Modeling, Reactive Current and ZVS-on of a Dual Active Bridge DC/DC Converter

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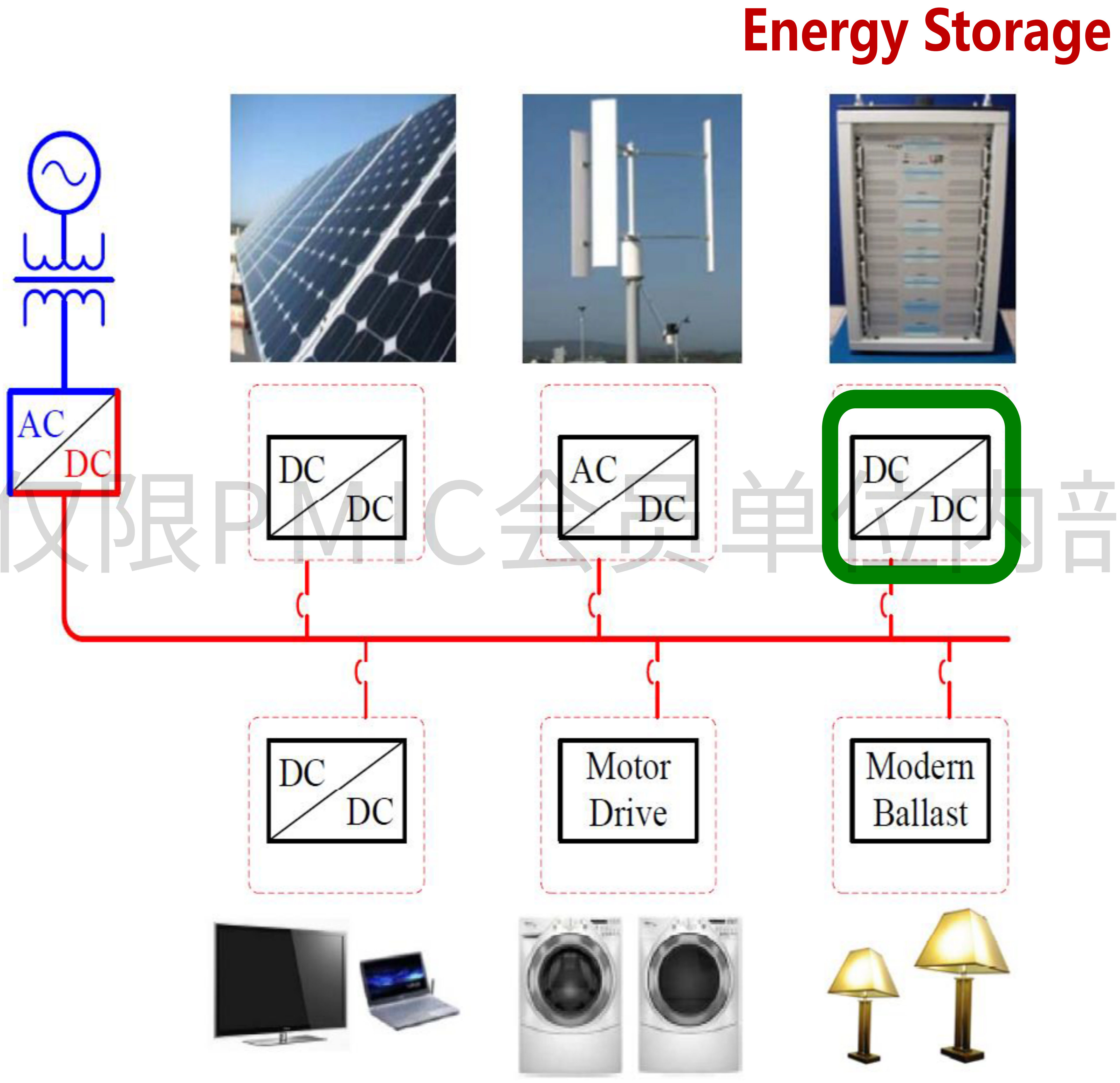
Zhejiang University

- In Hangzhou, 170km away from Shanghai
- Founded 1897
- 36 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
#68	#14	#3
QS World University Rankings >	Asia University Rankings >	Best Chinese Universities Ranking >
QS, 2019	Times Higher Education, 2019	ShanghaiRanking Consultancy, 2018

7 campus at Zhejiang University

DC Microgrid



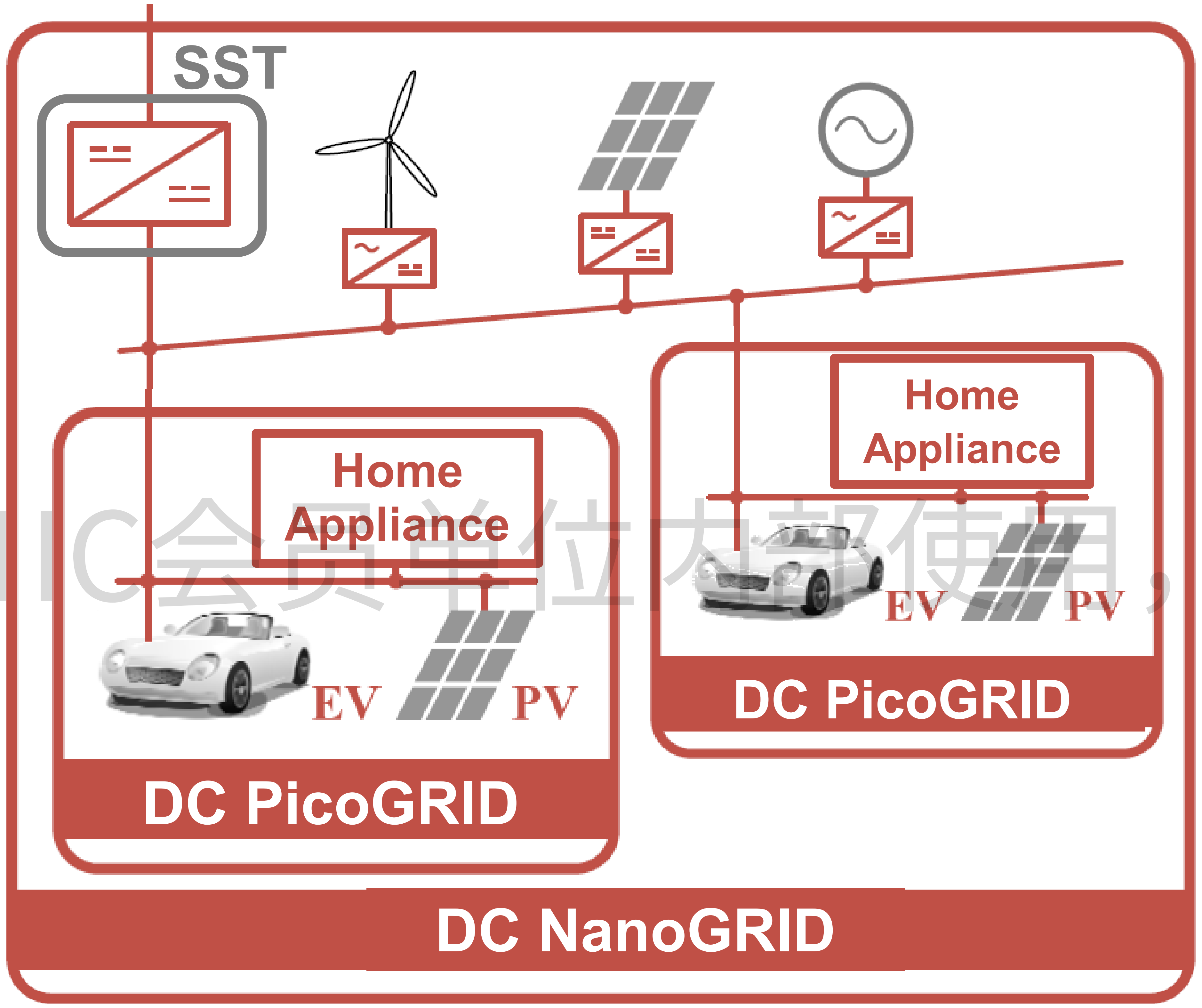
Compared with AC, a DC grid has:

- 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.

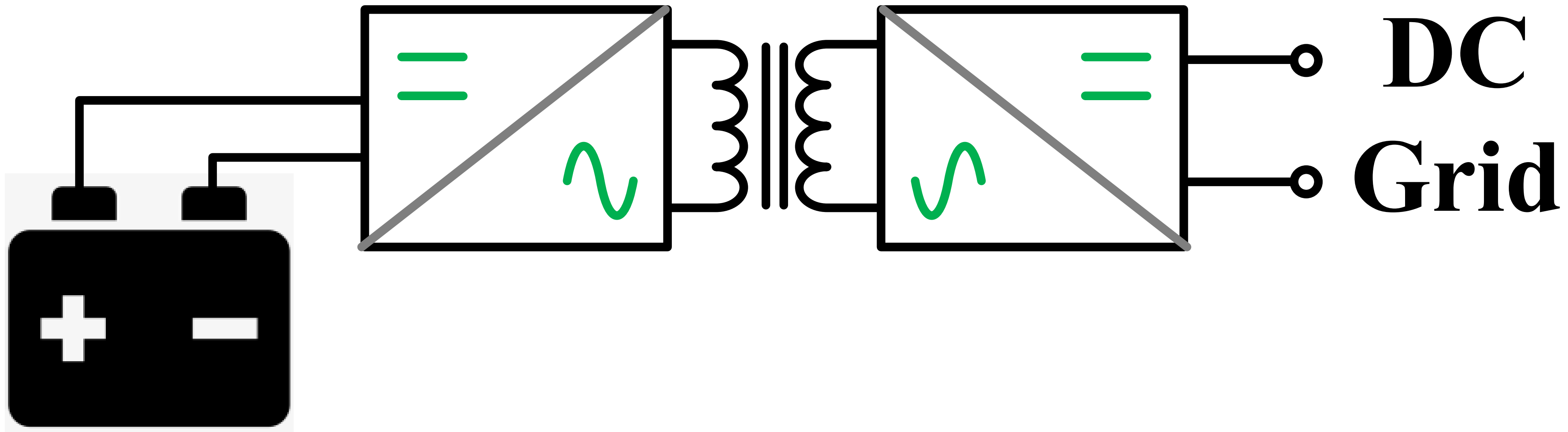
DC Smart Grid

PMIC
Power Management Innovation Consortium

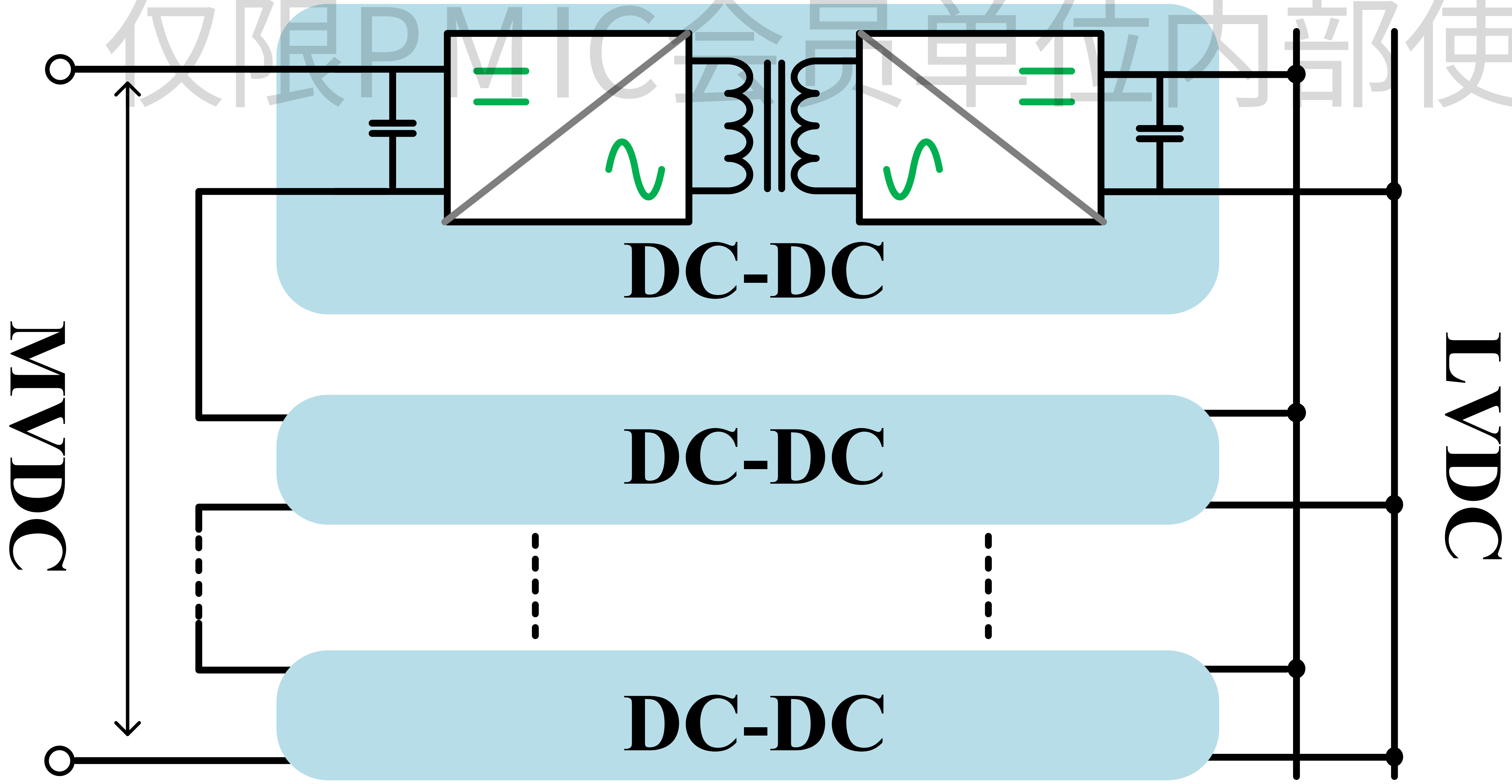


[1] Yunjie Gu, “Distributed Peer-to-Peer Control for Renewable Power Generation DC Microgrid”, Zhejiang University, PhD thesis, 2015
[2] D. Boroyevich, I. Cvetković, D. Dong, R. Burgos, F. Wang and F. Lee, "Future electronic power distribution systems a contemplative view," 2010 12th International Conference 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

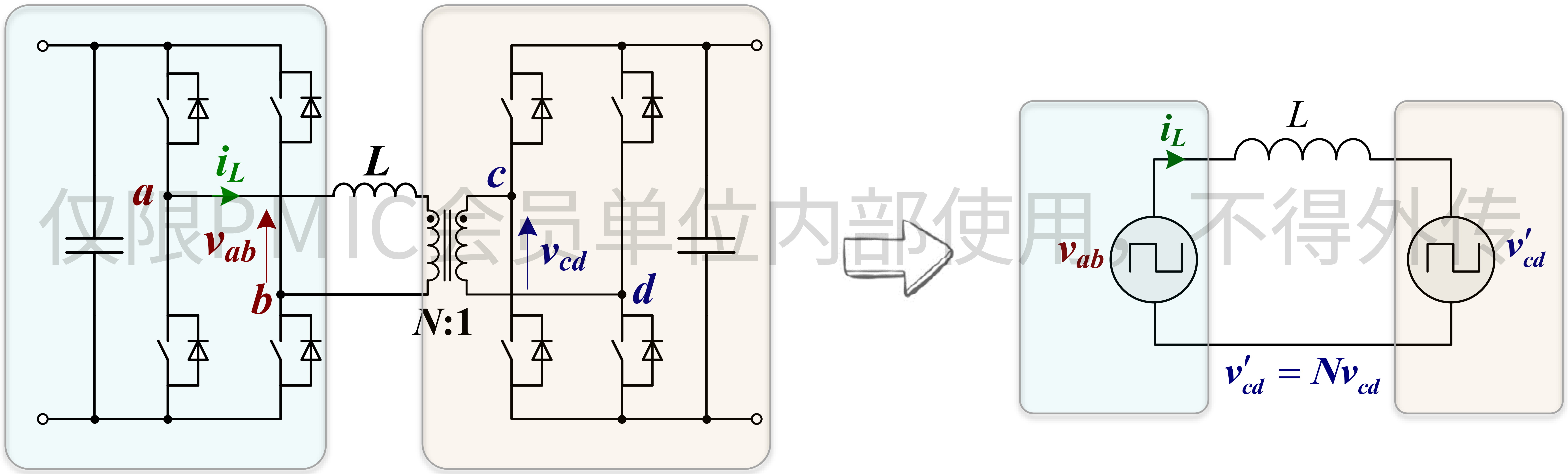
Bidirectional Resonant Converter

Dual Active Bridge (DAB)

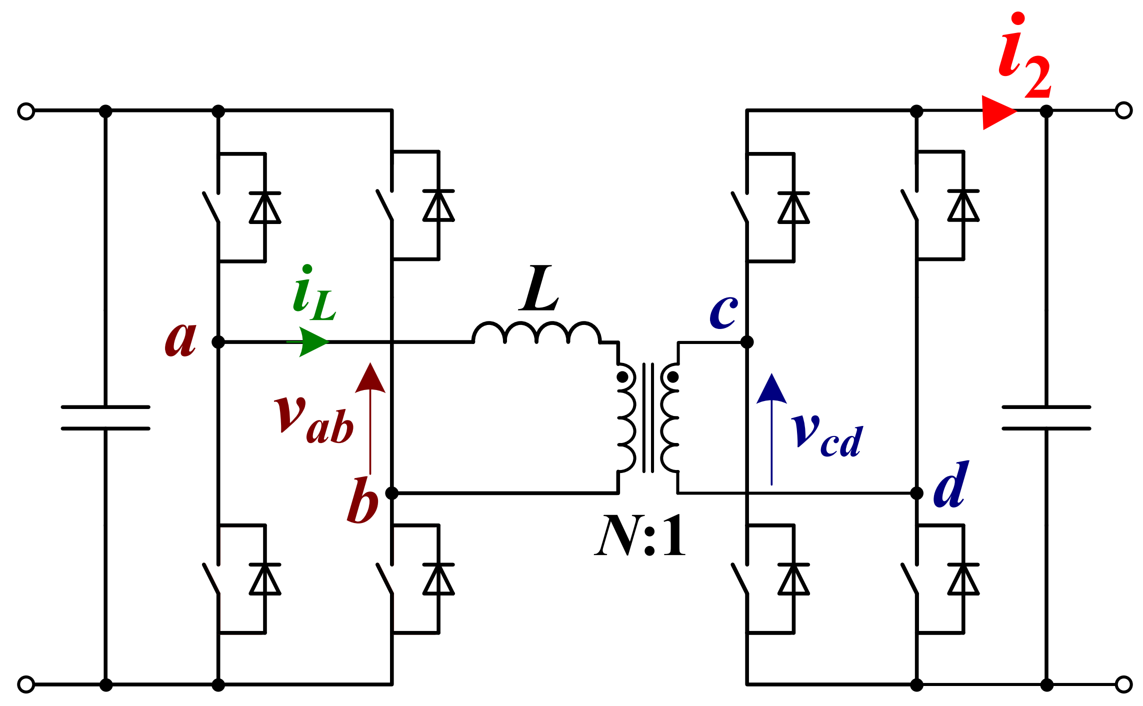
- Simple
- Auto-adjust bidirectional power flow
- Wide voltage conversion range
- Zero voltage switching (ZVS) capability

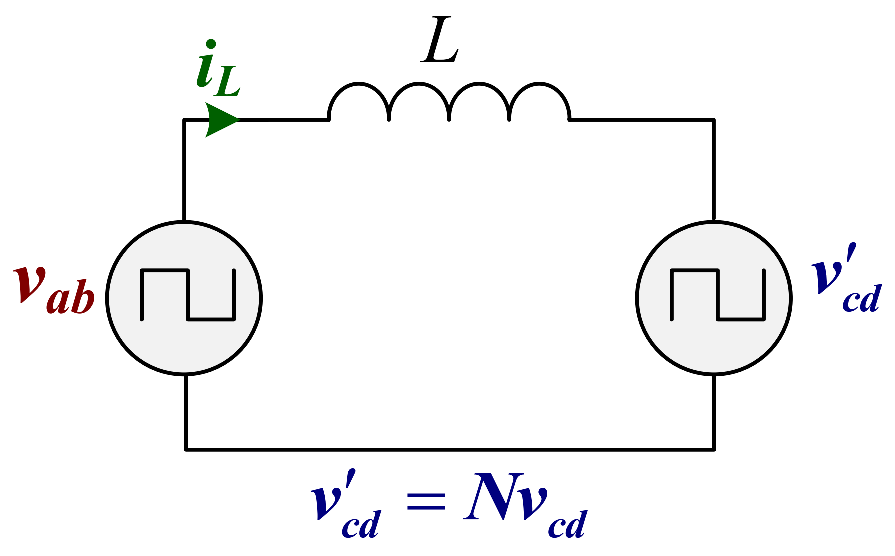
Dual Active Bridge

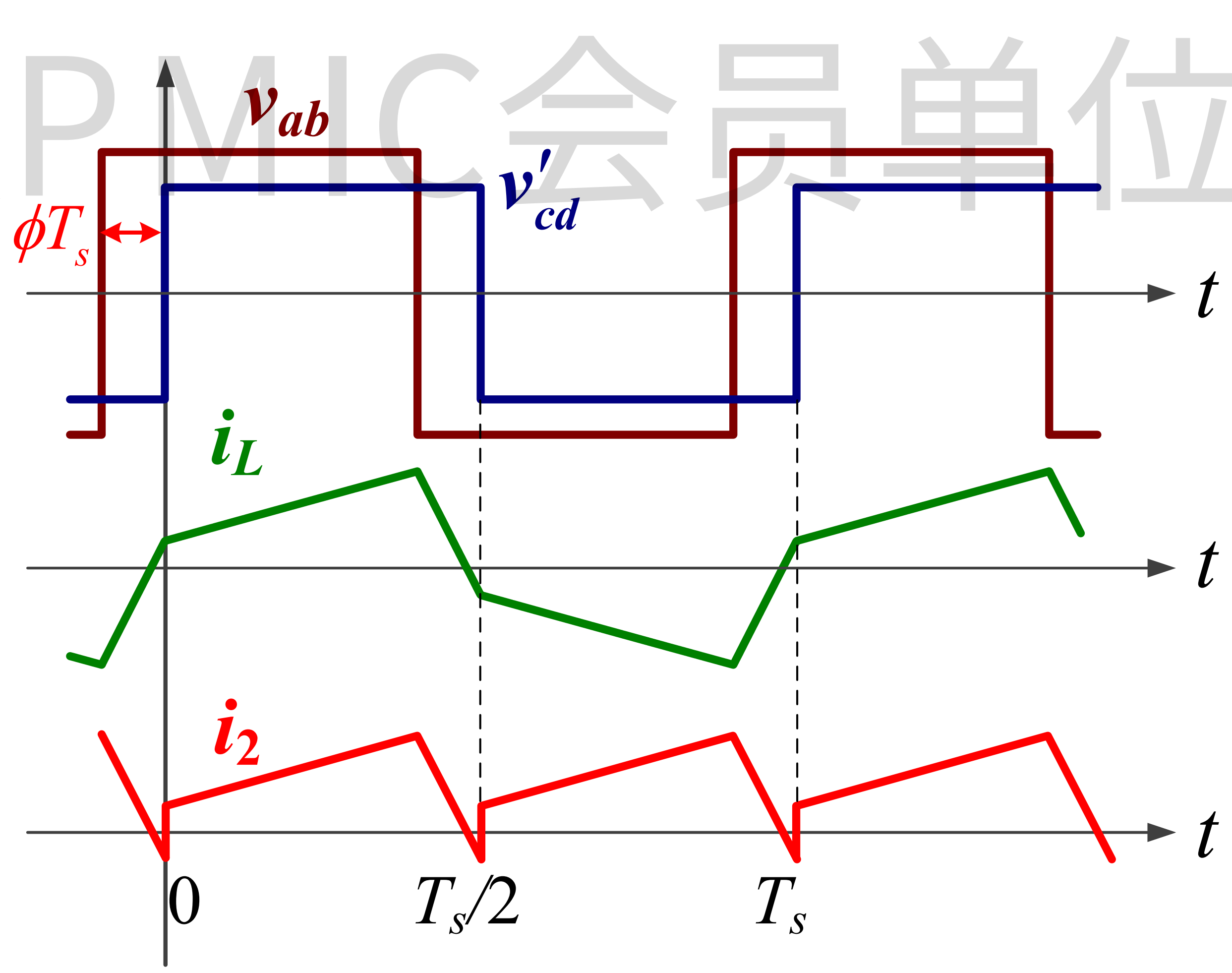
Simple structure



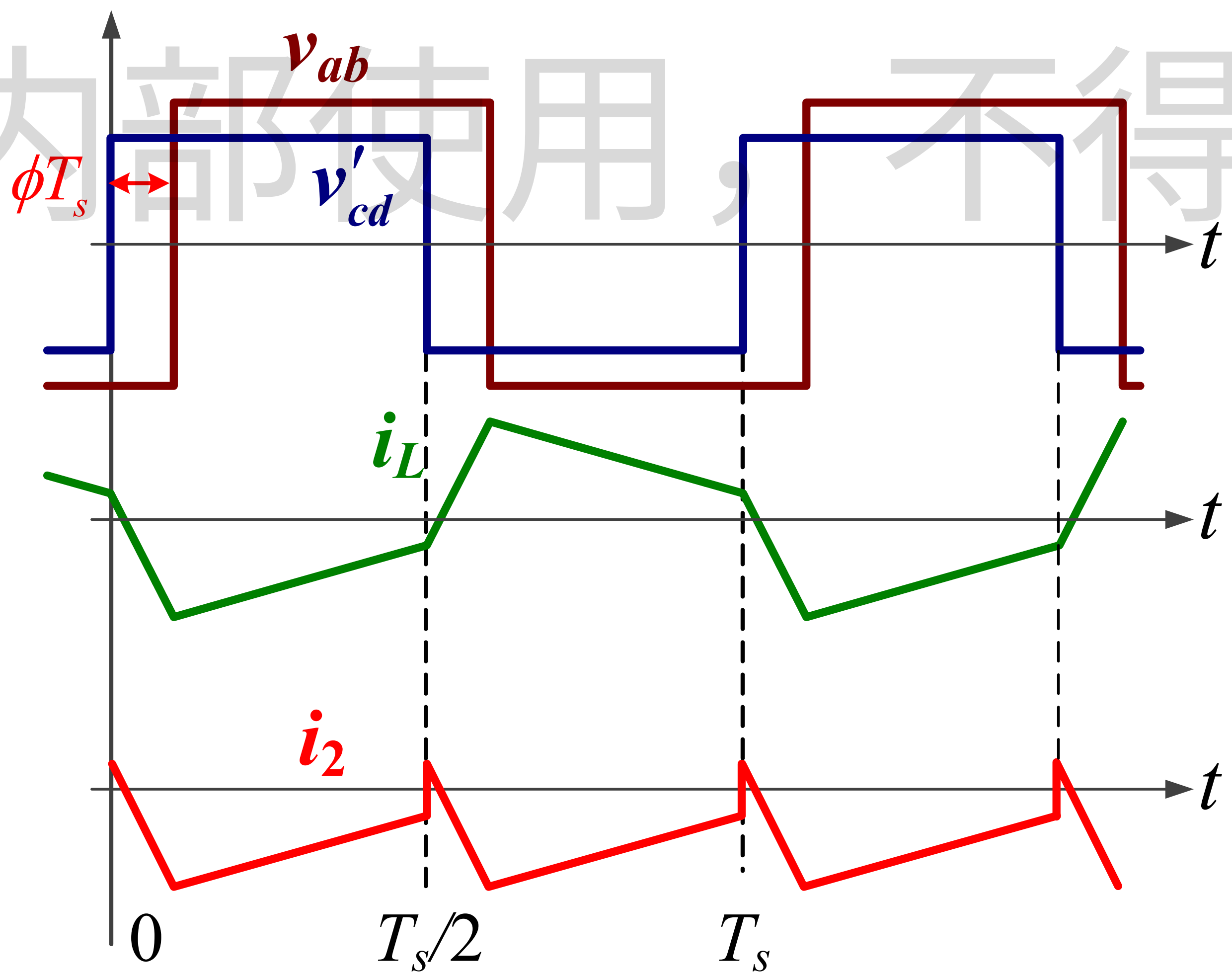
[1] R. Doncker, et. al. “A three-phase soft-switched high power density dc/dc converter for high power applications,” in Conference Record of the 1988 IEEE Industry Applications Society Annual Meeting, Oct 1988







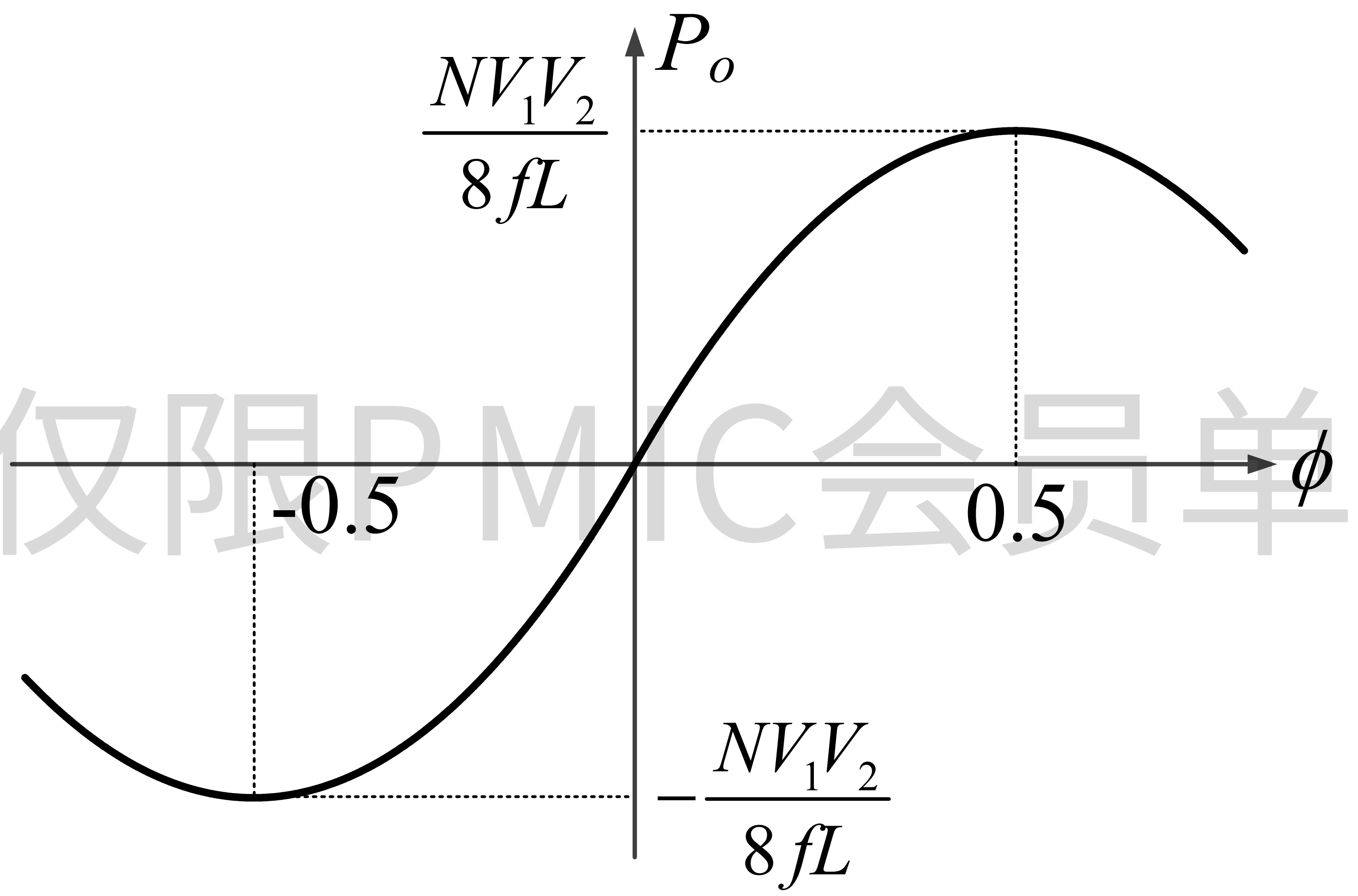
$\phi > 0$, **Positive power flow**

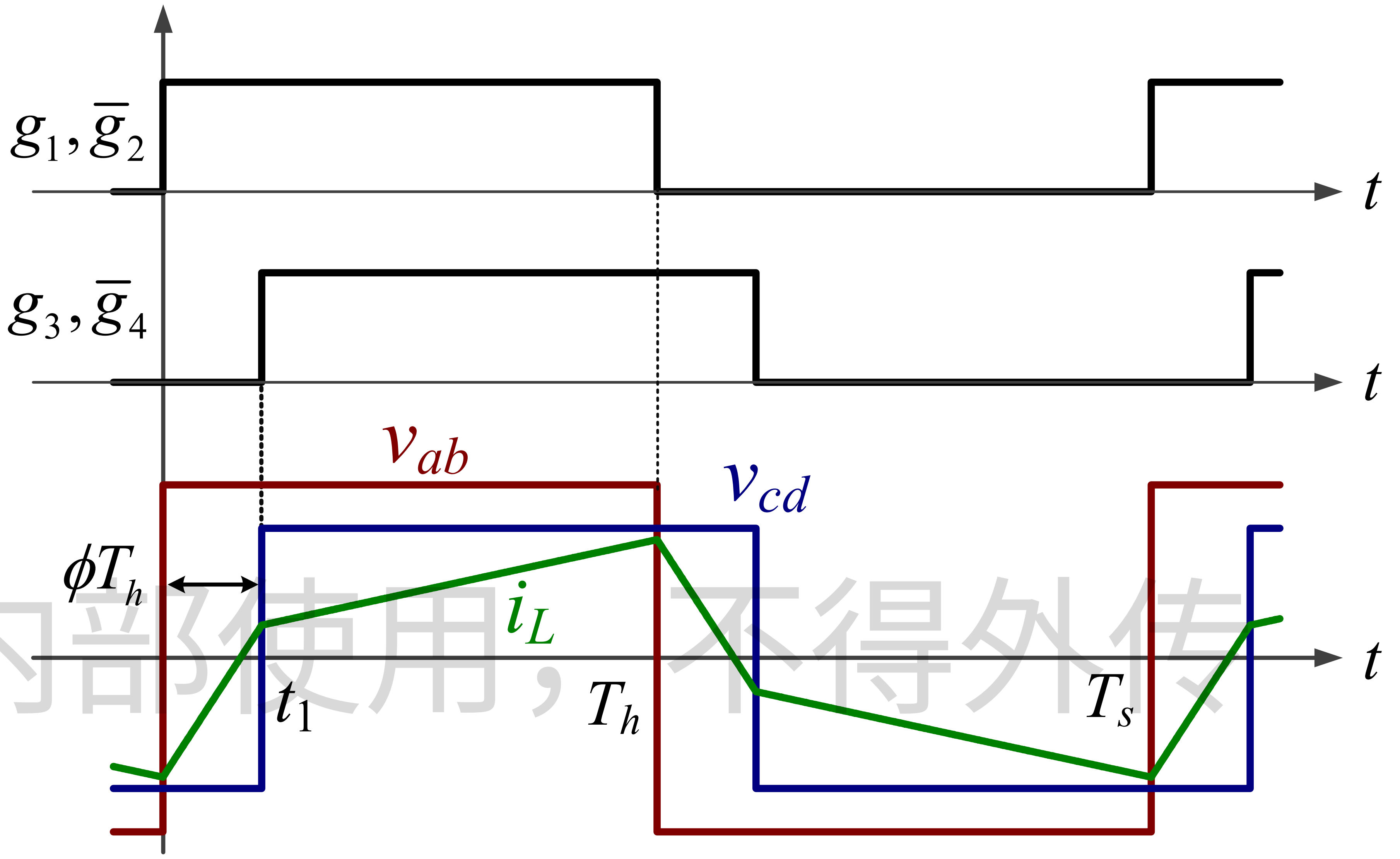


$\phi < 0$, **Negative power flow**

DAB output power

$$P_o = \frac{NV_1V_2\phi(1-|\phi|)}{2fL}$$





DAB waveforms using SPS modulation

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

Contents

1 Modeling of a DAB

2 Reactive current suppression

3 ZVS on of a DAB

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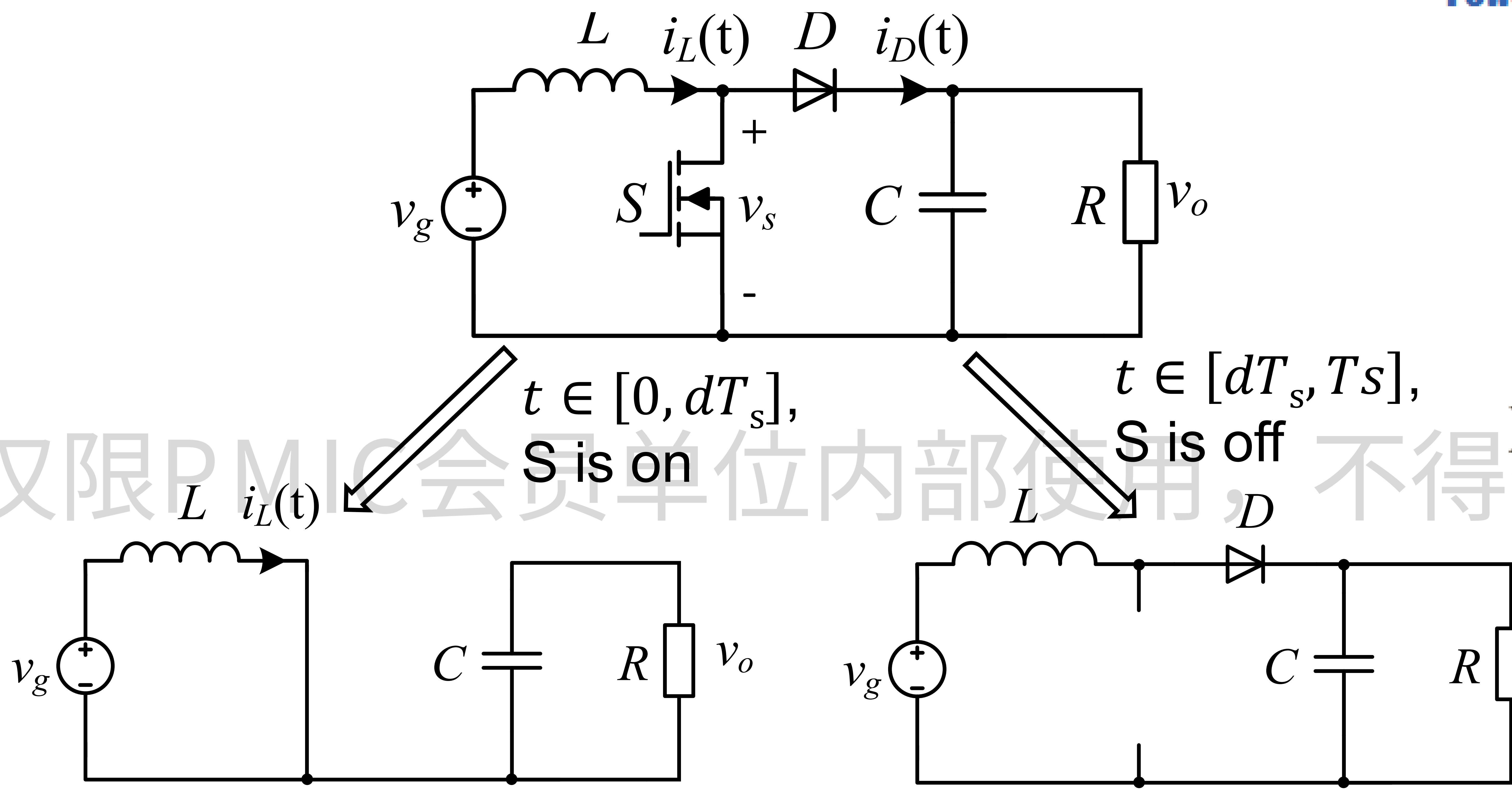
1 **Modeling of a DAB**

2 Reactive current suppression

3 ZVS on of a DAB

Modeling of conventional converters



$$\mathbf{X} = \begin{bmatrix} i_L \\ v_o \end{bmatrix}$$

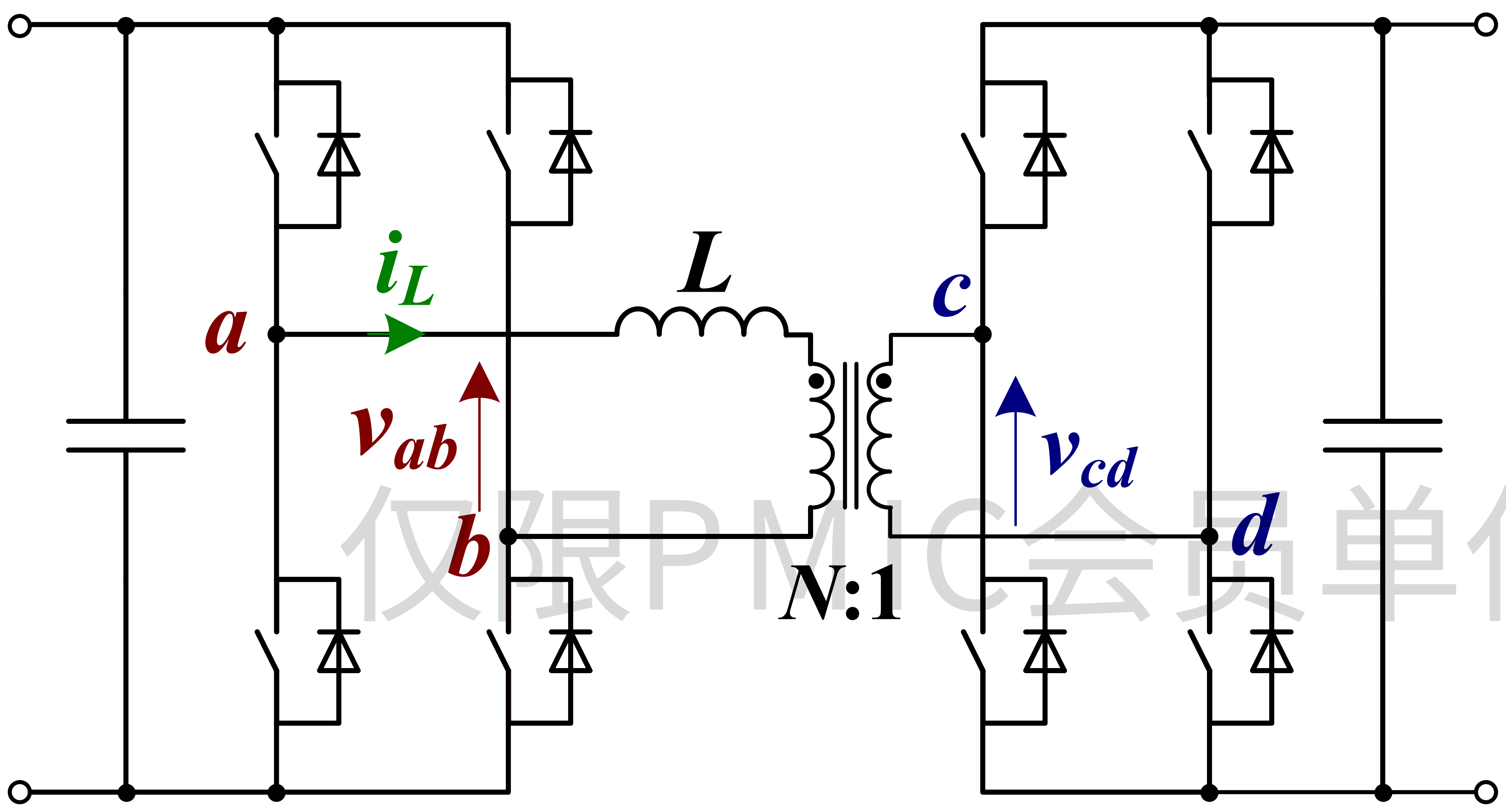
$$\dot{\mathbf{X}} = \mathbf{A}_1\mathbf{X} + \mathbf{B}_1\mathbf{U}$$

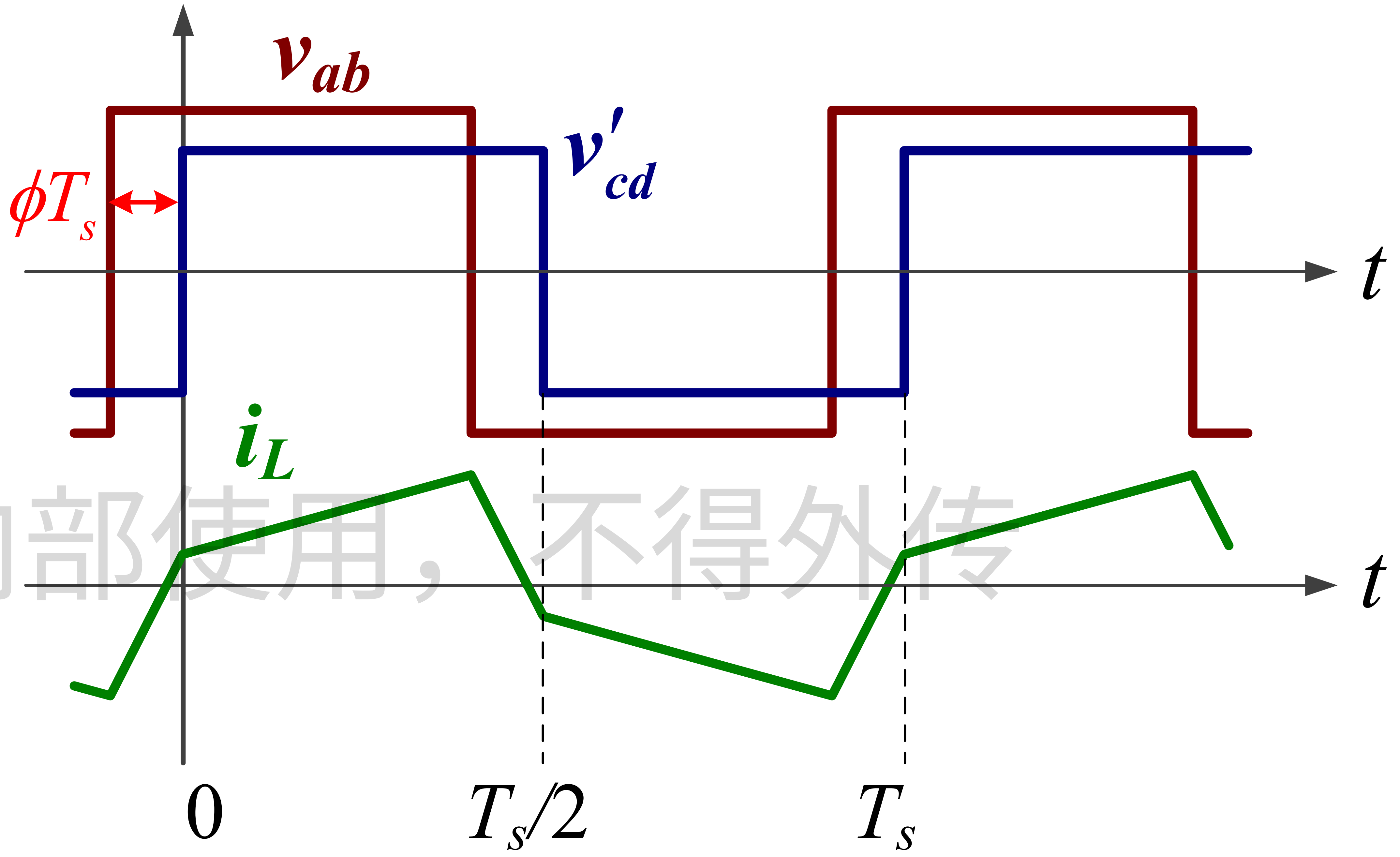
$$\dot{\mathbf{X}} = \mathbf{A}_2\mathbf{X} + \mathbf{B}_2\mathbf{U}$$

$$\Rightarrow \quad \dot{\mathbf{X}} = \mathbf{A}\mathbf{X} + \mathbf{B}\mathbf{U}$$

$$\begin{cases} \mathbf{A} = \mathbf{A}_1 D + \mathbf{A}_2(1-D) \\ \mathbf{B} = \mathbf{B}_1 D + \mathbf{B}_2(1-D) \end{cases}$$

Modeling of a DAB



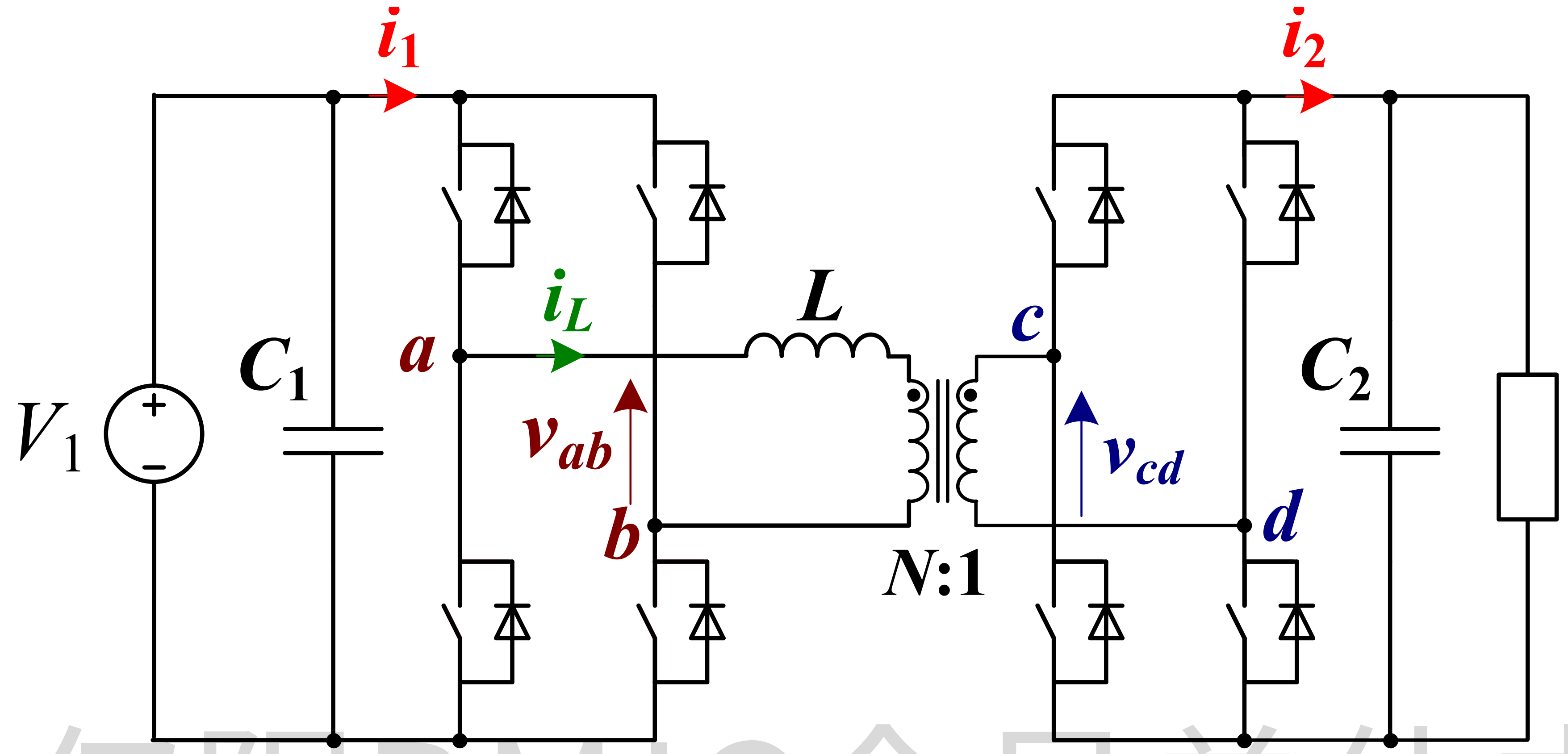


- i_L is purely ac with a averaging value 0, switching cycle average cannot be used.

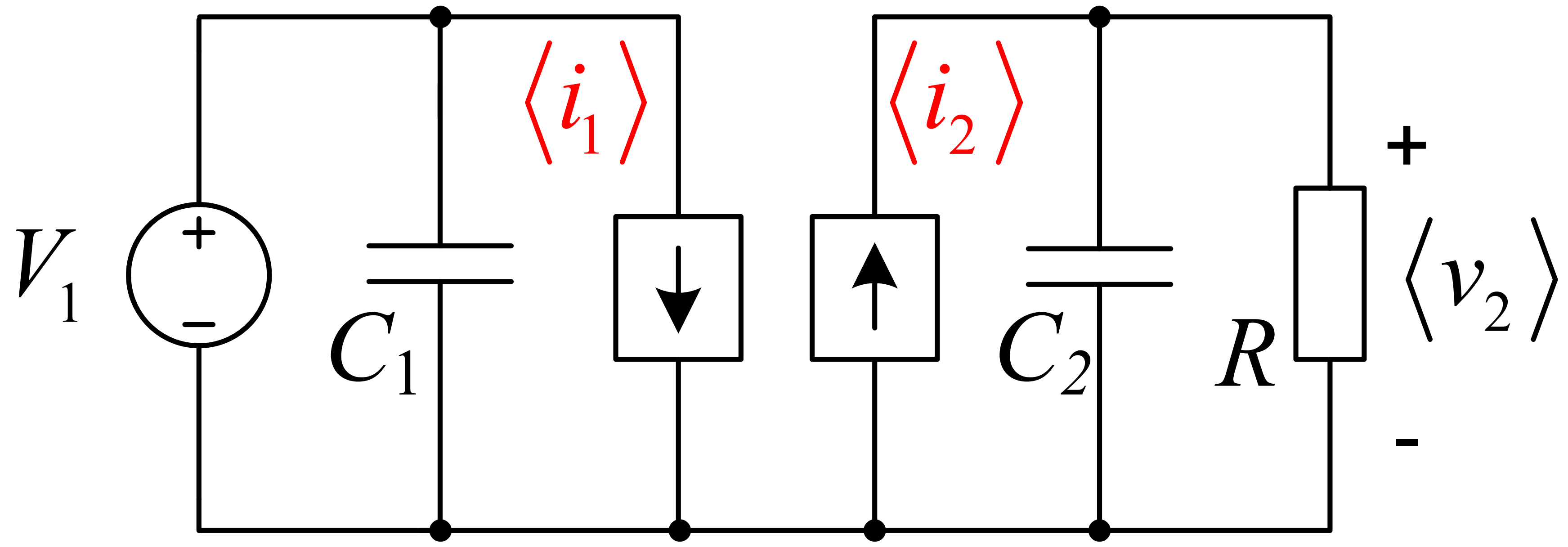
Modeling of a DAB

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

Reduced order model



Ignore the dynamics of i_L



$$P_o = \frac{NV_1V_2\phi(1-|\phi|)}{2fL}$$

$$\Rightarrow \langle i_2 \rangle = \frac{NV_1\phi(1-\phi)}{2fL}$$

By introducing perturbation at phase shift

$$\Rightarrow \hat{i}_2 = \frac{NV_1(1-2\Phi)}{2fL}\hat{\phi}$$

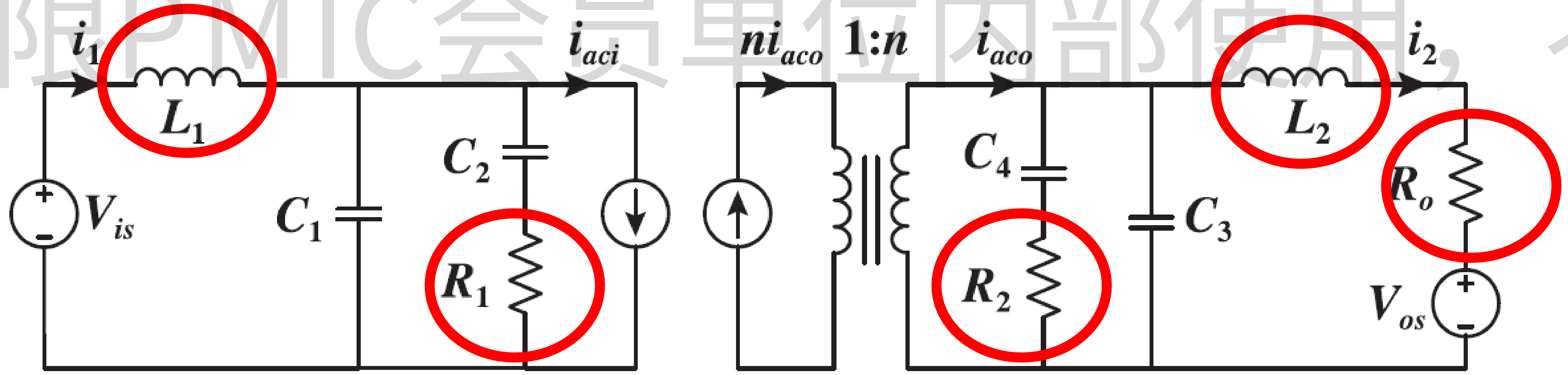
$$G_{v\phi} = \frac{\hat{v}_2}{\hat{\phi}} = \frac{NV_1(1-2\Phi)}{2fL}\frac{R}{RC_2s+1}$$

First order system

[1] H. Bai, C. Mi, C. Wang, and S. Gargies, “The dynamic model and hybrid phase-shift control of a dual-active-bridge converter,” in 2008 34th Annual Conference of IEEE Industrial Electronics, Nov 2008, pp. 2840–2845.

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.

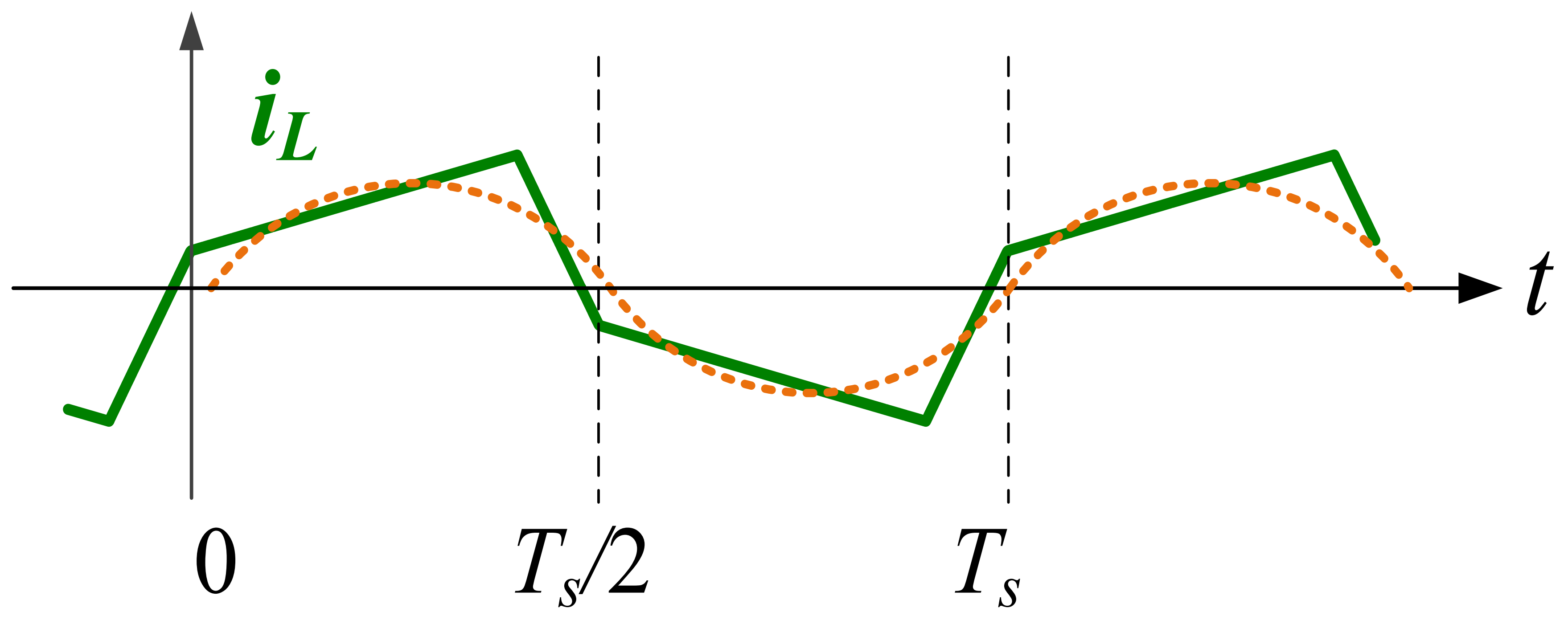
Generalized average model

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

$$x(\tau)=\sum_{-\infty}^{\infty}\langle x\rangle_k(t)e^{jk\omega_s\tau}$$

where $\langle x\rangle_k$ is the kth 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, small signal model

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

where

$$\mathbf{x} = \begin{bmatrix} \Delta v_{2(0)} & \Delta i_{LR(1)} & \Delta i_{LI(1)} \end{bmatrix}^T$$

$$\mathbf{y} = \begin{bmatrix} \Delta v_{2(0)} \end{bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} -\dfrac{1}{RC_o} & -\dfrac{4\sin(D\pi)}{\pi C_o} & \pi C_o \\ \dfrac{2\sin(D\pi)}{\pi L} & -\dfrac{R_t}{L} & \omega_s \\ \dfrac{2\cos(D\pi)}{\pi L} & -\omega_s & -\dfrac{R_t}{L} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \dfrac{4}{C_o}\left(I_{0I}\sin(\pi D) - I_{0R}\cos(\pi D)\right) \\ \dfrac{2V_{o0}}{L}\sin(\pi D) \\ -\dfrac{2V_{o0}}{L}\sin(\pi D) \end{bmatrix}$$

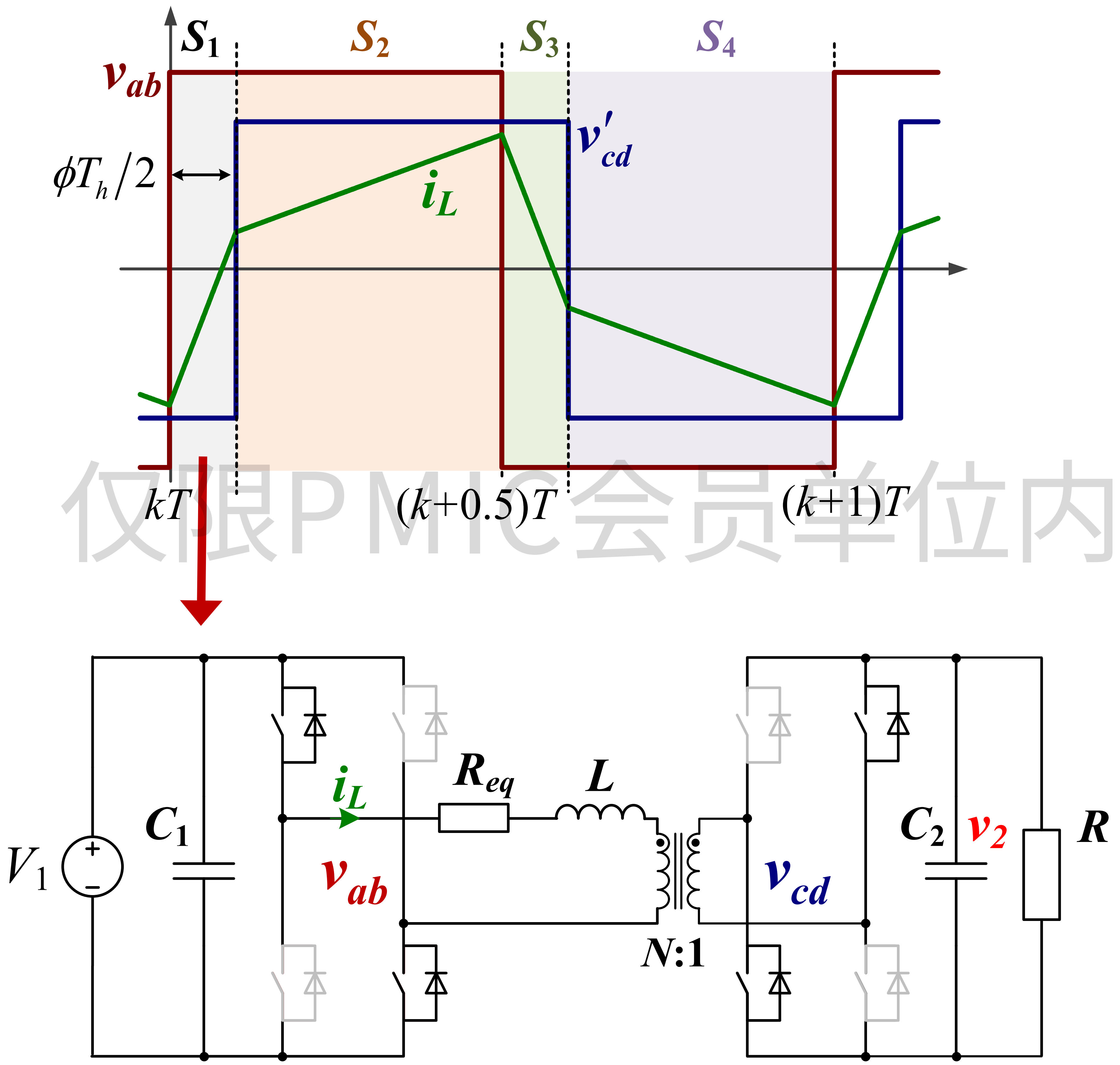
Transfer function

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

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

[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



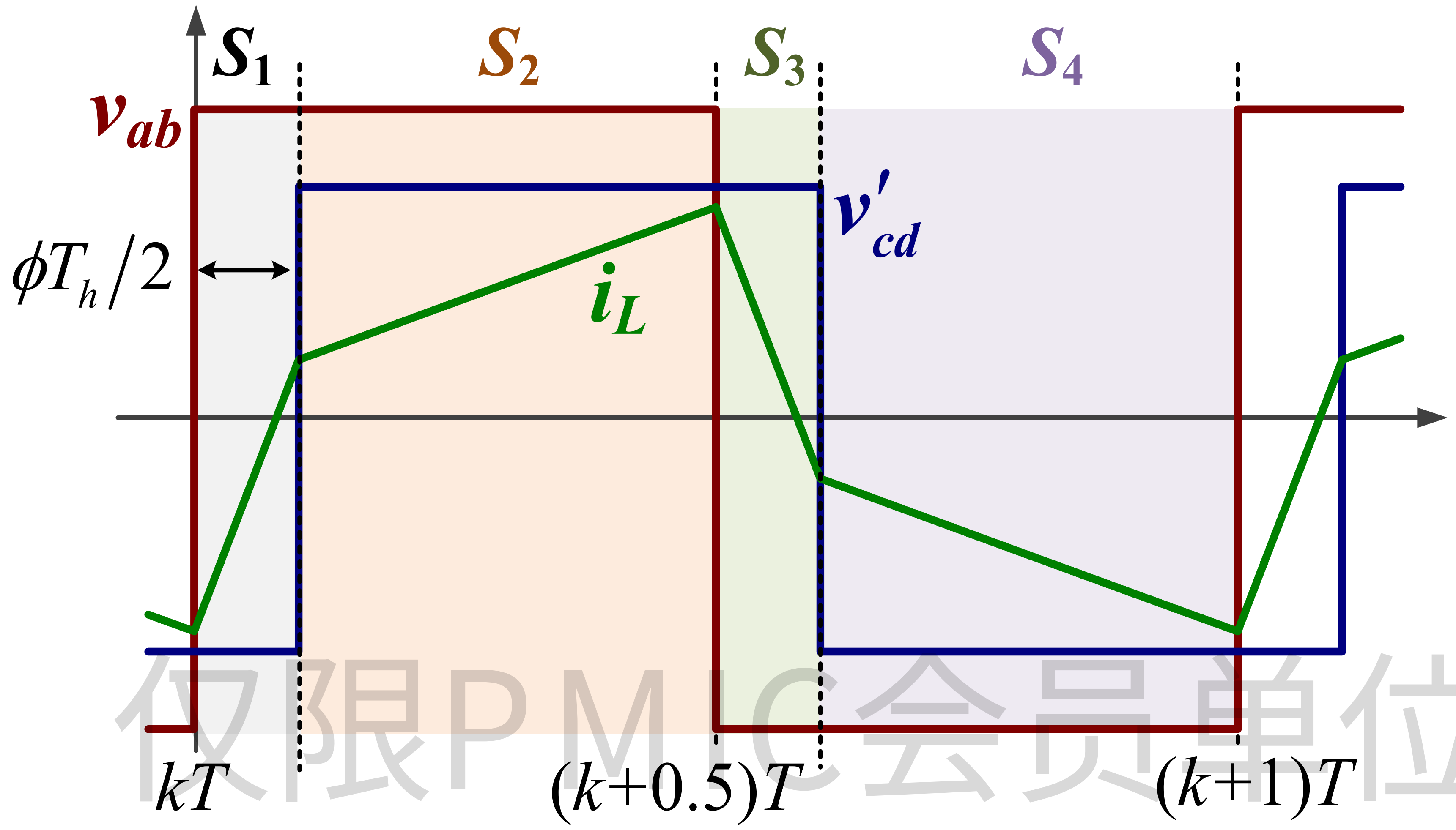
$$\begin{cases} L\dfrac{di_L}{dt} = -i_L R_{eq} + Nv_2 + V_1 \\ C_2\dfrac{dv_2}{dt} = -Ni_L - \dfrac{v_2}{R} \end{cases}$$

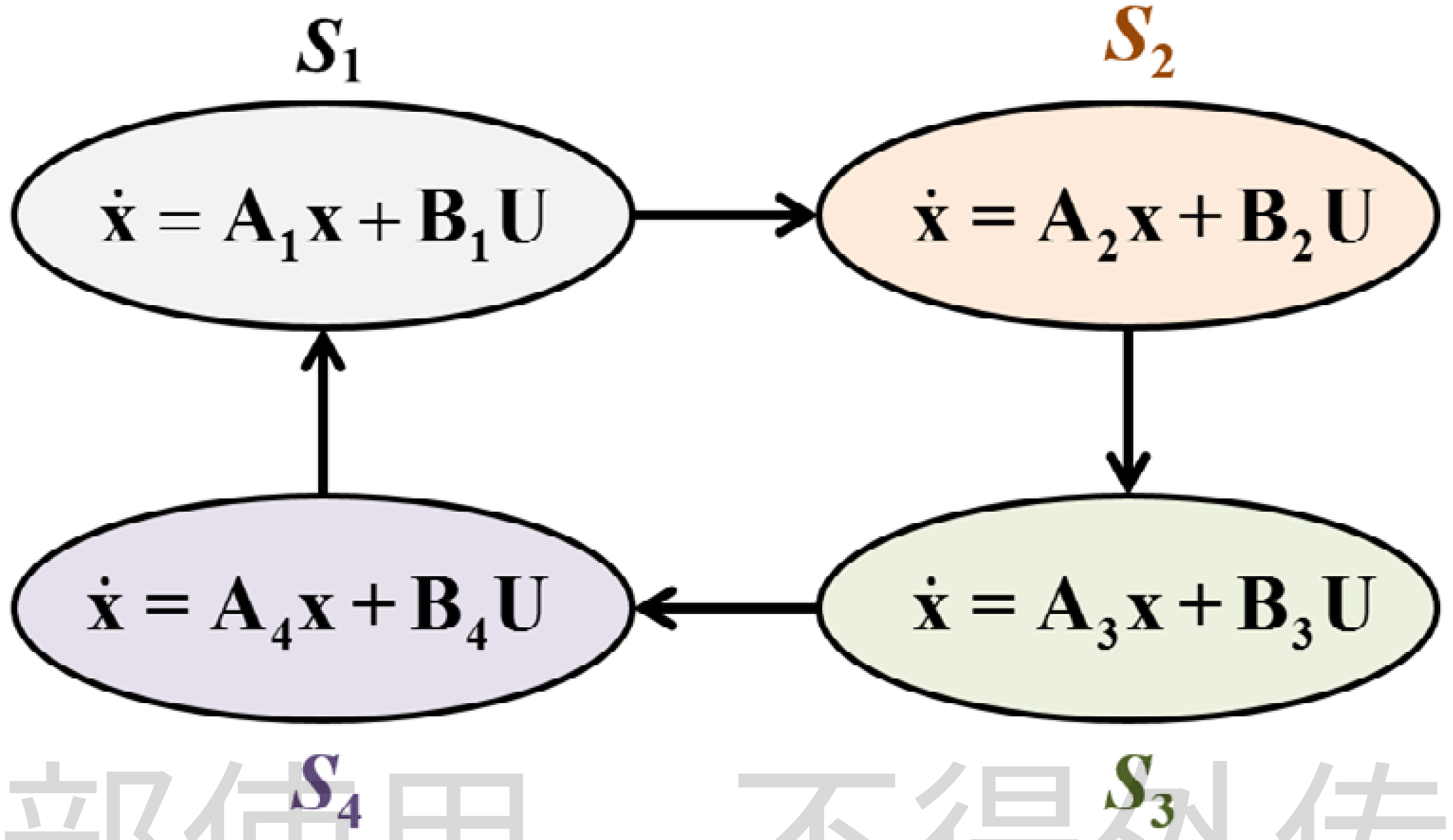
Let $\mathbf{x} = [i_L, v_2]^T$

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

[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

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

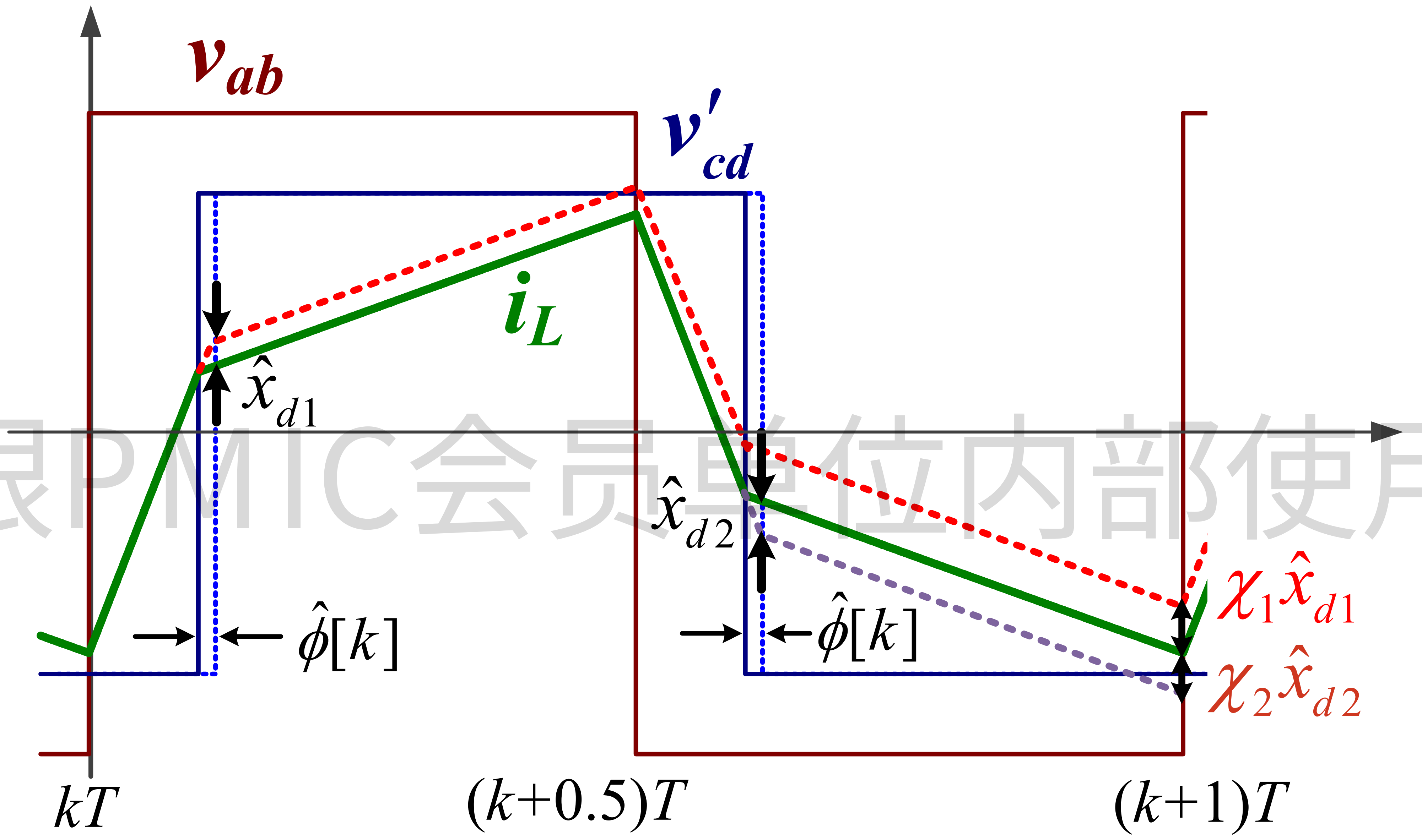
$$\mathbf{F} = e^{\mathbf{A}_4 t_{n4}} \cdot e^{\mathbf{A}_3 t_{n3}} \cdot e^{\mathbf{A}_2 t_{n2}} \cdot e^{\mathbf{A}_1 t_{n1}}$$

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

[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

- Introducing a phase perturbation $\hat{\phi}[k]$ around **x[t]**



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

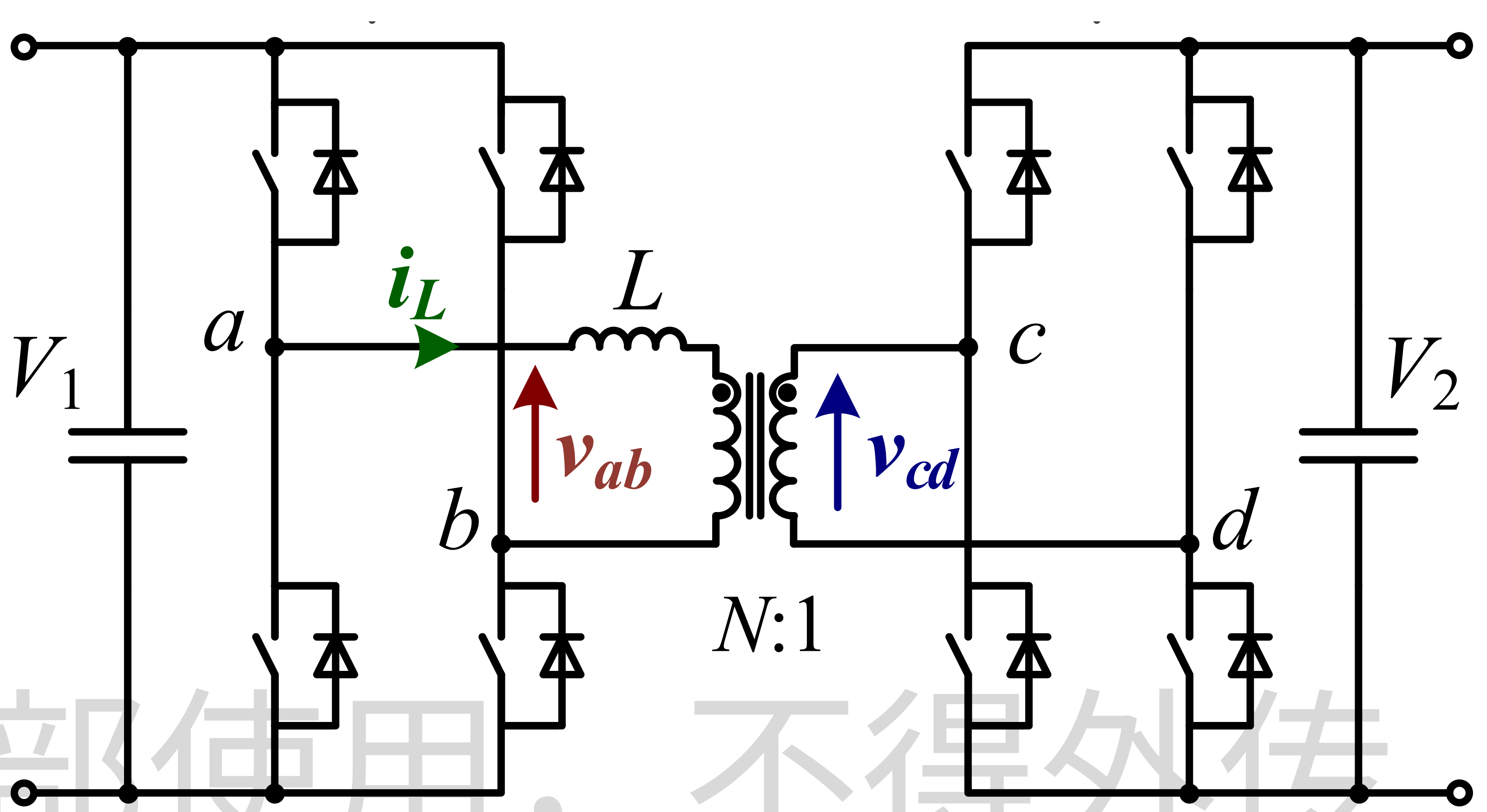
$$\hat{\mathbf{x}}[k+1] = \mathbf{F}\hat{\mathbf{x}}[k] + \mathbf{G}\hat{\phi}[k]$$

- Convert the state-space to transfer function

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

Comparison of different DAB modeling methods

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

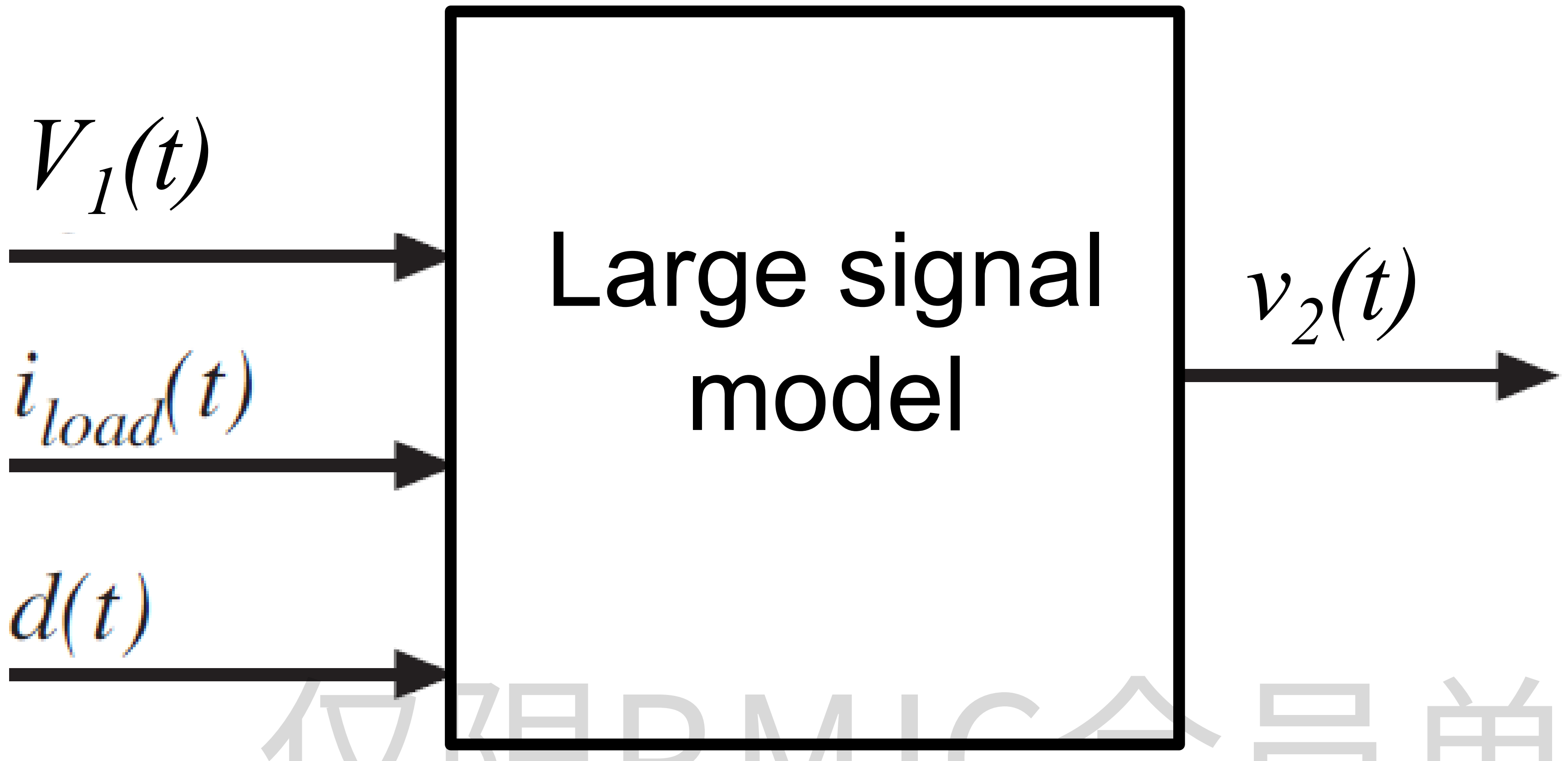


Parameters used for model comparison

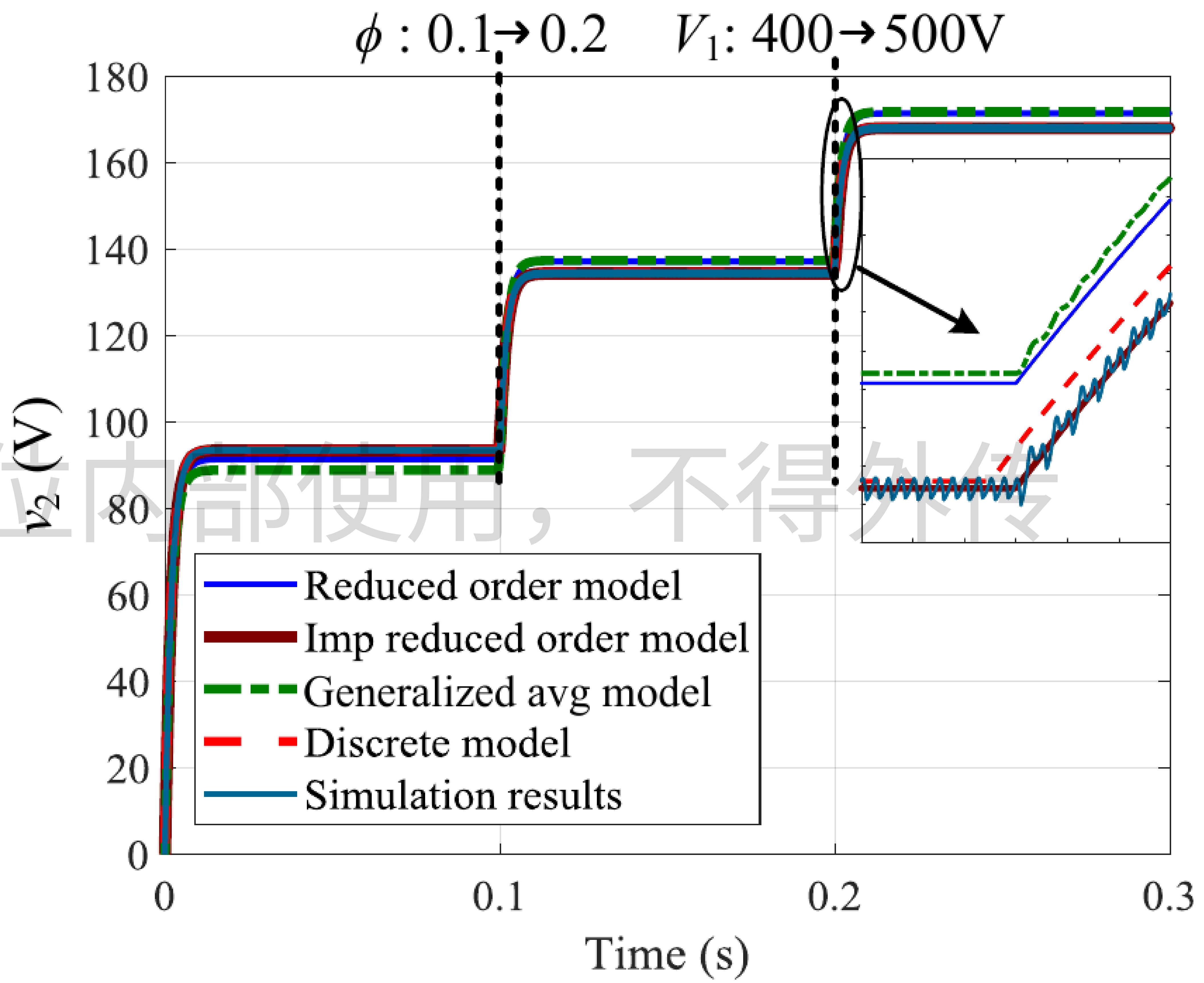
N	Transformer turns ratio	2:1
f	Switching frequency	20kHz
L	Inductor	70μF
R_{eq}	Equivalent resistance	0.4Ω
C_2	DC Capacitor 2	1mF
R	Load resistor	2Ω
T_d	Dead time	200ns

[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 model



- Reduced order model
- Improved reduced order model
- Generalized average model
- Discrete-time model

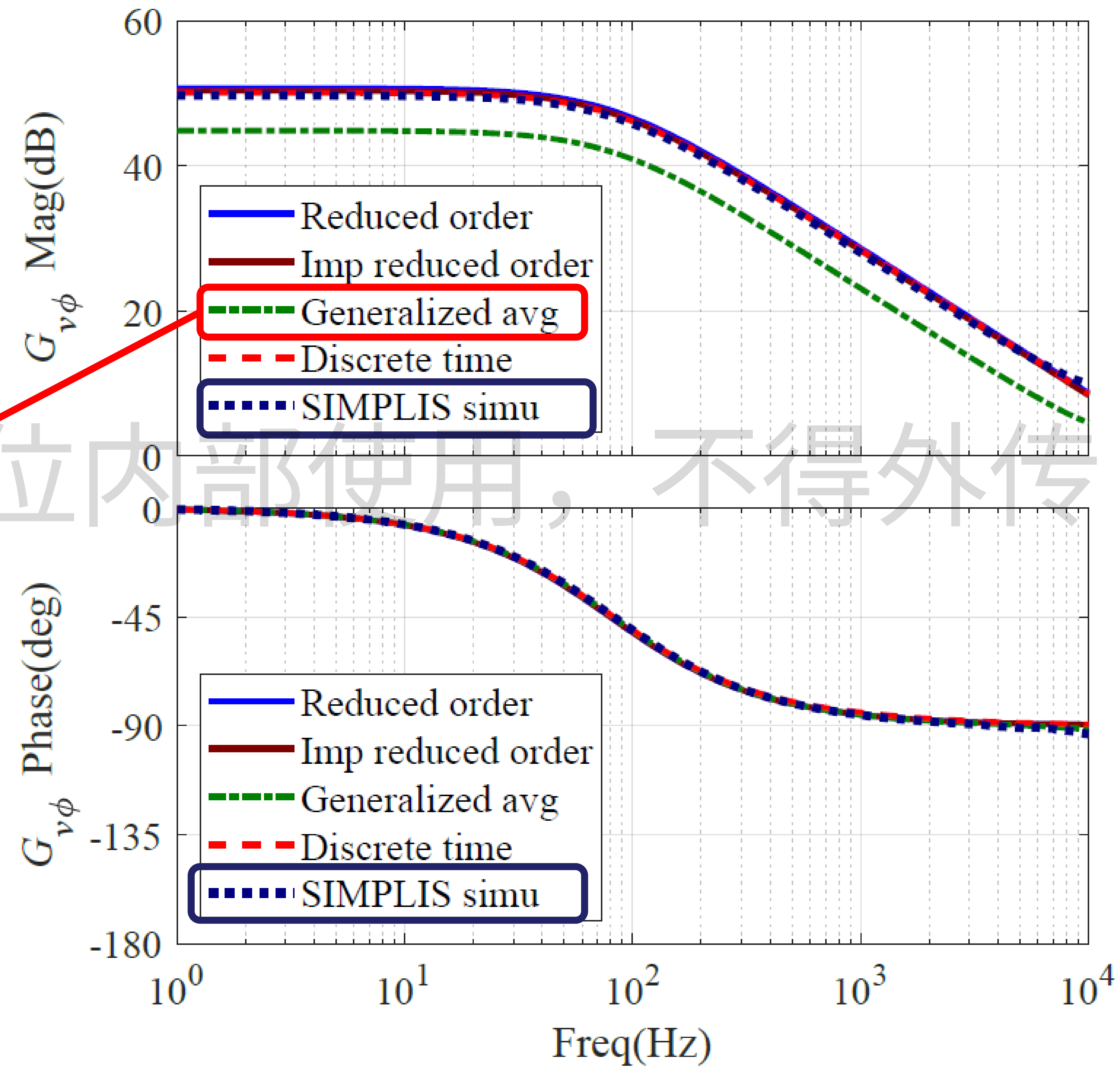


All of them have good accuracy.

Modeling comparison – Small signal model

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

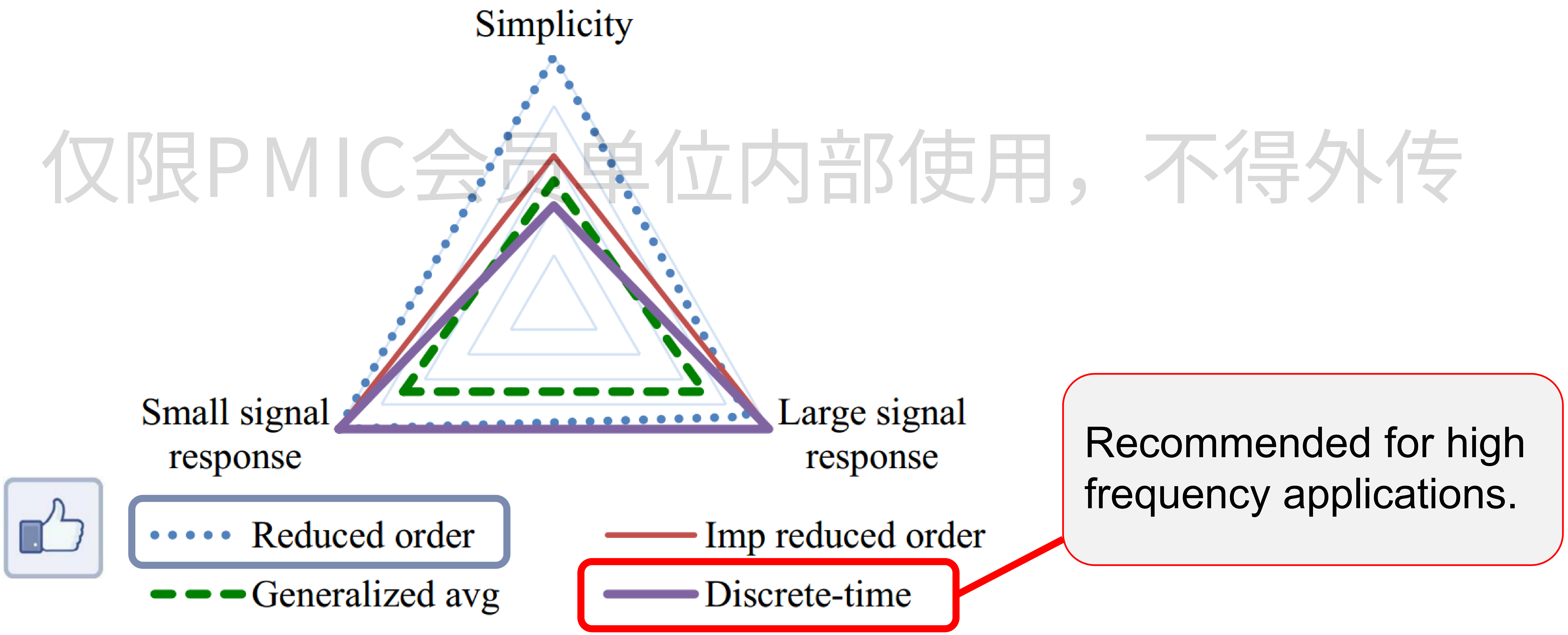
Have a magnitude error because the second and higher order components of i_L are ignored.



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

Comparison of the modeling methods

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



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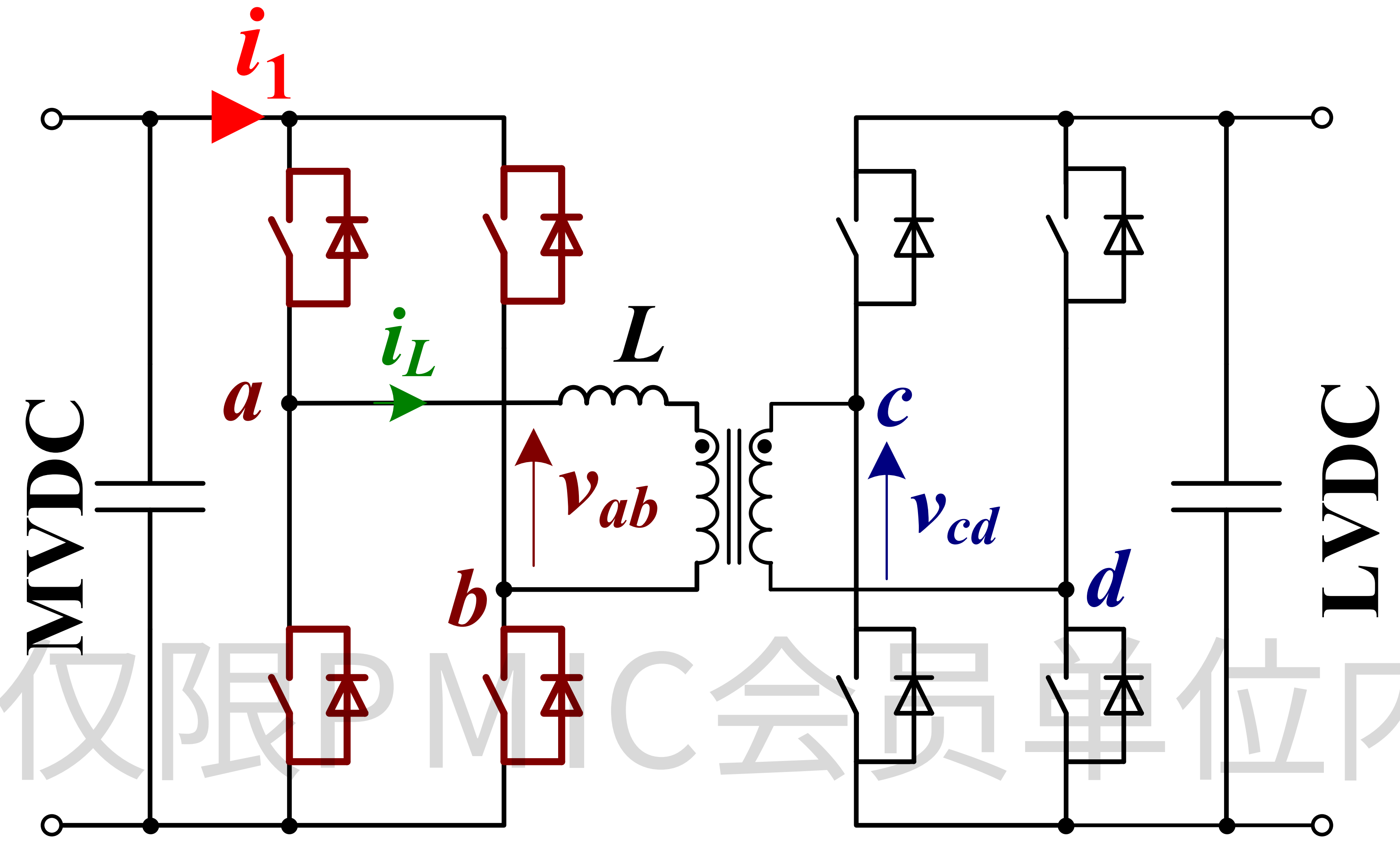
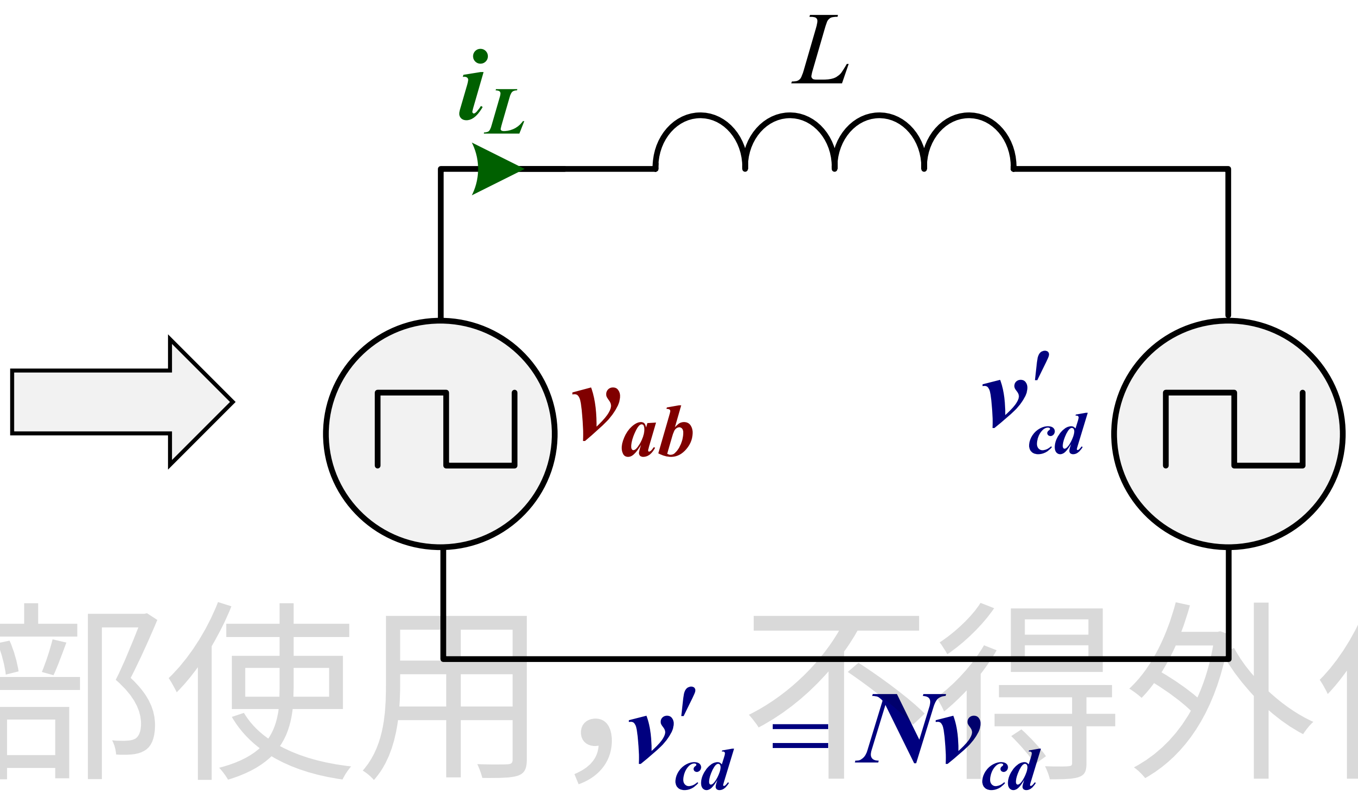
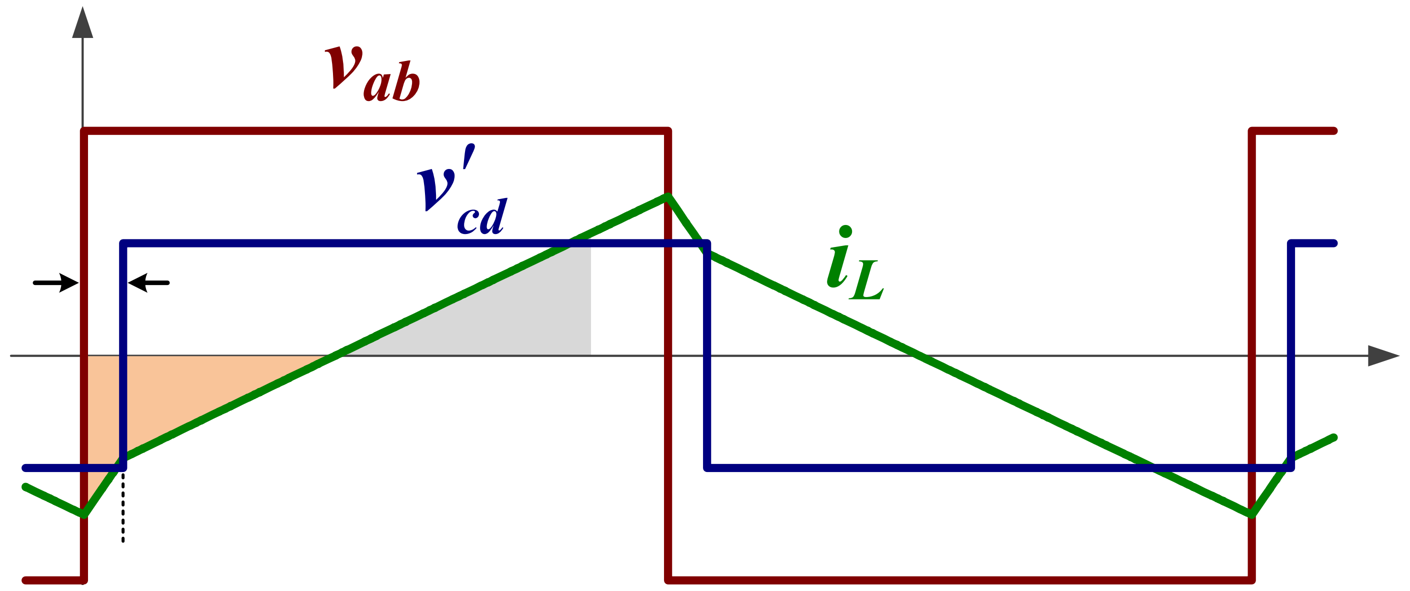
Reactive current in DAB



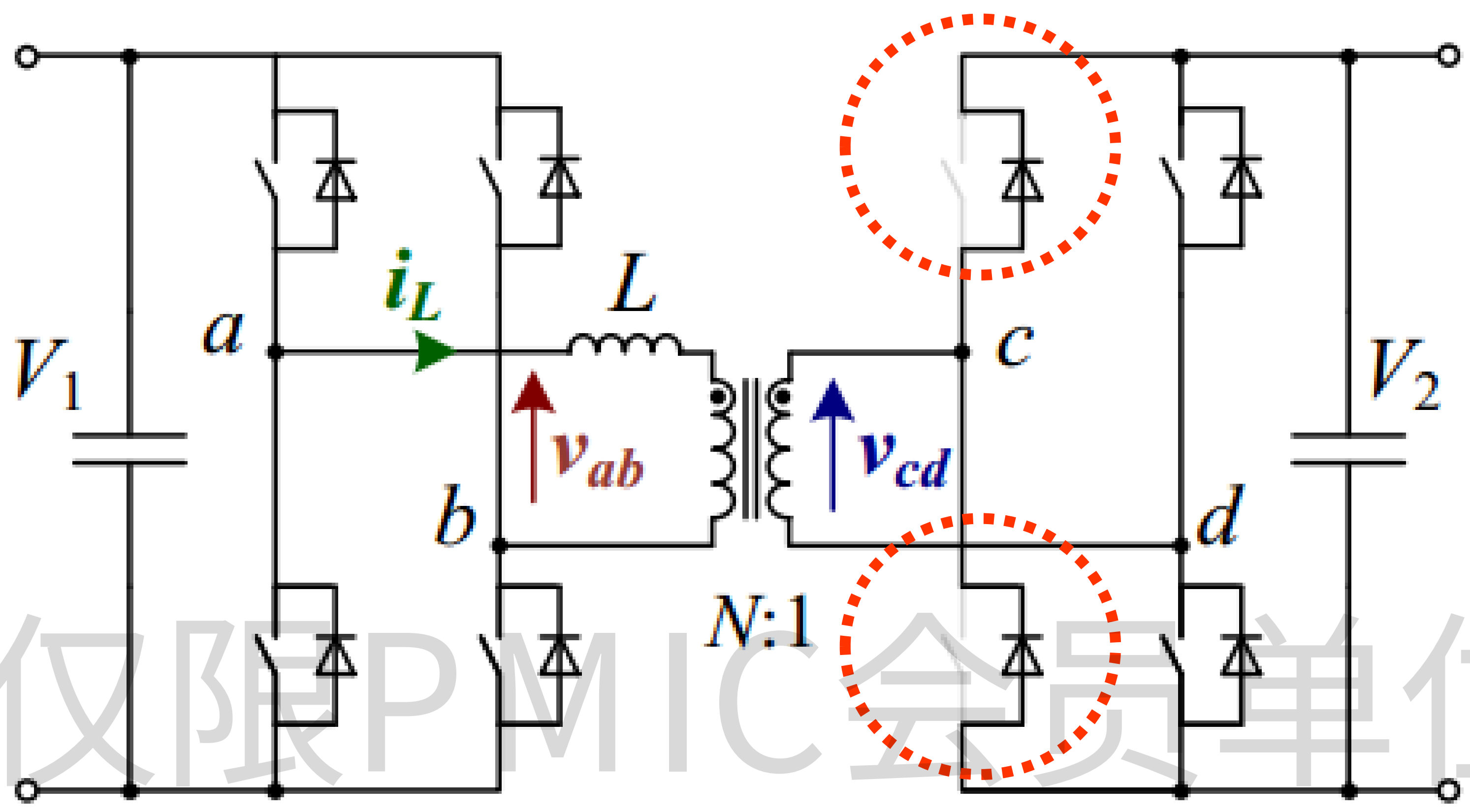




Reactive power does not transmit power, but increases the loss of the power devices, inductor and transformer.

Intuitive Methods to suppress reactive current

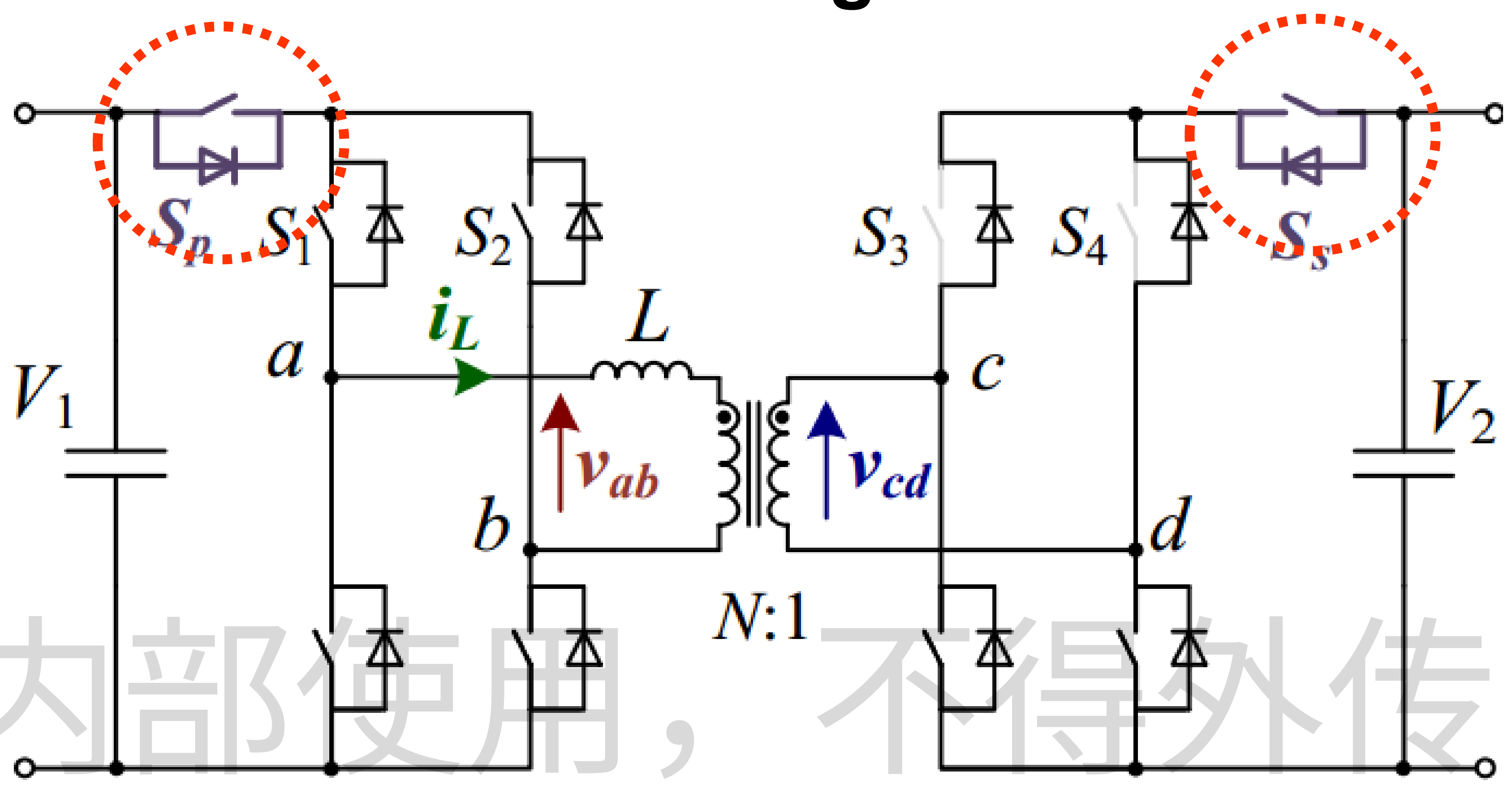
Unidirectional diodes



Disadvantage

- Sacrifice auto-adjust bidirectional power flow

Add blocking switches

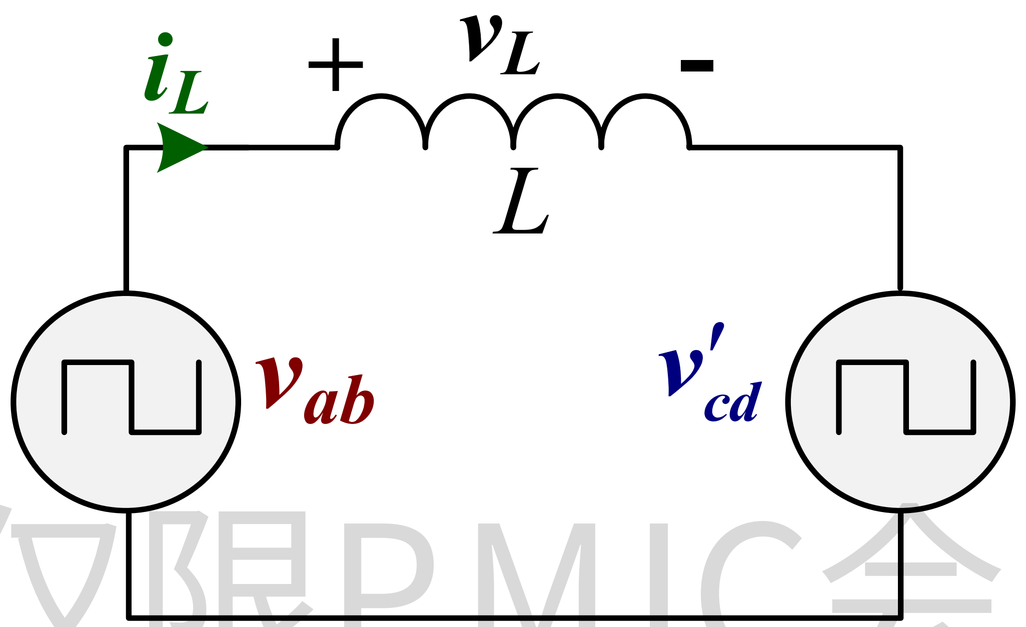


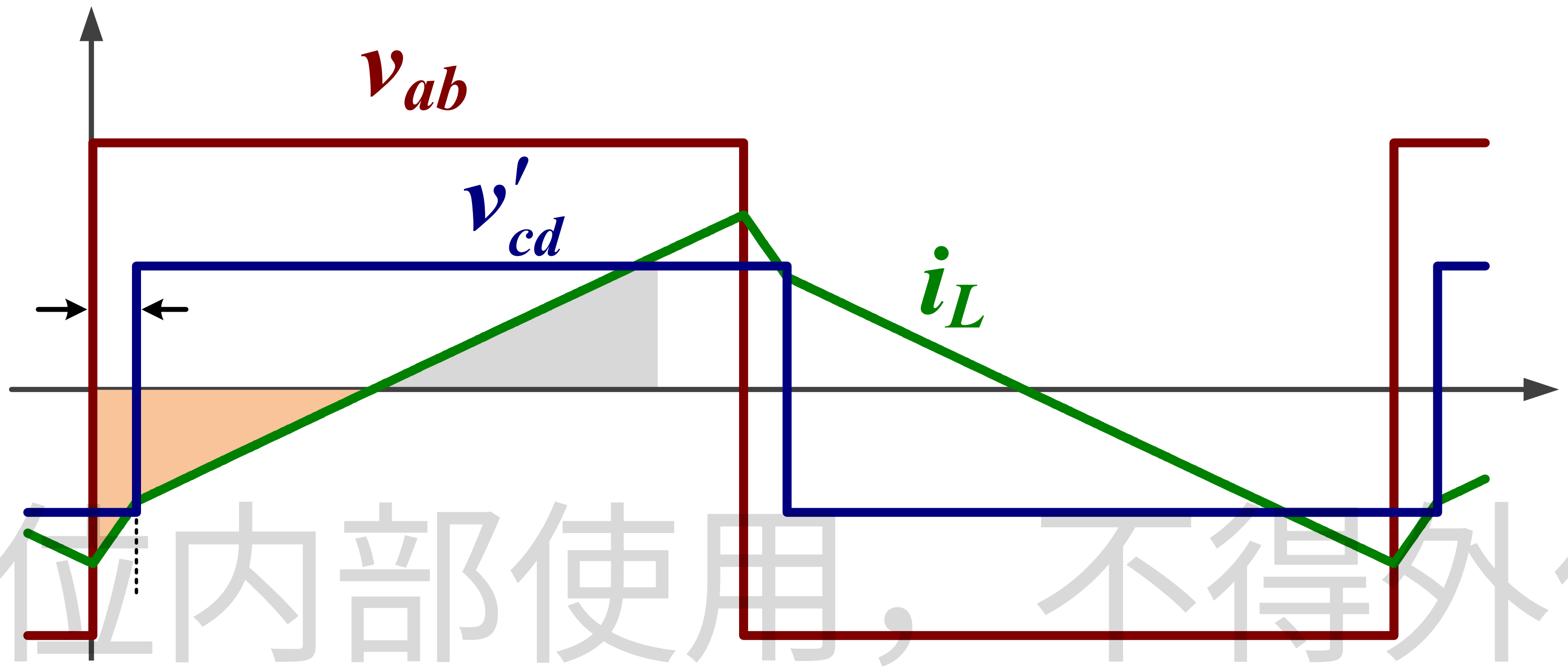
Disadvantage

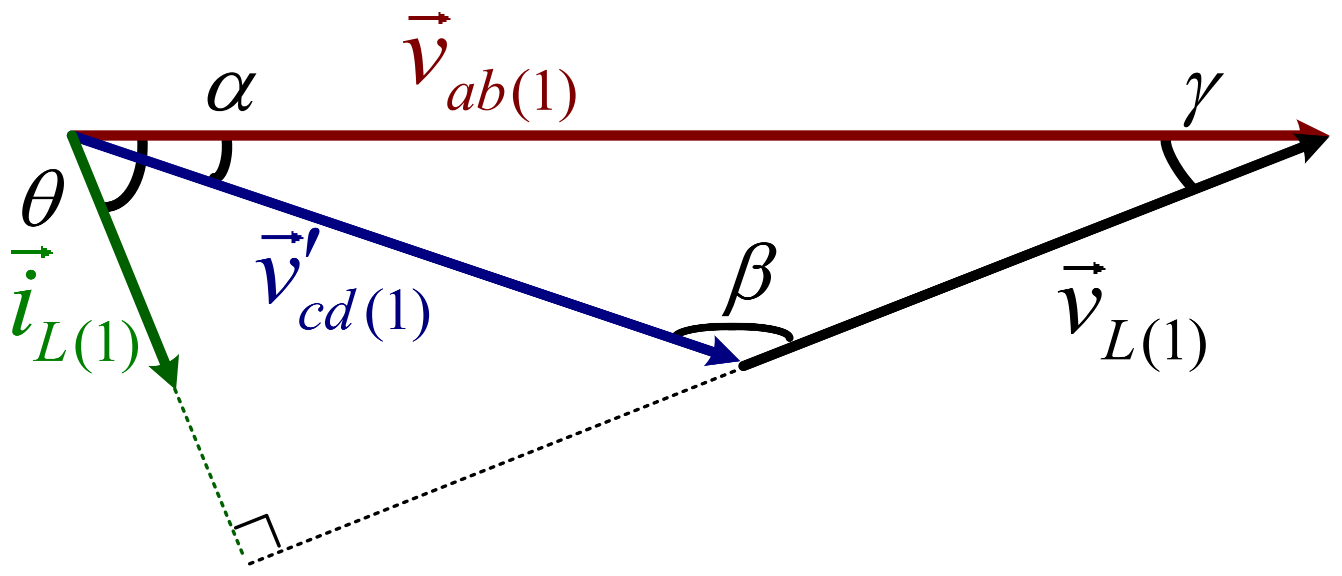
- Sacrifice auto-adjust bidirectional power flow
- Additional conductions losses
- Require careful modulation

[1] J. Zhang, F. Zhang, X. Xie, D. Jiao, and Z. Qian, “A novel zvs dc/dc converter for high power applications,” IEEE Transactions on Power Electronics, vol. 19, no. 2, pp. 420–429, March 2004.
[2] V. Karthikeyan and R. Gupta, “Frs-dab converter for elimination of circulation power flow at input and output ends,” IEEE Transactions on Industrial Electronics, vol. 65, no. 3, pp. 2135–2144, March 2018.

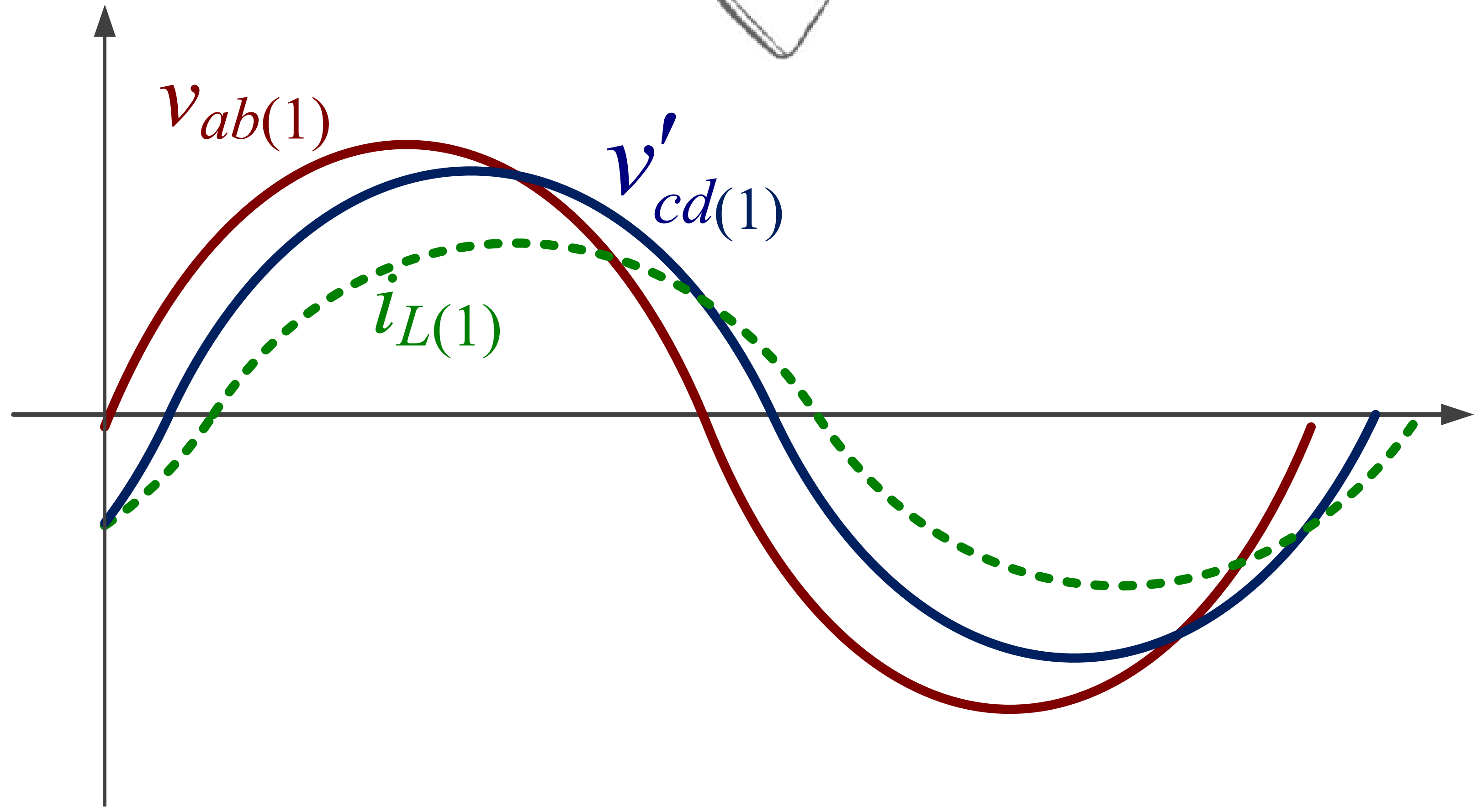
Fundamental component phasor diagram of DAB



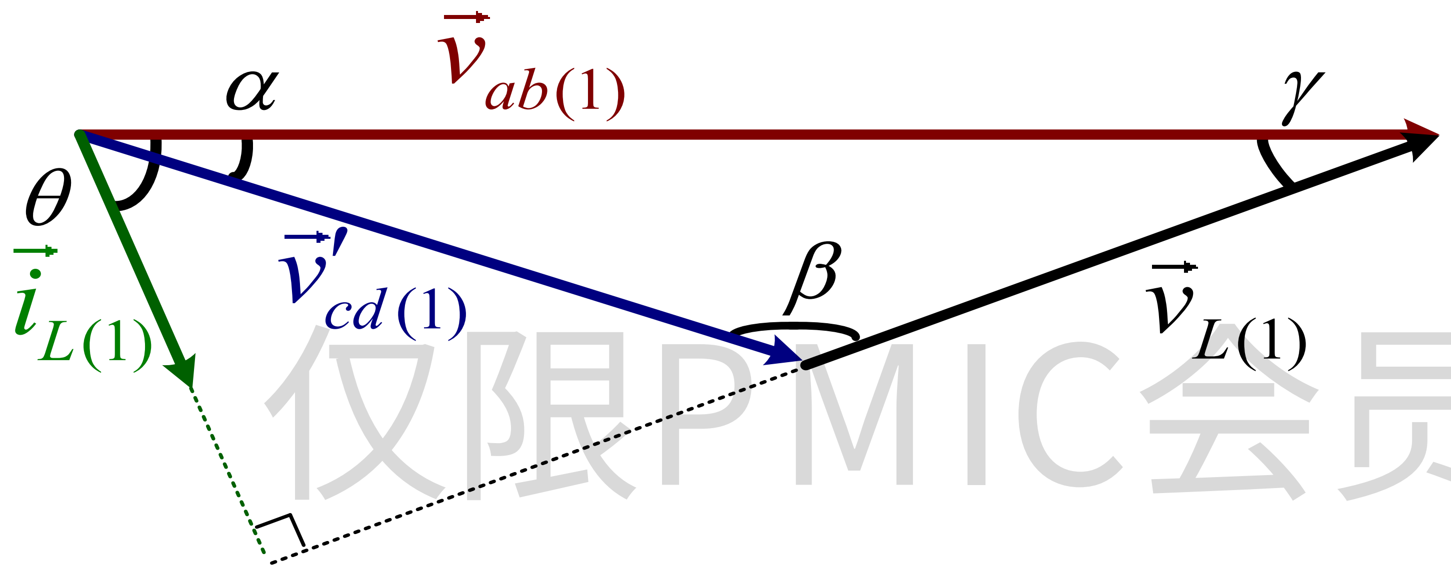




Phasor diagram



Fundamental component phasor diagram of DAB



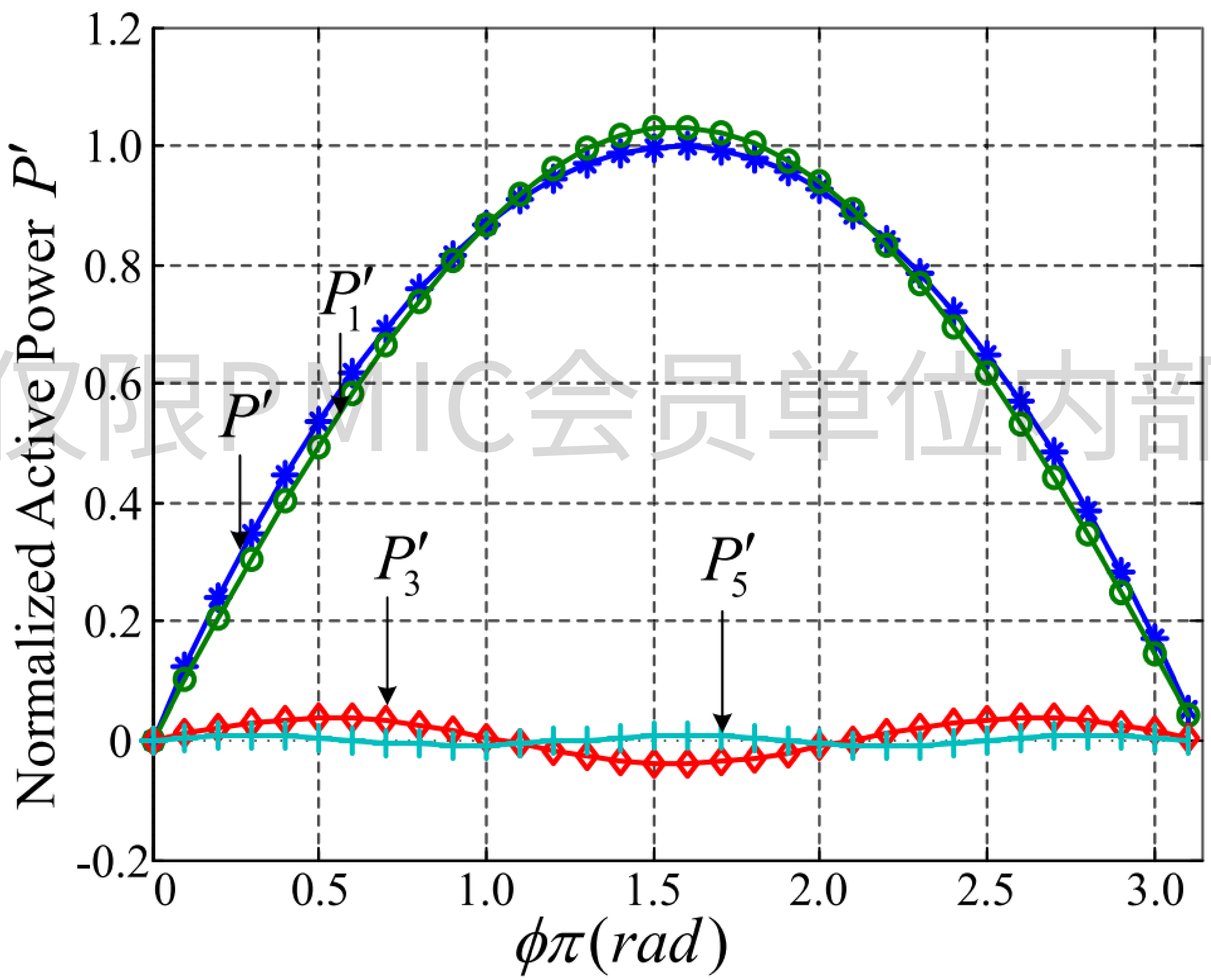
Phasor of Fundamental Components

Active Power $P = \left|\vec{v}_{ab(1)}\right|\left|\vec{i}_{L(1)}\right|\cos\theta$

Reactive Power $Q = \left|\vec{v}_{ab(1)}\right|\left|\vec{i}_{L(1)}\right|\sin\theta$

$$= \sqrt{\left(\left|\vec{v}_{ab(1)}\right|\left|\vec{i}_{L(1)}\right|\right)^2 - P^2}$$

Fundamental component analysis (FCA)

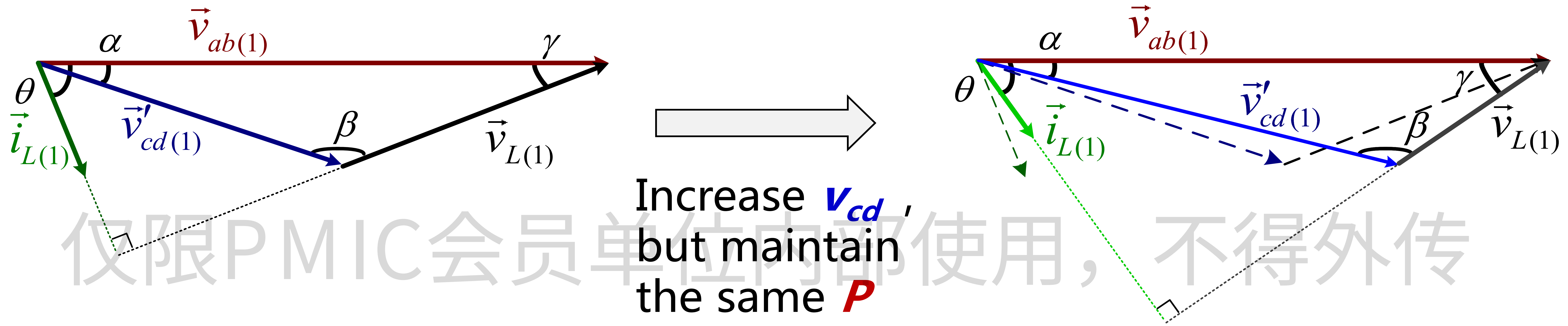


Fundamental component is dominant.

[1] B. Zhao, et. Al , ``Universal high-frequency-link characterization and practical fundamental-optimal strategy for dual-active-bridge DC-DC converter under PWM plus phase-shift control,'' IEEE Trans. Power Electron. 2015

Reactive current and voltage gain

- **The reactive power is affected by the voltage gain.**



$$\left|\vec{v}'_{cd(1)}\right| \nearrow \ \Rightarrow \gamma \nearrow \ \Rightarrow \theta = \frac{\pi}{2} - \gamma \searrow \ \Rightarrow \cos\theta \nearrow$$

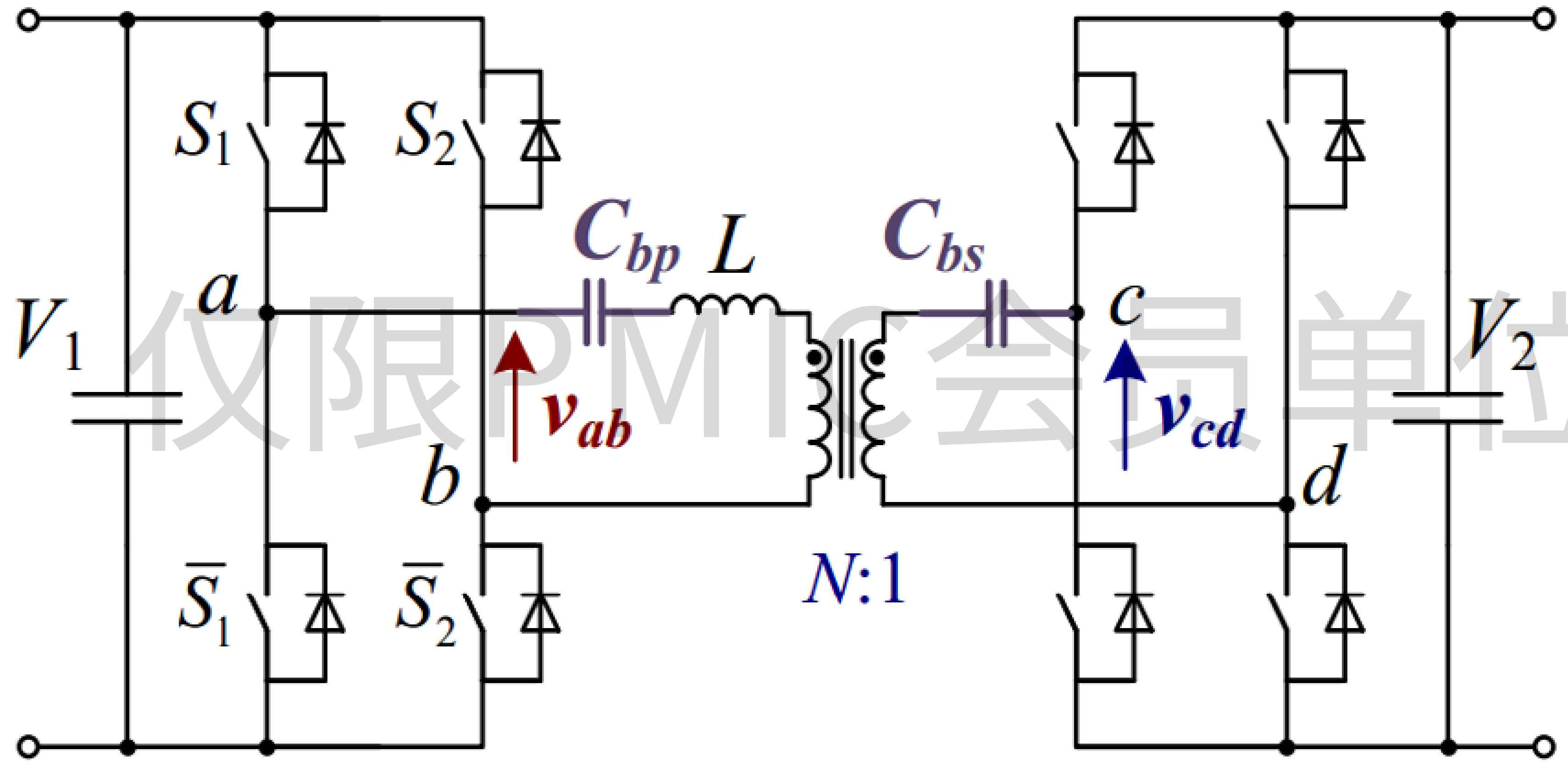
Since P and v_{ab} maintain the same, $P = \left|\vec{v}_{ab(1)}\right|\left|\vec{i}_{L(1)}\right|\cos\theta \Rightarrow \left|\vec{i}_{L(1)}\right| \searrow$

$$\Rightarrow Q = \sqrt{\left(\left|\vec{v}_{ab(1)}\right|\left|\vec{i}_{L(1)}\right|\right)^2 - P^2} \searrow$$

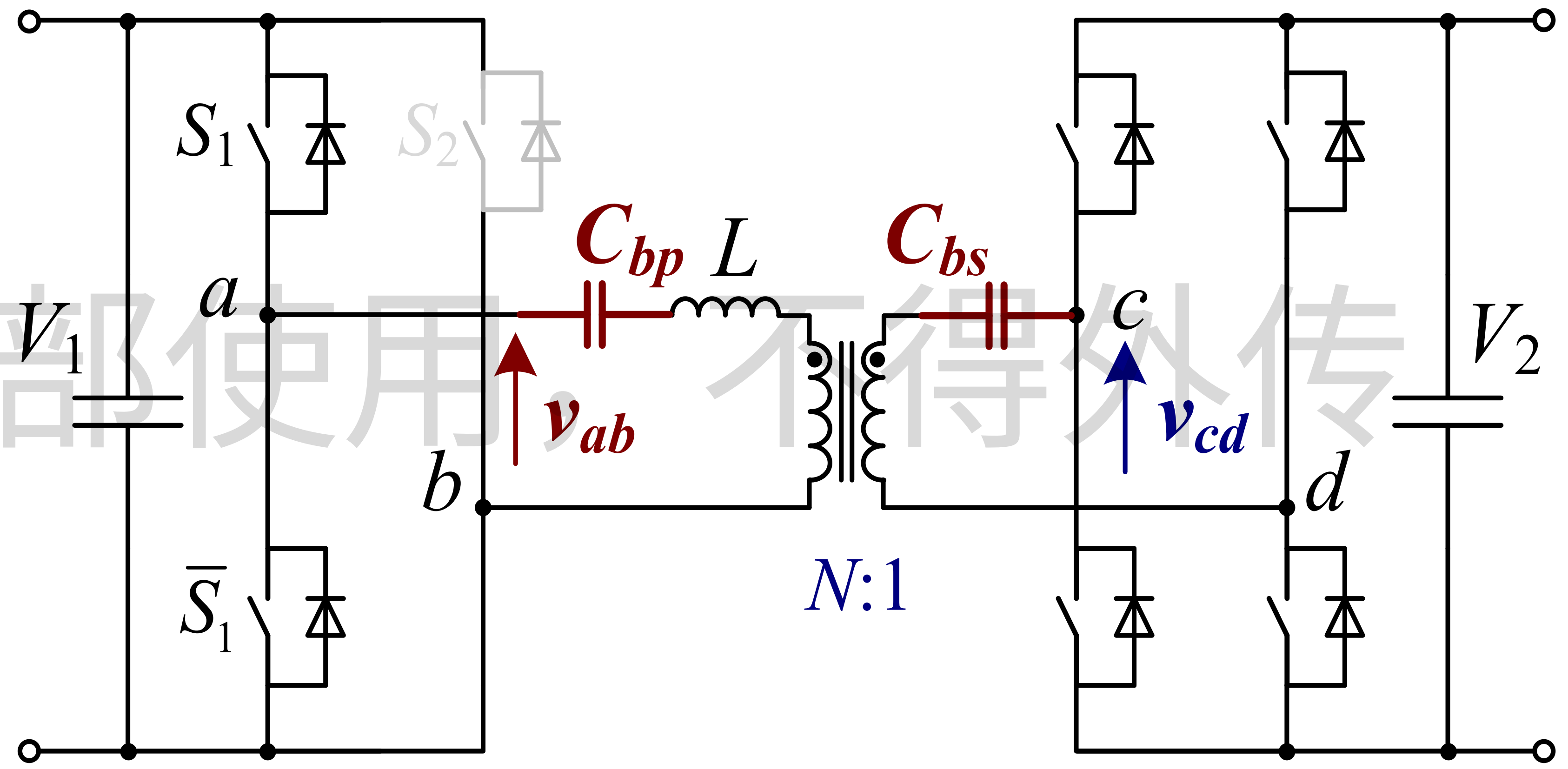
Varying the bridge circuit

- **Varying the bridge circuit between full and half bridge**

M is close 1, full bridge



M is close 0.5, half bridge



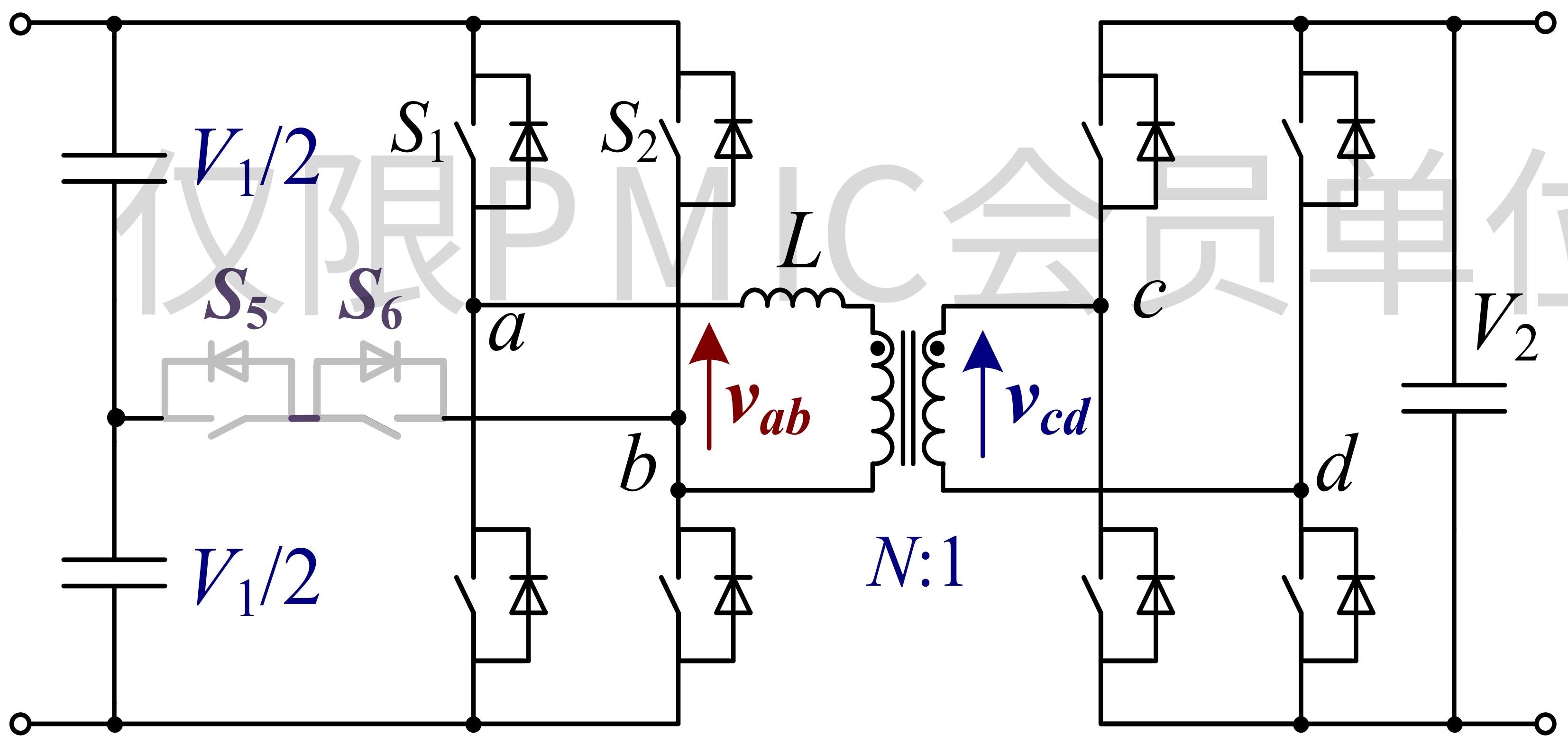
Conversion gain $M = \dfrac{Nv_2}{V_1}$

[1] Z. Qin, Y. Shen, P. C. Loh, H. Wang, and F. Blaabjerg, "A dual active bridge converter with an extended high-efficiency range by dc blocking capacitor voltage control," IEEE Transactions on Power Electronics, vol. 33, no. 7, pp. 5949–5966, July 2018.

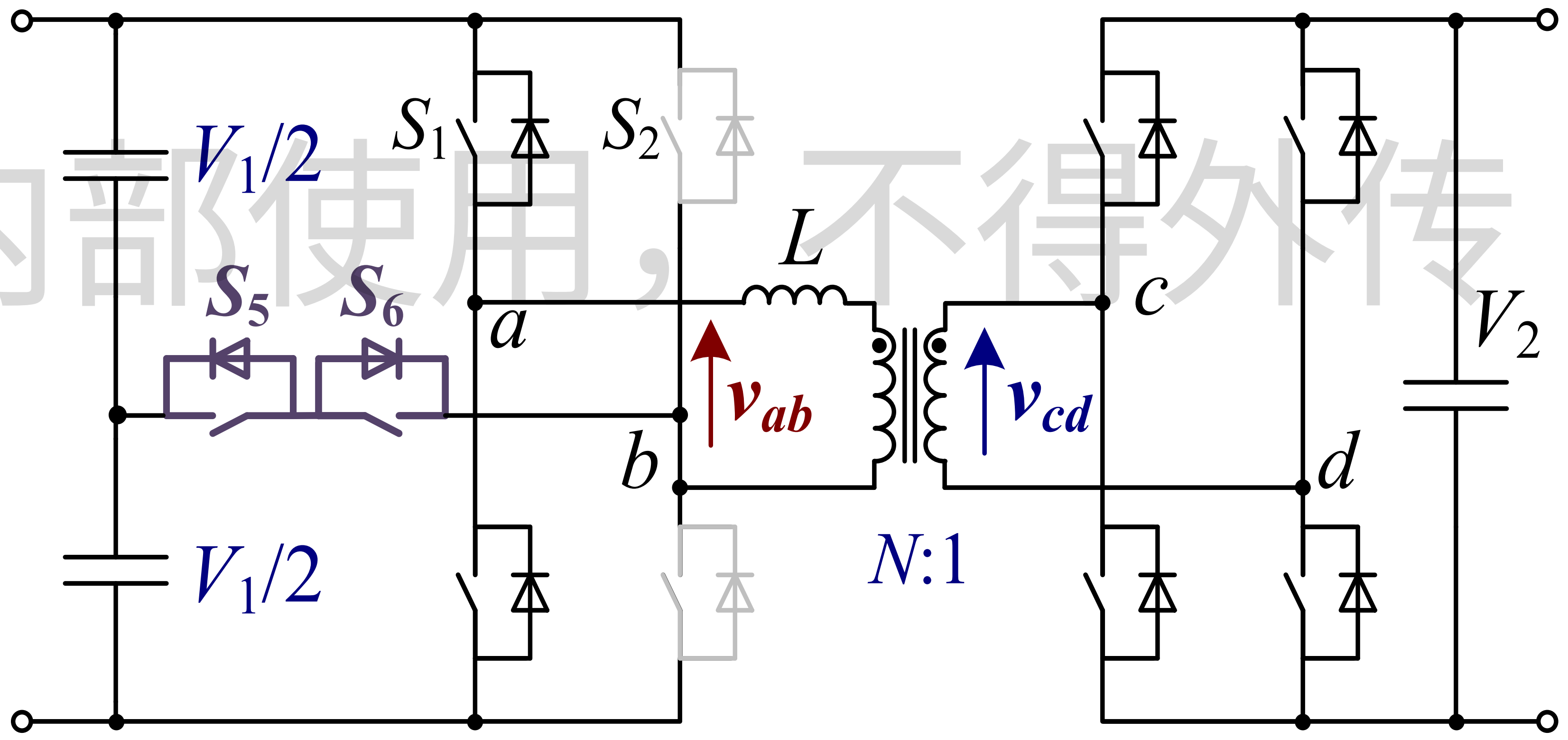
Varying the bridge circuit

- **Varying the bridge circuit between full and half bridge**

M is close 1, full bridge



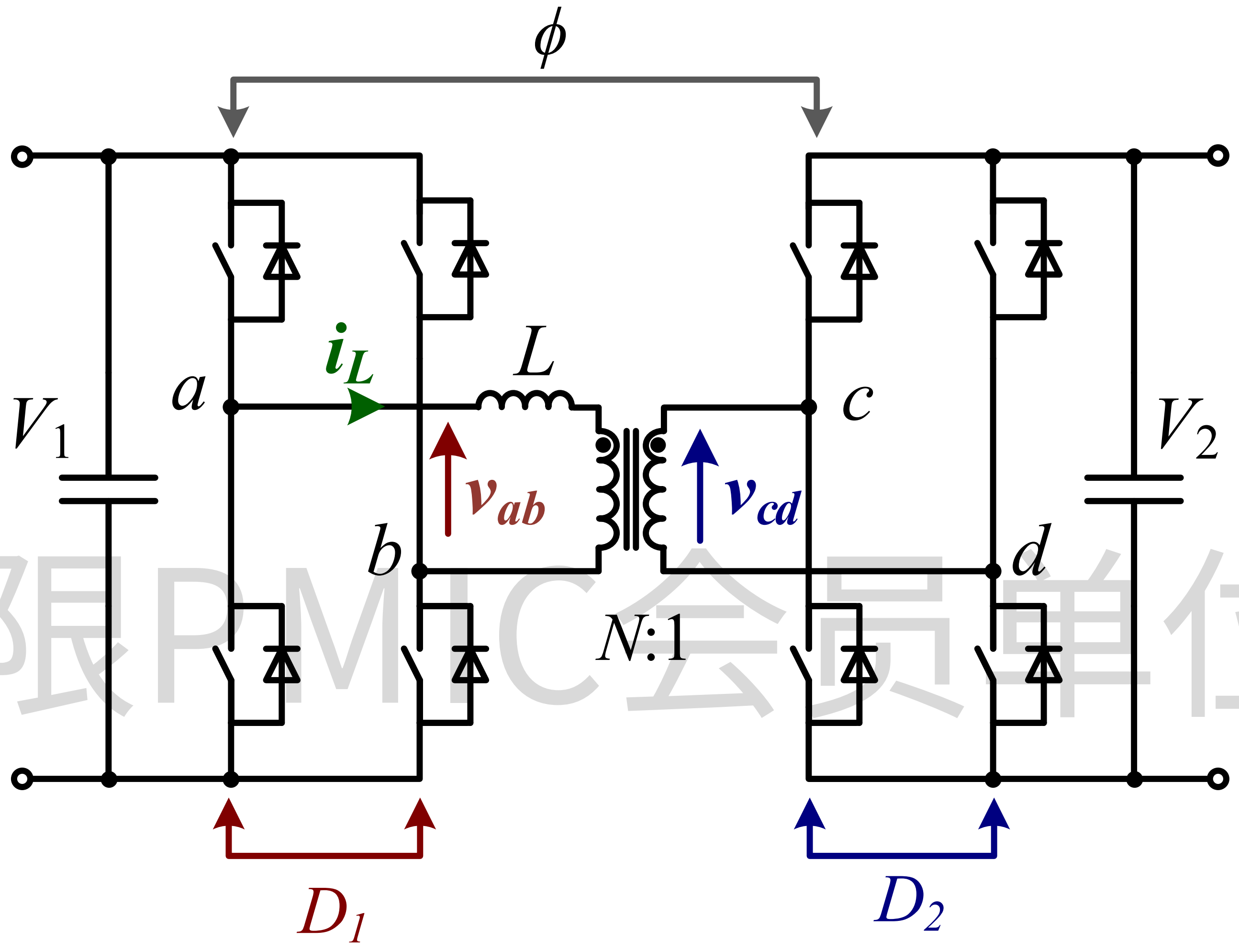
M is close 0.5, half bridge

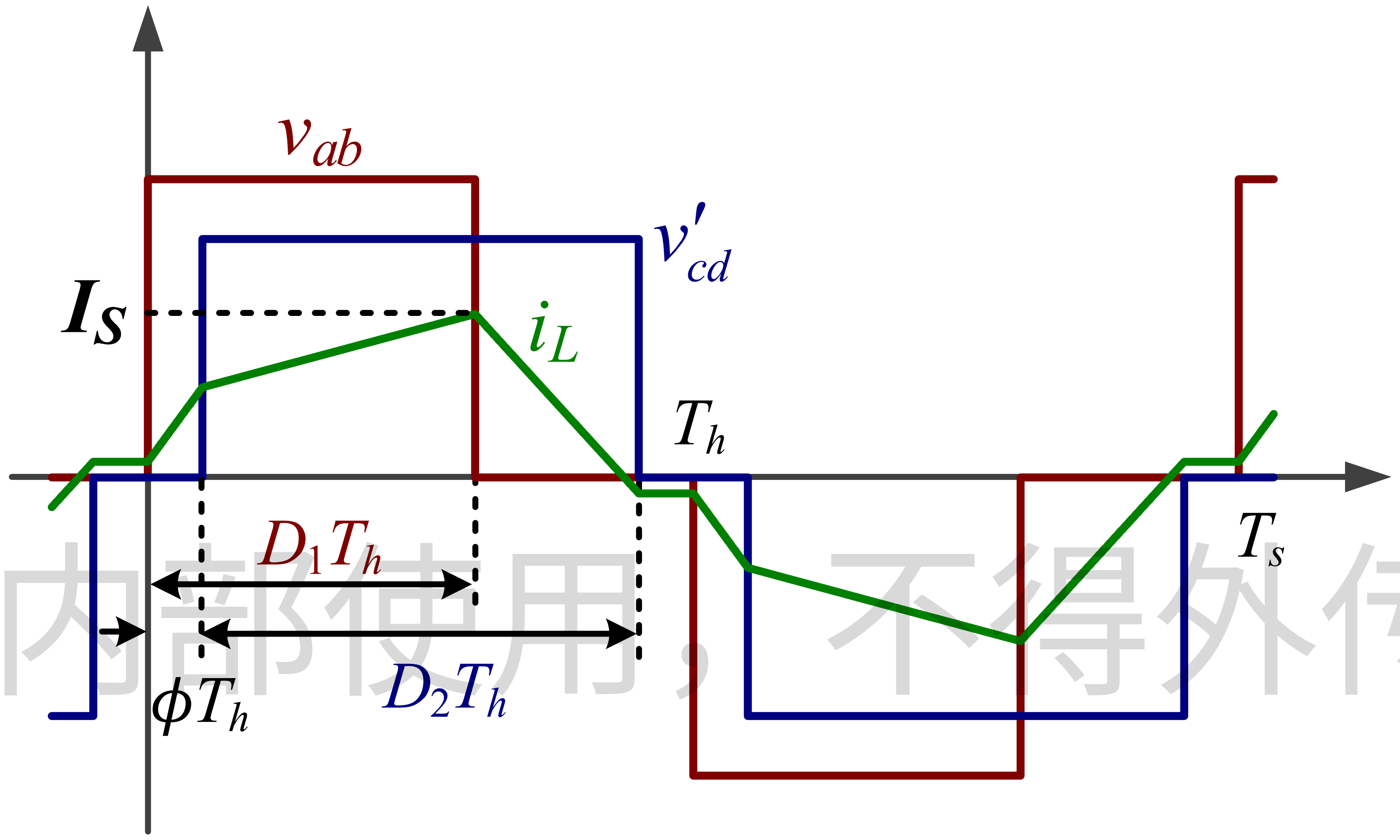


[1] G. Xu, D. Sha, Y. Xu, and X. Liao, ``Hybrid-bridge-based DAB converter with voltage match control for wide voltage conversion gain application,'' IEEE Trans. Power Electron., vol. 33, no. 2, pp. 1378-1388, Feb. 2018.

Duty cycle methods

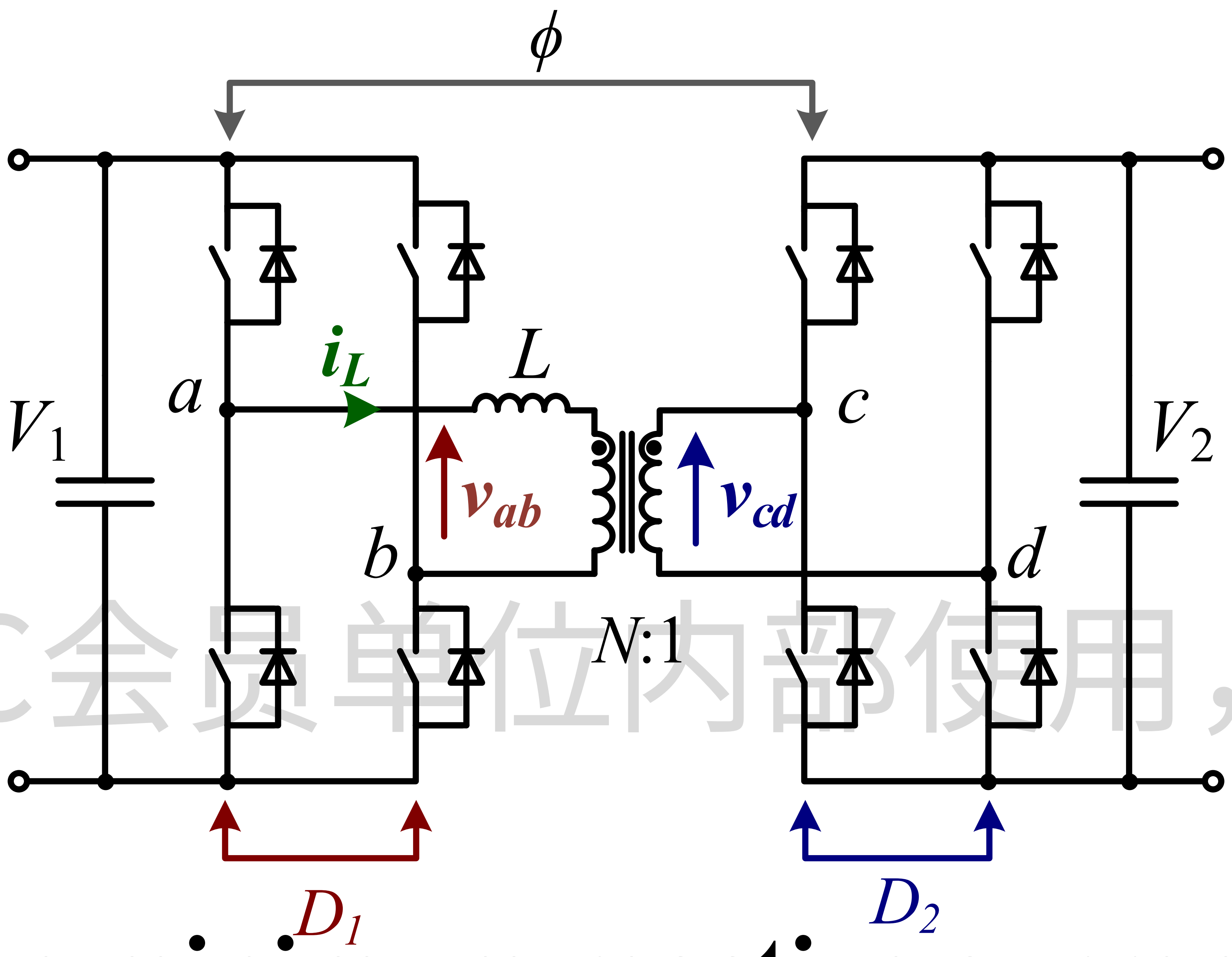
- **Adjusting *D*1 and *D*2**





$$|\vec{v}_{ab(n)}| = \frac{4\sin(n\pi/2)\sin(D_1 n\pi/2)}{n\pi} V_1, n = 1, 3, 5, \cdots$$

Adjusting D_1、D_2 can change the frequency components amplitude of v_{ab} and v_{cd}

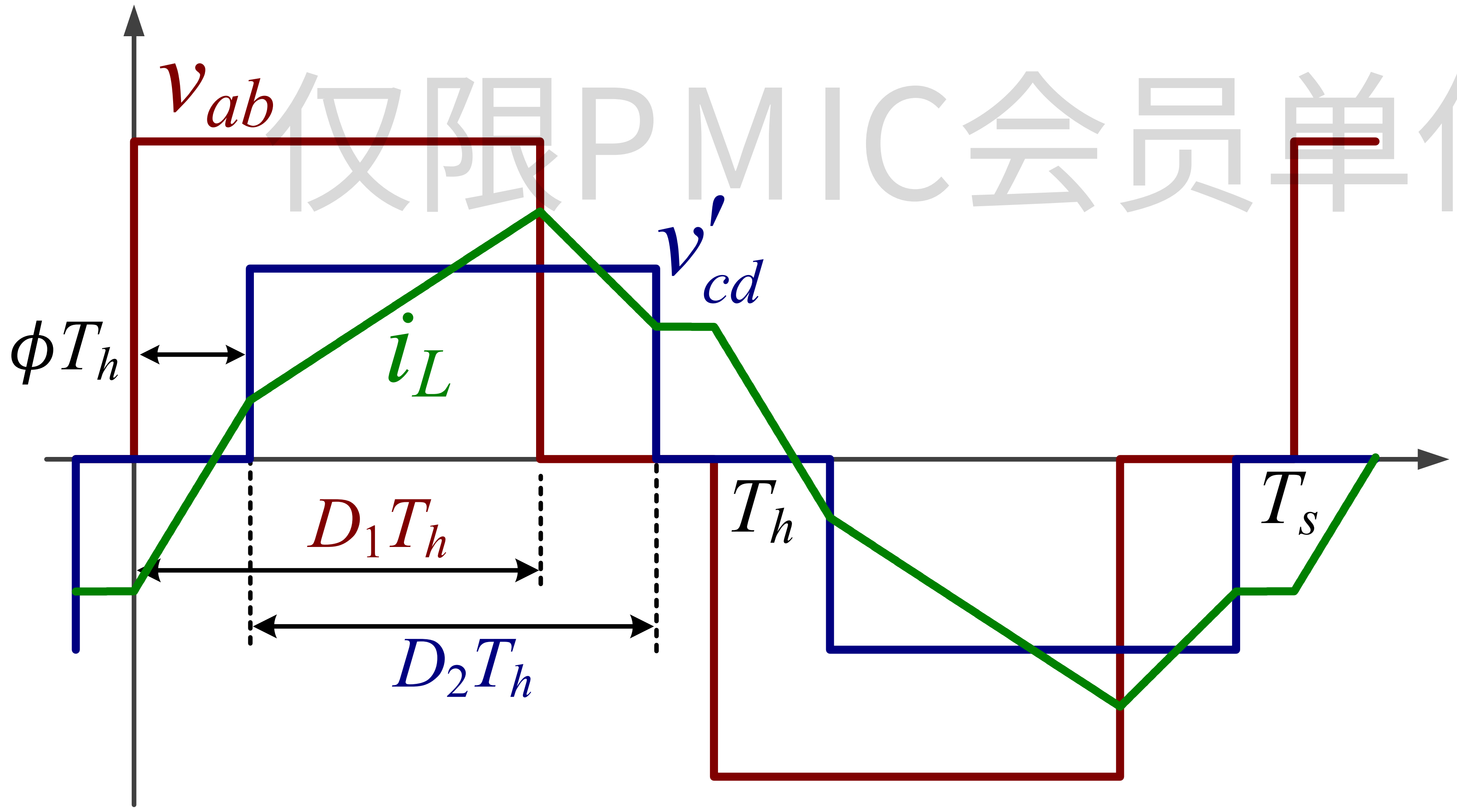


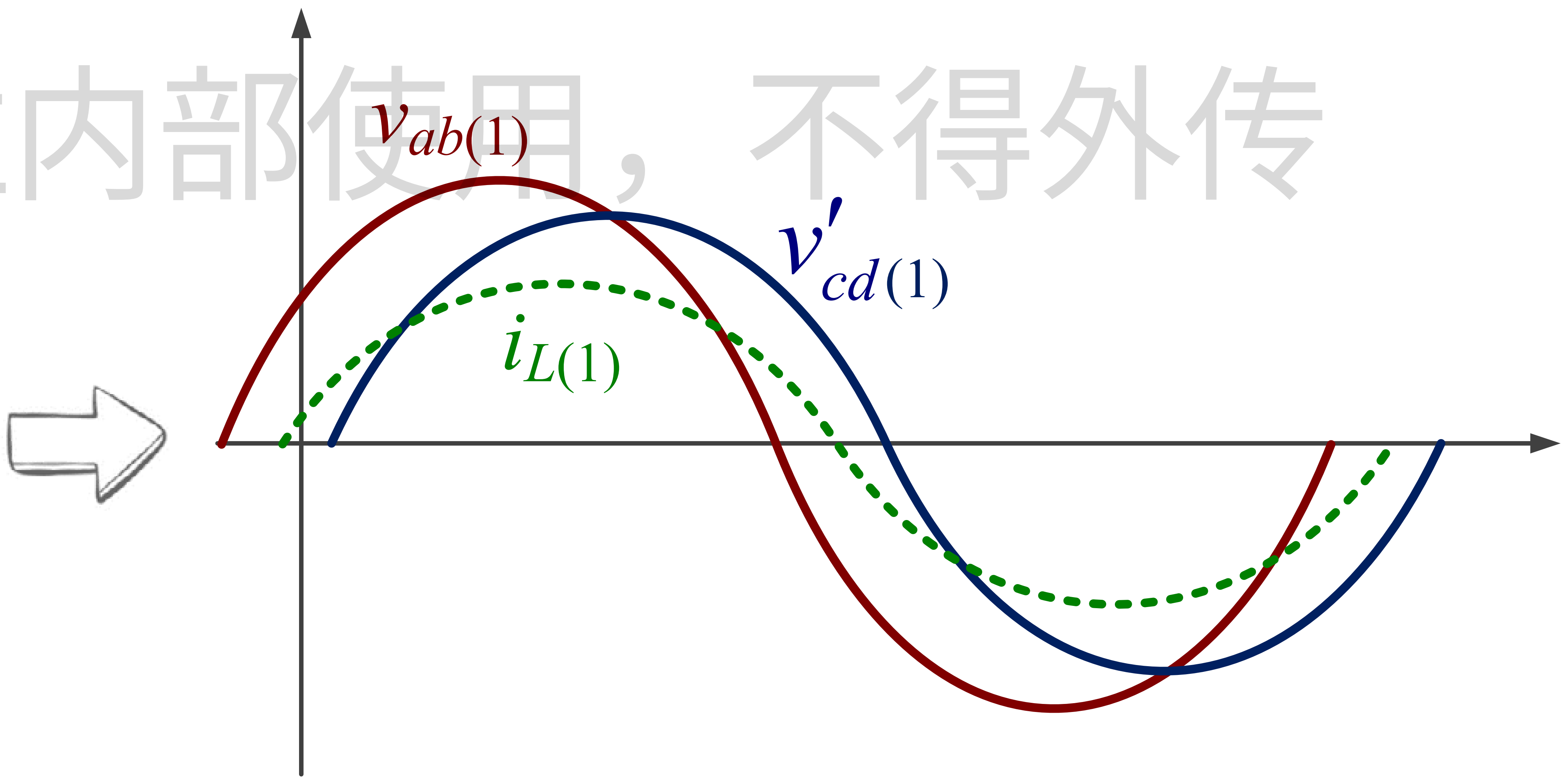
For the minimum reactive current

What is the optimal D_1,D_2 and ϕ ?

- **Fundamental component analysis (FCA)**
- **Time domain analysis**

- **Fundamental component analysis (FCA)**
  - **Only consider the fundamental component**





Optimization based on FCA

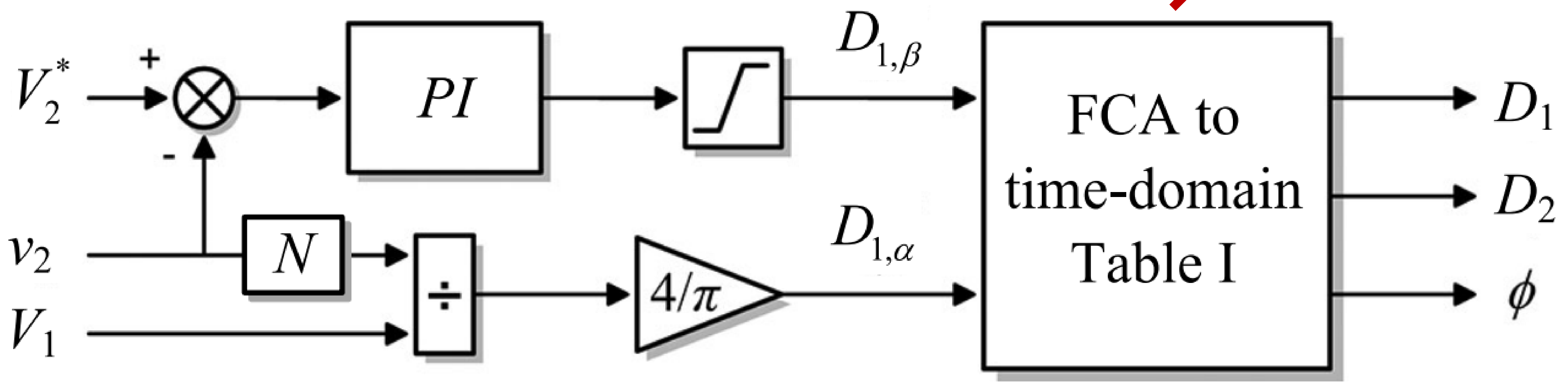
Optimal phase shift ratios

- Maximize fundamental power factor [1]
- Minimize amplitudes of i_L fundamental component [2]
- Minimize fundamental reactive power [3]

$$D_1 = \frac{1}{\pi}\arcsin\left(\frac{\pi}{4}\sqrt{D_{1,\alpha}^2 + D_{1,\beta}^2}\right), D_2 = 0.5$$

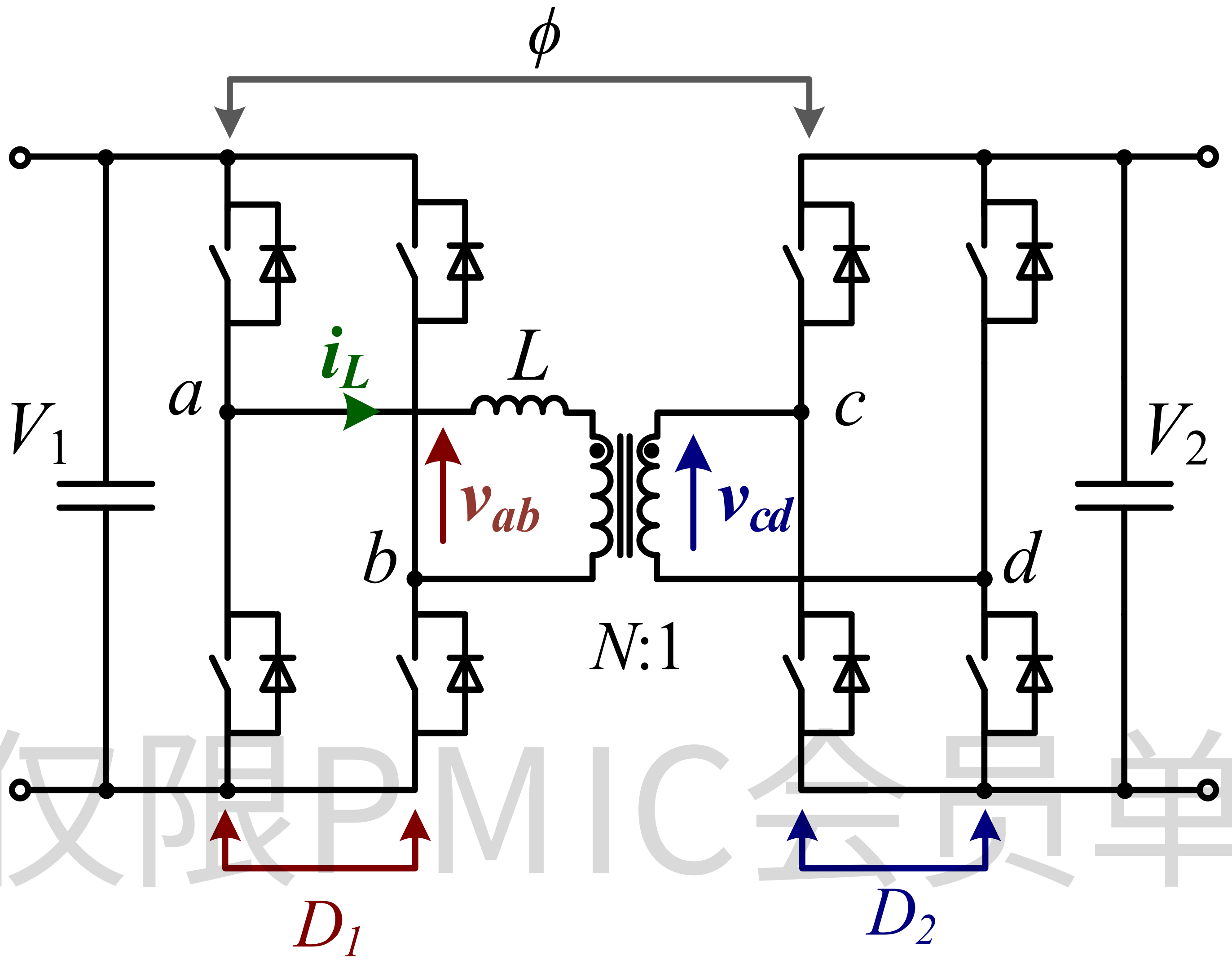
$$\phi = \frac{1}{2\pi}\arctan\left(D_{1,\beta} / D_{1,\alpha}\right)$$

where $D_{1,\alpha} = \frac{4}{\pi}M, D_{1,\beta}$ is the PI output

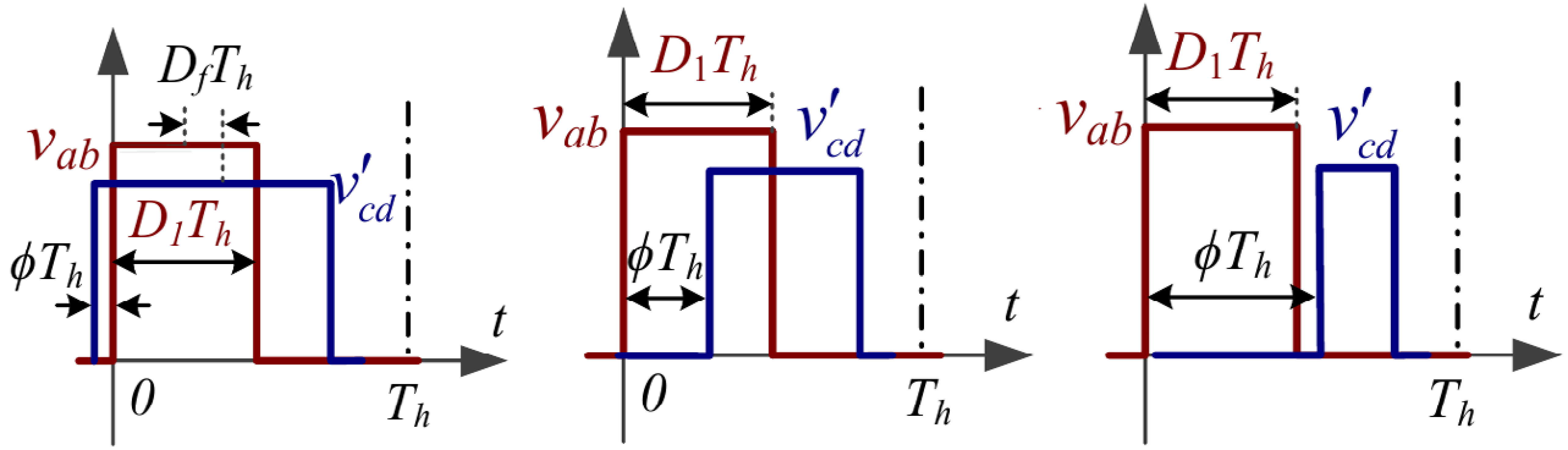


[1] B. Zhao, et. Al , ``Universal high-frequency-link characterization and practical fundamental-optimal strategy for dual-active-bridge DC-DC converter under PWM plus phase-shift control,'' IEEE Trans. Power Electron. 2015
[2] W. Choi, et.al, ``Fundamental duty modulation of dual-active-bridge converter for wide-range operation,'' *IEEE Trans. Power Electron*. 2016.

Time domain analysis



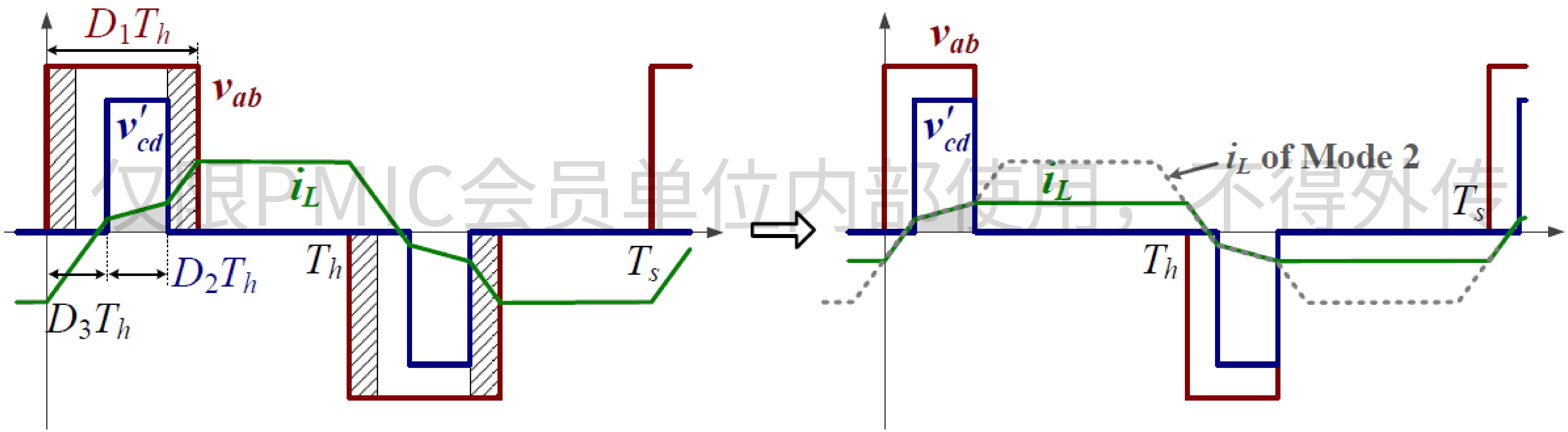
- In the time domain, there are 5 different operating modes.
- Different modes are classified based on the relative position of v_{ab} and v_{cd}.



(a) Mode 1 (b) Mode 2-4 (c) Mode 5

Simplify operating modes

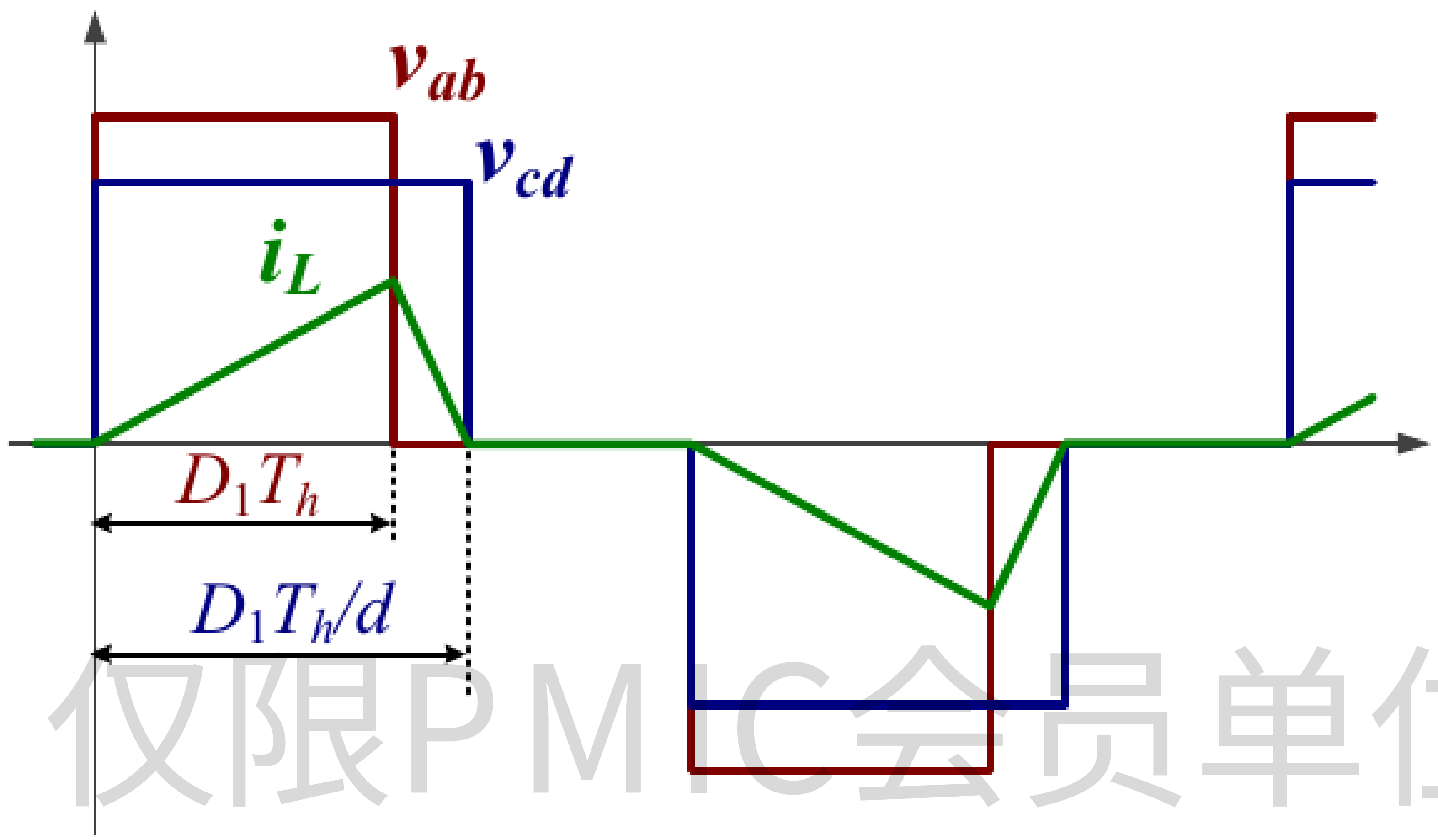
- **Mode 1,2,5 can be converted to Mode 3 with lower RMS.**

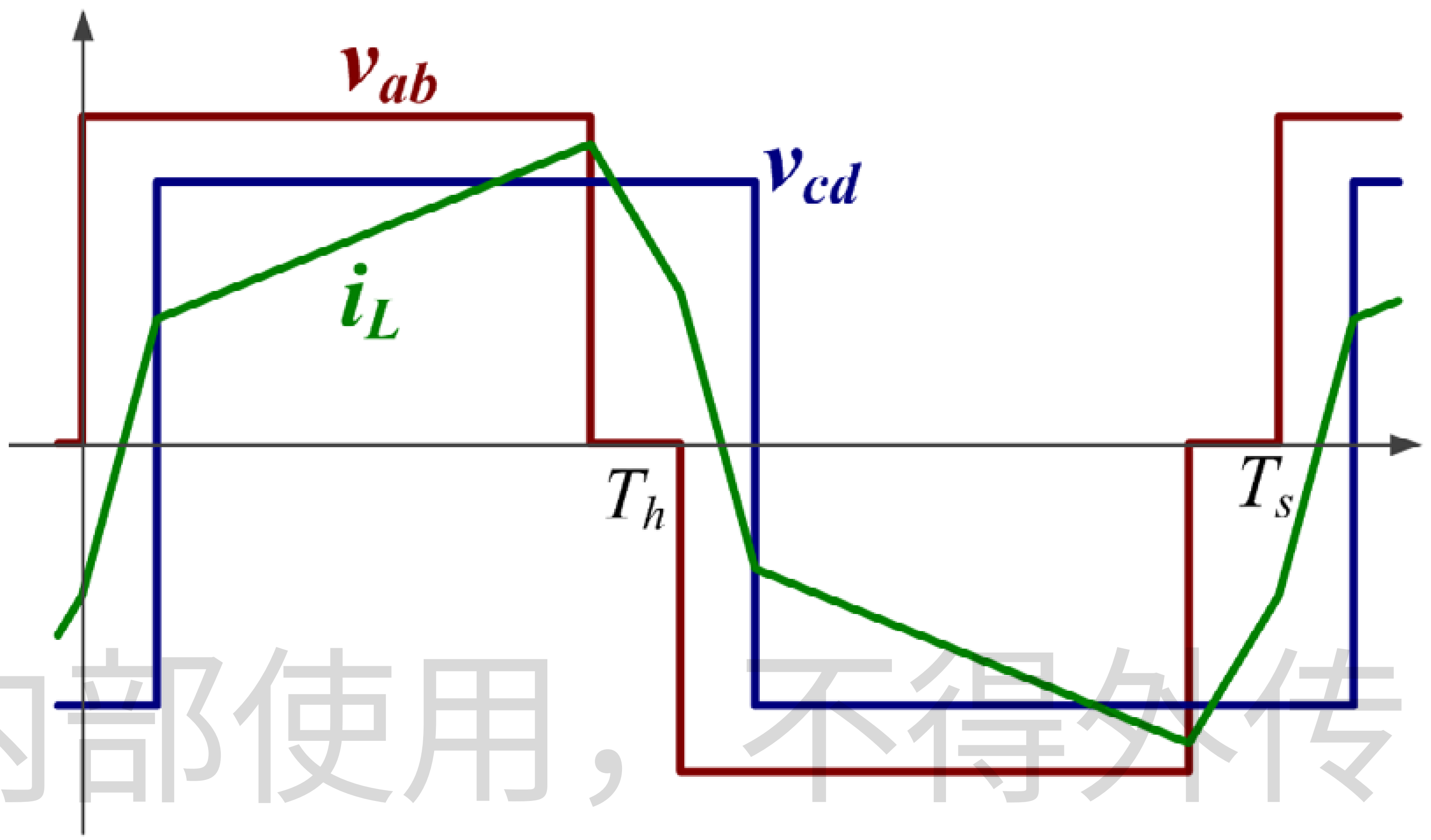


Mode 2 | Mode 3

Only two modes (Mode 3 and 4) requires detailed analysis.

Optimal phase shift ratios based on time domain analysis





$$P_o \in [0, \frac{d(1-d)}{2}] \quad \begin{cases} D_1 = \sqrt{\dfrac{2dP_o}{1-d}} \\ D_2 = \dfrac{D_1}{d}, D_3 = 0 \end{cases}$$

$$P_o \in [\frac{d(1-d)}{2}, \frac{1}{4}] \quad \begin{cases} D_1 = 1 - (1-d)\sqrt{\dfrac{1-4P_o}{1-2d+2d^2}} \\ D_2 = 1, D_3 = \dfrac{D_1 - d}{2(1-d)} \end{cases}$$

P_o is unified output power $P_o = P / P_b, P_b = \dfrac{NV_1V_2}{2Lf_s}$

[1] S. Shao, M. Jiang, W. Ye, Y. Li, J. Zhang, and K. Sheng, "Optimal phase shift control to minimize reactive power for a dual active bridge dc-dc converter," IEEE Transactions on Power Electronics, pp. 1–1, 2019.

Phase shift ratios to minimize reactive current

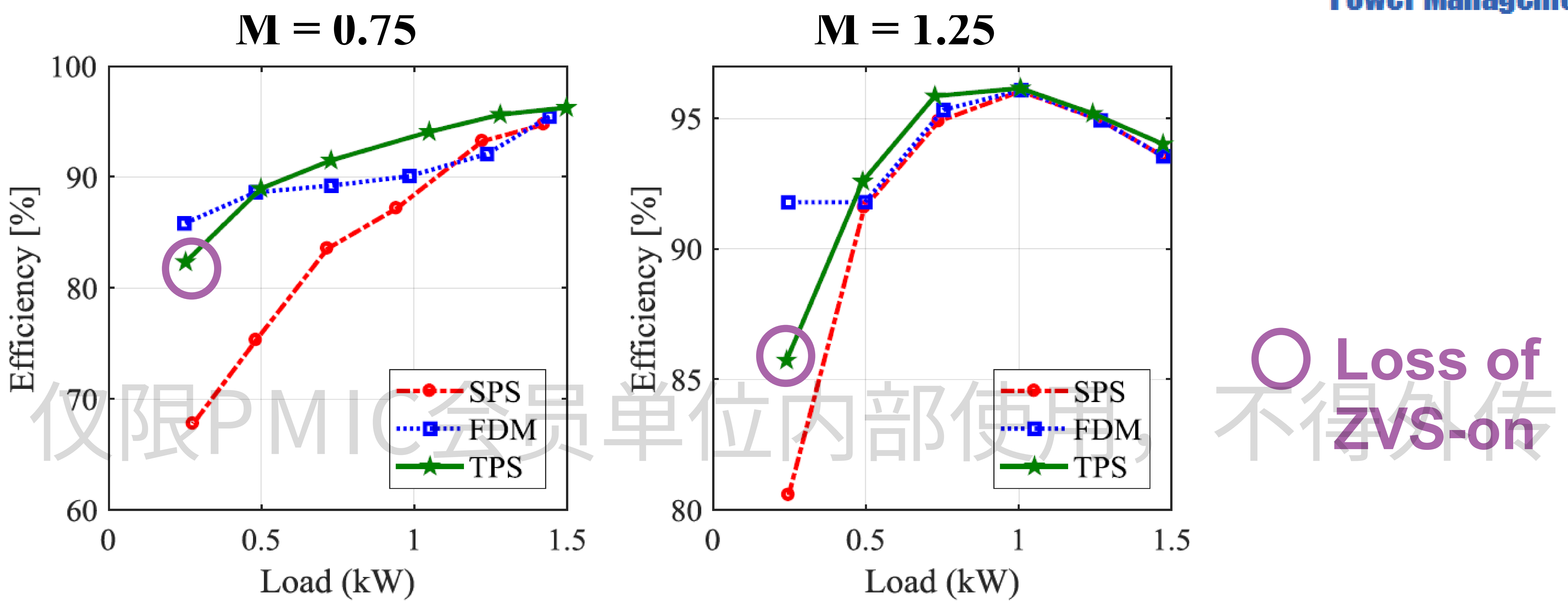
Authors	Phase shift ratios	Optimization target
Zhao *et al.* [39]	$D_1 = 1 - \arccos M, D_2 = 1, \phi$ regulated by v_o	Maximal fundamental active power
Choi *et al.* [52]	$D_1 = \frac{1}{\pi}\arcsin(\frac{\pi}{4}\sqrt{D_{1,\alpha}^2 + D_{1,\beta}^2}), D_2 = 0.5$ $\phi = \frac{1}{2\pi}\arctan(D_{1,\beta}/D_{1,\alpha}),$ $where\ D_{1,\alpha} = \frac{4}{\pi}M, D_{1,\beta}\ is\ the\ PI\ output$	Minimal amplitude of i_L fundamental component
Shi *et al.* [53]	$D_1 = 1 - \frac{2}{\pi}\arccos(M/2)\cdot(1-p*), D_2 = 1$ $\phi = \frac{1}{\pi}\arccos\frac{M}{2\cos((1-D_1)\pi/2)} + \frac{D_1 - D_2}{2}$ $where\ p^*is\ the\ PI\ output$	Minimal fundamental reactive power
Jain *et al.* [55]	$\begin{cases} D_1 = \sqrt{\frac{2MP_n}{1-M}} \\ D_2 = \frac{D_1}{M}, \phi = 0 \end{cases}$ $P_n \in [0, \frac{M(1-M)}{2}]$	Minimal i_L peak value (current stress)
Huang *et al.* [56]		
Hou *et al.* [57]	$\begin{cases} D_1 = 1-(1-M)\sqrt{\frac{1-4P_n}{1-2M+2M^2}} \\ D_2 = 1, \phi = \frac{D_1 - M}{2(1-M)} \end{cases}$ $P_n \in [\frac{M(1-M)}{2}, \frac{1}{4}]$	
Tong *et al.* [58]		Minimal i_L RMS value

FCA (Zhao, Choi, Shi)

Time domain Analysis (Jain, Huang, Hou, Tong)

[1] S. Shao, H. Chen, X. Wu, J. Zhang and K. Sheng, "Circulating Current and ZVS-on of a Dual Active Bridge DC-DC Converter: A Review," in *IEEE Access*, vol. 7, pp. 50561-50572, 2019.

Comparison



Single phase shift

Optimized phase shift based on FCA

Optimized phase shift based on time domain analysis

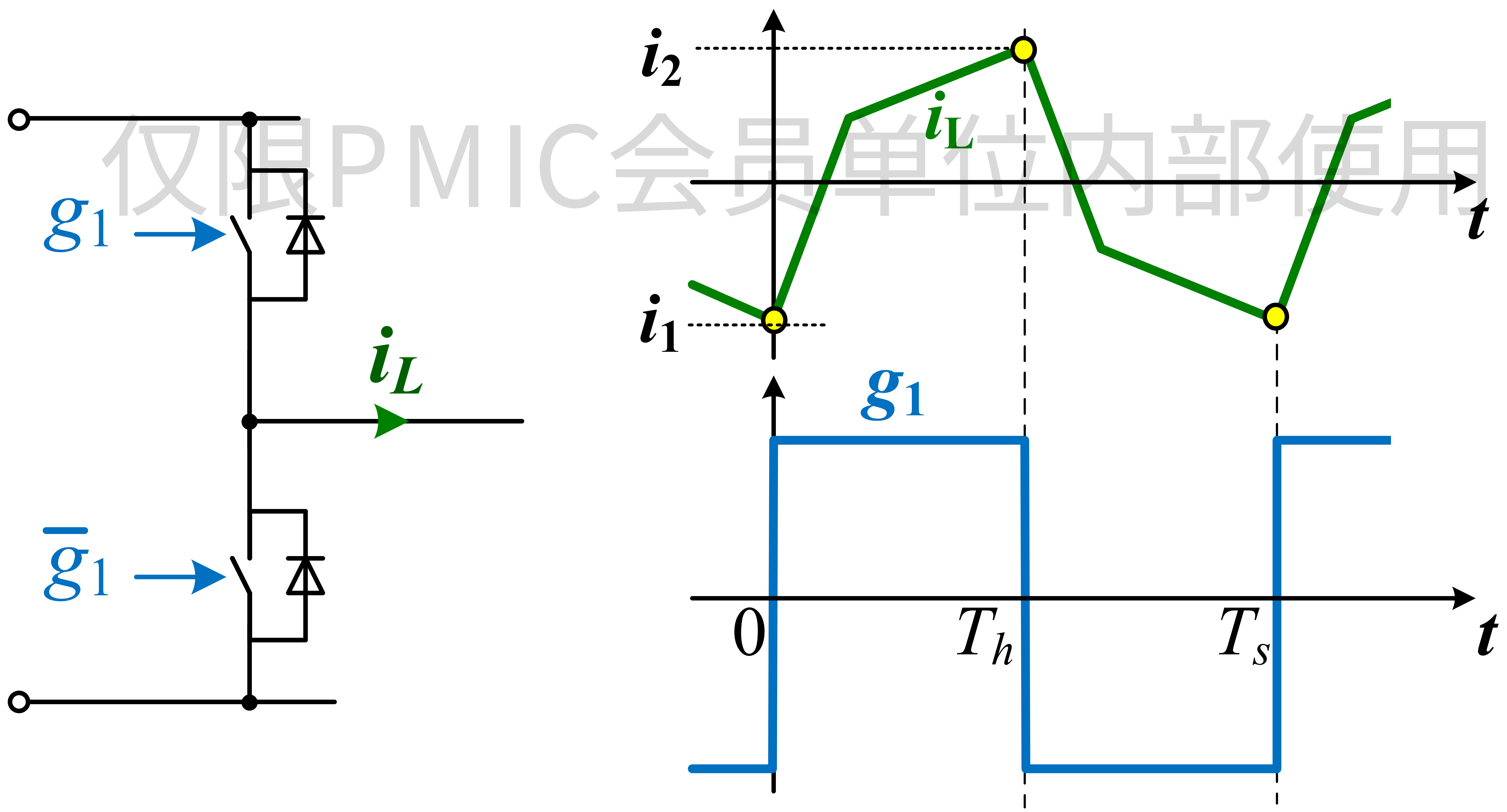
[1] S. Shao, M. Jiang, W. Ye, Y. Li, J. Zhang, and K. Sheng, “Optimal phase shift control to minimize reactive power for a dual active bridge dc-dc converter,” IEEE Transactions on Power Electronics, pp. 1–1, 2019.

Contents

1 Modeling of a DAB
2 Reactive current suppression
3 ZVS on of a DAB

ZVS–on for power switches

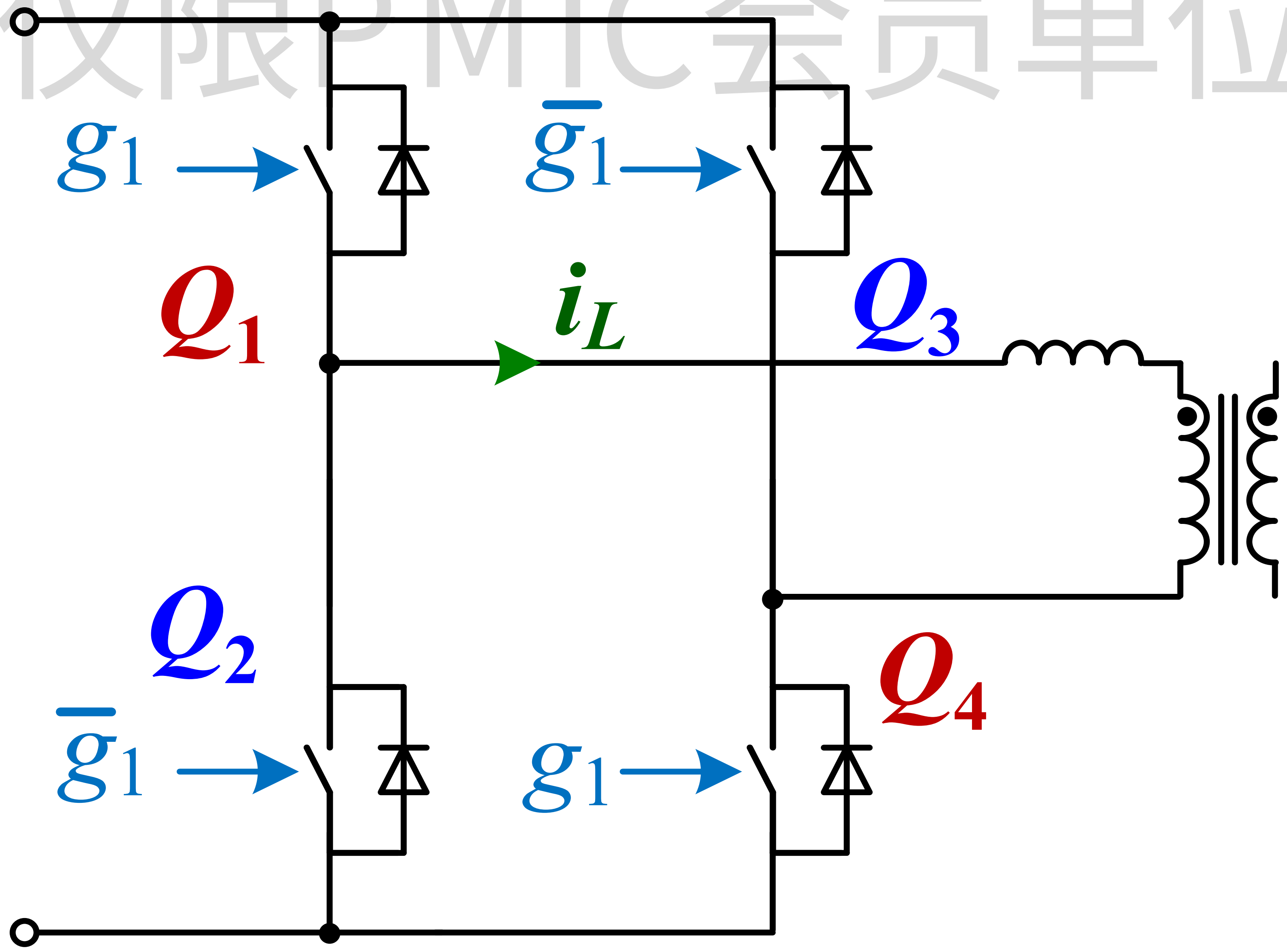
- **ZVS-on is desirable for converters using MOSFETs**
  - **Turn on loss is dominant in switching losses**
  - **No reverse recovery loss in diode**
  - **Low EMI**

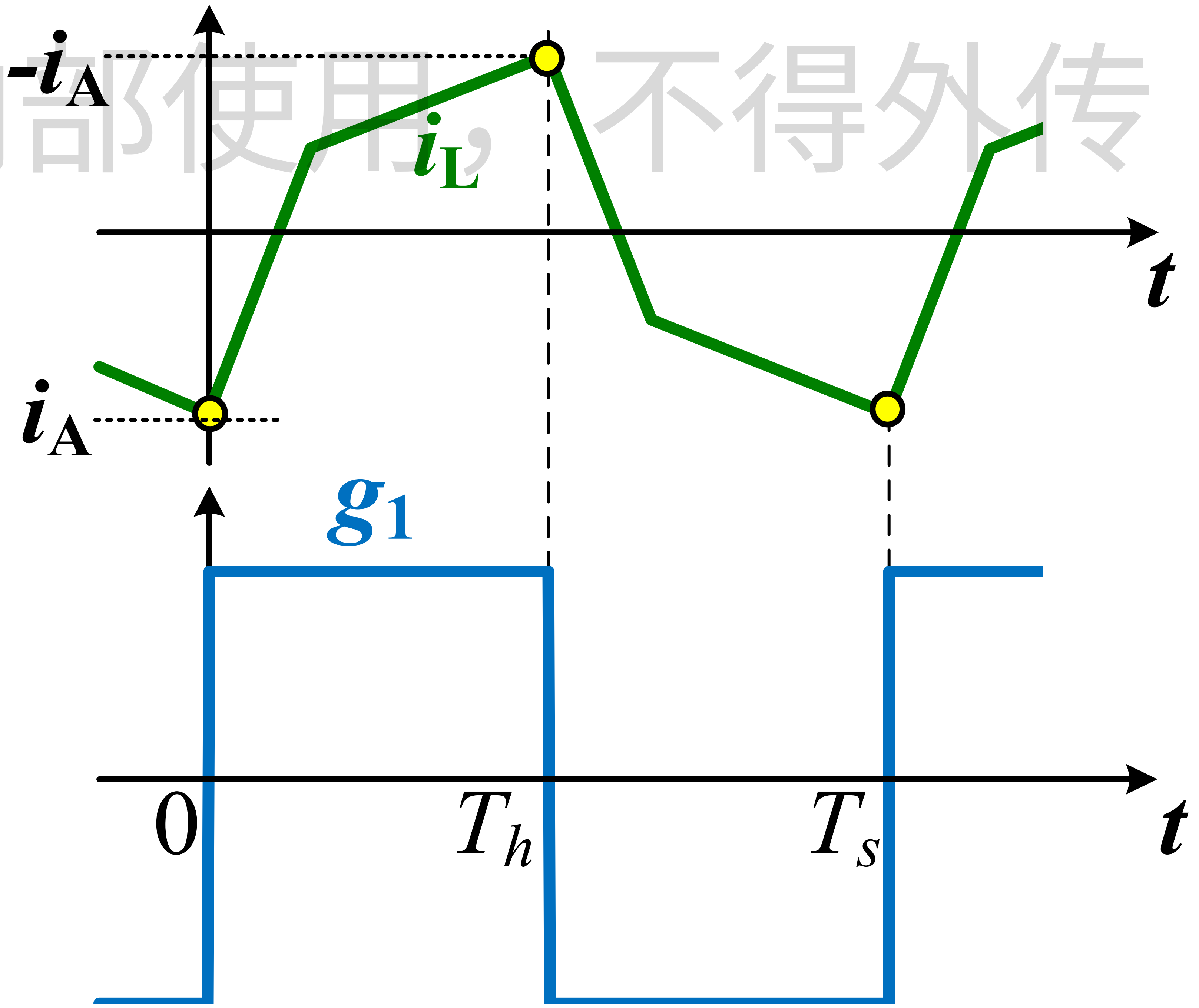


When $i_1 < 0$, $i_2 > 0$, both devices can achieve ZVS-on.

ZVS–on for primary side

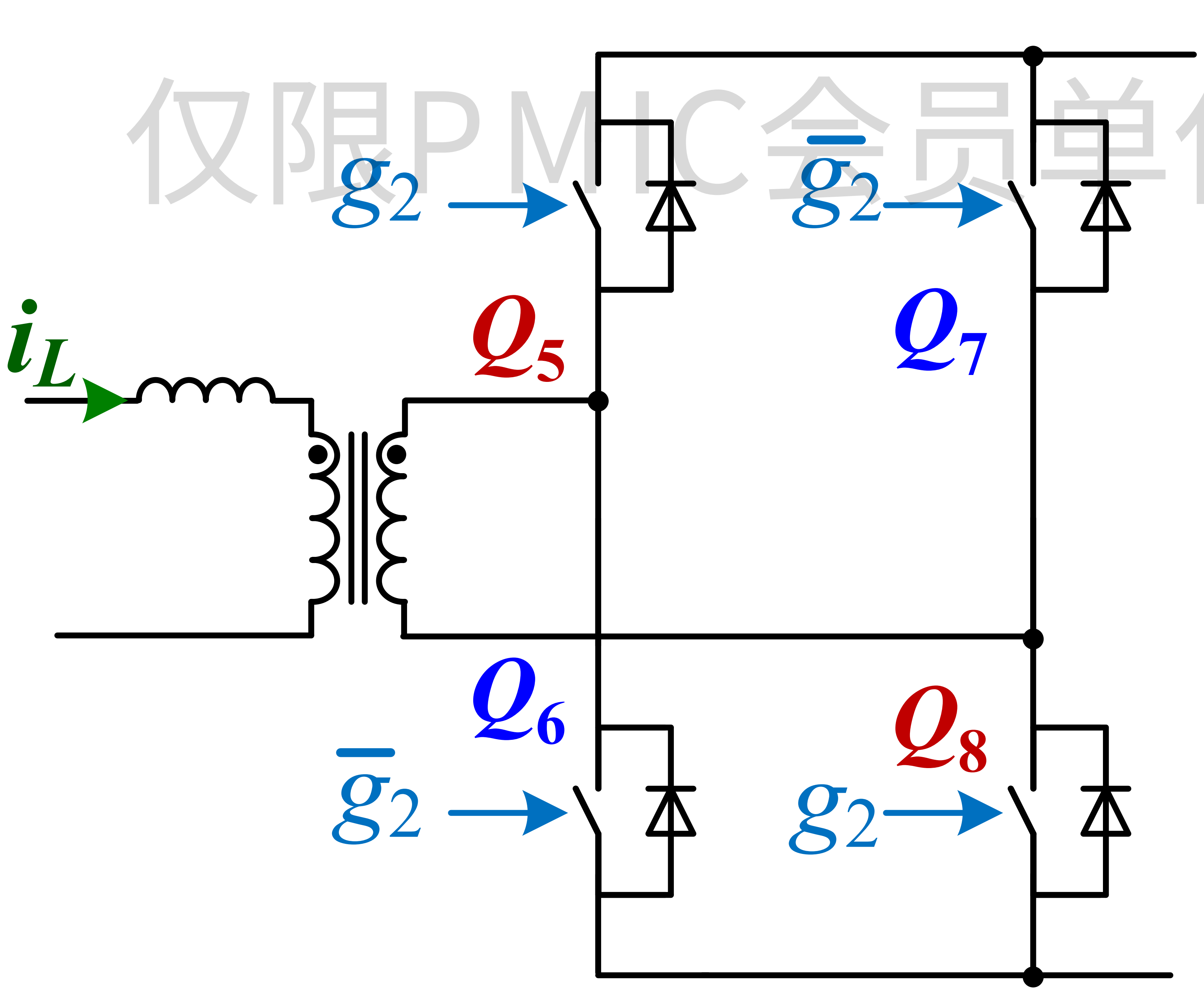
- **When DAB modulated using single phase shift**
  - **Q_1 and Q_4 have the same ZVS-on characteristics**
  - **Q_2 and Q_3 have the same ZVS-on characteristics**
  - **Inductor current i_L is symmetrical**
  - **If $i_A < 0$, then Q_1~Q_4 can all achieve ZVS-on**

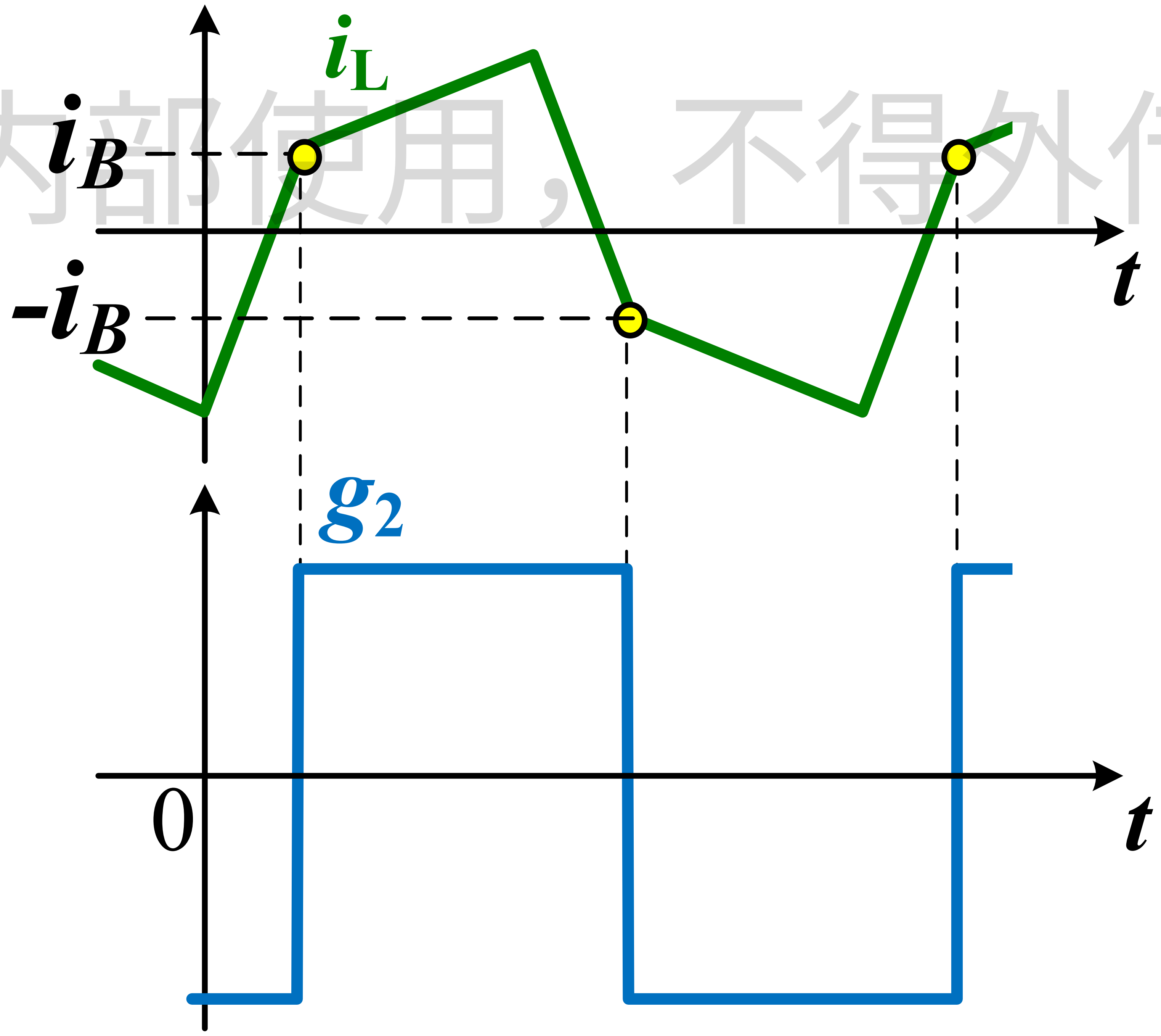




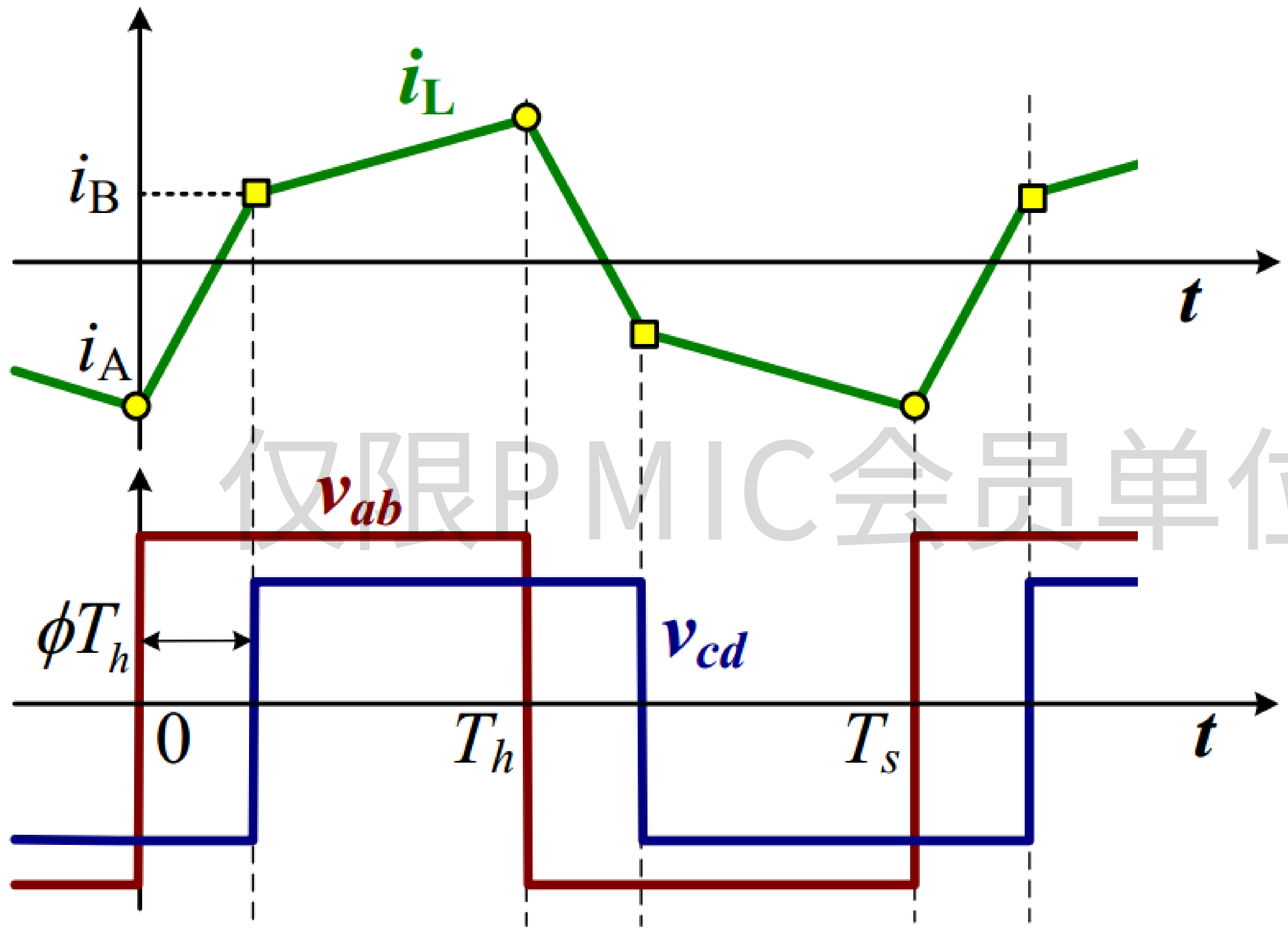
ZVS–on for secondary side

- **When DAB modulated SPS**
  - **Q_5 and Q_8 have the same ZVS-on characteristics**
  - **Q_6 and Q_7 have the same ZVS-on characteristics**
  - **If i_B > 0, then Q_5~Q_8 can all achieve ZVS-on**

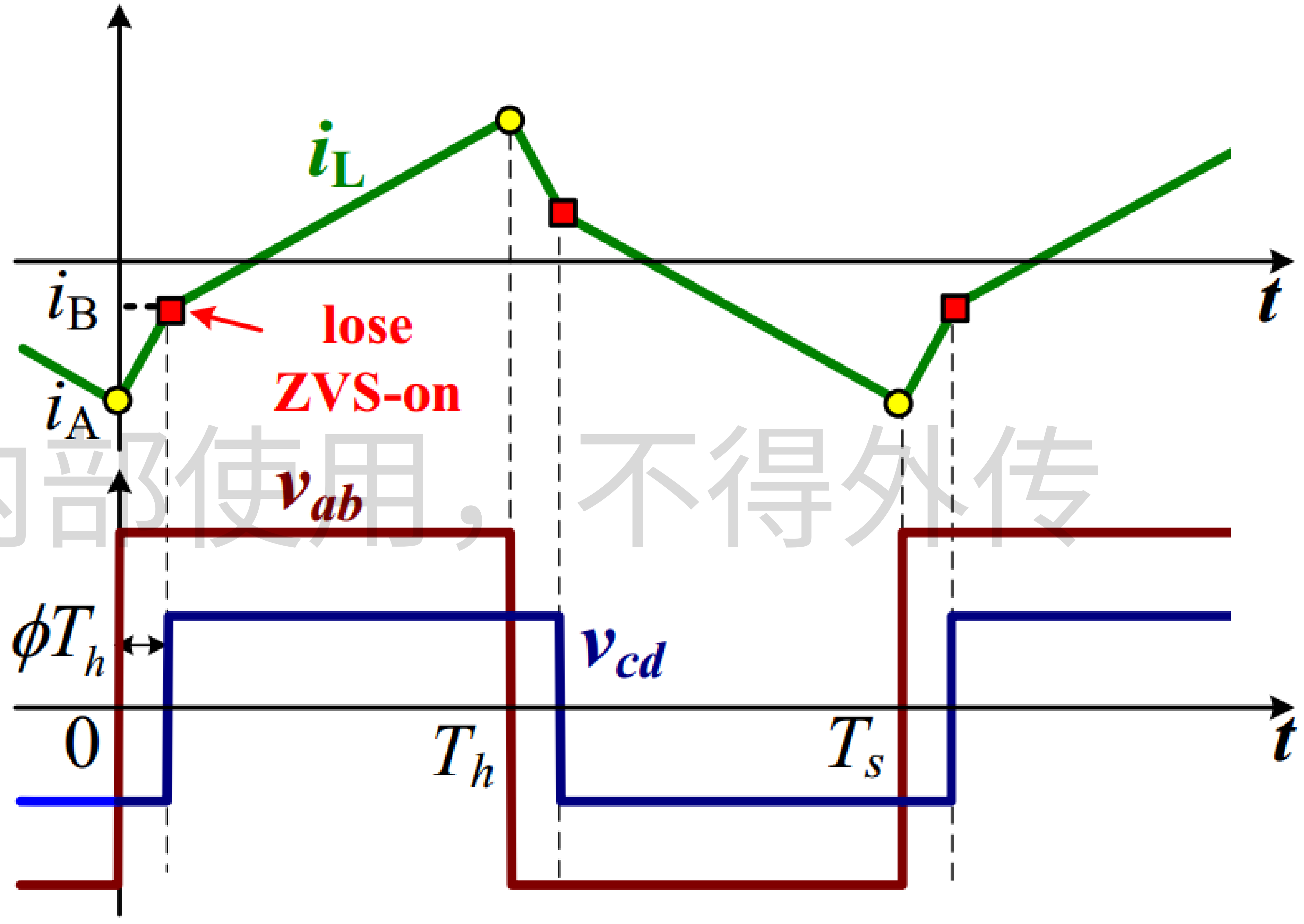




ZVS–on for power switches

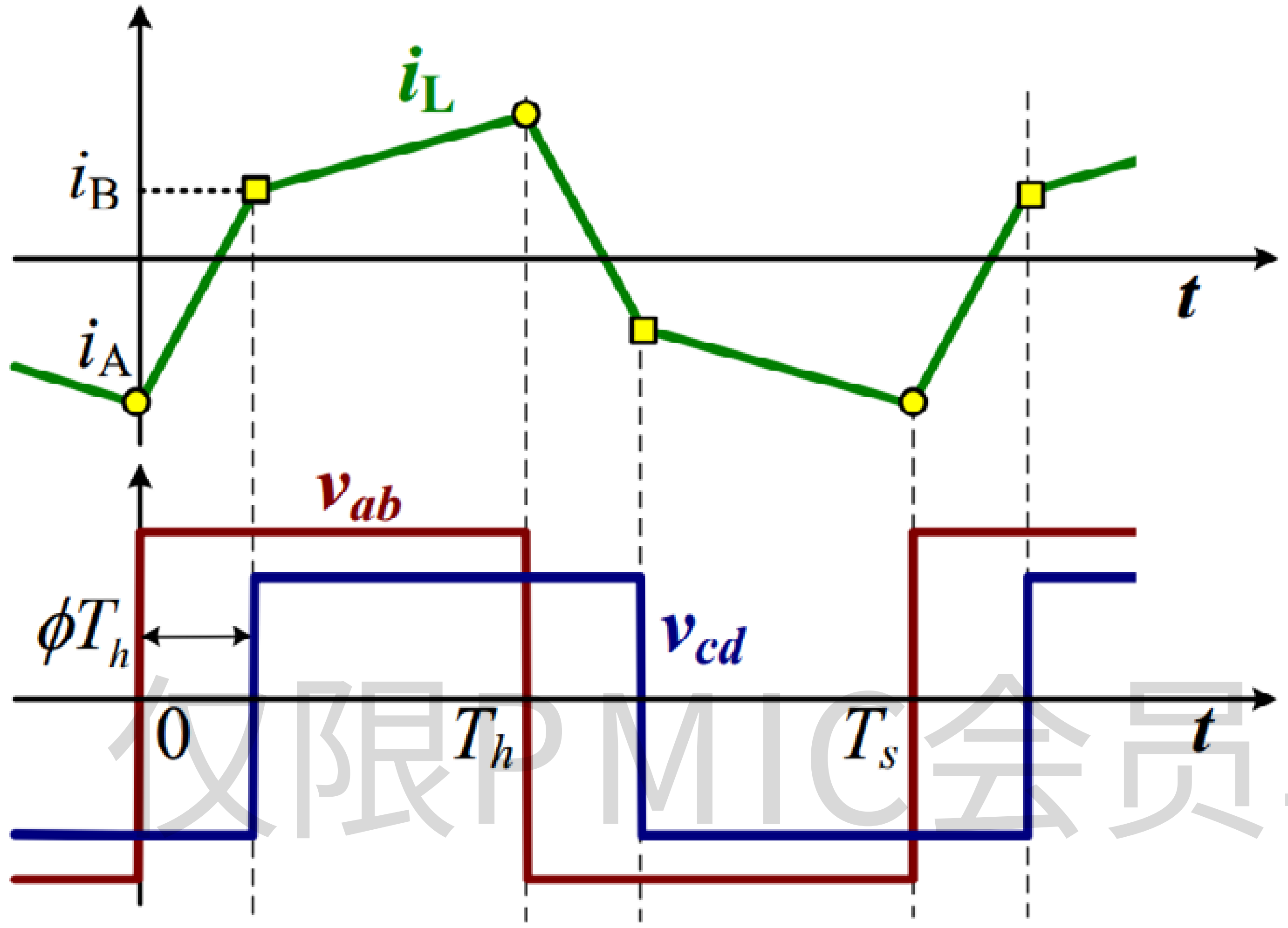


(a) All power devices achieve ZVS-on

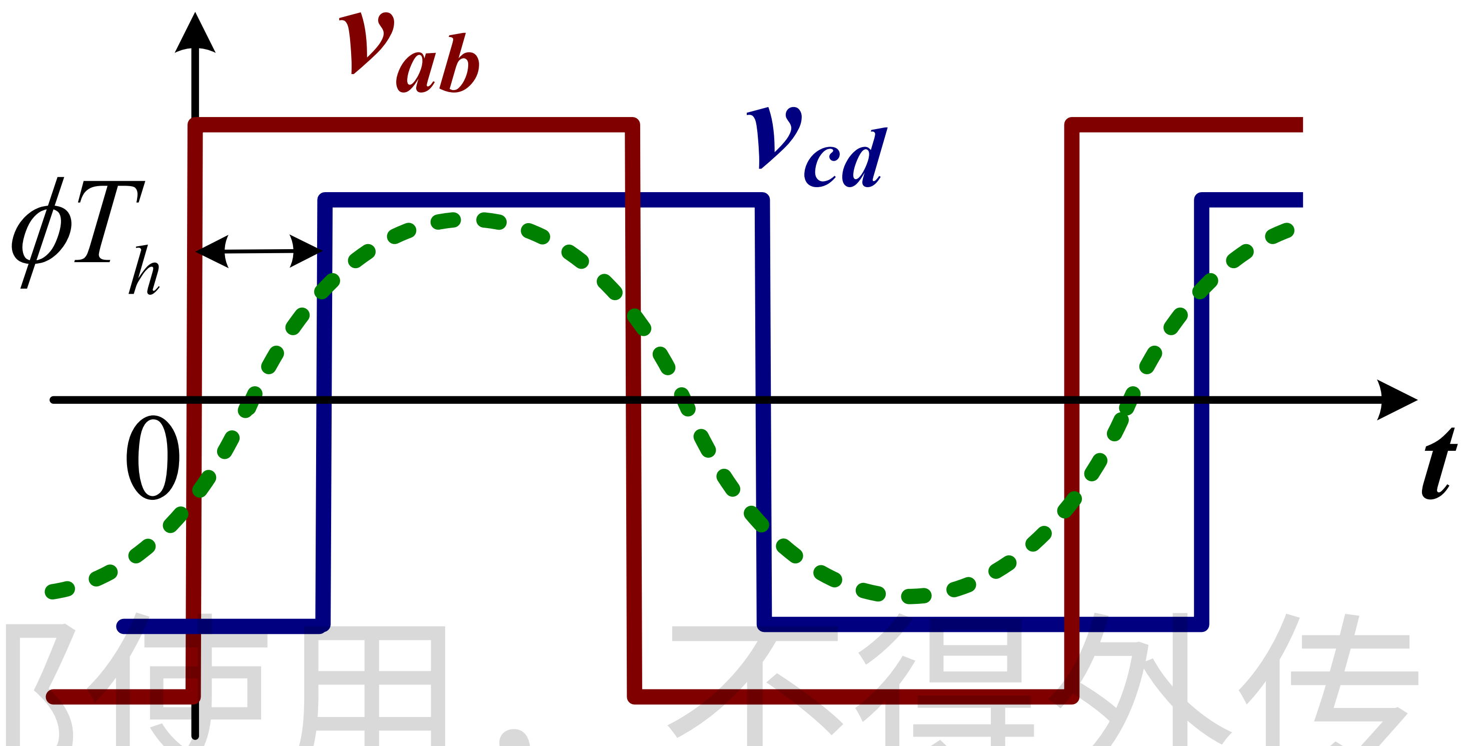


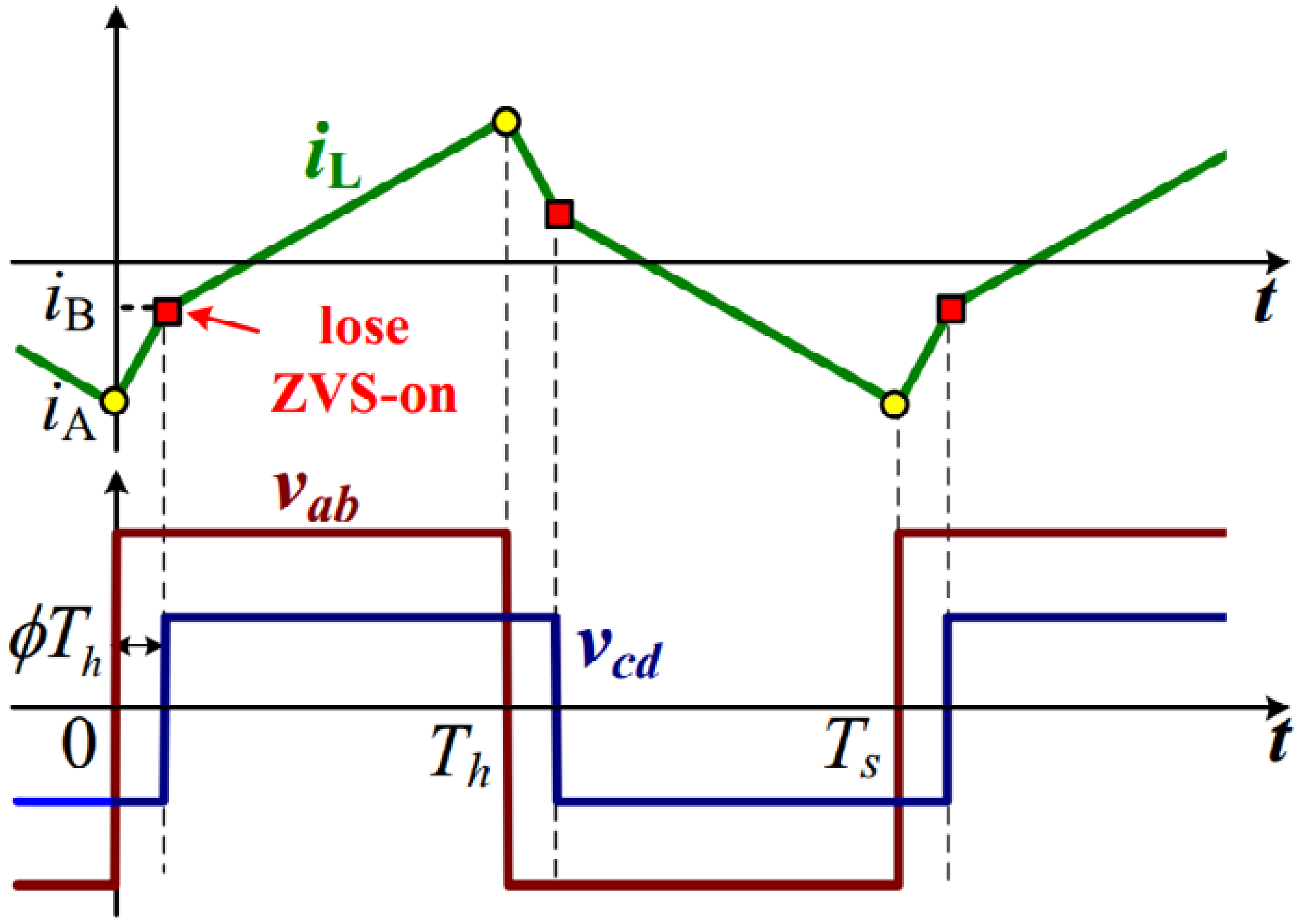
(b) Secondary devices lose ZVS-on

Conditions to achieve ZVS–on

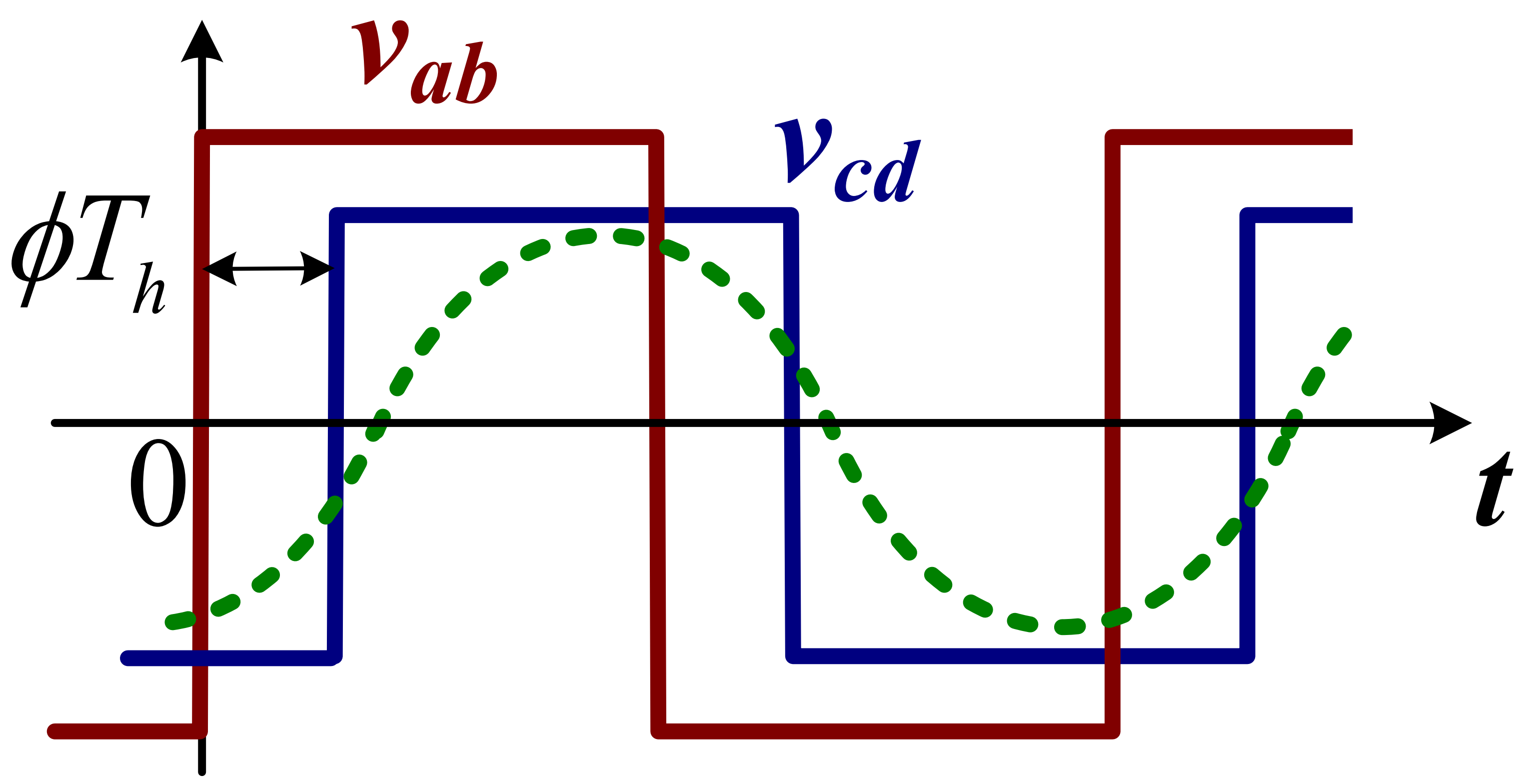


Achieve ZVS-on

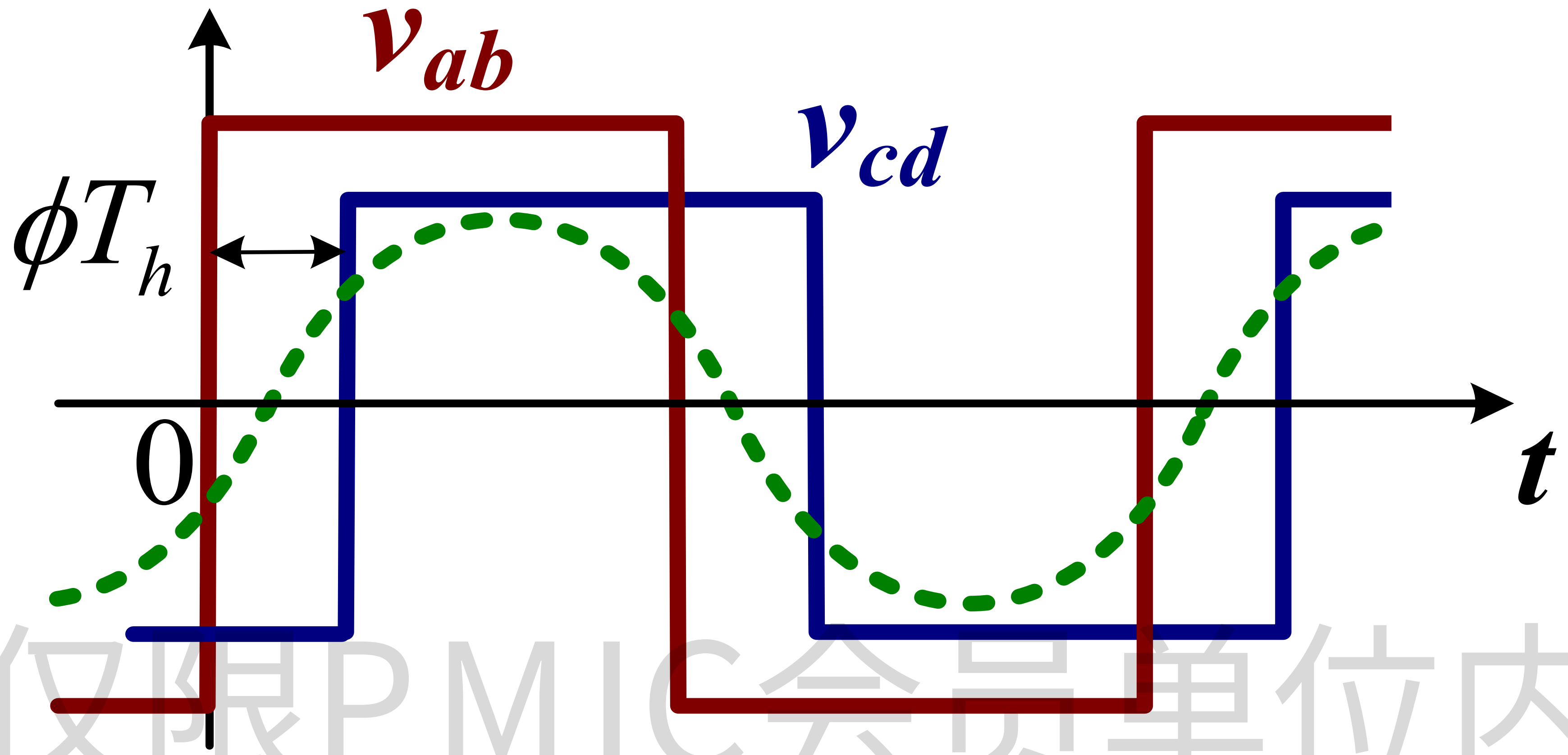


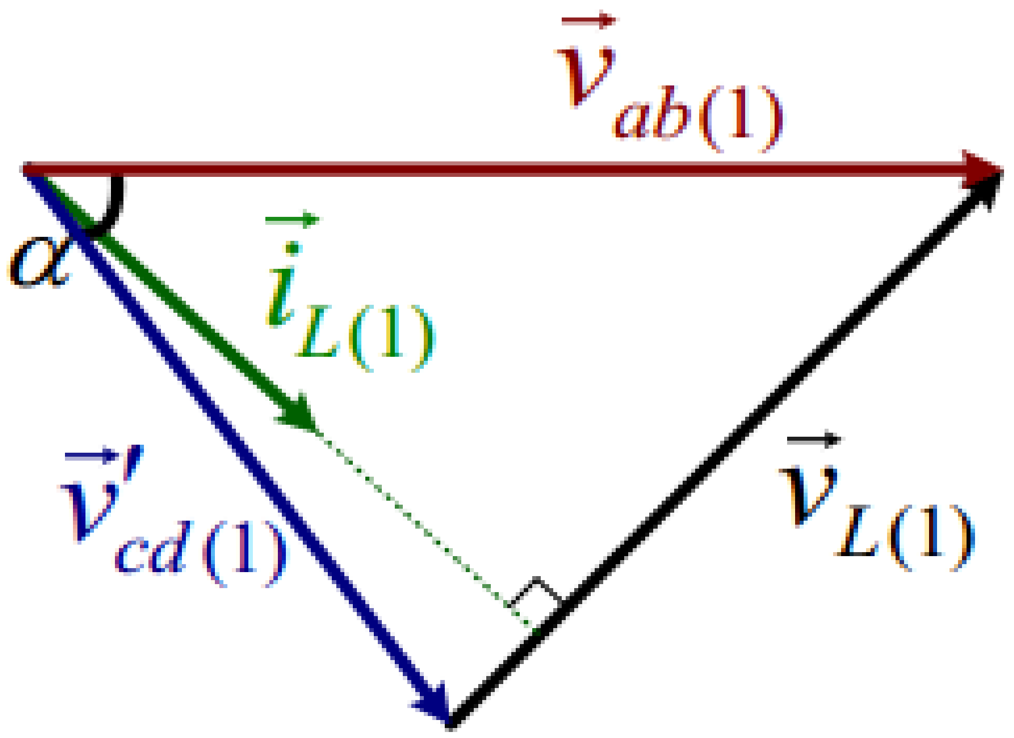


The secondary side lose ZVS-on

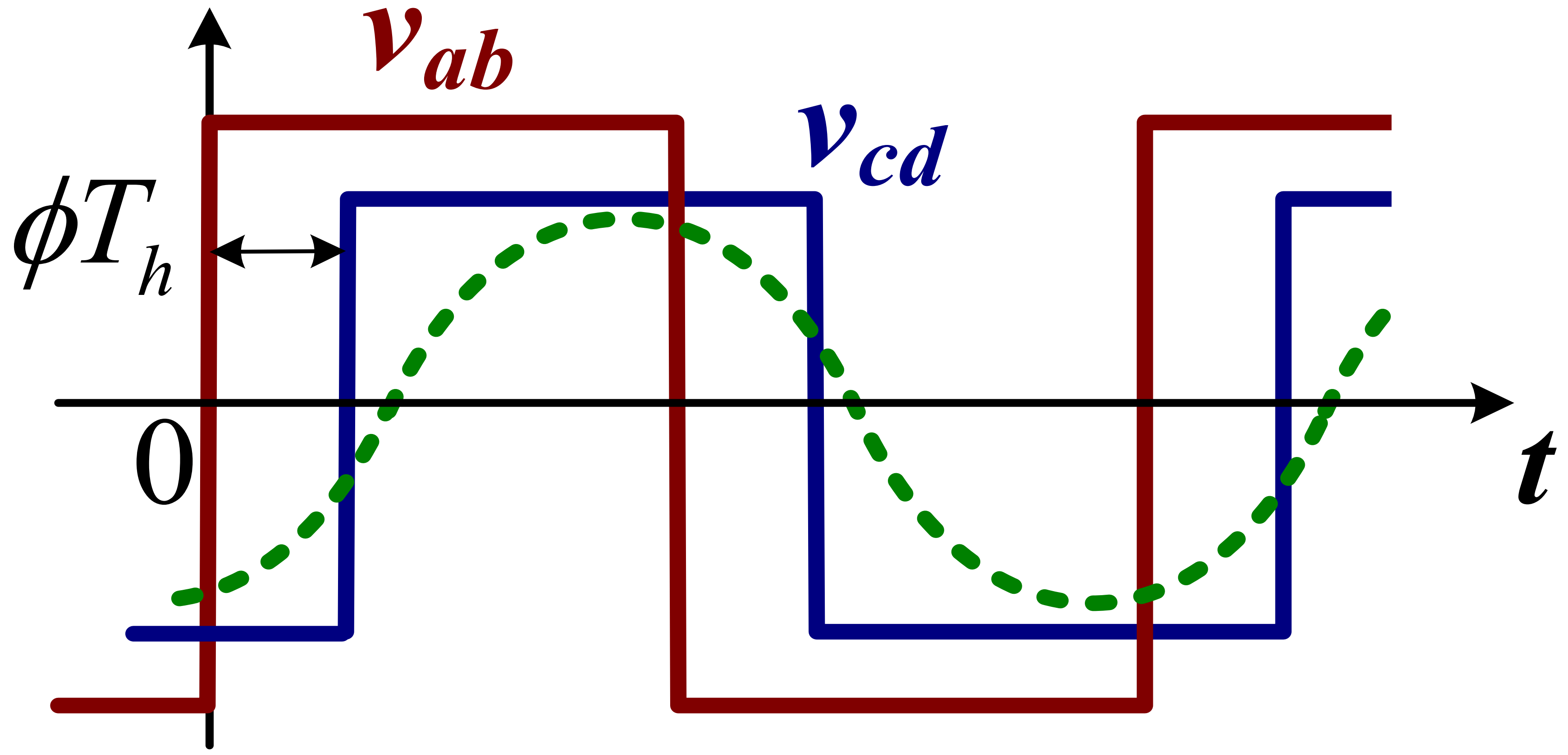


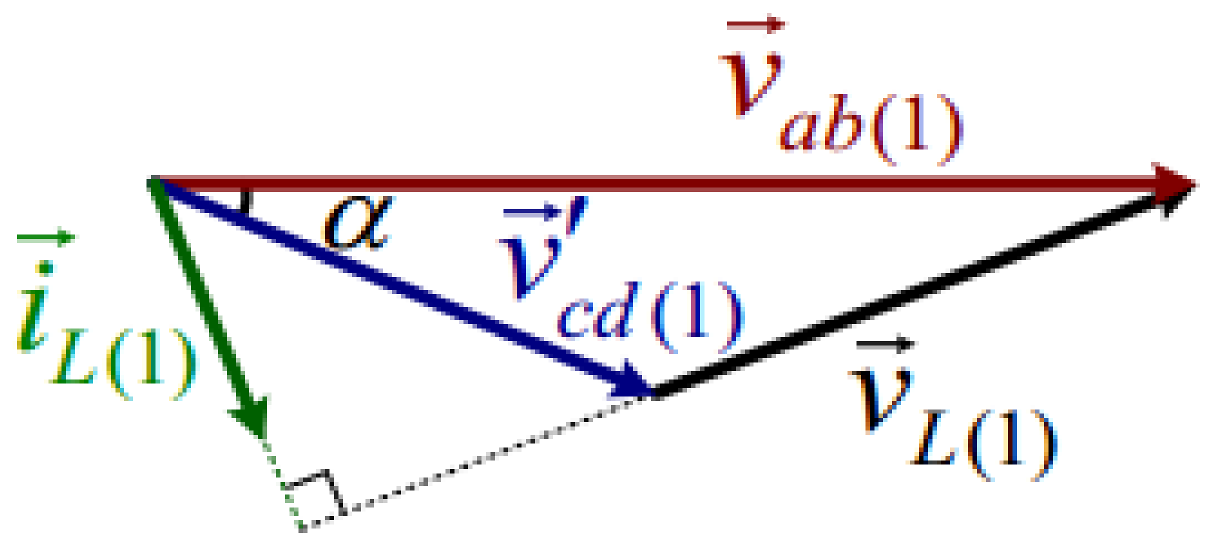
Conditions to achieve ZVS–on





Achieve ZVS-on



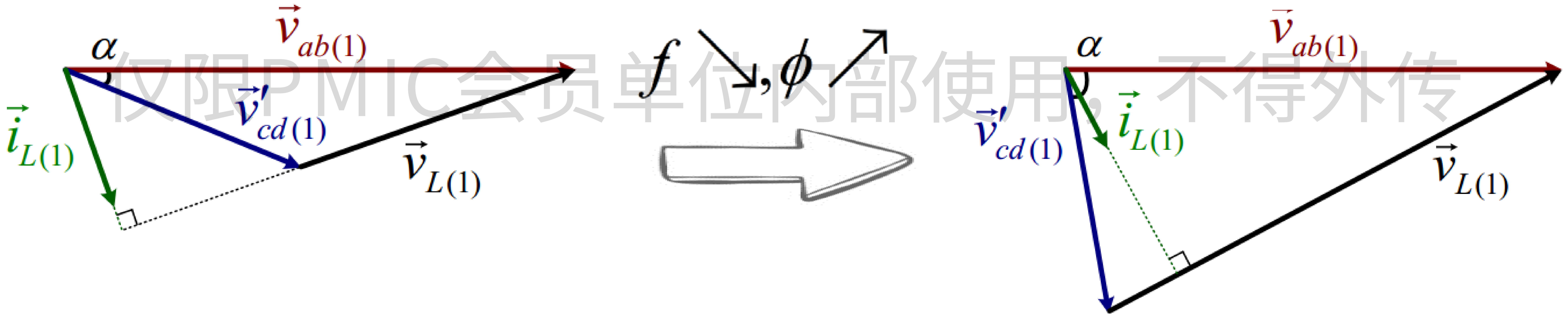


The secondary side lose ZVS-on

Methods to expand ZVS range

- **Frequency regulation**

$$P_o = \frac{NV_1V_2\phi(1-|\phi|)}{2fL} \qquad \alpha = \phi\pi$$



Loss of ZVS-on **Realize ZVS-on**

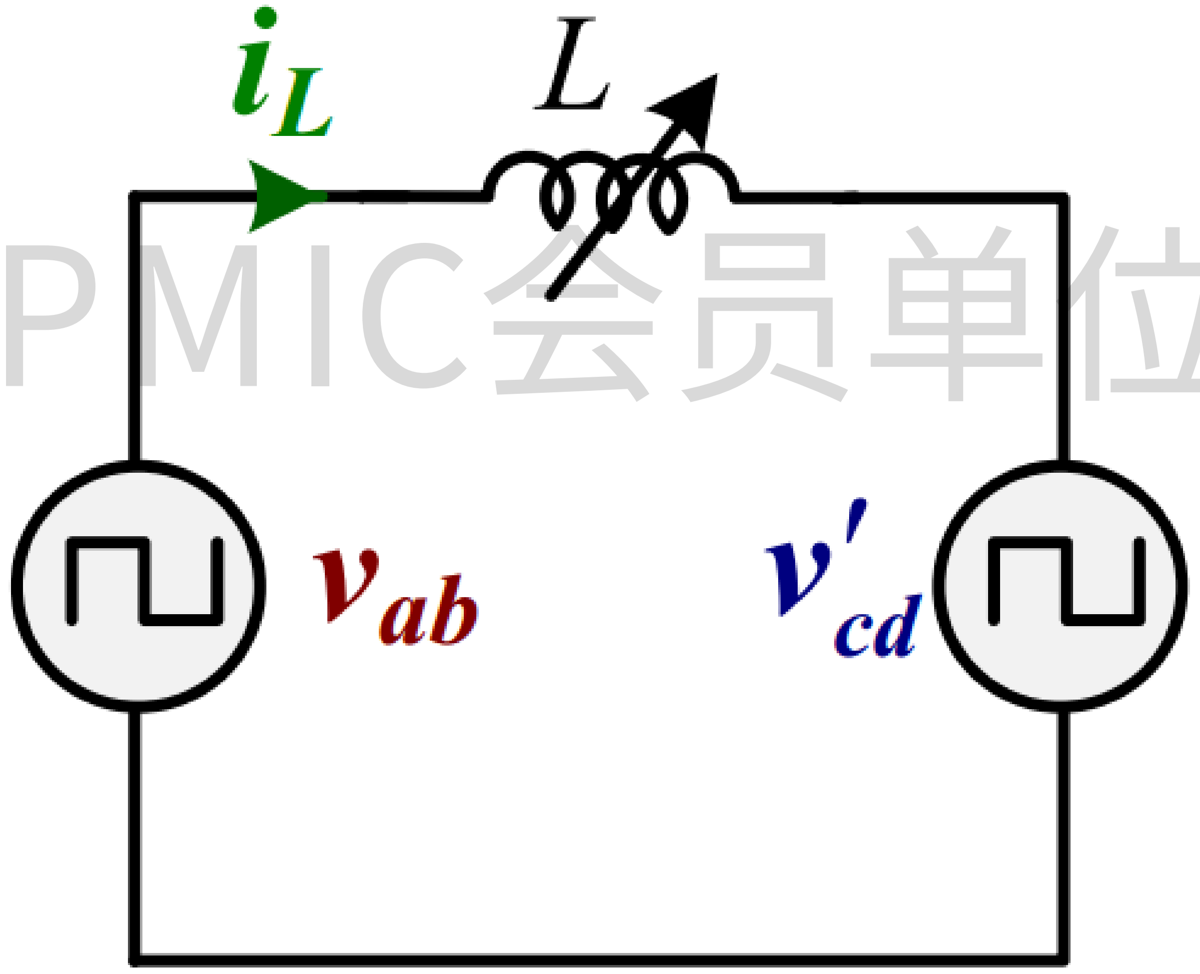
[1] J. Hiltunen, V. Väisänen, R. Juntunen and P. Silventoinen, "Variable-Frequency Phase Shift Modulation of a Dual Active Bridge Converter," in IEEE Transactions on Power Electronics, vol. 30, no. 12, pp. 7138-7148, Dec. 2015.

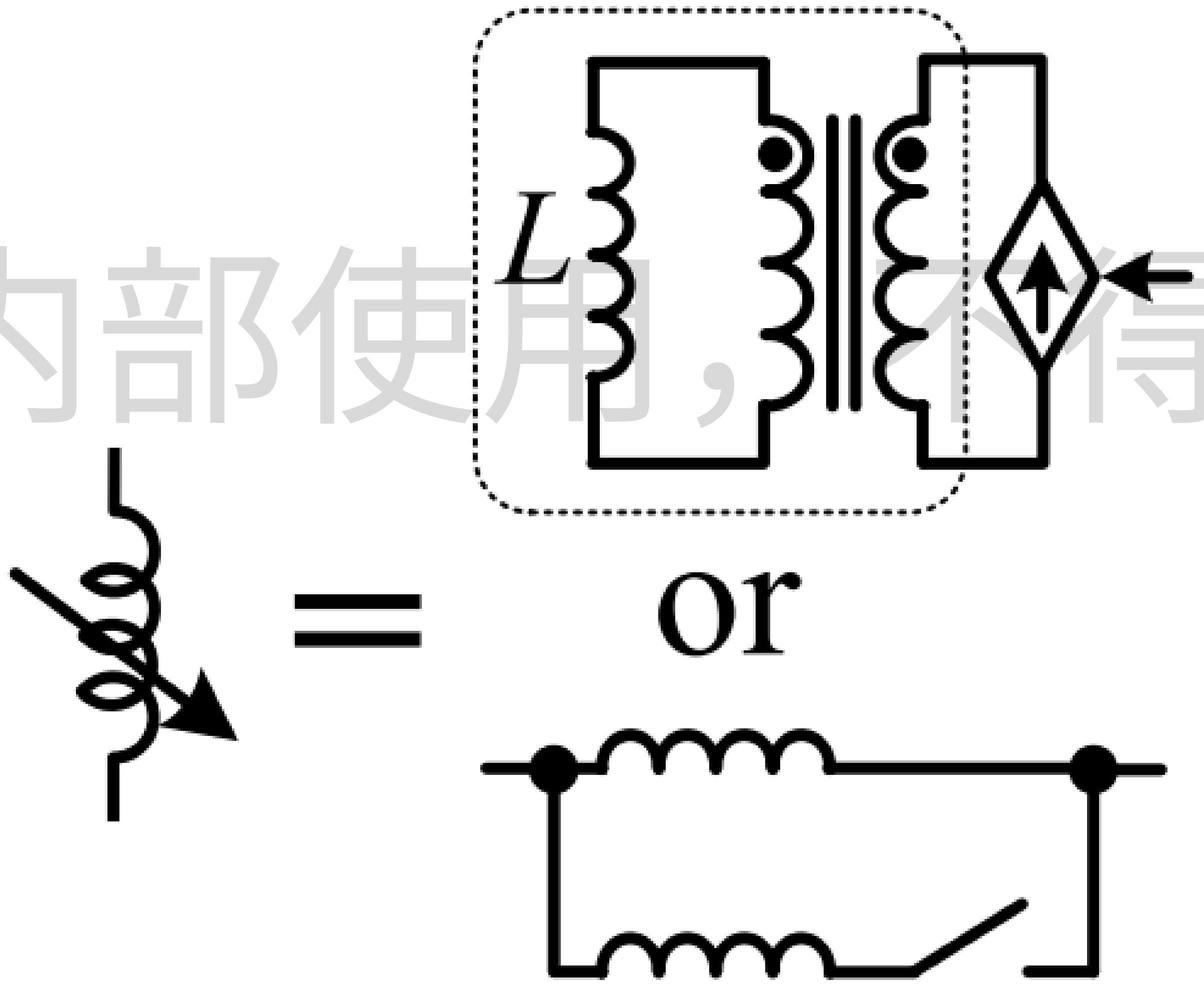
Methods to expand ZVS range

- **Hardware methods--- Adjustable inductor**

$$P_o = \frac{N V_1 V_2 \phi (1 - |\phi|)}{2 f L}$$

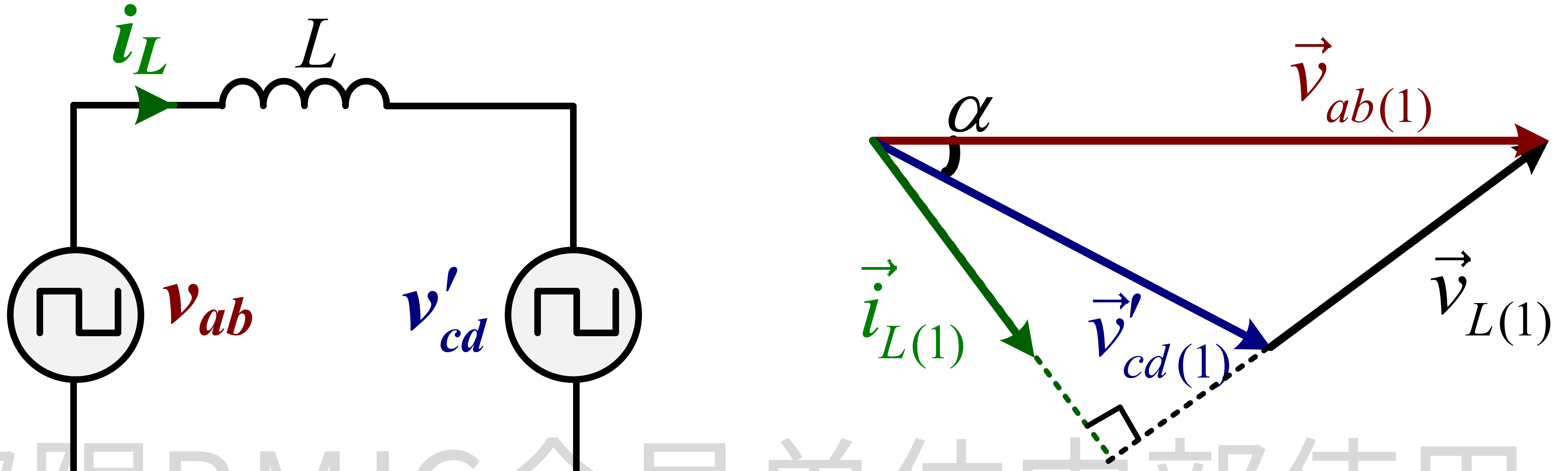
$$P_o \propto 1/L$$



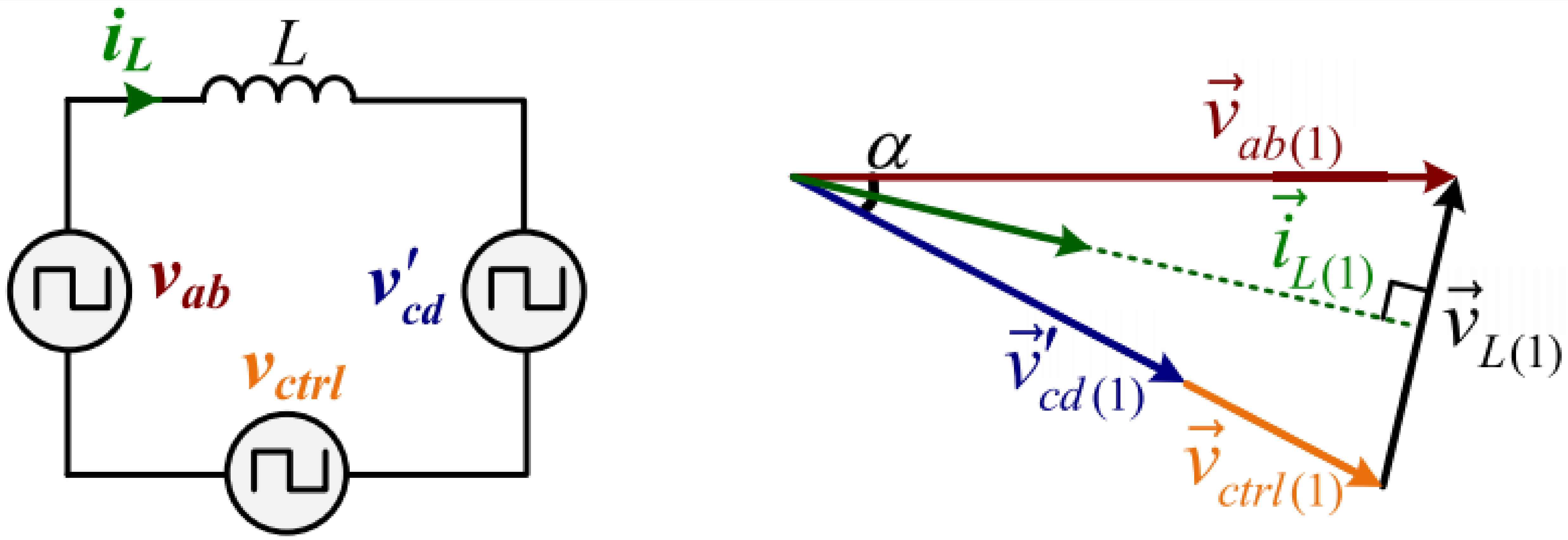


[1] H. Fan and H. Li, “High-frequency transformer isolated bidirectional dc-dc converter modules with high efficiency over wide load range for 20 kva solid-state transformer,” IEEE Transactions on Power Electronics, 2011.
[2] G. Guidi et al, “Improvement of light load efficiency of dual active bridge dc-dc converter by using dual leakage transformer and variable frequency,” in 2010 IEEE Energy Conversion Congress and Exposition, Sept 2010

- **Hardware methods: additional controlled voltage source**



Loss of ZVS-on

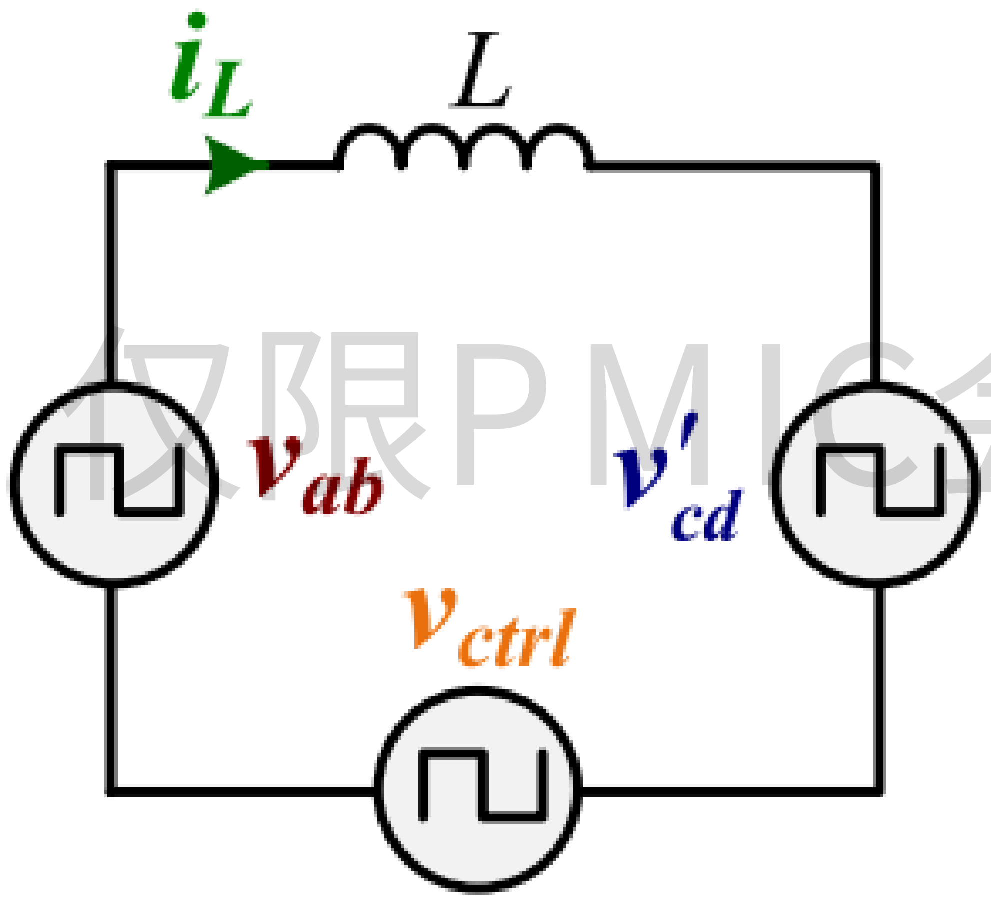


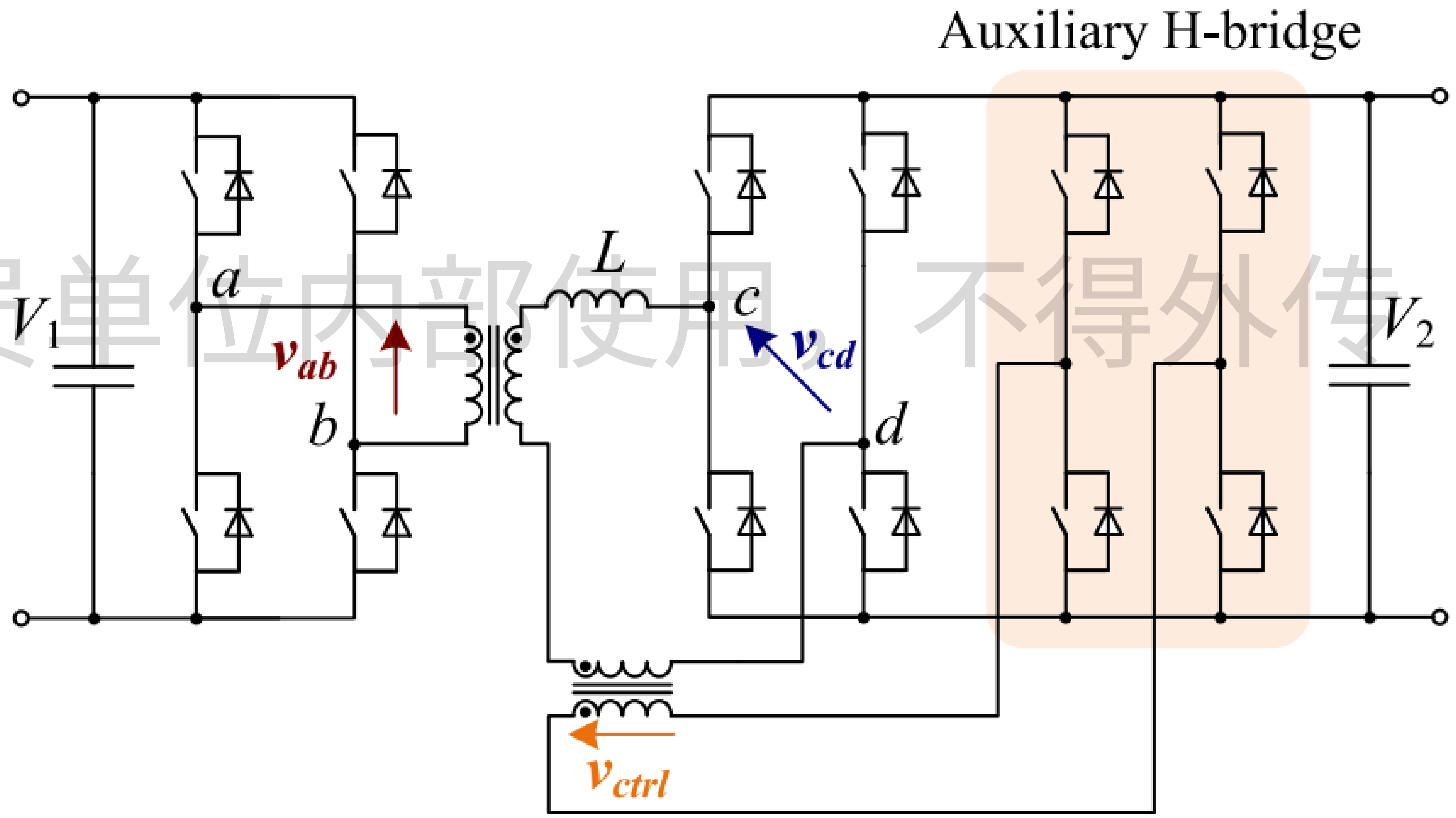
Realize ZVS-on

[1] A. K. Tripathi, et al. "A novel zvs range enhancement technique of a high-voltage dual active bridge converter using series injection," IEEE Transactions on Power Electronics, vol. 32, no. 6, pp. 4231–4245, June 2017.

Methods to expand ZVS range

■ **Hardware methods---using additional controlled voltage source**

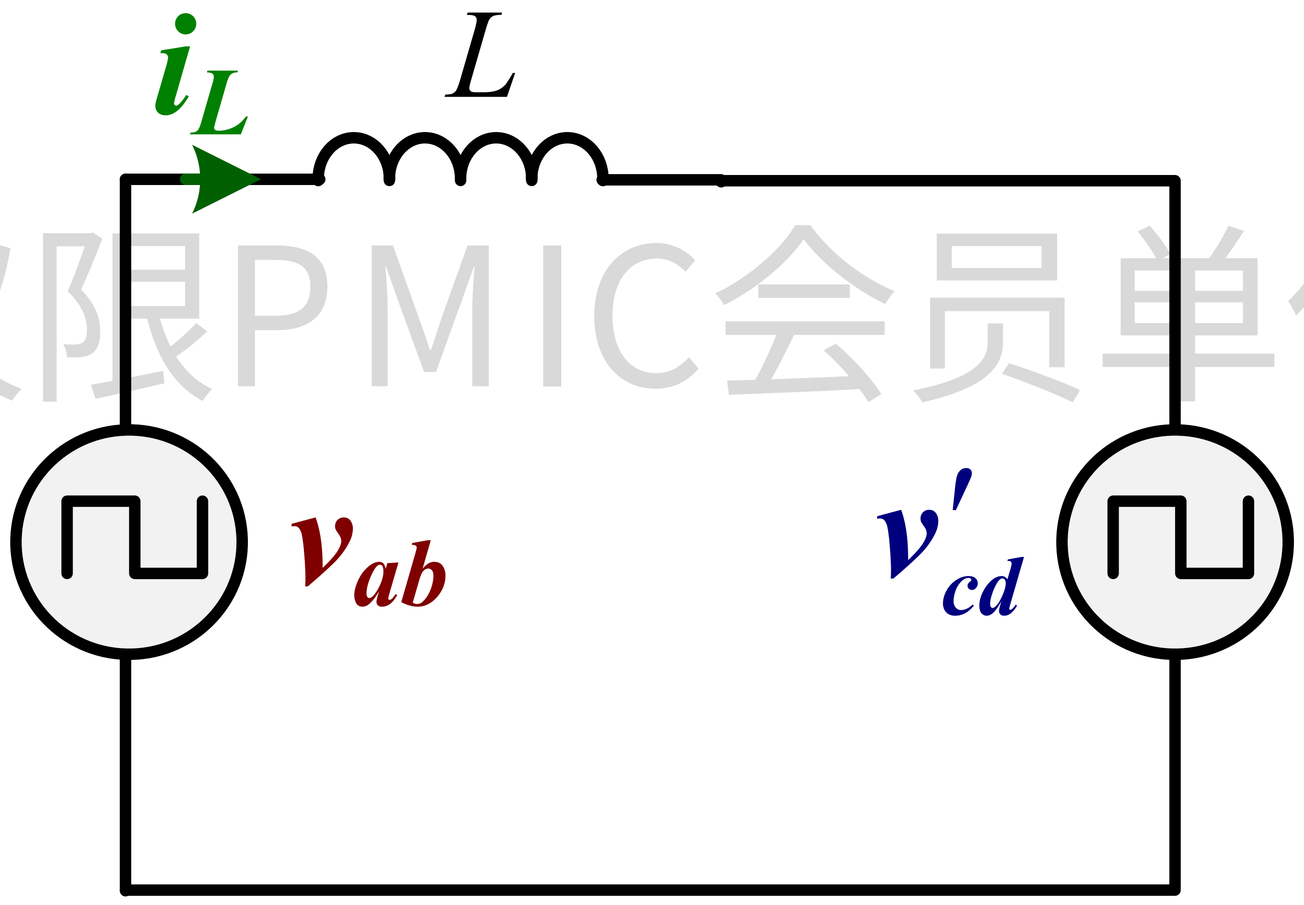


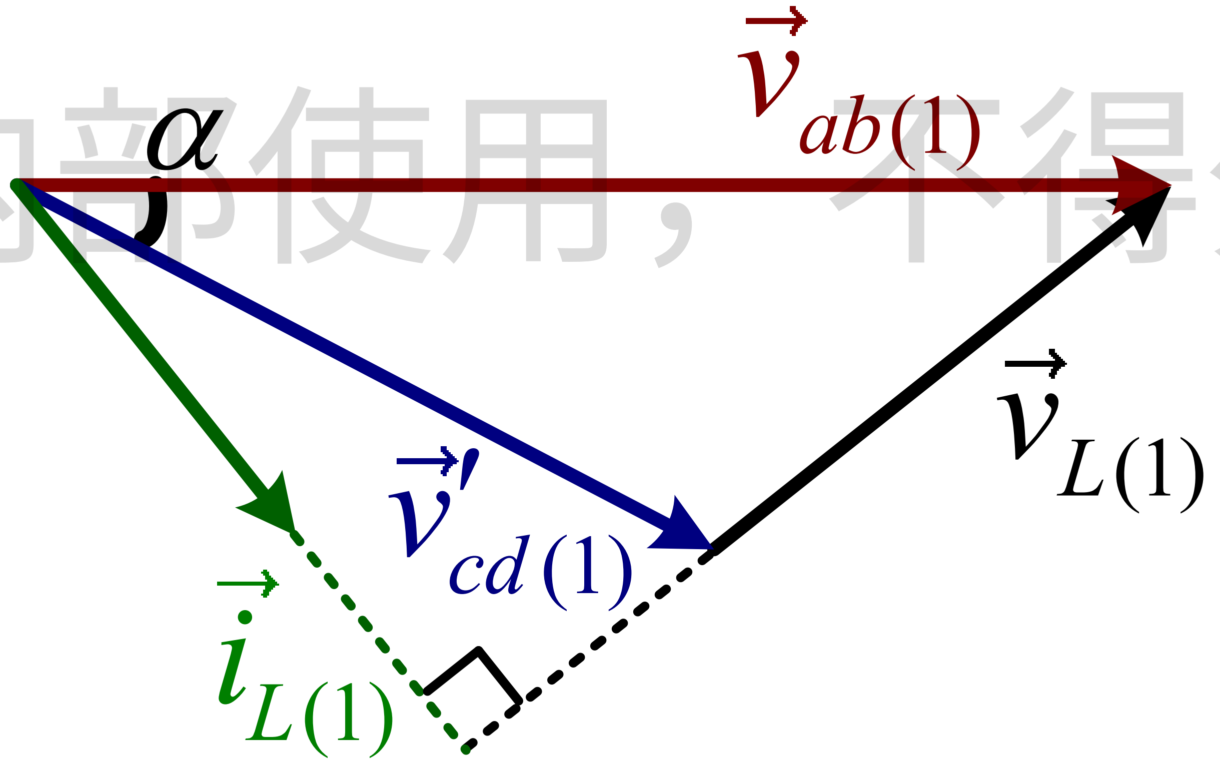


[1] A. K. Tripathi, et al. "A novel zvs range enhancement technique of a high-voltage dual active bridge converter using series injection," IEEE Transactions on Power Electronics, vol. 32, no. 6, pp. 4231–4245, June 2017.

Methods to expand ZVS range

- **Hardware methods: paralleling a switch controlled inductor**

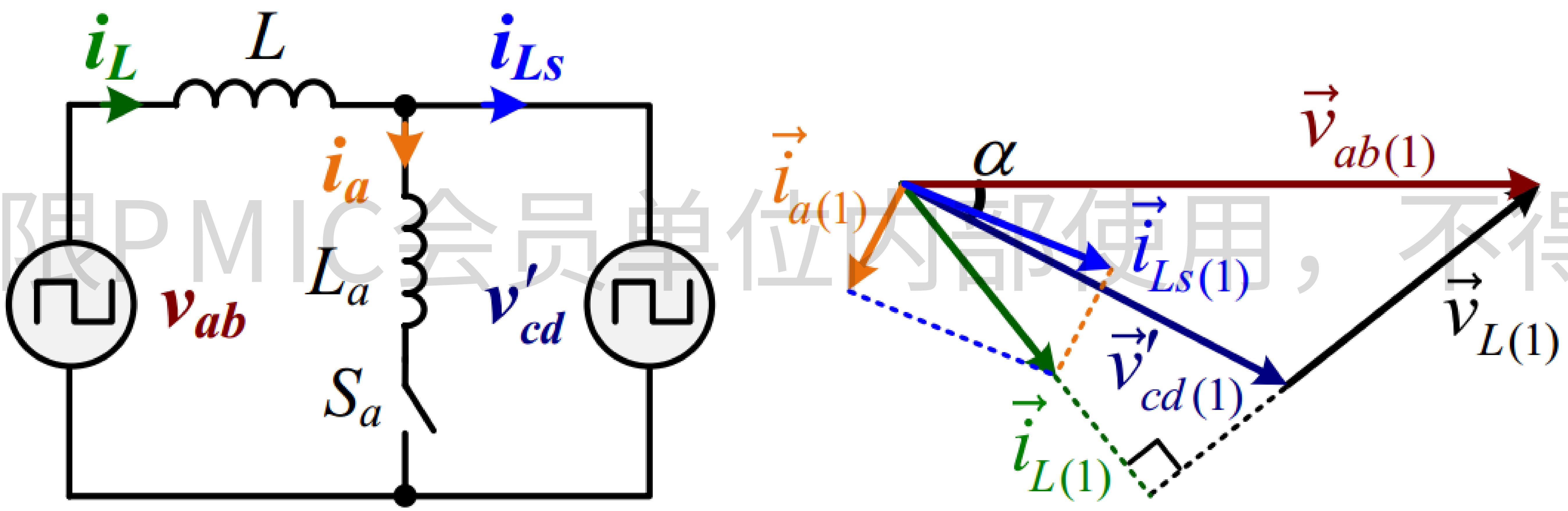




Secondary side lose ZVS,

i_L lags v_{cd}

Hardware methods: paralleling a switch controlled inductor



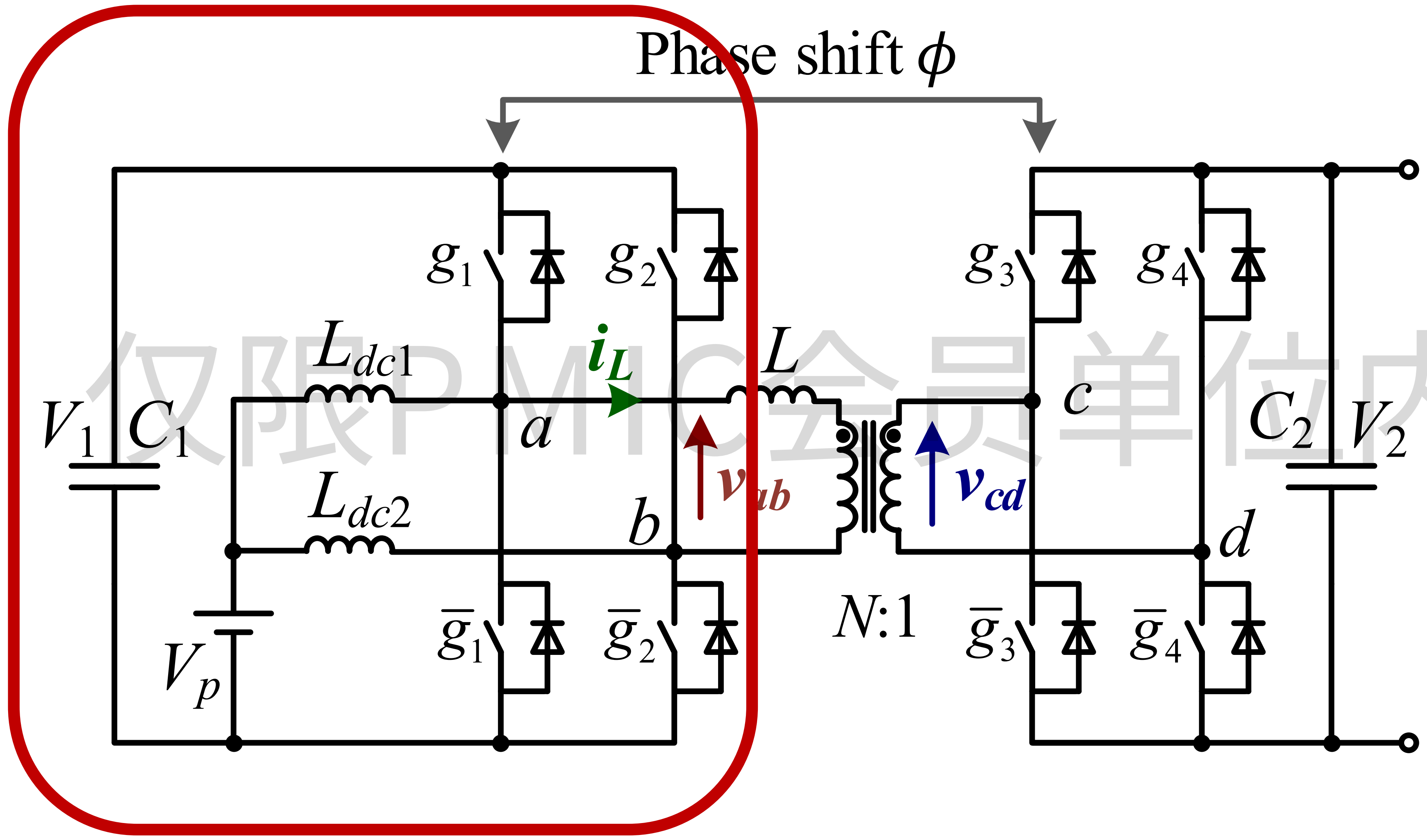
- All the power devices can achieve ZVS

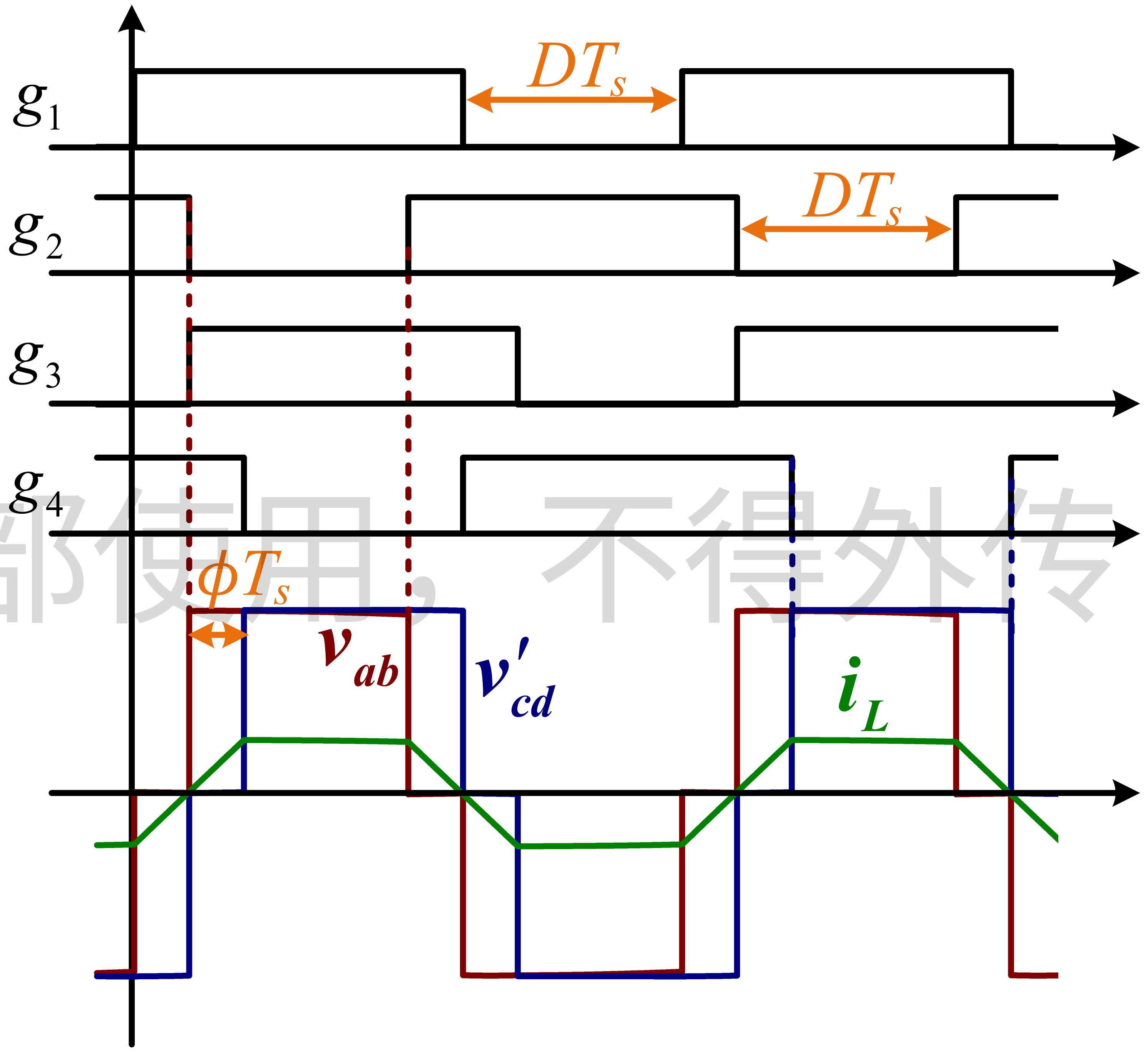
[1] M. Yaqoob, K. H. Loo, and Y. M. Lai, “Extension of soft-switching region of dual-active-bridge converter by a tunable resonant tank,” IEEE Transactions on Power Electronics, vol. 32, no. 12, pp. 9093–9104, Dec 2017.

Methods to expand ZVS range

- **Hardware methods--current fed DAB (CF-DAB) converter.**

Boost Converter





[1] Y. Shi, R. Li, Y. Xue, and H. Li, "Optimized operation of current-fed dual active bridge dc-dc converter for pv applications," IEEE Transactions on Industrial Electronics, vol. 62, no. 11, pp. 6986–6995, Nov 2015.
[2] D. Sha, X. Wang, and D. Chen, "High-efficiency current-fed dual active bridge dc-dc converter with zvs achievement throughout full range of load using optimized switching patterns," IEEE Transactions on Power Electronics, Feb 2018.

Conclusion

- **Reduced order model is recommended for closed-loop controller;**
- **Unmatched voltage gain and light load are the primary reasons of the large circulating current and loss of ZVS;**
- **The reactive current can be suppressed by hardware modification or duty cycle modulation;**
- **The ZVS-on range can be expanded using frequency modulation, or hardware methods.**

For more information…

[1] S. Shao, H. Chen, X. Wu, J. Zhang and K. Sheng, "Circulating Current and ZVS-on of a Dual Active Bridge DC-DC Converter: A Review," in *IEEE Access*, vol. 7, pp. 50561-50572, 2019.

[2] S. Shao, M. Jiang, W. Ye, Y. Li, J. Zhang, and K. Sheng, “Optimal phase shift control to minimize reactive power for a dual active bridge dc-dc converter,” IEEE Transactions on Power Electronics, pp. 1–1, 2019.

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- Modeling of bidirectional DC/DC converters
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- Coordination control of paralleled DC/DC converters
- Modulation methods of bidirectional DC/DC converters
- Advanced hardware design of bidirectional DC/DC converters
- Design and analysis of medium frequency transformer in high power bidirectional DC-DC converters
- Modeling and control for DC-DC solid state transformers
- Stabilization of constant power loads
- Reliability enhanced bidirectional DC/DC converters (life-time enhancement, fault tolerant, etc.)
- Enhanced performance of bidirectional DC/DC converters (fast dynamic response and robustness)

Thank you!

Shuai Shao
shaos@zju.edu.cn