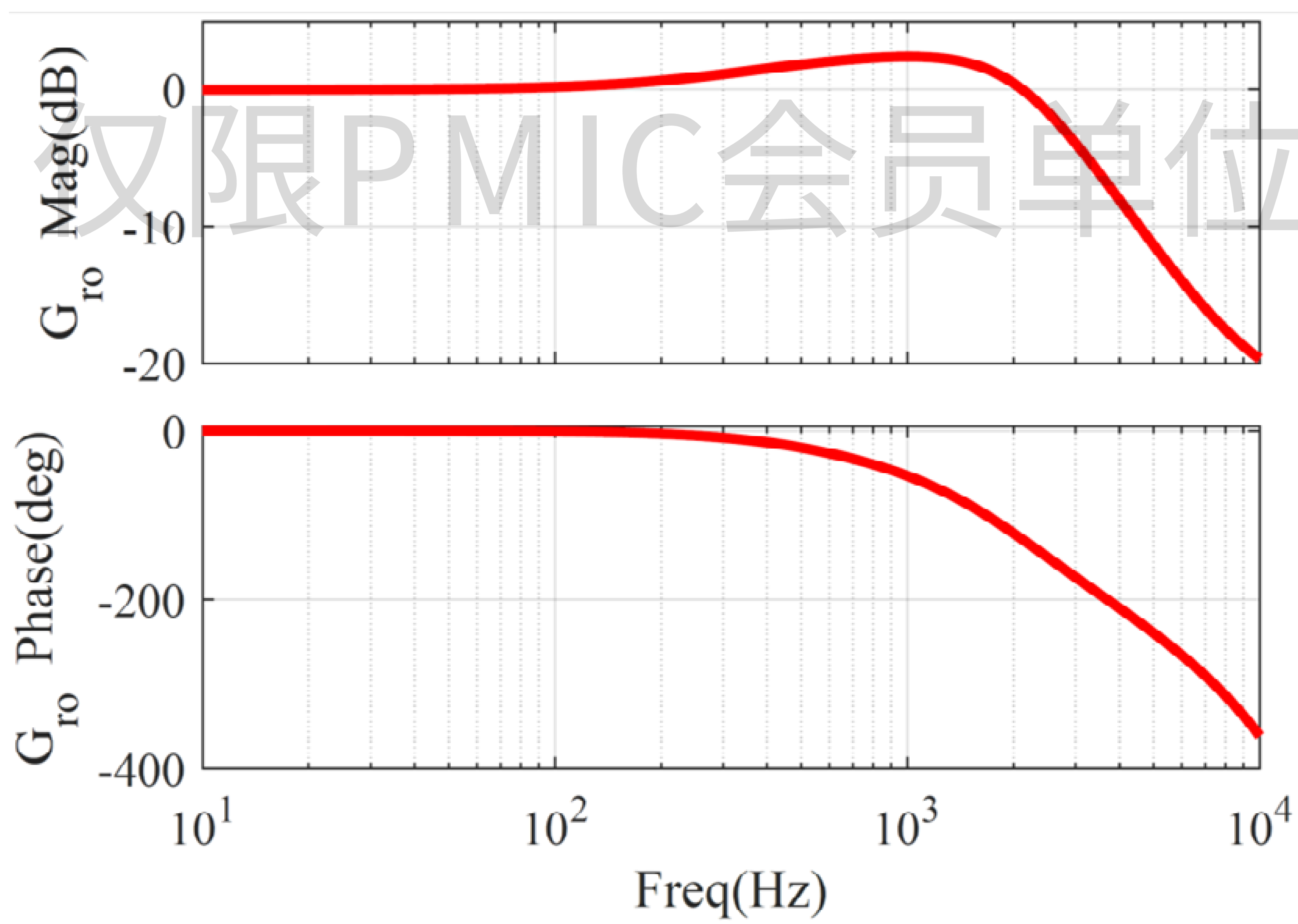
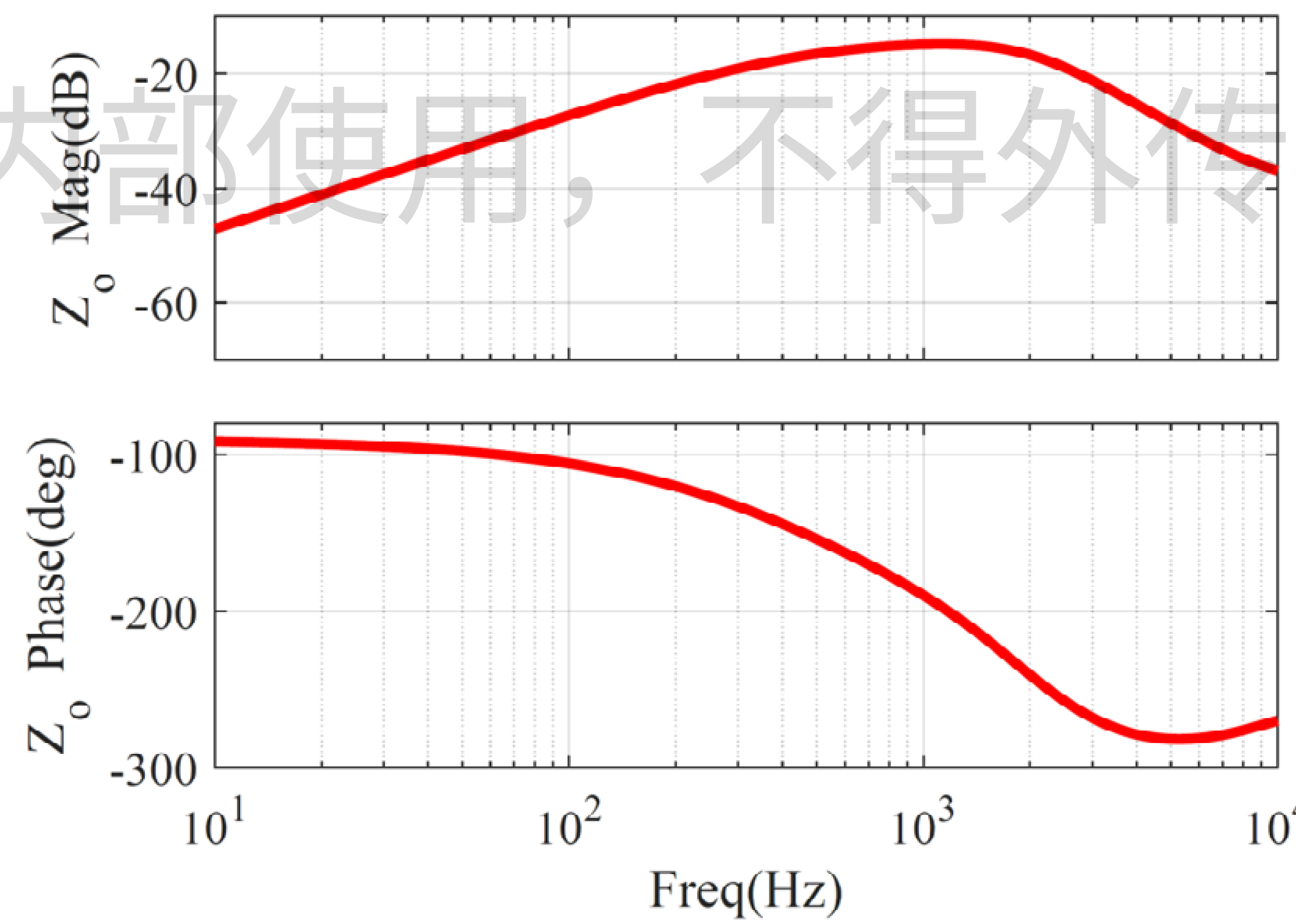
How to fairly compare these control methods?

Evaluation methods

- **The following metrics are employed to assess the control methods:**
  - **Reference-to-output:** ability in voltage tracking performance.
  - **Output impedance:** ability in rejecting load disturbance.

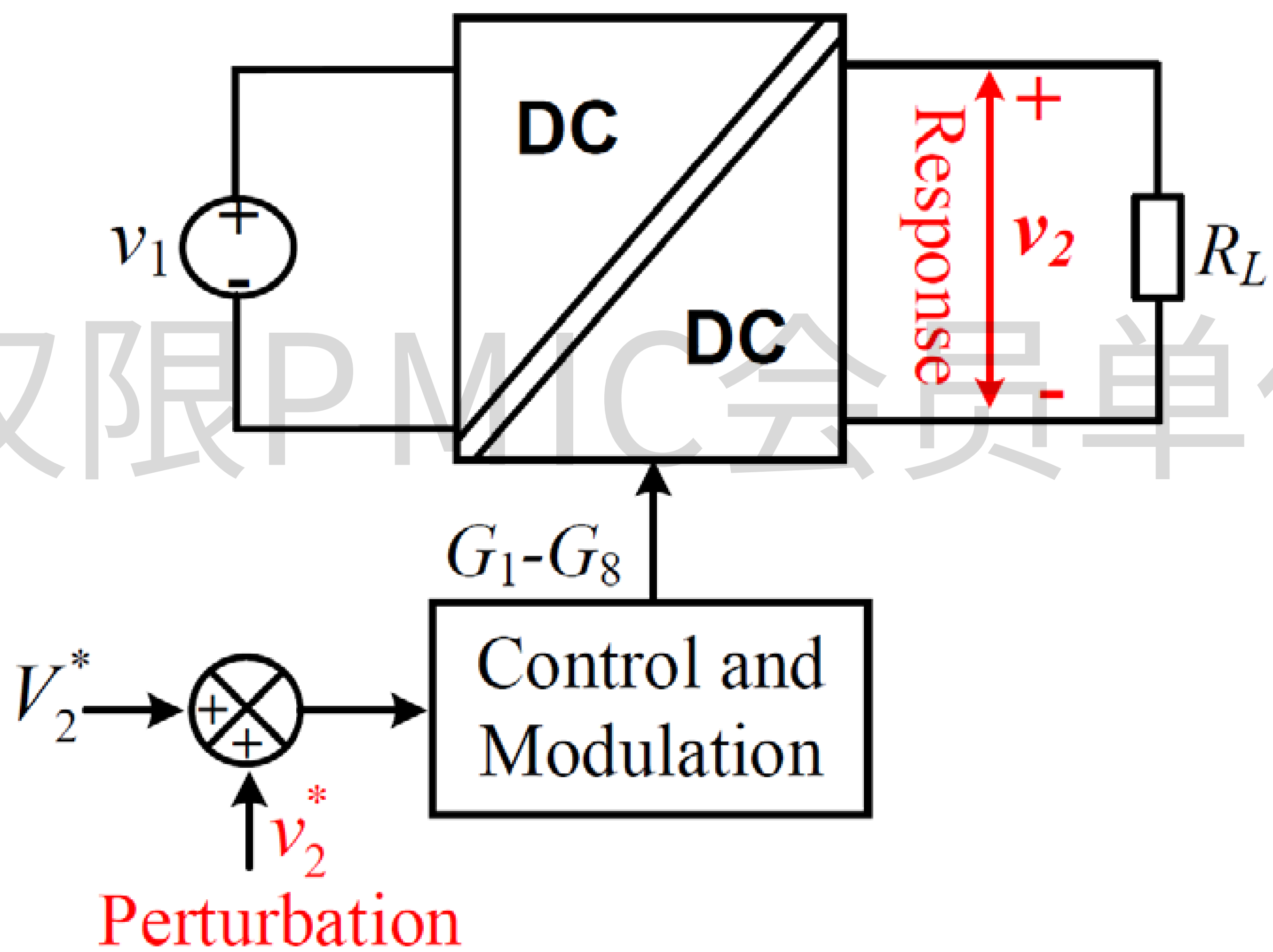




How to obtain the frequency response

- The method to obtain closed-loop reference-to-output response

DAB converter

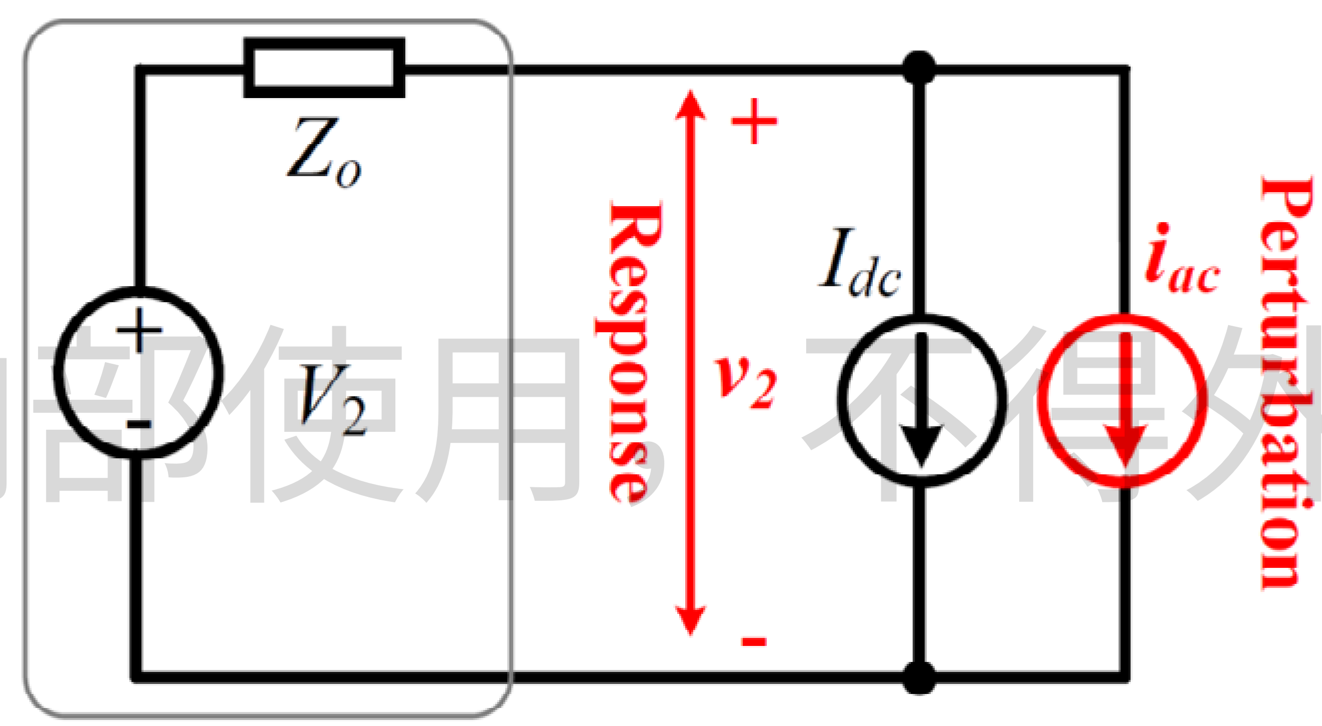


Reference-to-output response

$$G_{ro}(f) = \frac{v_2(f)}{v_2^*(f)}$$

- The method to obtain output impedance

DAB converter



Output impedance

$$Z_o(f) = \frac{v_2(f)}{i_{ac}(f)}$$

Simulation tool

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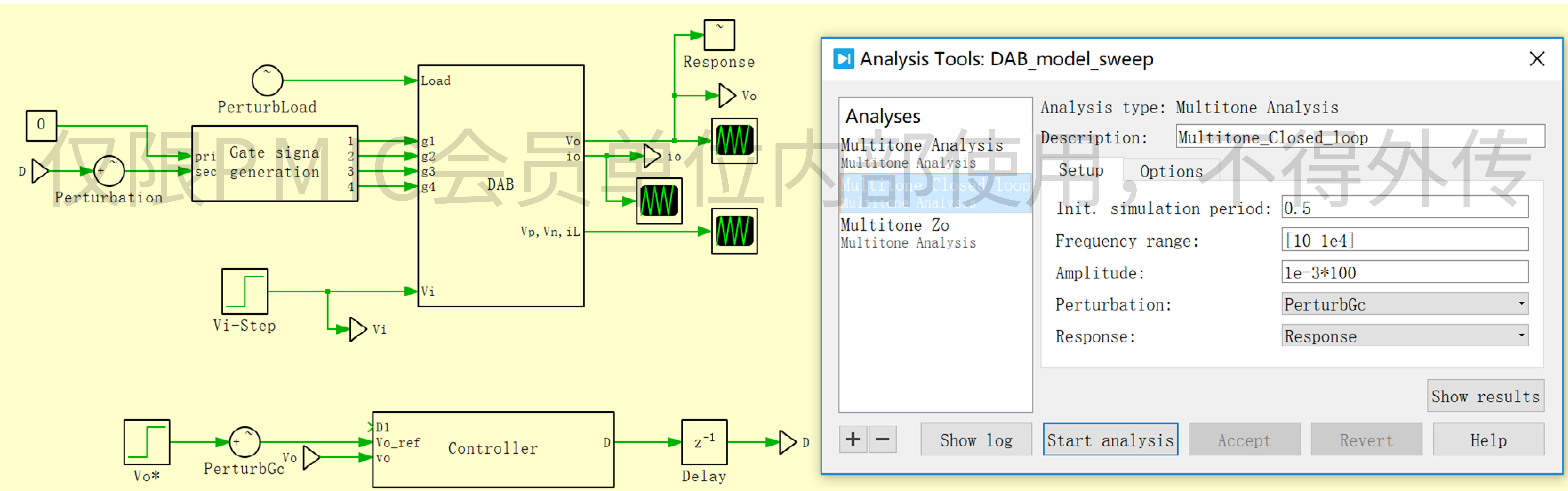
- ***The Multitone Analysis tool in PLECS***[1] is employed to obtain the reference-to-output frequency response and output impedance.



[1] https://www.plexim.com/

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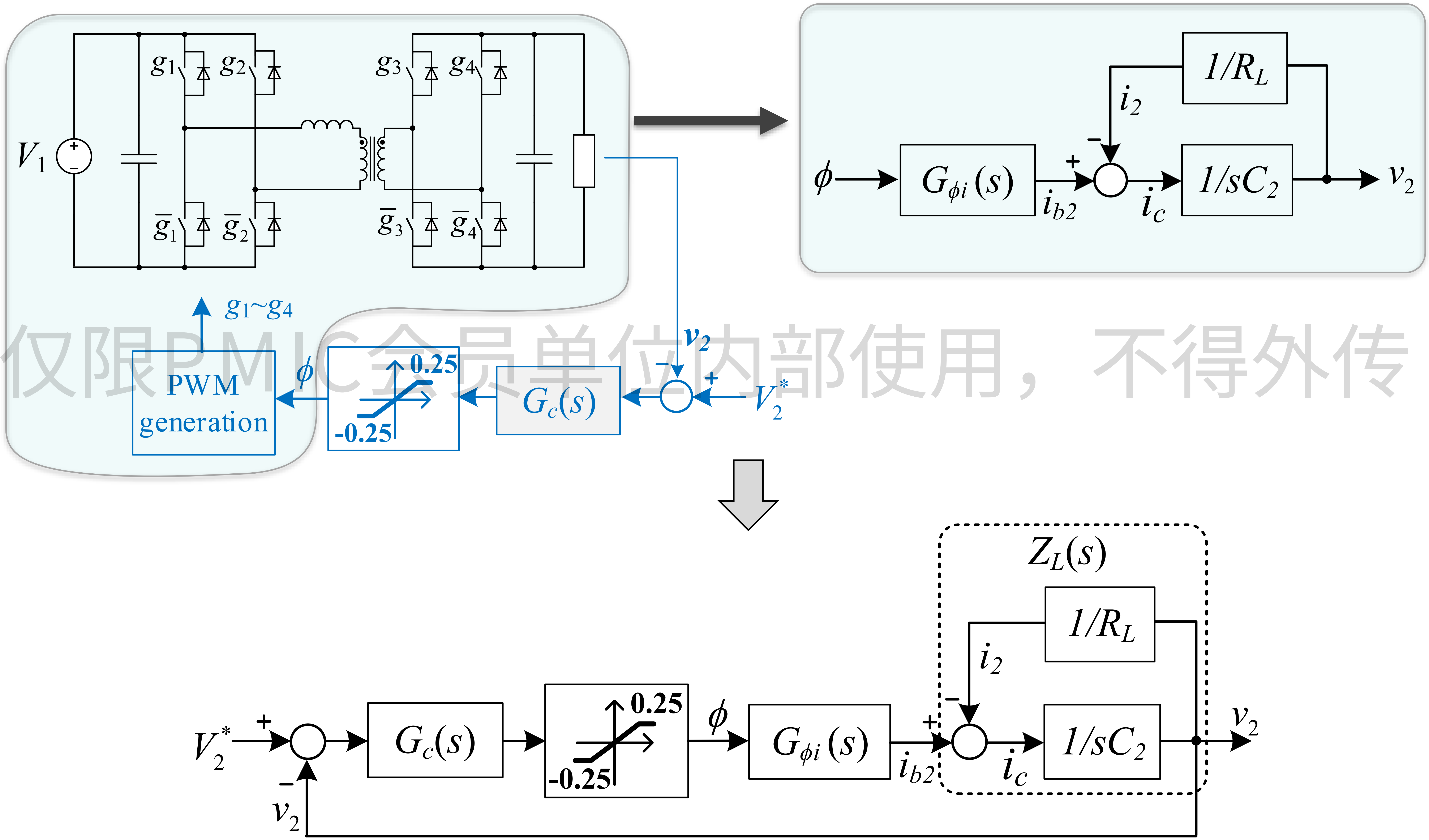
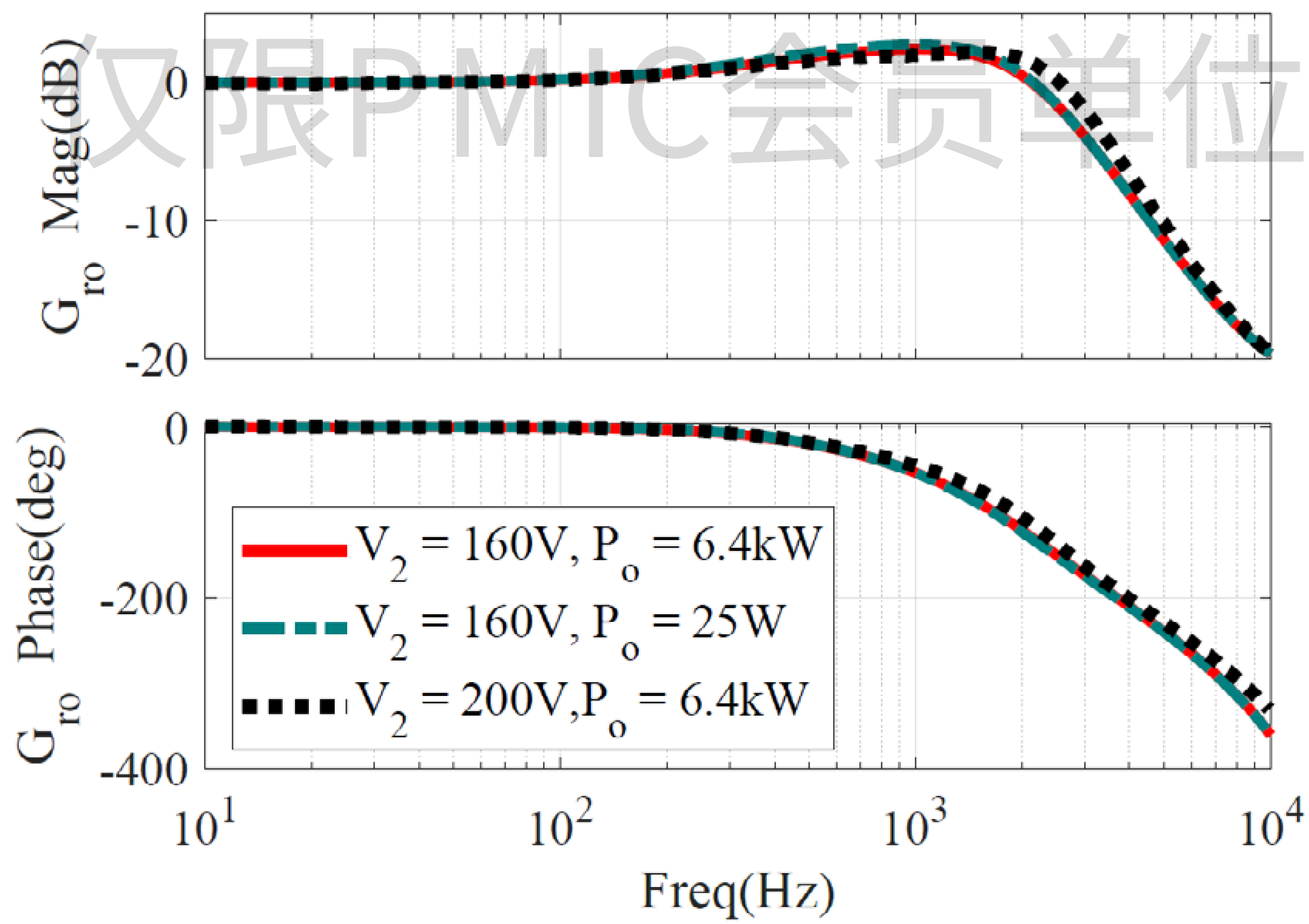
Feedback only control



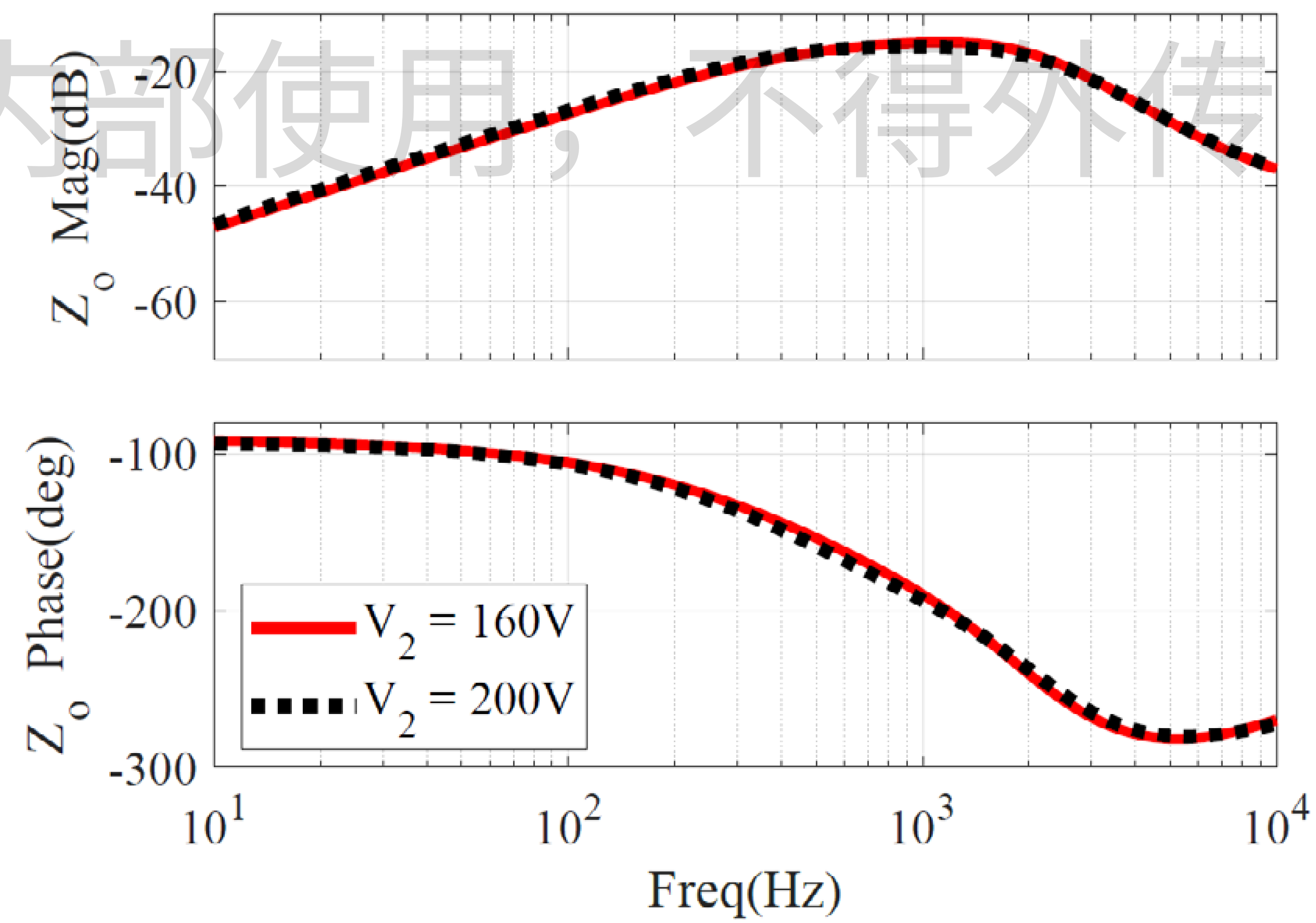
Feedback only control

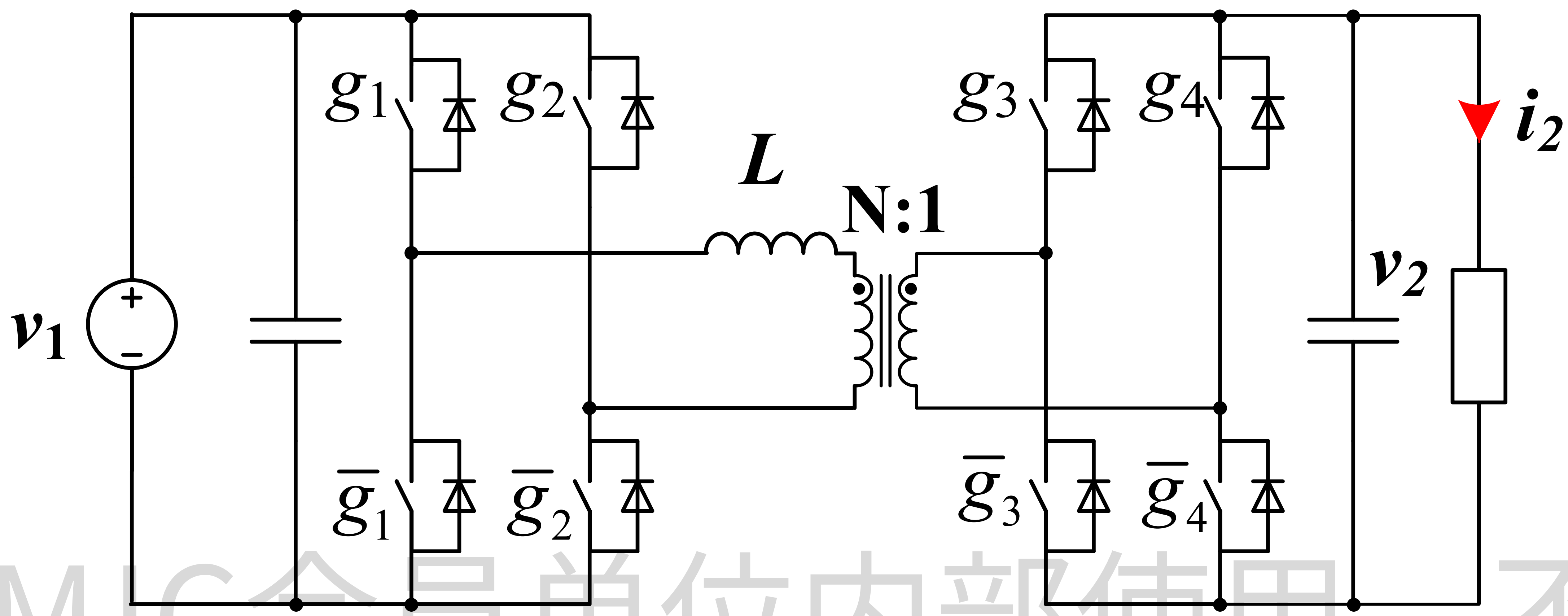
- Set the crossover frequency as 1.2*k*Hz with phase margin 45°:
  $k_p = 0.0193$, $k_i = 37.6$.
- Different output voltage/power has minor influence on the output-to-reference response and output impedance.

Reference-to-output



Output impedance





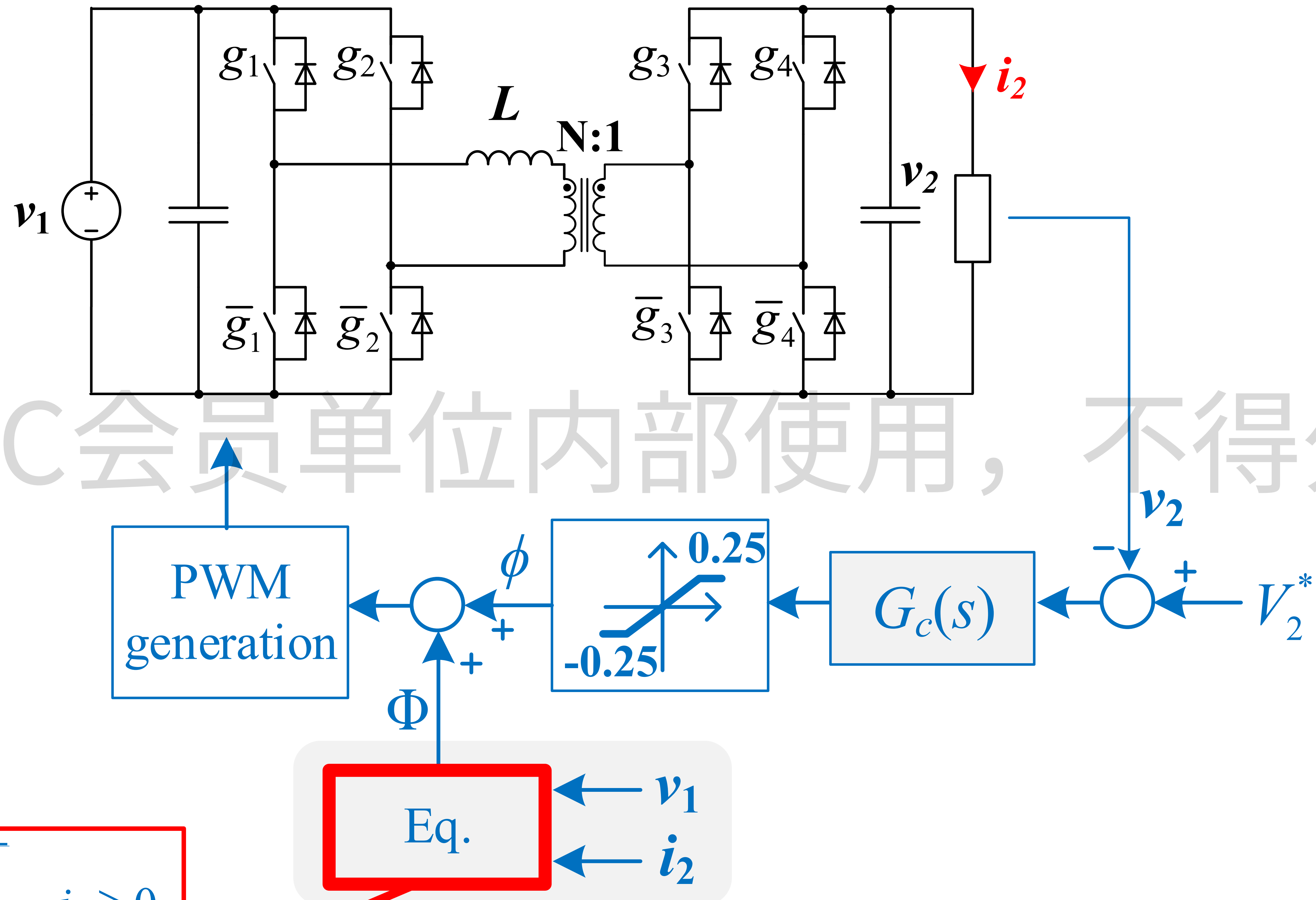
Output power $P_o = \dfrac{Nv_1v_2\phi(1-2|\phi|)}{f_sL} = v_2i_2$

$$\Rightarrow \quad \phi = \begin{cases} \dfrac{1}{4} - \sqrt{\dfrac{1}{16} - \dfrac{f_sLi_2}{2Nv_1}} & i_2 \geq 0 \\ -\dfrac{1}{4} + \sqrt{\dfrac{1}{16} + \dfrac{f_sLi_2}{2Nv_1}} & i_2 < 0 \end{cases}$$

Phase shift ϕ can be calculated using v_1 and i_2

Feedback plus feedforward control

- **Feedback plus feedforward control block diagram**



$$
\Phi=\begin{cases}\dfrac{1}{4}-\sqrt{\dfrac{1}{16}-\dfrac{f_sLi_2}{2Nv_1}} & i_2\geq 0\\[2ex] -\dfrac{1}{4}+\sqrt{\dfrac{1}{16}+\dfrac{f_sLi_2}{2Nv_1}} & i_2<0\end{cases}
$$

The change on v_1 or i_2 can be measured and counterbalanced before it affects the output.

Feedback plus feedforward control

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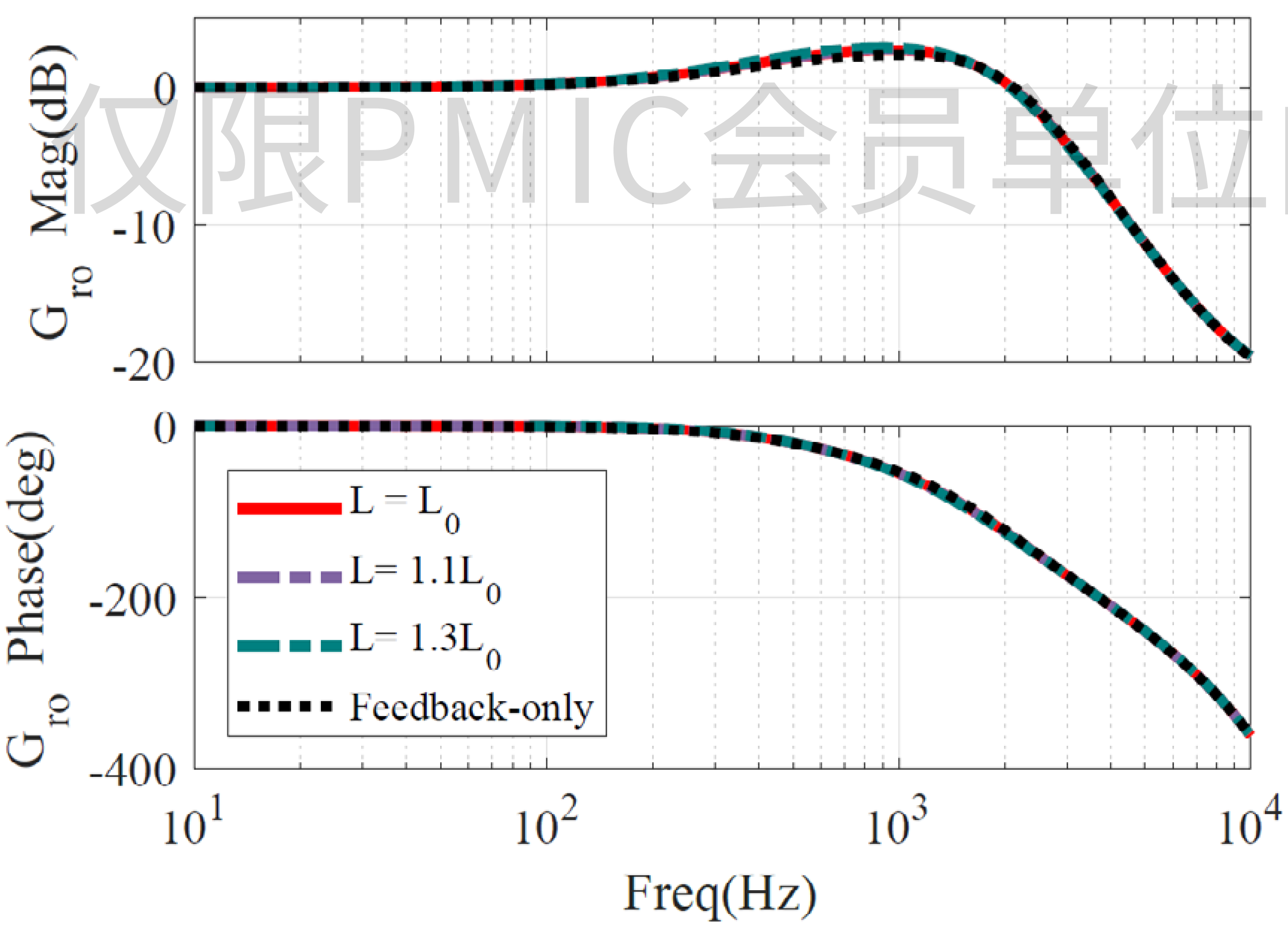
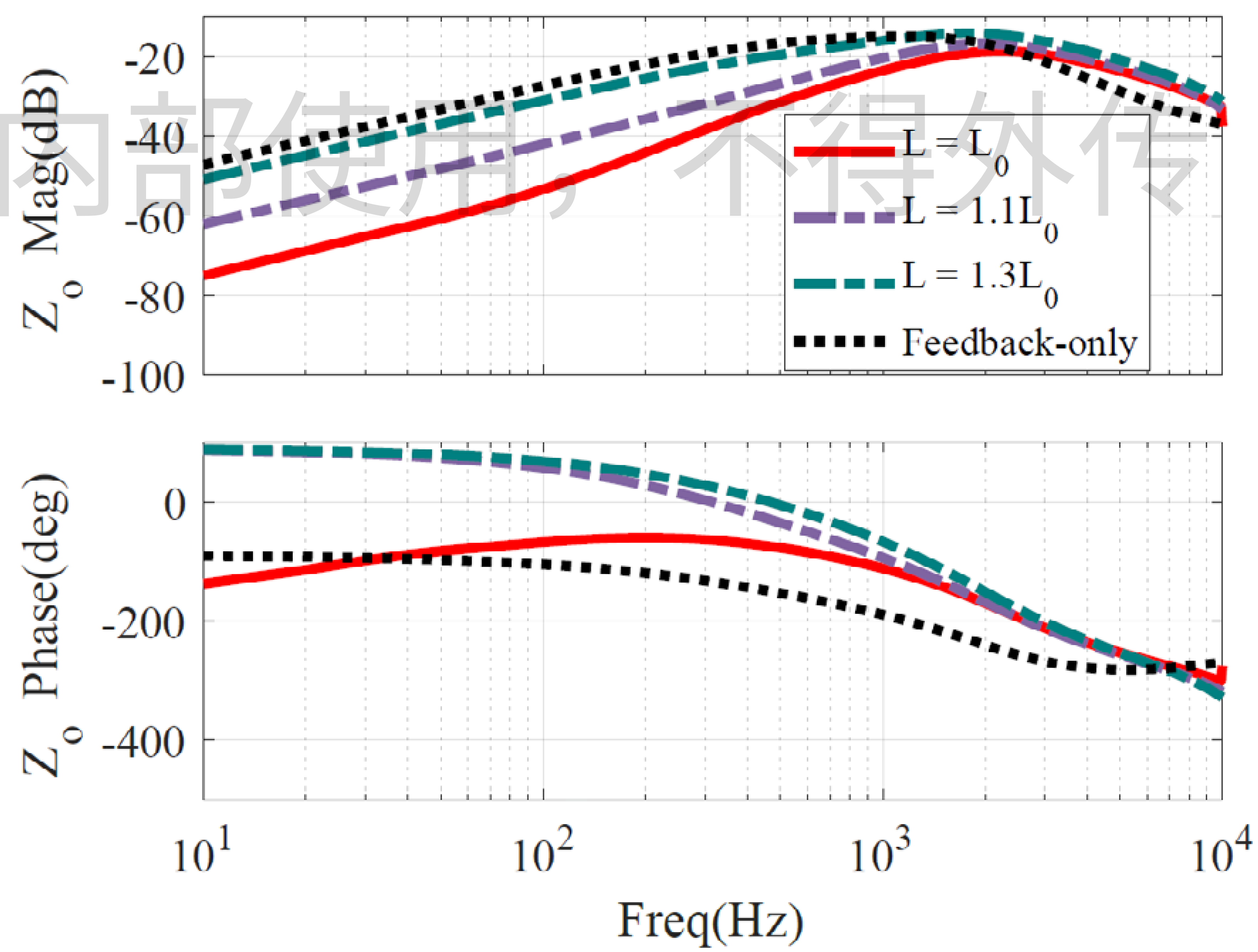
- **Feedback plus feedforward control** can significantly reduce output impedance and present perfect load current disturbance rejection capability
- However, **its performance deteriorates quickly** when circuit parameters used in the control are different from the actual ones

Reference-to-output



Output impedance



Virtual Direct Power Control (VDPC)

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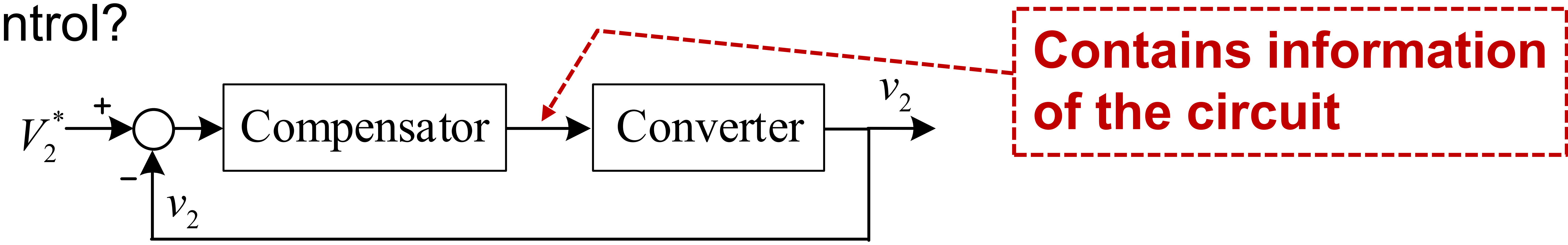
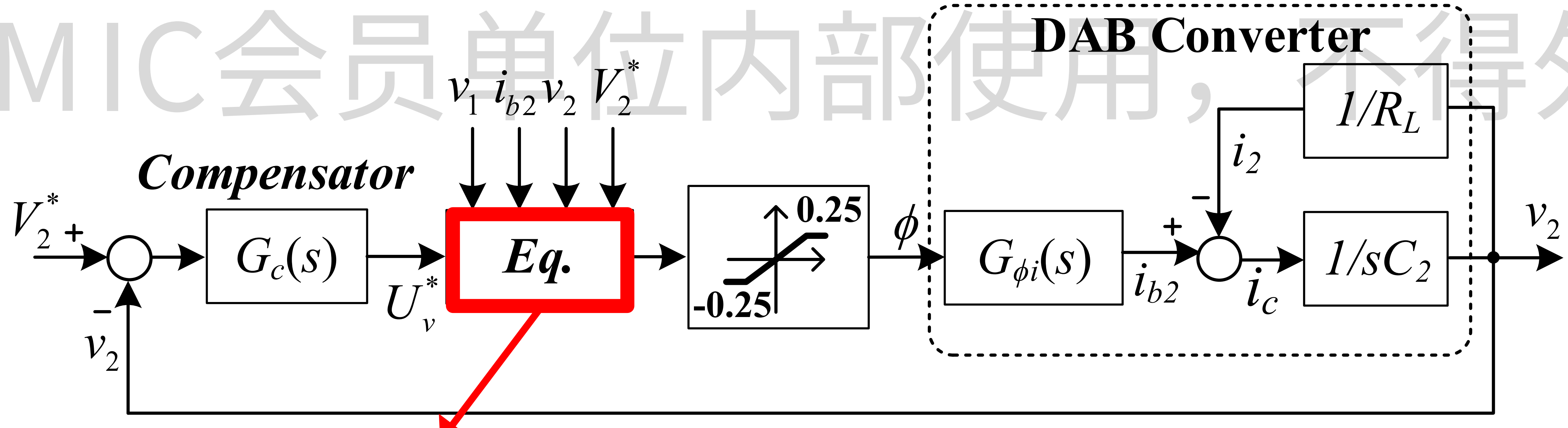
- How to avoid the influence the parameter variation in feedforward control?



- The VDPC calculates ϕ based on the compensator output

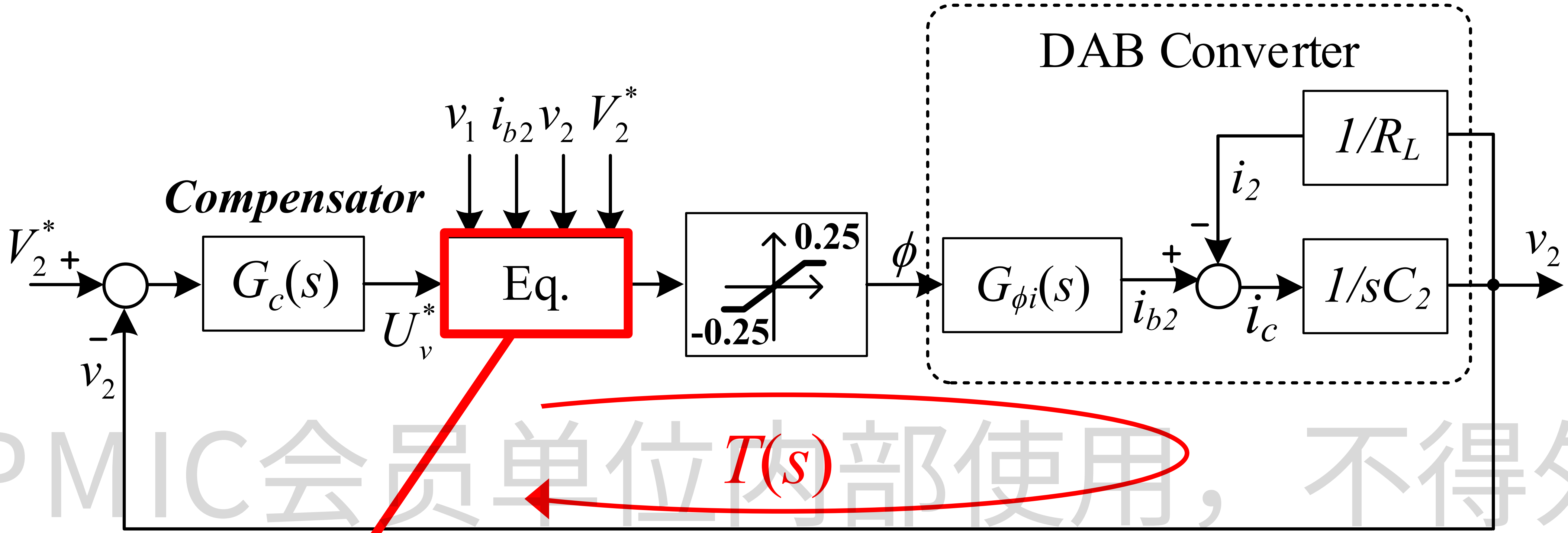


$$\phi = \begin{cases} \frac{1}{4} - \sqrt{\frac{1}{16} - \frac{V_2^* U_v^* i_2}{4 v_2^2 v_1}} & i_2 \geq 0 \\ -\frac{1}{4} + \sqrt{\frac{1}{16} + \frac{V_2^* |U_v^*| i_2}{4 v_2^2 v_1}} & i_2 < 0 \end{cases}$$

No circuit parameters are involved in the calculation.

[1] W. Song, N. Hou, and M. Wu, "Virtual direct power control scheme of dual active bridge dc-dc converters for fast dynamic response," IEEE Transactions on Power Electronics, vol. 33, no. 2, pp. 1750–1759, Feb 2018.

Virtual Direct Power Control (VDPC)



$$\phi = \begin{cases} \frac{1}{4} - \sqrt{\frac{1}{16} - \frac{V_2^* U_v^* i_2}{4 v_2^2 v_1}} & i_2 \geq 0 \\ -\frac{1}{4} + \sqrt{\frac{1}{16} + \frac{V_2^* |U_v^*| i_2}{4 v_2^2 v_1}} & i_2 < 0 \end{cases}$$

When i_2 is small (close to *0*), the loop gain $|T(j\omega)| \approx 0$

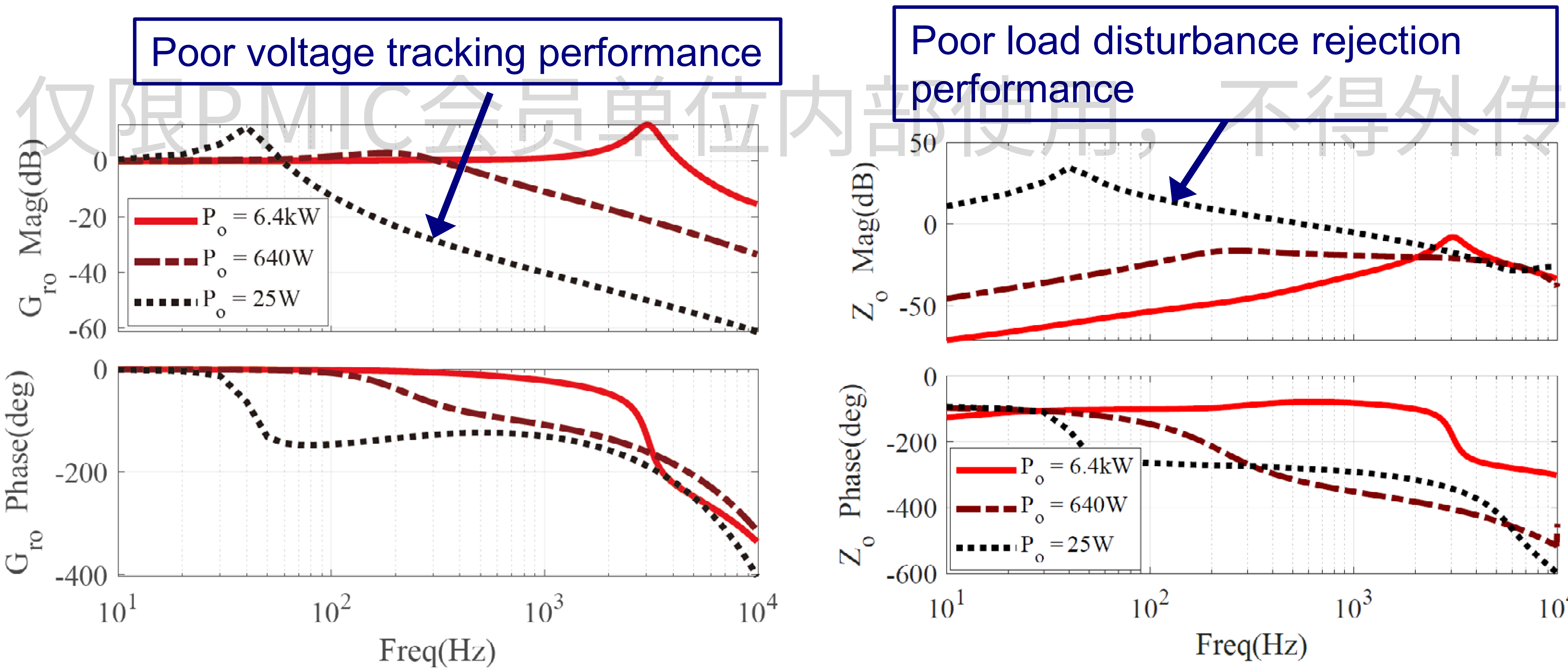
⇩

Poor performance on voltage tracking and disturbance rejection.

[1] W. Song, N. Hou, and M. Wu, “Virtual direct power control scheme of dual active bridge dc-dc converters for fast dynamic response,” IEEE Transactions on Power Electronics, vol. 33, no. 2, pp. 1750–1759, Feb 2018.

Virtual Direct Power Control (VDPC)

- Setting the crossover frequency as 1.2*k*Hz with phase margin 45°: $K_p = 90$, $k_i = 10^5$.
- Under light load conditions, the bandwidth is too narrow and output impedance is too high, leading to poor performance on voltage tracking and load current disturbance rejection.



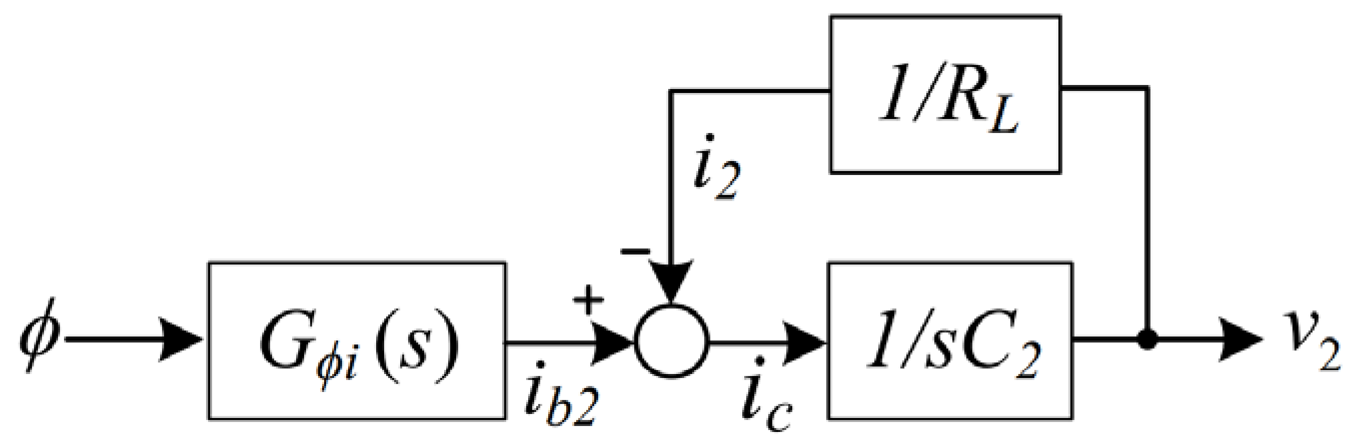
Disturbance–Observer–Based Control

- VDPC cannot tackle the parameter sensitivity problem.
- Disturbances and uncertainties exist in all power converter control systems.
- These disturbances and uncertainties include input voltage and load variation, model uncertainty, circuit parameter variations due to temperature or aging effects, etc..
- Disturbance-observer-based control (DOBC) employs an observer to estimate the total disturbances and uncertainties, and corresponding compensation is then generated by making use of the estimate.

[1] W. Chen, J. Yang, L. Guo, and S. Li, “Disturbance-observer-based control and related methods—an overview,” IEEE Transactions on Industrial Electronics, vol. 63, no. 2, pp. 1083–1095, 2016.
[2] M. Ali, M. Yaqoob, L. Cao, and K. H. Loo, “Disturbance-observerbased dc-bus voltage control for ripple mitigation and improved dynamic response in two-stage single-phase inverter system,” IEEE Transactions on Industrial Electronics, vol. 66, no. 9, pp. 6836–6845, 2019.
[3] F. Xiong, J. Wu, Z. Liu, and L. Hao, “Current sensorless control for dual active bridge dc-dc converter with estimated load-current feedforward,” IEEE Transactions on Power Electronics, vol. 33, no. 4, pp. 3552–3566, April 2018.

Disturbance–Observer–Based Control

- Derivation of disturbance observer



$$\frac{d\hat{v}_2}{dt} = -\frac{\hat{v}_2}{R_L C_2} + \frac{NV_1(1-4\Phi)}{f_s L C_2}\hat{\phi}$$

$$\Rightarrow \frac{d\hat{v}_2}{dt} = a\hat{v}_2 + b\hat{\phi}$$ where $a = -\frac{1}{R_L C_2}, b = \frac{NV_1(1-4\Phi)}{f_s L C_2}$

$$\Rightarrow \frac{d\hat{v}_2}{dt} = f_t\left(\hat{v}_2, \hat{\phi}\right) + b_0\hat{\phi}$$

Total disturbance

where $f_t\left(\hat{v}_2, \hat{\phi}\right) = a\hat{v}_2 + (b - b_0)\hat{\phi}$ $\quad b_0 = \frac{NV_{10}\left(1-4\Phi_0\right)}{f_s L_0 C_{20}}$

[1] M. Ali, M. Yaqoob, L. Cao, and K. H. Loo, “Disturbance-observerbased dc-bus voltage control for ripple mitigation and improved dynamic response in two-stage single-phase inverter system,” IEEE Transactions on Industrial Electronics, vol. 66, no. 9, pp. 6836–6845, 2019.

- Derivation of disturbance observer

$$\frac{d\hat{v}_2}{dt} = f_t\left(\hat{v}_2, \hat{\phi}\right) + b_0\hat{\phi}$$

- Observer to estimate the output voltage and disturbance

$$\frac{d\tilde{\hat{v}}_2}{dt} = \tilde{f}_t + \beta_1\left(\hat{v}_2 - \tilde{\hat{v}}_2\right) + b_0\hat{\phi}$$

$$\frac{d\tilde{f}_t}{dt} = \beta_2\left(\hat{v}_2 - \tilde{\hat{v}}_2\right)$$

$\tilde{\hat{v}}_2$ and $\tilde{f}_t$ are the estimated values of $\hat{v}_2$ and f_t respectively.

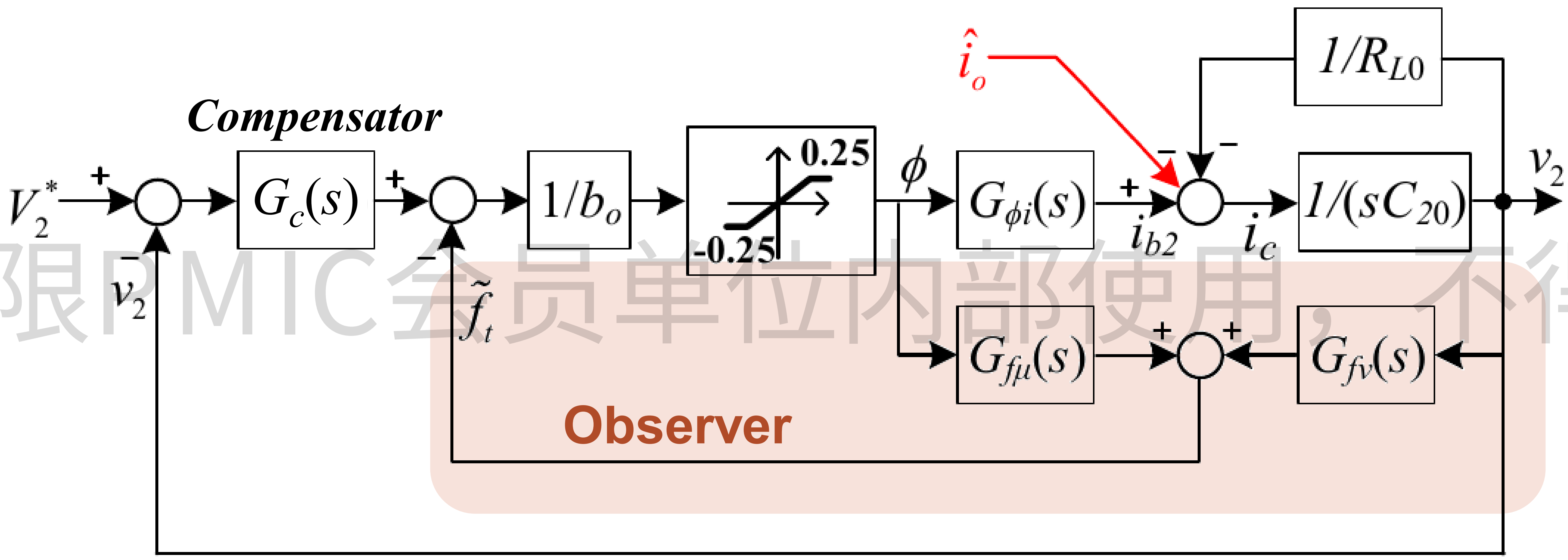
- When choosing β_1, β_2 positive, we can prove that

$$\tilde{\hat{v}}_2 \to \hat{v}_2, \tilde{f}_t \to f_t$$

[1] M. Ali, M. Yaqoob, L. Cao, and K. H. Loo, "Disturbance-observerbased dc-bus voltage control for ripple mitigation and improved dynamic response in two-stage single-phase inverter system," IEEE Transactions on Industrial Electronics, vol. 66, no. 9, pp. 6836–6845, 2019.

Disturbance–Observer–Based Control

- **The estimated disturbance is used to compensate the control system.**

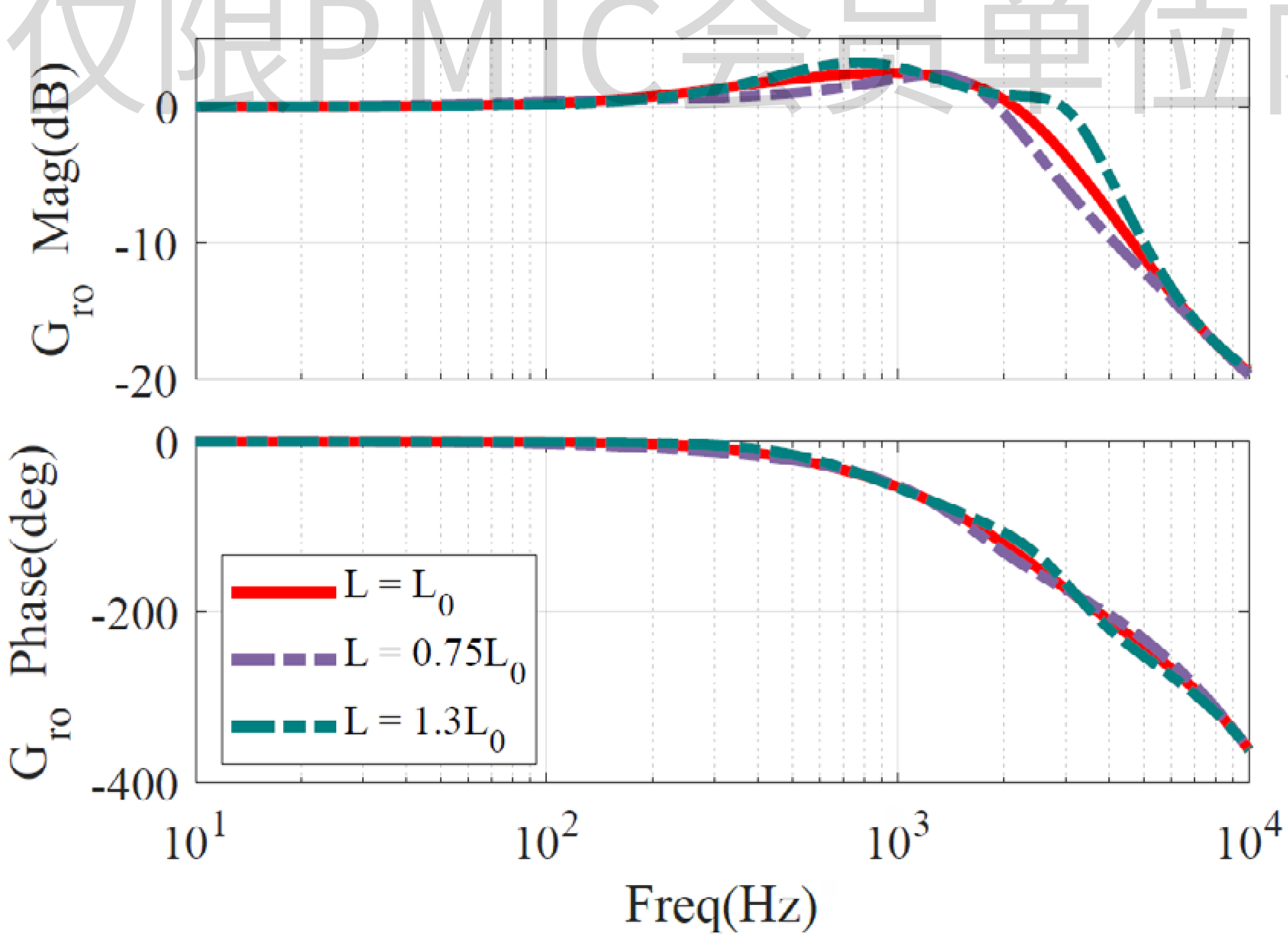


[1] M. Ali, M. Yaqoob, L. Cao, and K. H. Loo, "Disturbance-observerbased dc-bus voltage control for ripple mitigation and improved dynamic response in two-stage single-phase inverter system," IEEE Transactions on Industrial Electronics, vol. 66, no. 9, pp. 6836–6845, 2019.

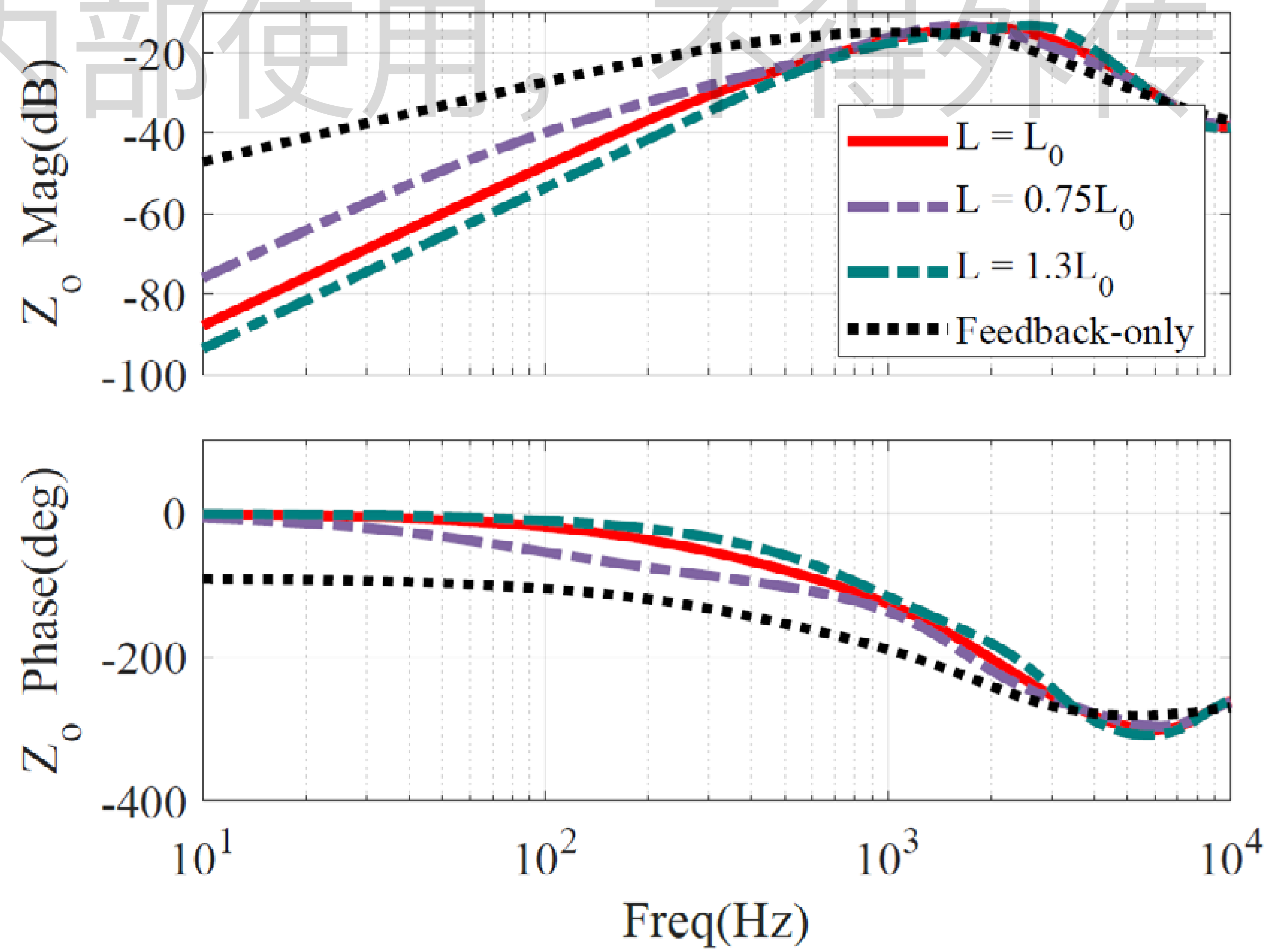
Disturbance–Observer–Based Control

- Set the crossover frequency as 1.2*k*Hz with phase margin 45°:
  $k_p = 7.53 \times 10^3$, $k_i = 1.37 \times 10^7$
- Parameter variations have minor influence on the control bandwidth and output impedance.
- The output impedance is much smaller than that of the feedback only control

Reference-to-output



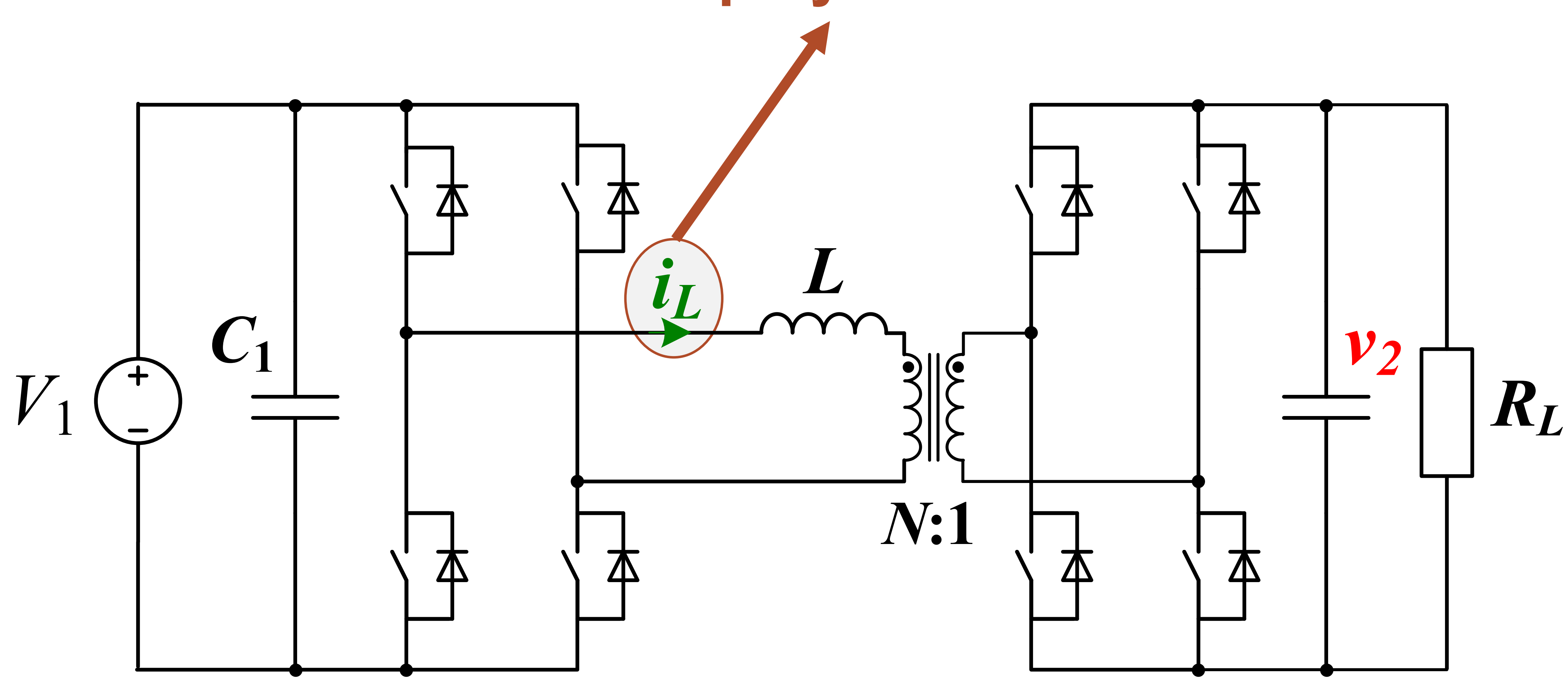
Output impedance



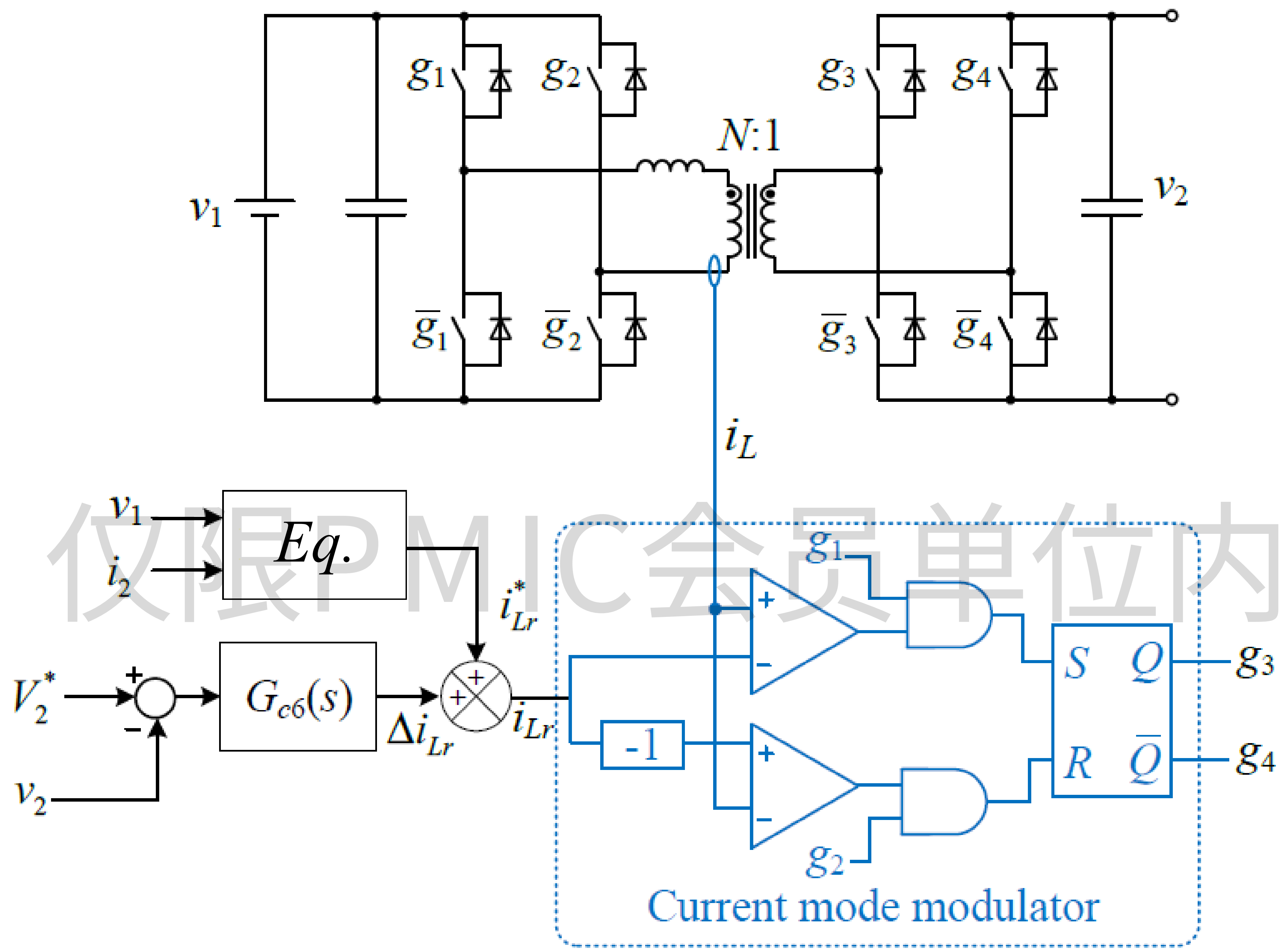
Current mode control

- The inductor current is involved in the control to improve the dynamic performance.
- Two types of current mode control are introduced here:
  - Feedforward current control
  - Predictive current control

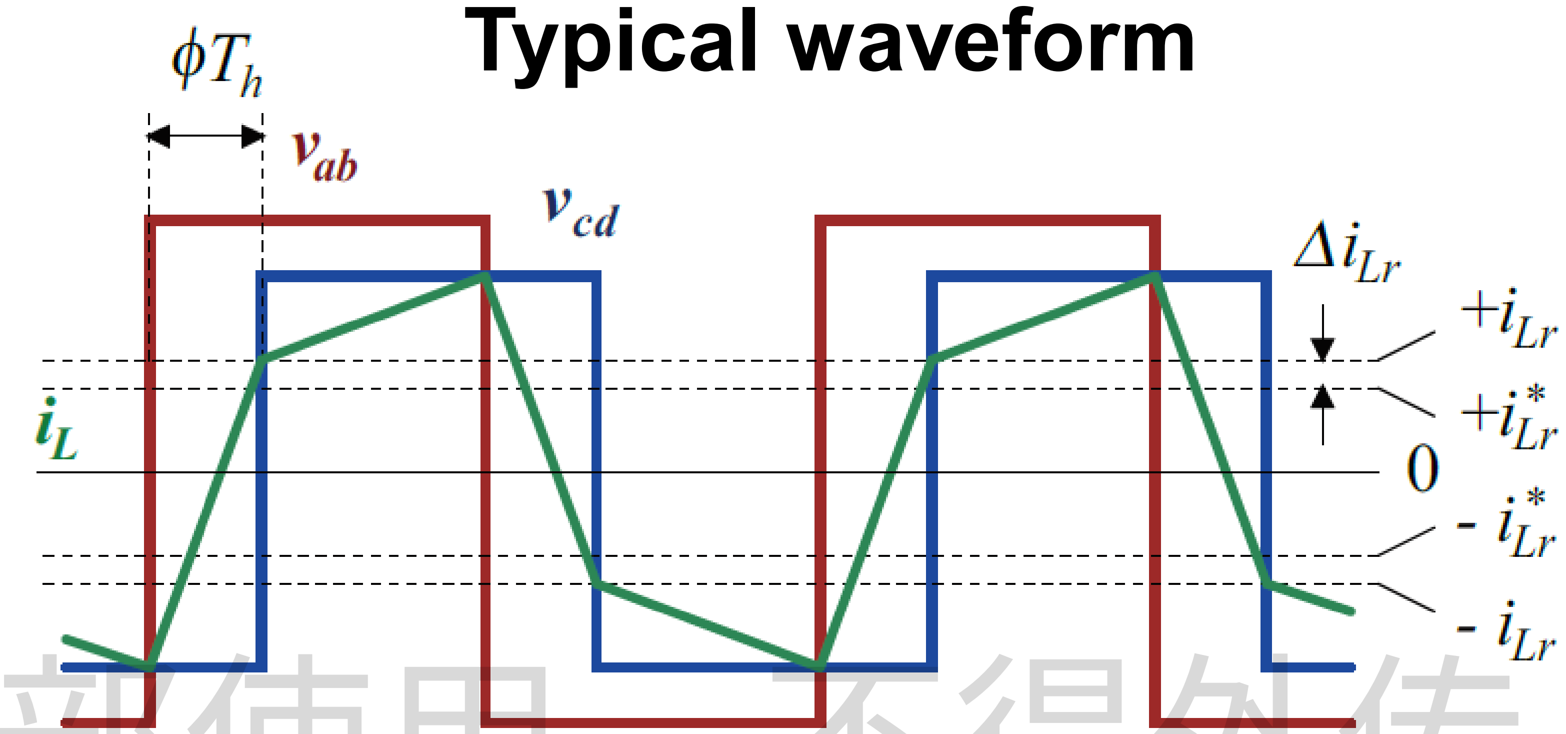
Employed for control



Feed–forward current control (FFCC)



Typical waveform



Calculated based on load current

$$i_{Lr}^{*} = \frac{i_2}{N}\frac{2}{1+\sqrt{1-\frac{8 i_2 L f_s}{V_1 N}}}$$

The current reference $i_{Lr} = i_{Lr}^{*} + \Delta i_{Lr}$

Generated from the compensator

[1] Z. Shan, J. Jatskevich, H. H. Iu, and T. Fernando, “Simplified load-feedforward control design for dual-active-bridge converters with current-mode modulation,” IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 6, no. 4, pp. 2073–2085, Dec 2018.

Feed–forward current control (FFCC)

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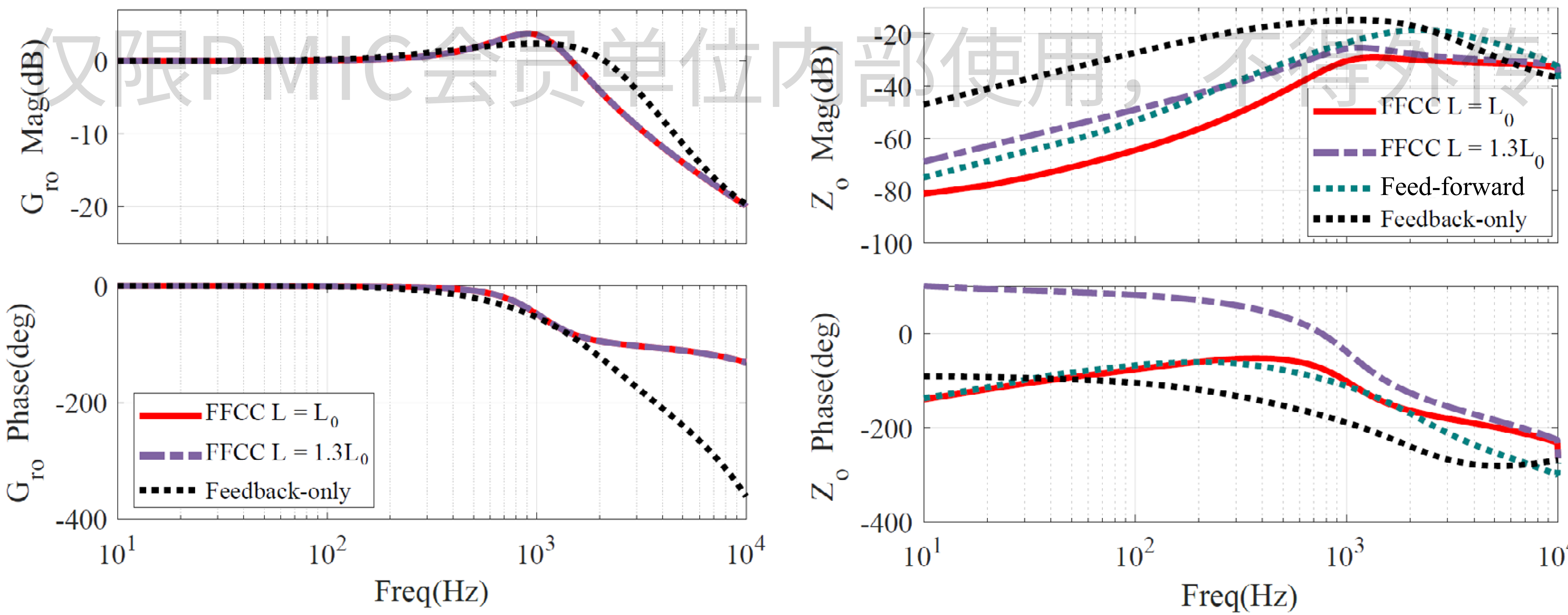
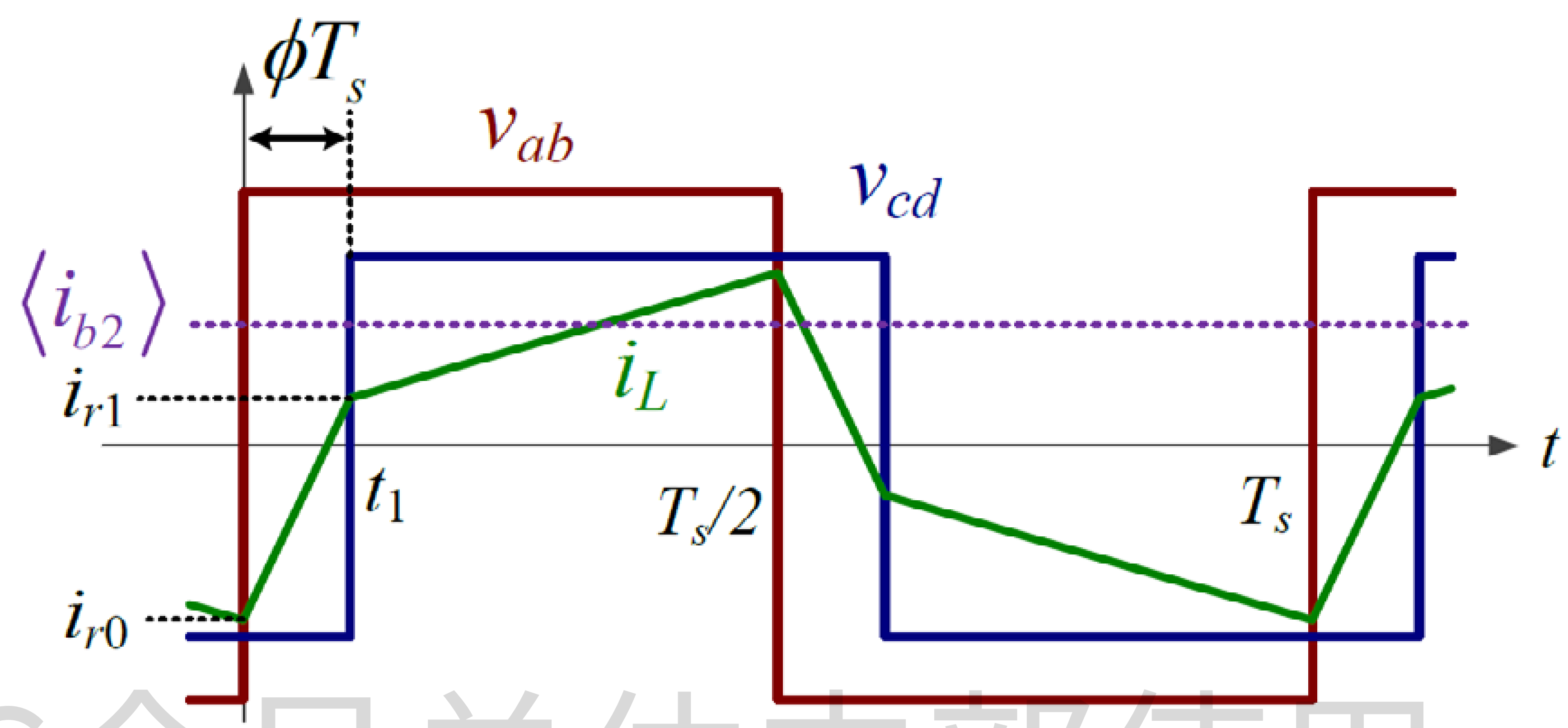
- Set the crossover frequency as 1.2*k*Hz with phase margin 45°:
  K_p = 4.35, k_i = 3.17x10^4.
- Good dynamic performance, not sensitive to parameter variation.
- Can be affected by the switching noise, especially when the DAB loses ZVS-on.



Predictive current control



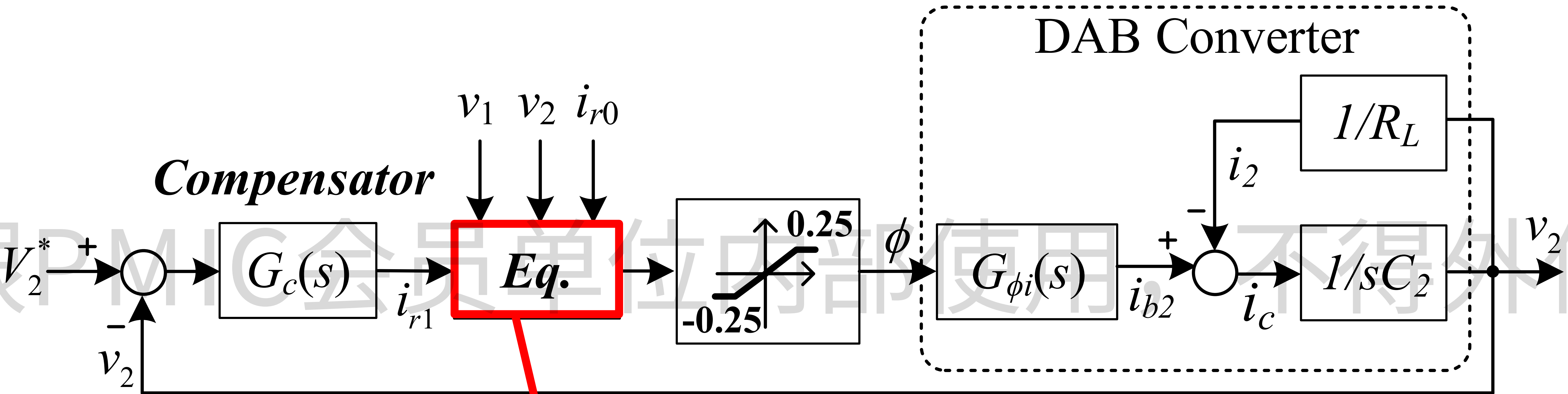
The phase shift ϕ can be calculated as

$$\phi = \frac{i_{r1} - i_{r0}}{T_s} \frac{L}{v_1 + N v_2}$$

[1] S. Dutta, S. Hazra, and S. Bhattacharya, “A digital predictive current mode controller for a single-phase high-frequency transformer-isolated dual-active bridge dc-to-dc converter,” IEEE Transactions on Industrial Electronics, vol. 63, no. 9, pp. 5943–5952, Sep. 2016.

Predictive current control

- **Not suitable for high frequency applications, i_{ro} should be sampled every switching cycle.**



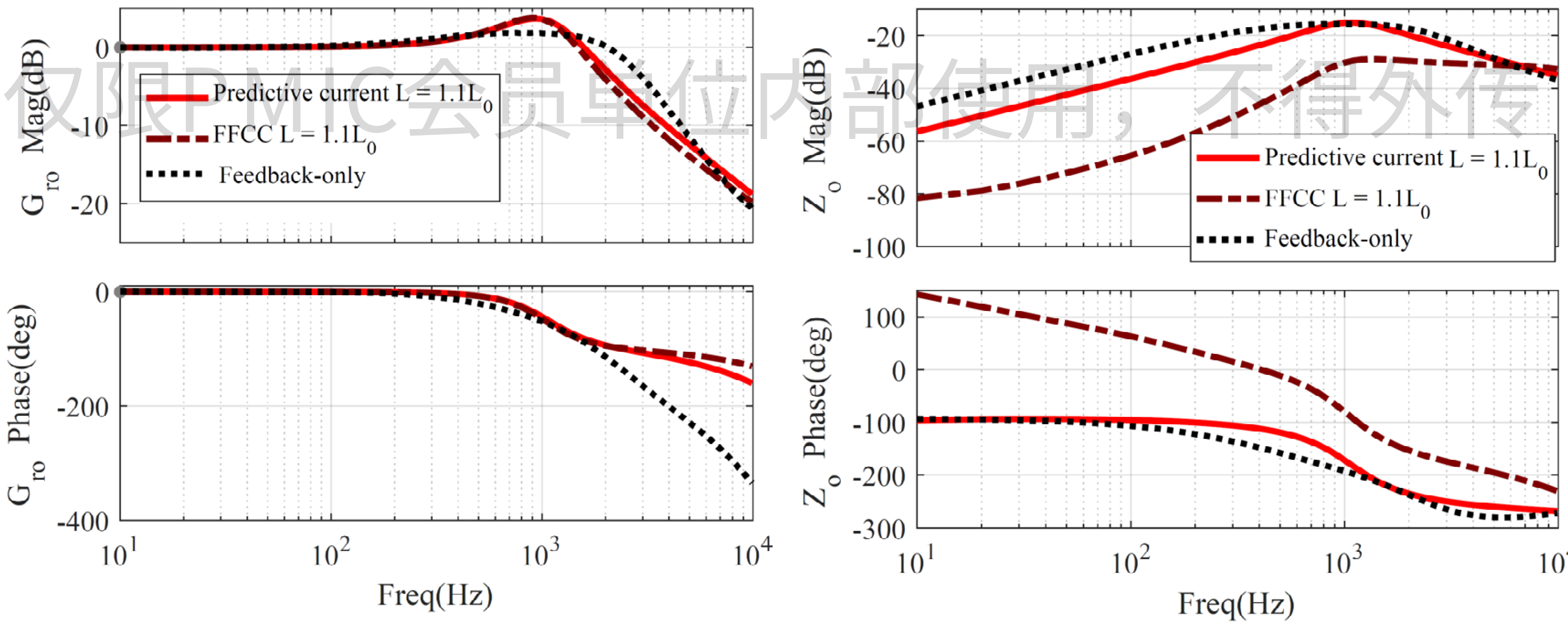
$$\phi = \frac{i_{r1} - i_{r0}}{T_s} \frac{L}{v_1 + N v_2}$$

- i_{r1} is generated by the compensator.
- i_{r0}, v_1 and v_2 are sampled each switching cycle.

[1] S. Dutta, S. Hazra, and S. Bhattacharya, “A digital predictive current mode controller for a single-phase high-frequency transformer-isolated dual-active bridge dc-to-dc converter,” IEEE Transactions on Industrial Electronics, vol. 63, no. 9, pp. 5943–5952, Sep. 2016.

Predictive current control

- Set the crossover frequency as 1.2*k*Hz with phase margin 45°:
  $K_p = 24.8$, $k_i = 1.45\text{x}10^5$.
- Good dynamic performance, but sensitive to parameter variation.
- Not suitable for high frequency applications.



MDCS–MPC

- MDCS-MPC: Moving discretized control set--model predictive control
- For DAB, the phase shift ratio ϕ is used to control the output power.

$$\phi \in [-0.25, 0.25]$$

ϕ is discretized to adapt the digital control:

$$\phi \in \{-0.25, \cdots, 0, \Delta_f, 2\Delta_f, \cdots, 0.25\}$$

where Δ_f is the discretized unit.

[1] L. Chen, S. Shao, Q. Xiao, L. Tarisciotti, T. Dragicevic, and P. Wheeler, “Model-predictive-control for dual-active-bridge converters supplying pulsed power loads in naval dc microgrids,” IEEE Transactions on Power Electronics, pp. 1–1, 2019.
[2] L. Chen, L. Lin, S. Shao, F. Gao, Z. Wang, P. W. Wheeler, and T. Dragicevi ˇ c, “Moving discretized control set model-predictive control ´ for dual-active bridge with the triple-phase shift,” IEEE Transactions on Power Electronics, vol. 35, no. 8, pp. 8624–8637, 2020.

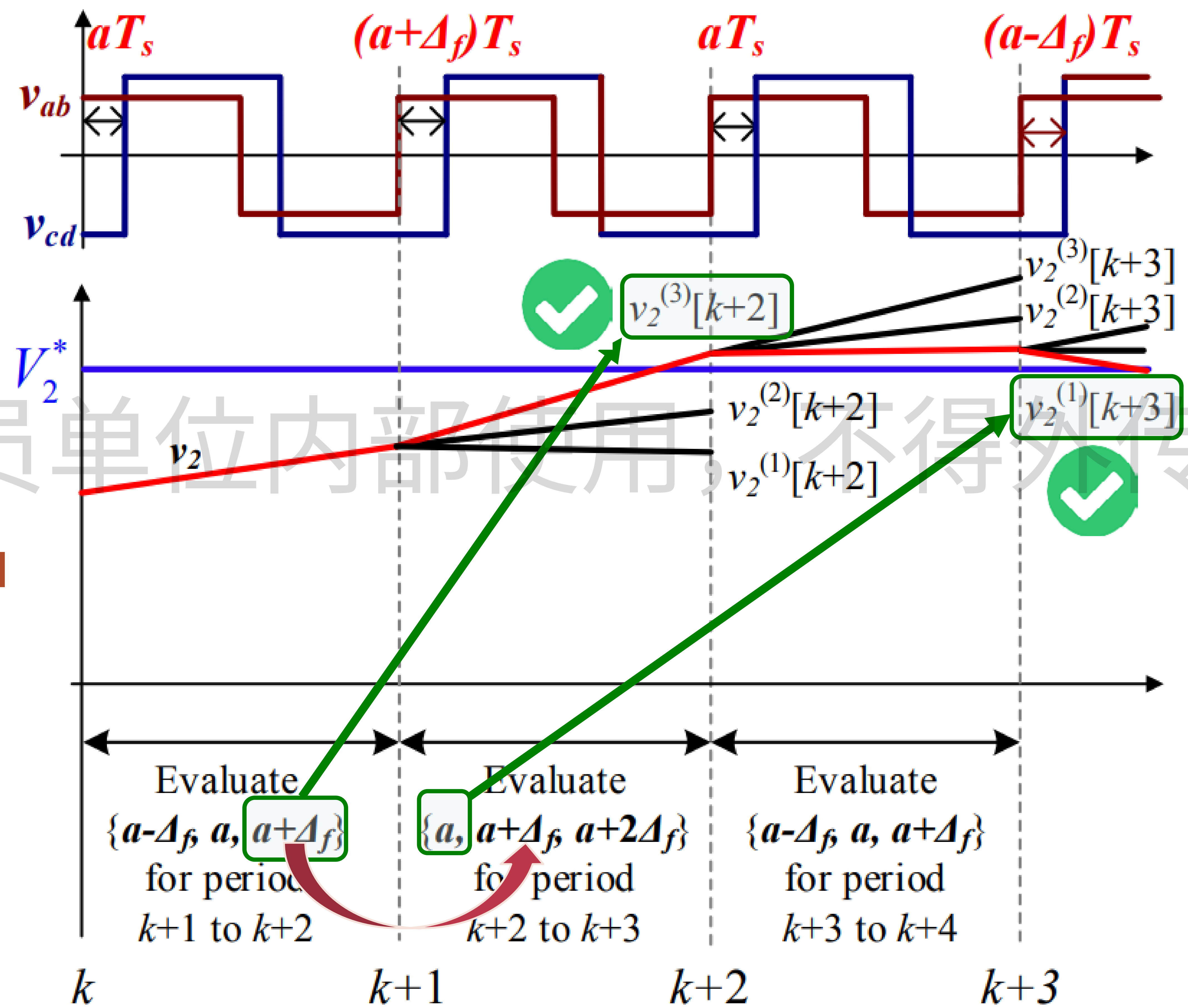
MDCS–MPC

To illustrate the operating principle, a simple cost function is considered:

$$ct = \left(V_2^* - v_2[k+2]\right)^2$$

Output reference

Calculated using reduced order model



[1] L. Chen, S. Shao, Q. Xiao, L. Tarisciotti, T. Dragicevic, and P. Wheeler, "Model-predictive-control for dual-active-bridge converters supplying pulsed power loads in naval dc microgrids," IEEE Transactions on Power Electronics, pp. 1–1, 2019.

MDCS–MPC

- **To provide damping and enhance the resistance to AD sampling noise, the cost function can be chosen as:**

$$ct = \alpha_1 G_1 + \alpha_2 G_2$$

$$\begin{cases} G_1 = \left(V_2^* - v_2[k+2]\right)^2 \\ G_2 = \left(v_2[k+2] - v_2[k]\right)^2 \end{cases}$$

Responsible for regulation of the output voltage

Takes charge of voltage deviation reduction

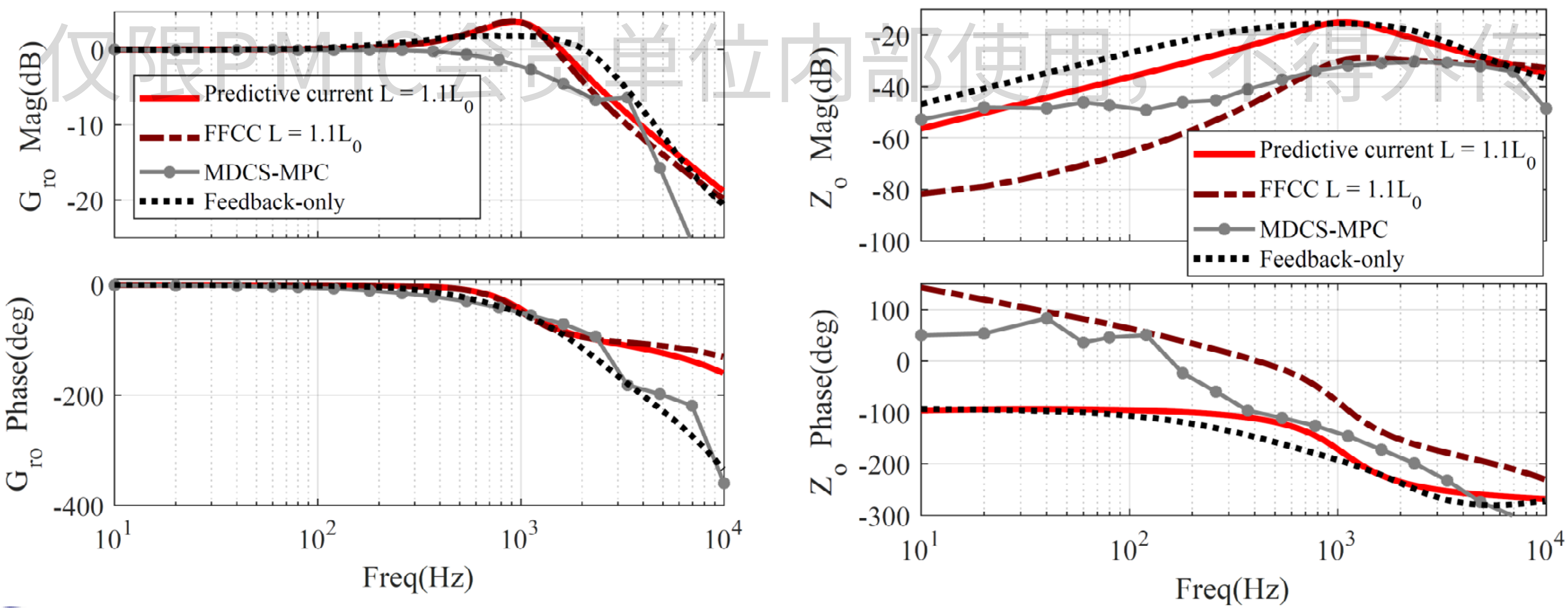
α_1, α_2 are the coefficients need to be tuned.

[1] L. Chen, S. Shao, Q. Xiao, L. Tarisciotti, T. Dragicevic, and P. Wheeler, "Model-predictive-control for dual-active-bridge converters supplying pulsed power loads in naval dc microgrids," IEEE Transactions on Power Electronics, pp. 1–1, 2019.
[2] L. Chen, L. Lin, S. Shao, F. Gao, Z. Wang, P. W. Wheeler, and T. Dragicevic, "Moving discretized control set model-predictive control ´ for dual-active bridge with the triple-phase shift," IEEE Transactions on Power Electronics, vol. 35, no. 8, pp. 8624–8637, 2020.

MDCS–MPC

- Set the crossover frequency as 1.2*k*Hz with phase margin 45°:

  $\alpha_1 = 1$, $\alpha_2 = 0.5$, $\mu = 11$, $\lambda = 1$, $V_m = 10\text{V}$.
- Good dynamic performance.
- Control parameters are chosen based on trial and error or the machine learning.



Comparison of the control methods

- **Feedback only:** simple and accept performance.
- **Feedforward:** excellent dynamic performance, but its performance degrades quickly when there are parameter variations.
- **Virtual direct power control:** not suitable for applications with different load conditions.
- **Disturbance observer based control:** excellent dynamic performance, not affected by the disturbances.
- **Feedforward current control:** excellent dynamic performance, but its performance can be affected by switching noise.
- **Predictive current control:** excellent dynamic performance, but not suitable for high frequency applications.
- **MDCS-MPC:** excellent dynamic performance, but the control parameters should be tuned by trial and error or machine learning.

Comparison of the control methods

Control Methods	Implementation complexity	Dynamic performance	Robustness against parameter variation	No. of sensors
Feedback only	Low	++	++++	1
Feed-forward	Medium	++++	++	3
Virtual direct power control	Medium	+++	+	3
Disturbance observer based control	Medium	++++	++++	1
Feed-forward current control	High	++++	+++	3
Predictive current control	Medium	++++	++	3
MDCS-MPC	High	++++	+++	3

Note: + = **Poor**; ++ = **Average**; +++ = **Good**; ++++ = **Excellent**

Contents

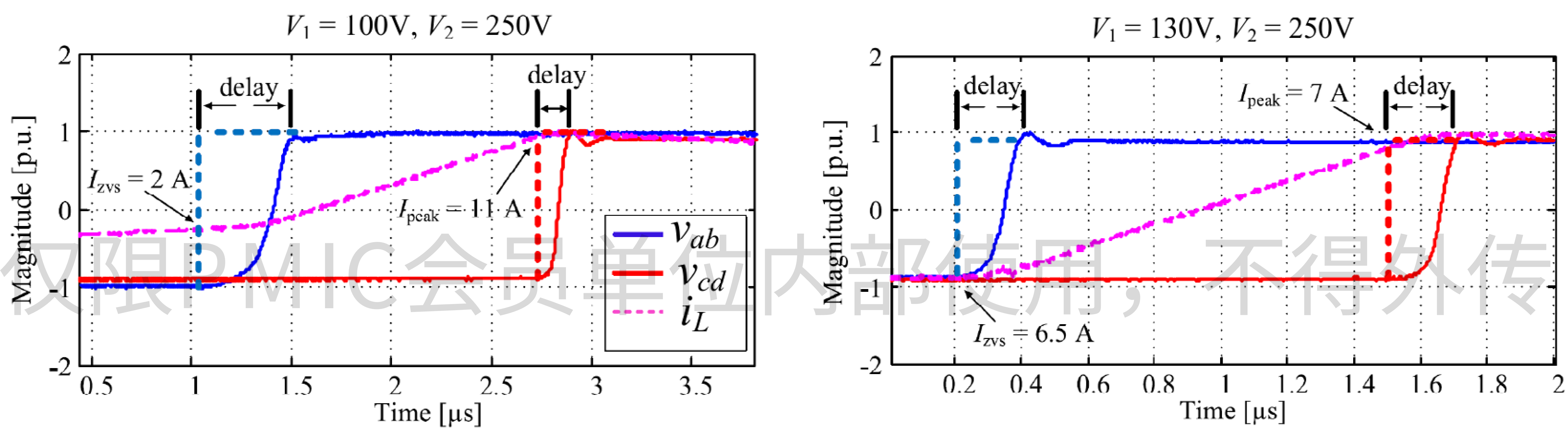
- DAB modeling methods, quantitatively compare the following models:
  - Reduced order model
  - Generalized average model
  - Discrete-time model
- DAB control, quantitatively compare the following control methods:
  - Conventional feedback control
  - Feedforward plus feedback control
  - Virtual direct power control
  - Disturbance observed based control
  - Feedforward current control
  - Predictive current control
  - Model predictive control
- **Practical control issues of DAB**
  - **Phase drift**
  - **Steady state magnetizing flux bias**
  - **Transient magnetizing flux bias**

Phase drift

- **Phase drift:** In the DAB converter, the actual phase shift ratio can be different from the theoretical one. There are three reasons:
  - Dead time
  - Switching delay during the ZVS transition.
  - Voltage drop on power devices and other components

Phase drift caused by the ZVS transition

- A large inductor current will shorten the ZVS transition period.

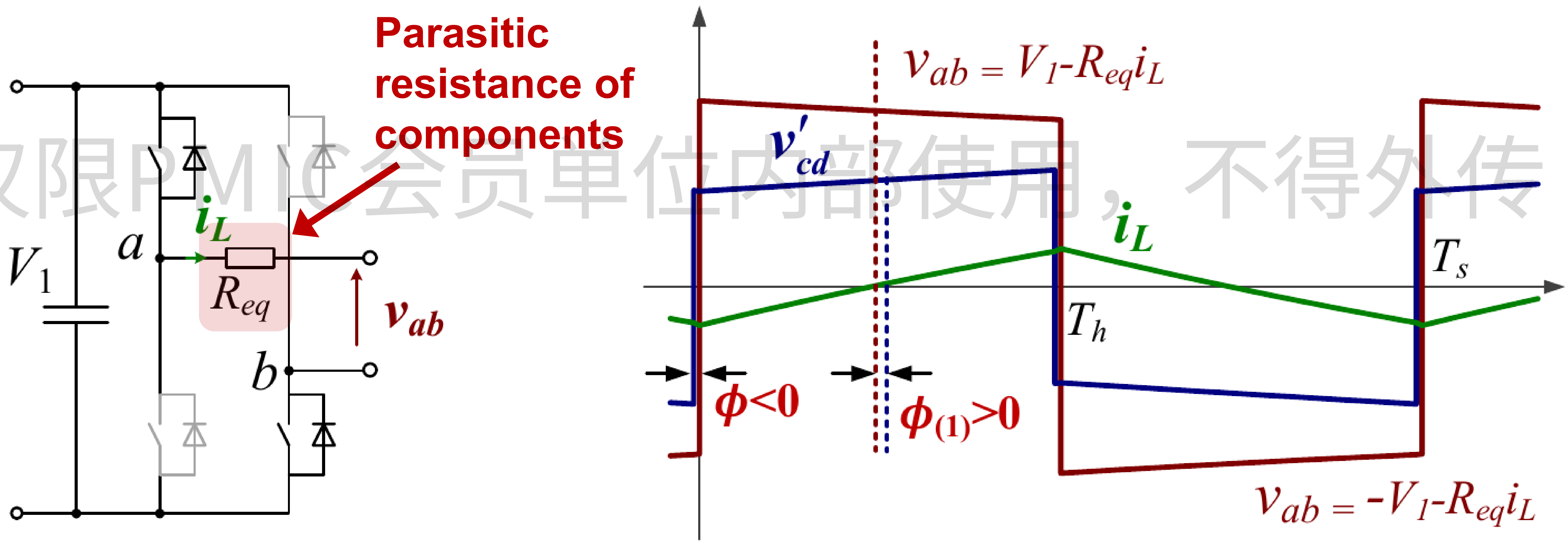


Large phase drift **Small phase drift**

[1] J. Hiltunen, V. Vaisanen, R. Juntunen, and P. Silventoinen, "Variable-frequency phase shift modulation of a dual active bridge converter," IEEE Transactions on Power Electronics, vol. 30, no. 12, pp. 7138– 7148, Dec 2015.

Phase drift caused by the voltage drop

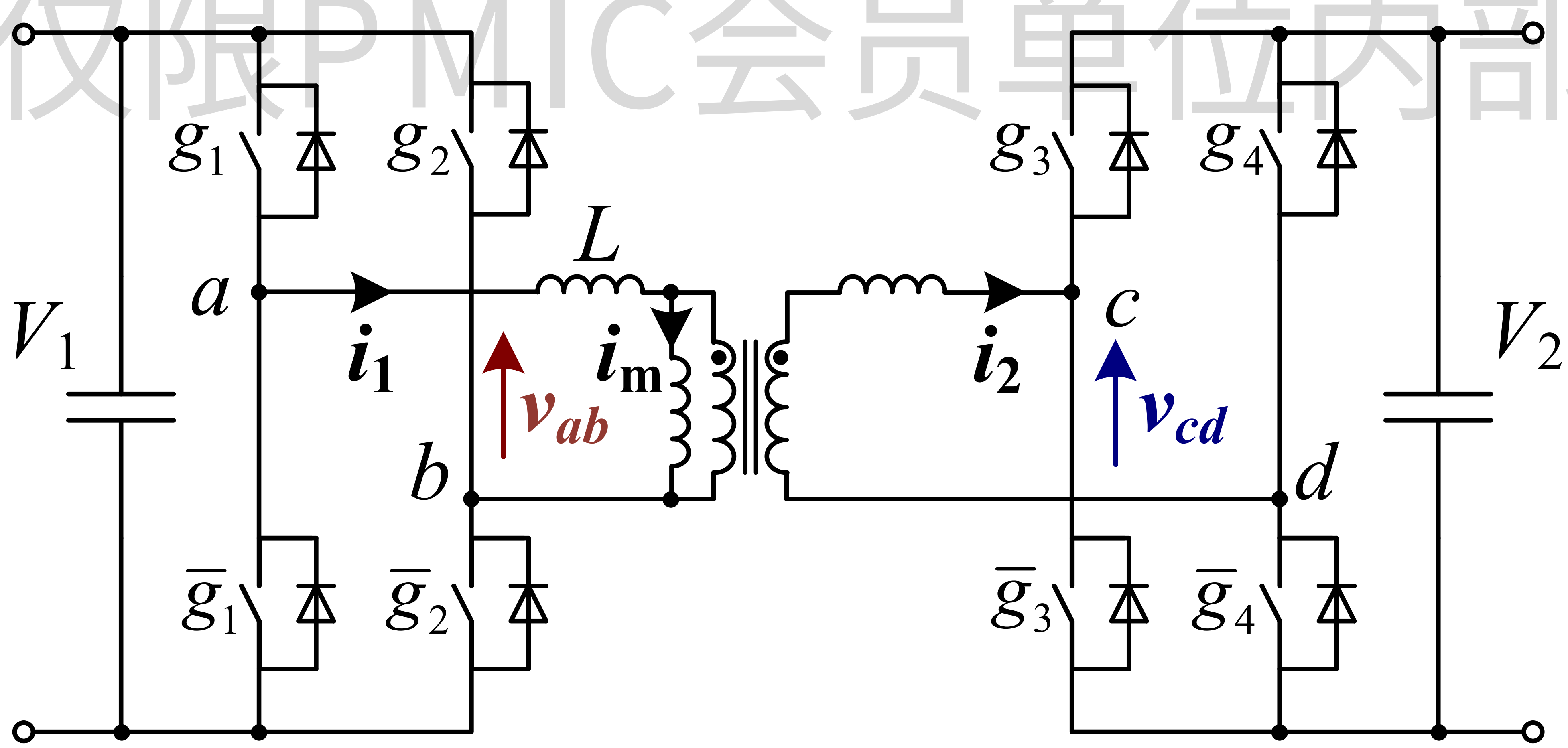
- Due to the parasitic resistance
  - the equivalent phase of $\boldsymbol{v}_{ab}$ shift to left
  - the equivalent phase of $\boldsymbol{v}_{cd}$ shift to right

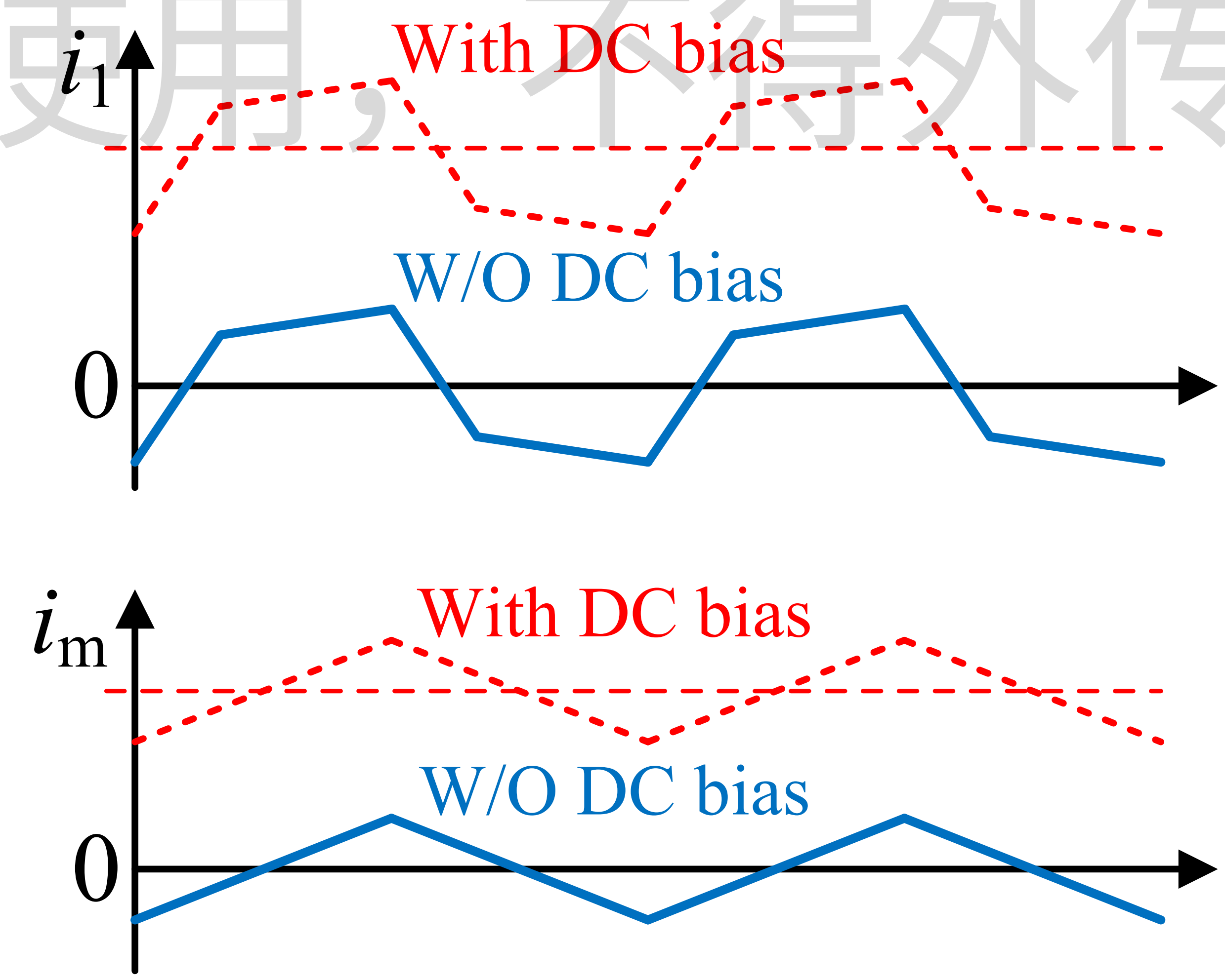


The given phase $\phi < 0$, however, the power is transferred from primary to secondary side.

Steady magnetic flux bias

- The steady DC bias can be caused by
  - gate signal difference
  - gate driver delay
- The steady DC bias can lead to
  - loss of ZVS-on
  - extra conduction loss



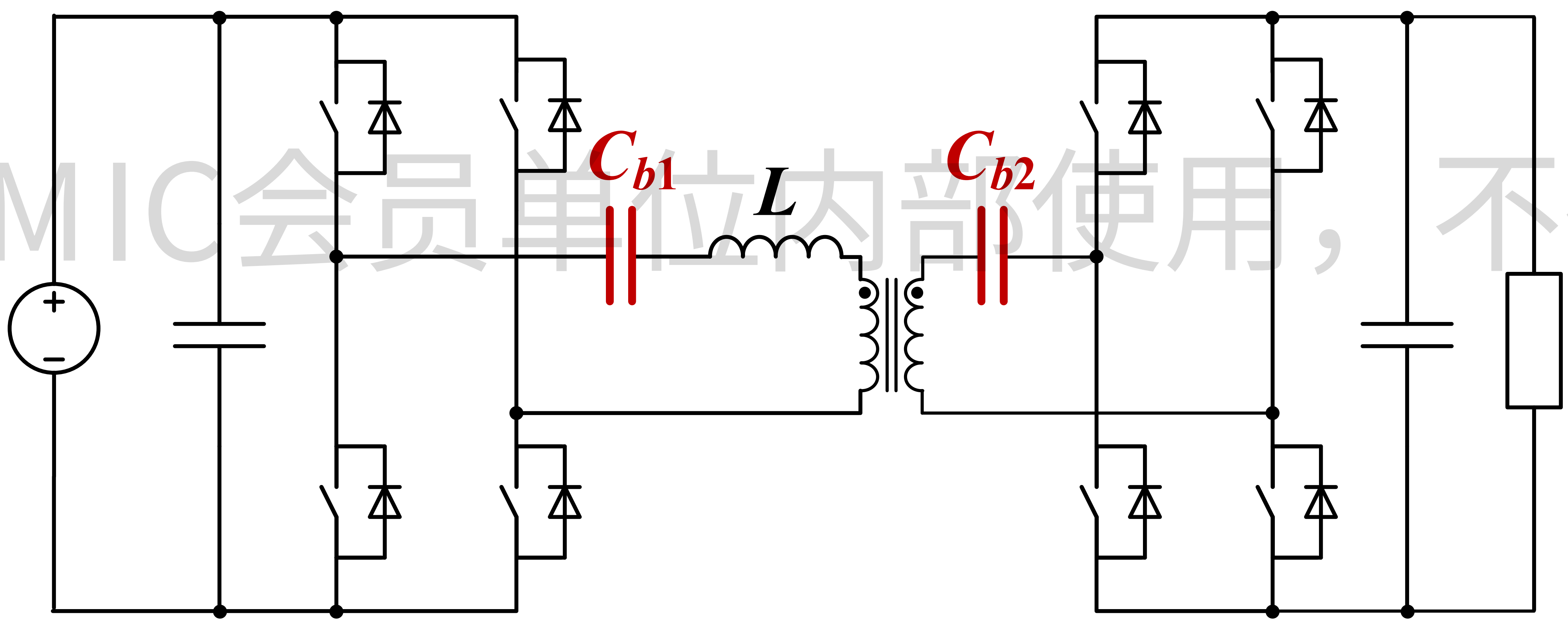


[1] B. Zhang, S. Shao, L. Chen, X. Wu, and J. Zhang, "Steady state and transient dc magnetic flux bias suppression methods for a dual active bridge converter," IEEE Journal of Emerging and Selected Topics in Power Electronics, pp. 1–1, 2019.

Steady DC bias suppression

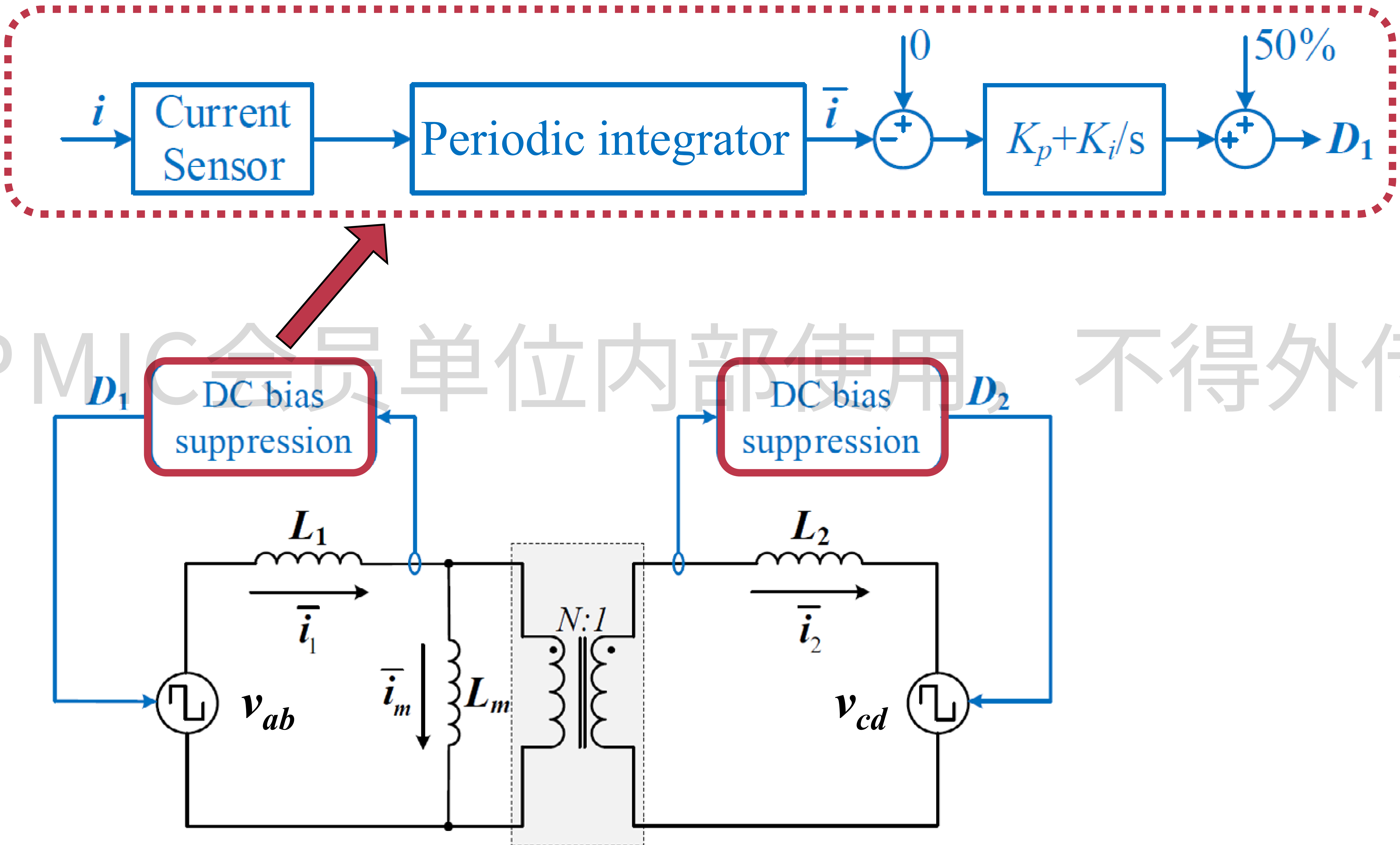
DC block capacitor

- Simple
- Not suitable for high voltage applications---large volume capacitor will be required.



Steady DC bias suppression

- **Active control**



[1] B. Zhang, S. Shao, L. Chen, X. Wu, and J. Zhang, “Steady state and transient dc magnetic flux bias suppression methods for a dual active bridge converter,” IEEE Journal of Emerging and Selected Topics in Power Electronics, pp. 1–1, 2019.

Transient DC bias

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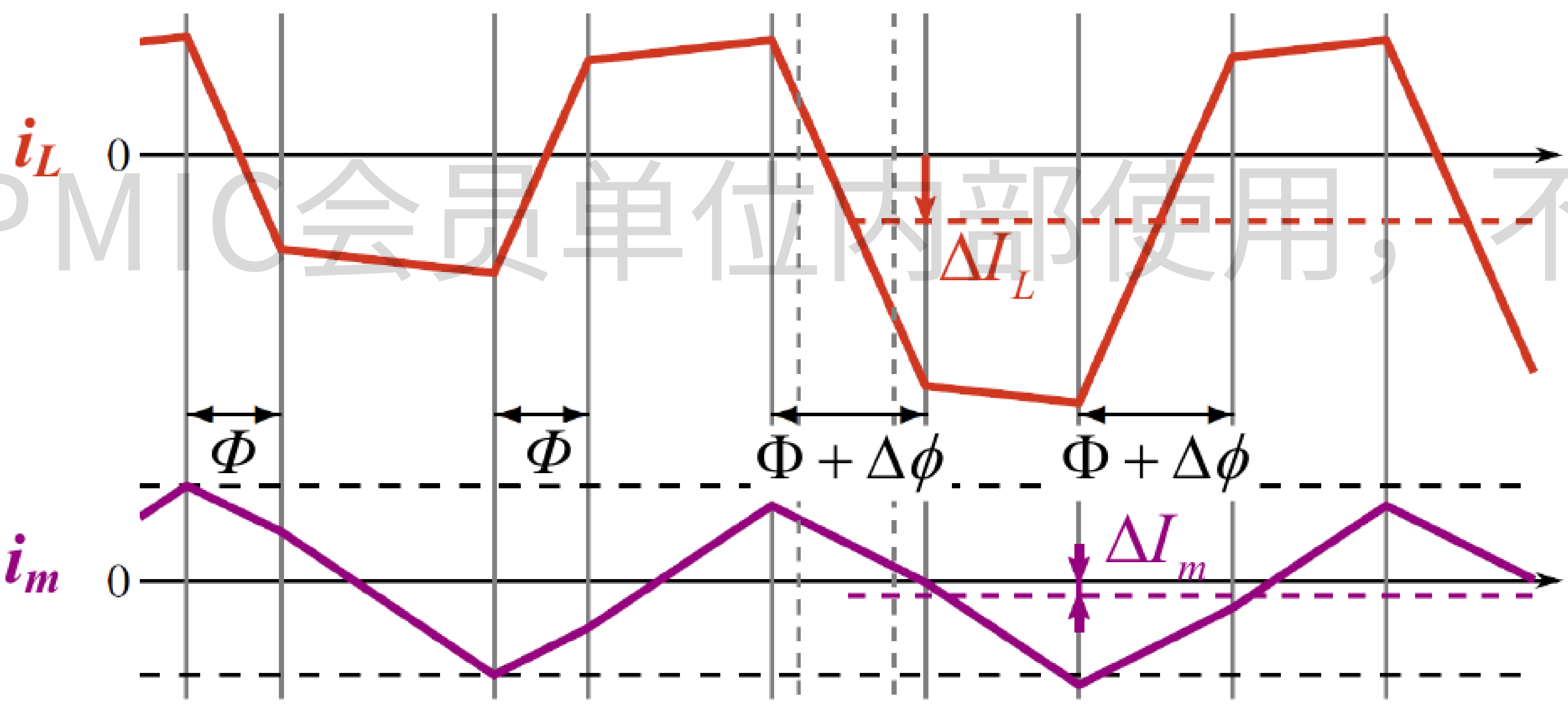
- Because of the update on the phase shift ratio, the inductor current can have a temporary spike.
- Transient DC bias can lead to saturation of magnetic components.



[1] K. Takagi and H. Fujita, “Dynamic control and performance of a dual active-bridge dc–dc converter,” IEEE Transactions on Power Electronics, pp. 1–1, 2017.

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Transient DC bias suppression

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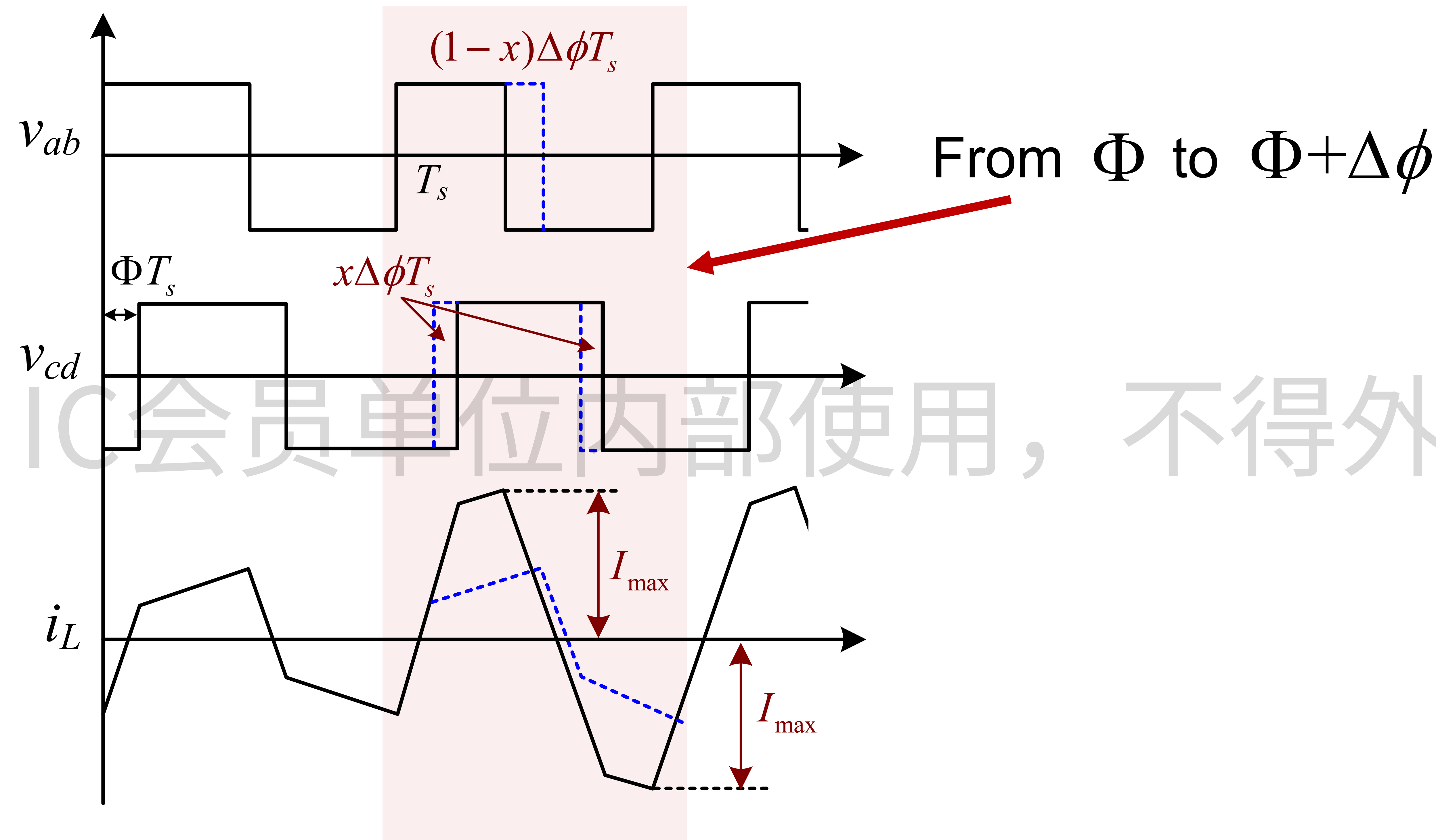
- Change the phase shift ratio in two steps.



When the voltage gain $M < 1$, $x = 1/(1+M)$

[1] X. Li and Y. F. Li, "An optimized phase-shift modulation for fast transient response in a dual-active-bridge converter," IEEE Transactions on Power Electronics, vol. 29, no. 6, pp. 2661–2665, June 2014.

Conclusion

- **Three different modeling methods are reviewed and quantitatively compared, the reduced order model is recommended.**
- **Seven different control methods are reviewed and quantitatively compared, their pros and cons are introduced.**
- **Several practical control issues are introduced.**

Thank you!

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