模块化的三相多电平功率因数校正技术

Modularized Three-phase Multilevel Power Factor Correction Technology

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Server Power Architecture Develops towards ±400V(800V)

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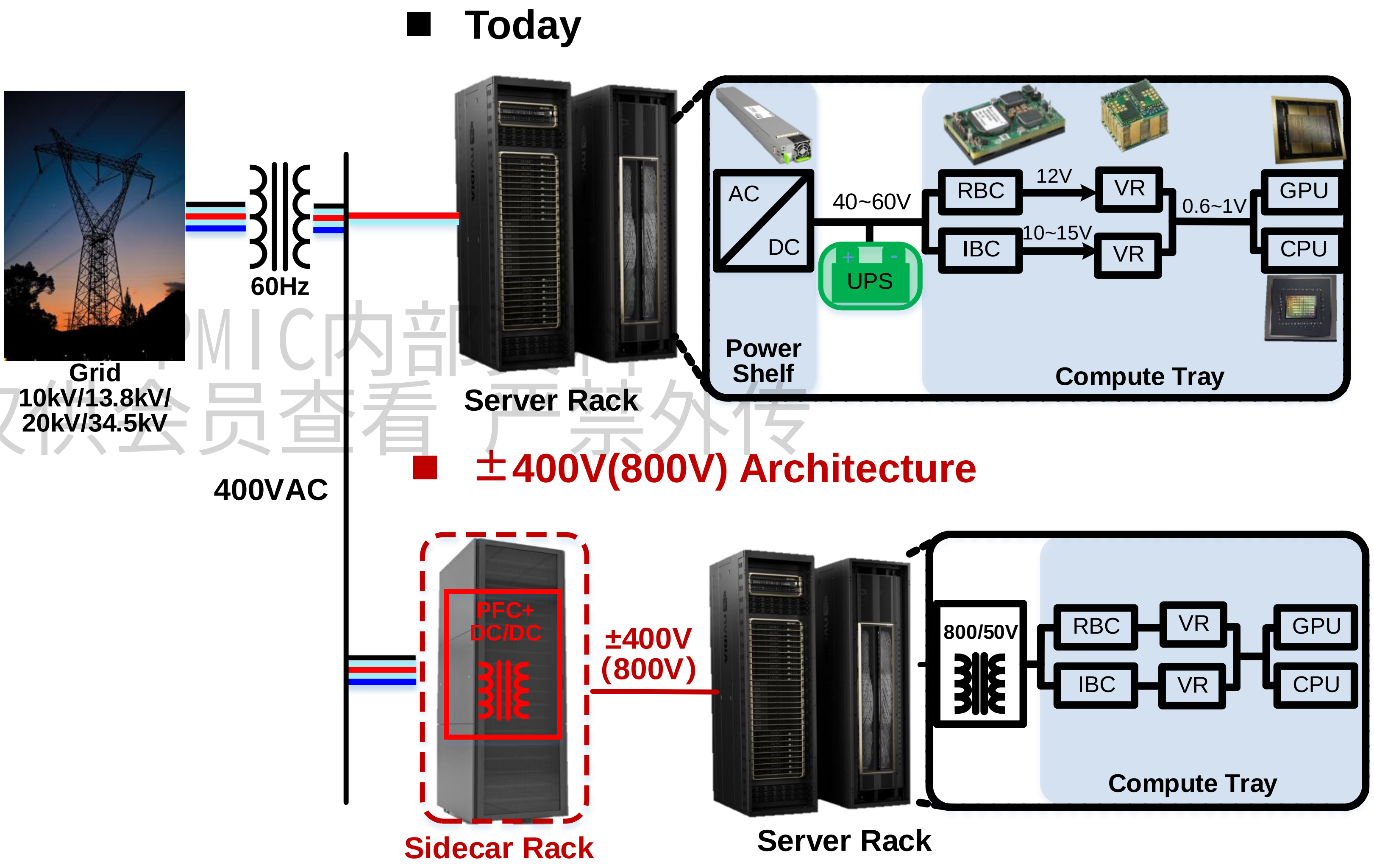
12V PSU

- **2004**
- **2012** — Gen1: 12V POL
- **2013** — Gen2: 48V Rack&UPS
- **2015** — Multi48VtoPoL solutions
- **2017** — Open Rack V2.0 48V through OCP
- **2024.10** — OCP ±400Vdc(800V) Power supply

(year)



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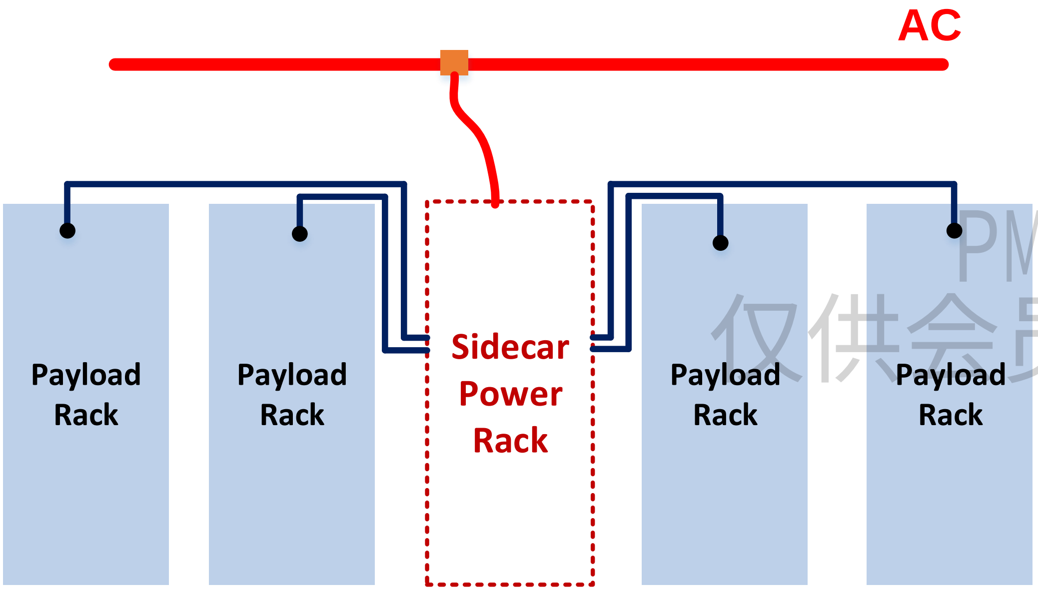
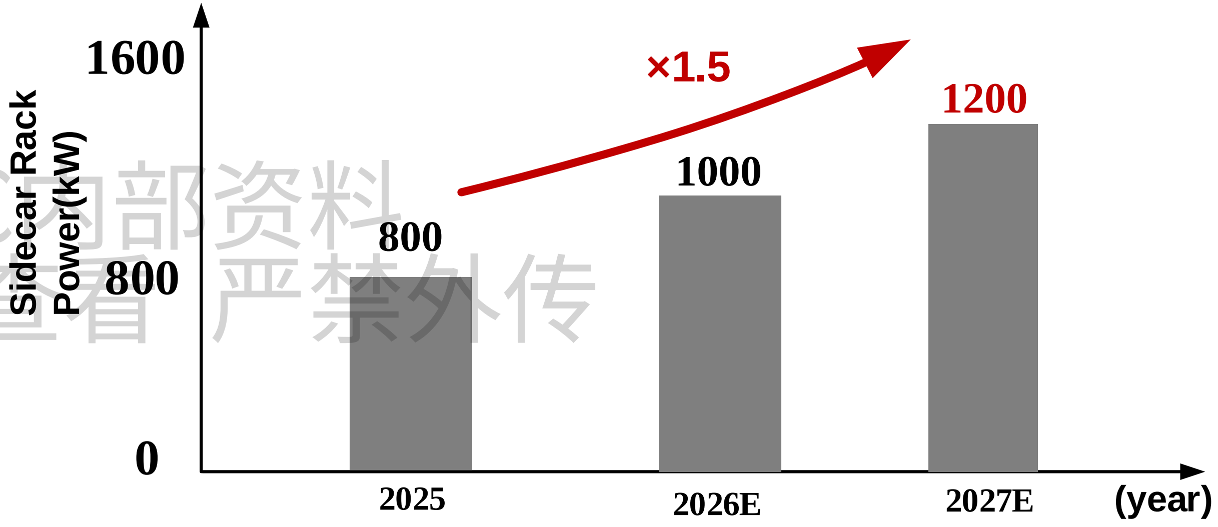
- https://www.nvidia.cn/on-demand/session/gtc25-s73978/

Trend of Sidecar Rack Power





➢The power of server rack has been rapidly increasing

• OCP Global Summit 2024 - Google

High Efficiency High Density for Server PSU

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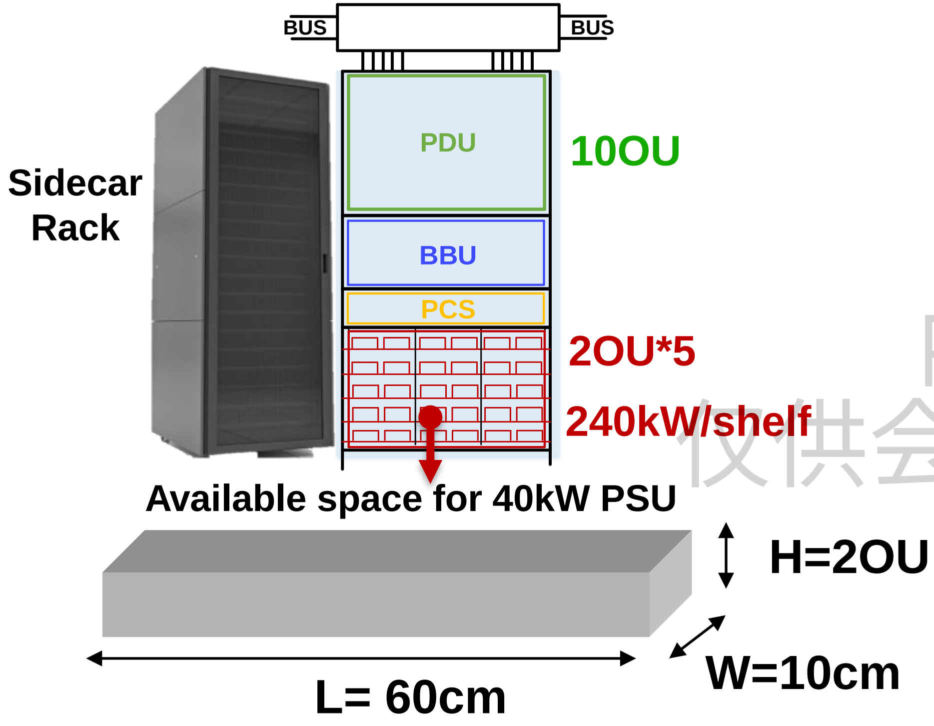
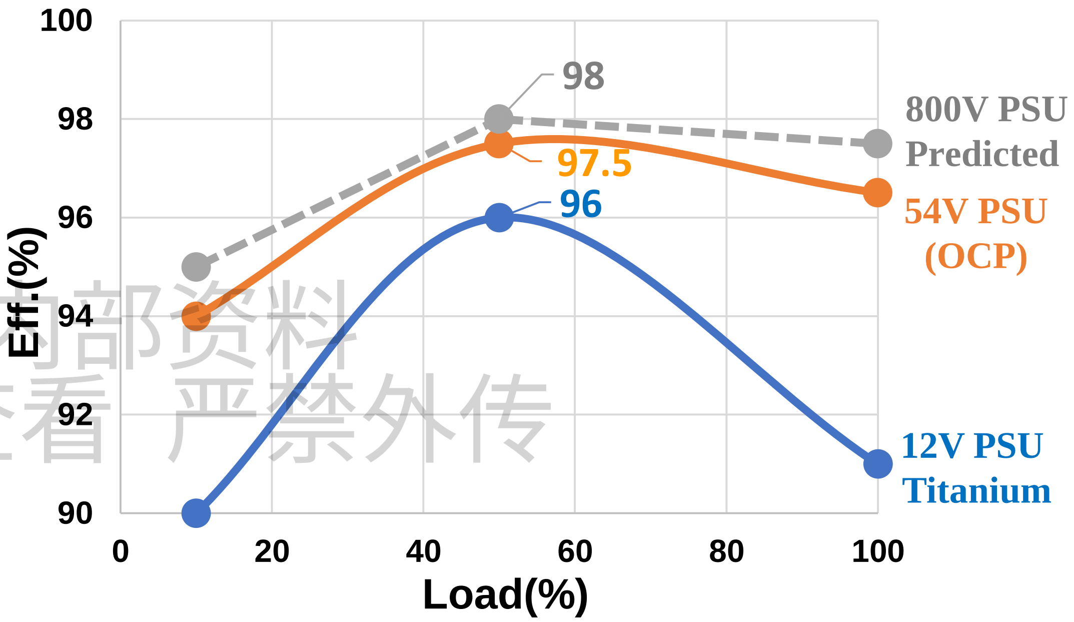
➢ High Power Density



Power Density: >150W/in³

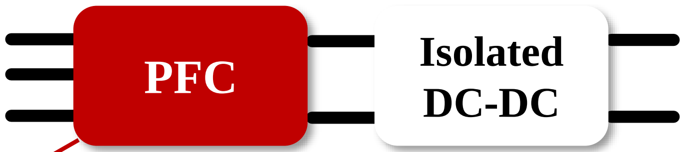
➢ High Efficiency

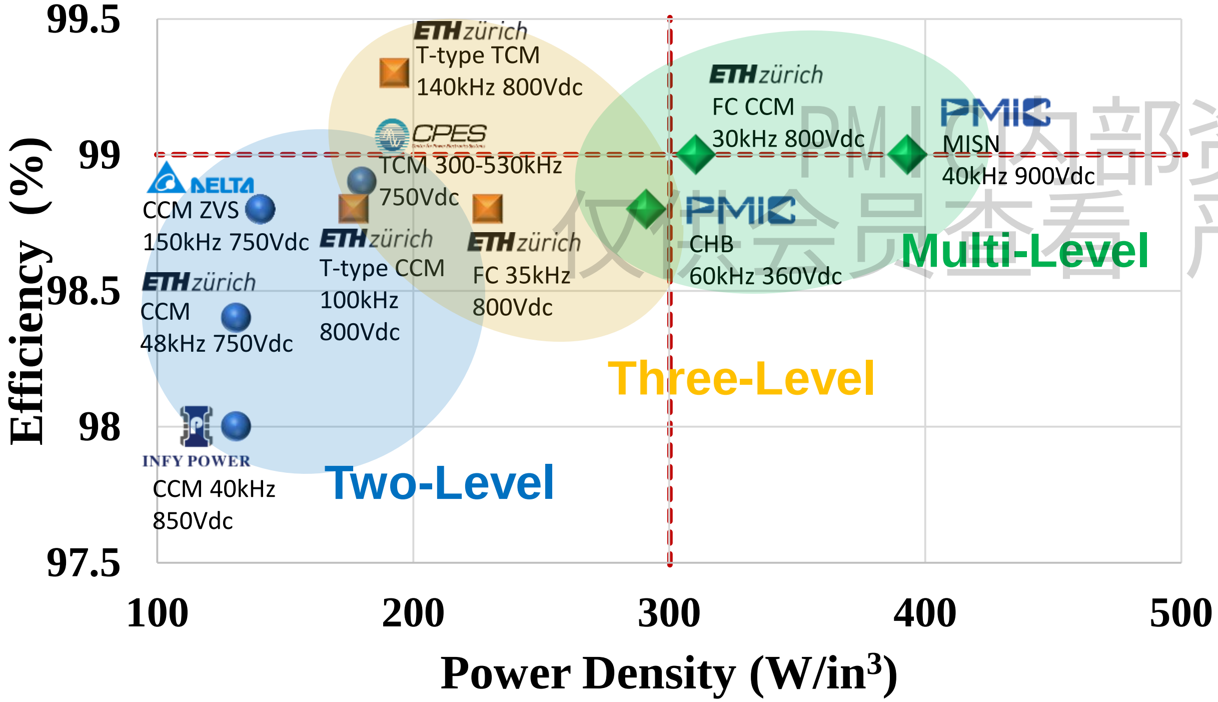


Efficiency: >98%

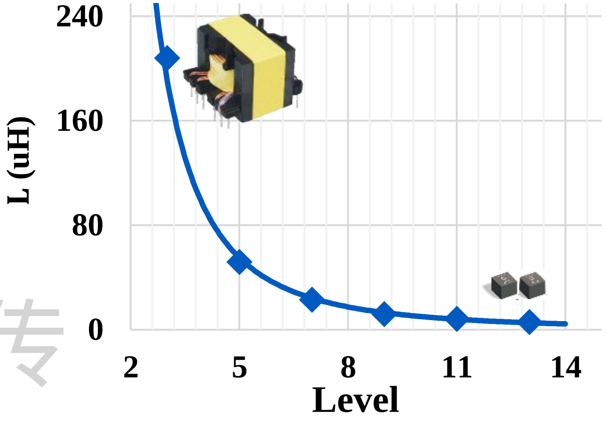
State-of-the-art of High Power 3-phase PFC Converter

Power density: $> 300W/in^3$
Efficiency: $> 99\%$

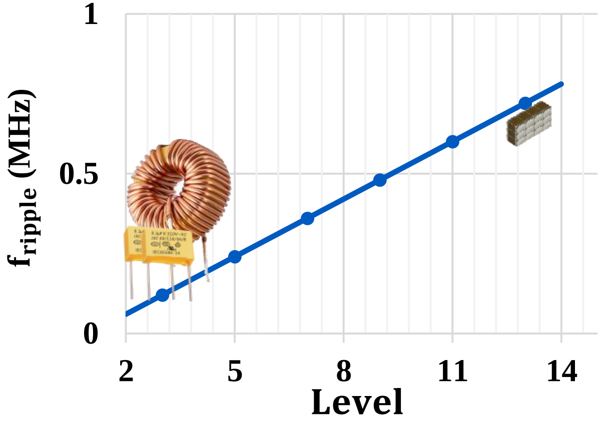




- **The Influence of Multilevel Converter**
  - Lower Volt-second



  - Higher Frequency



Comparison the Different Multilevel Topologies

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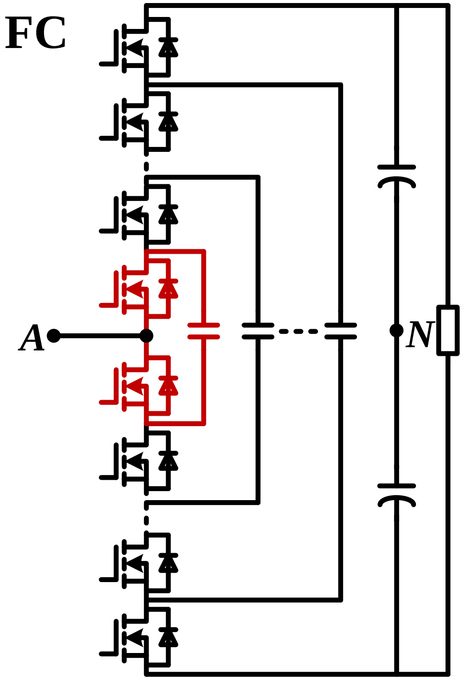
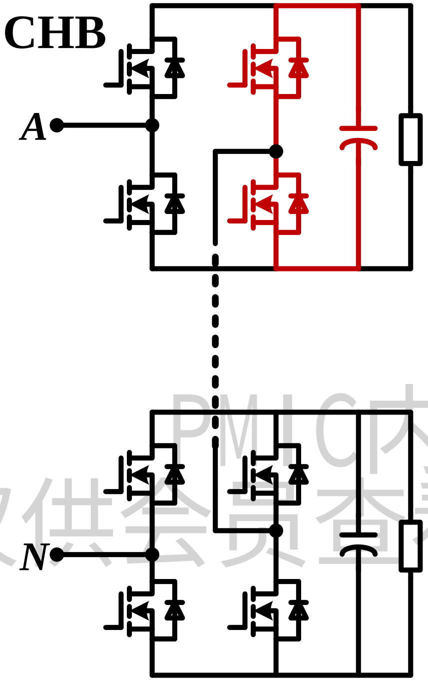
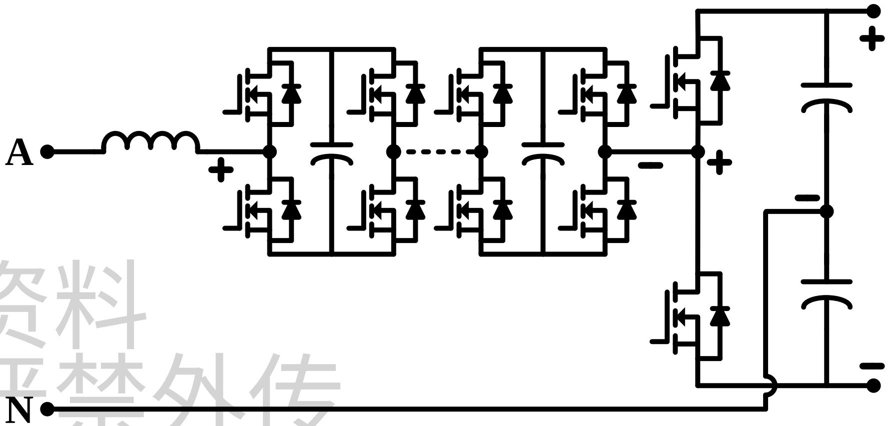
➢ FC



➢ CHB



➢ MISN (Modular Inductive Switching Network)



FC

- ✓ Single DC Bus
- ✗ Bad Modularity
  - Short fault protect
  - Redundancy

CHB

- ✓ Good Modularity
- ✗ Multiple DC Bus
  - Complicated structure
  - Bulky Capacitor

MISN

- ✓ Single DC Bus
- ✓ Good Modularity
- ✗ Line-frequency Bridge

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- Zhao, W., T. Huang and X. Wu, Three Phase PFC Converter With Multilevel Inductive Switching Network. TPEL, 2023.
- Zhao, W., T. Huang and X. Wu, Control Strategies and Design Guideline for Single Phase MISN PFC Converter. TIE, 2025.

Catalogue

Operating Principle of Diode-Based MISN Converter (Unregulated)

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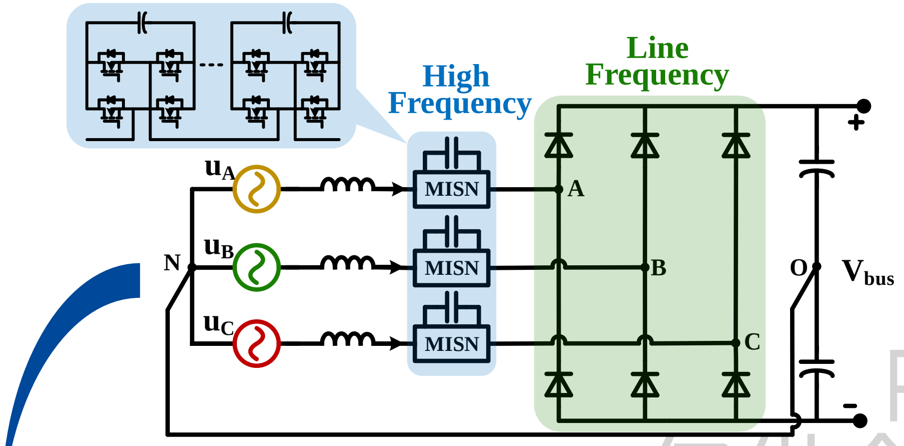
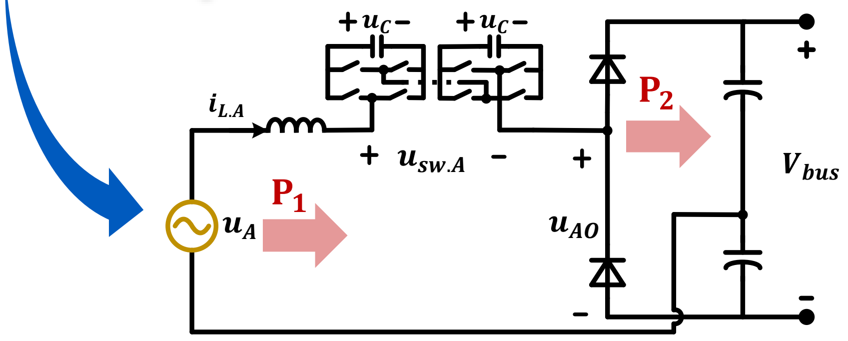
➢ **Diode-Based MISN-PFC Converter**

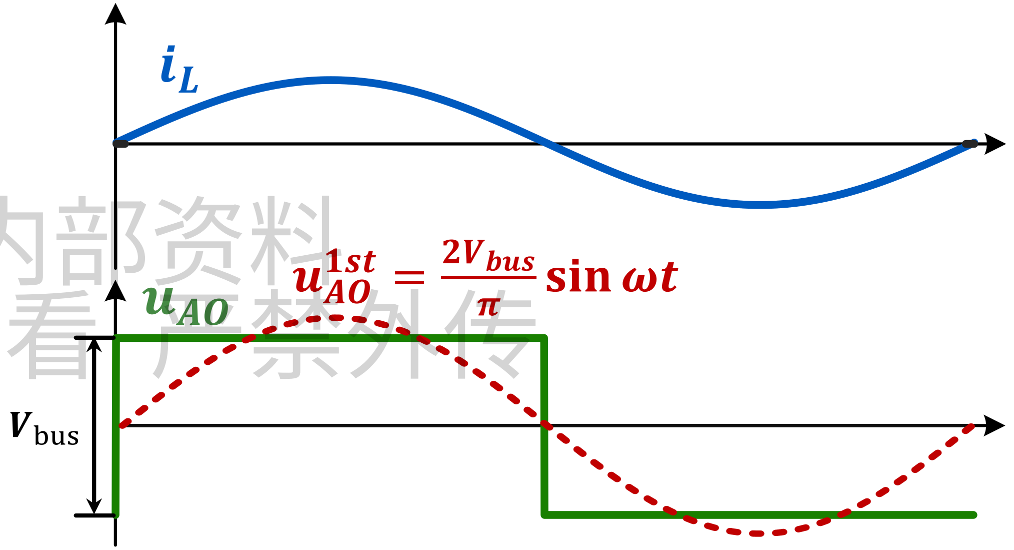


➢ **Equivalent Circuit of Phase-A**



$P_2 = P_1 \xrightarrow{u_{sw}^{1st} = 0} u_{AO}^{1st} = u_A$

- **Assuming:**
  1. $PF = 1, and\ i_L^{1st}\ is\ considerd;$
  2. $No\ loss;$

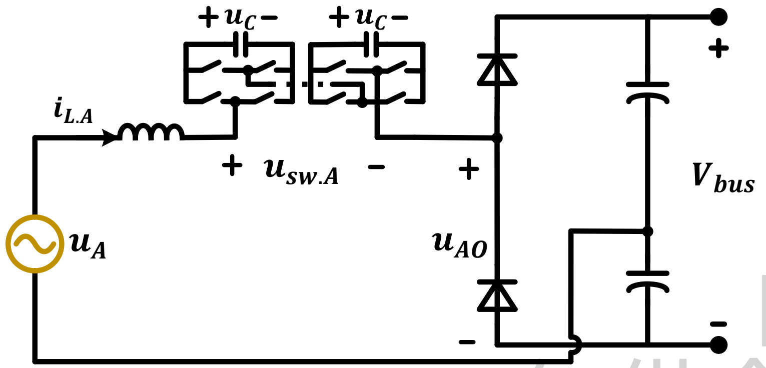


$$V_{bus} = \frac{\pi}{\sqrt{2}} U_A$$

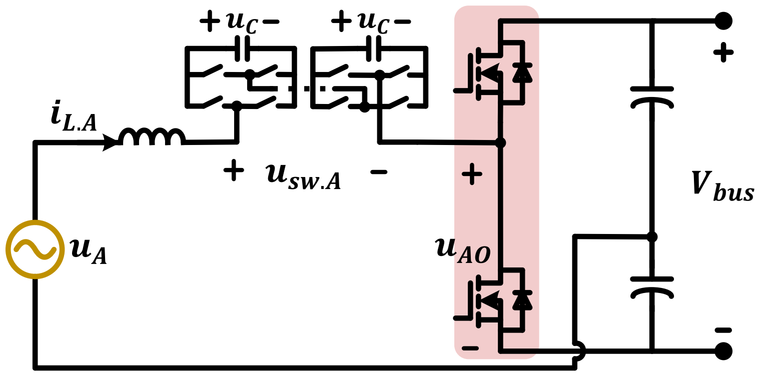
- MISN: Modular Inductive Switching Network

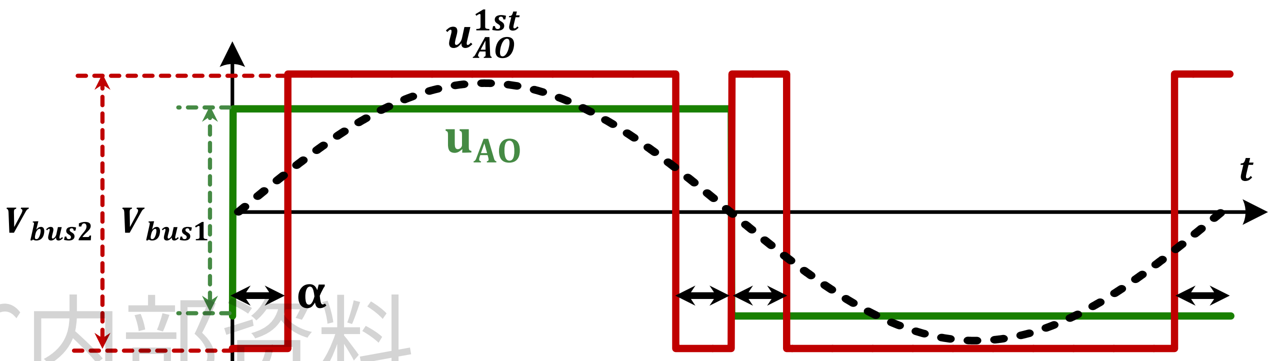
Regulated DC Bus Voltage for MISN Converter

- **Diode Based** $\left(V_o = \frac{\pi}{\sqrt{2}} U_A\right)$



- **Switch Based**

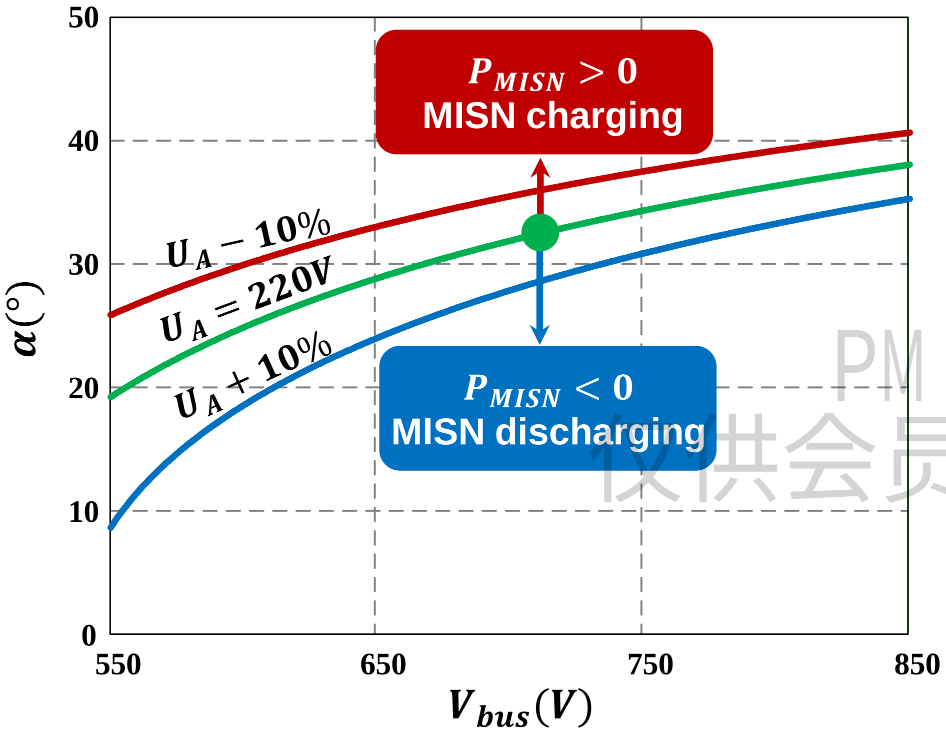




$$u_{AO}^{\alpha} = \frac{2V_{bus}}{\pi}(2\cos\alpha - 1)\sin\omega t + \cdots$$

$$\alpha = \arccos\left(\frac{\sqrt{2}\pi U_A}{4V_{bus}} + \frac{1}{2}\right)$$

The Principle for MISN Voltage Control



$$\alpha = arccos\left(\frac{\sqrt{2}\pi U_A}{4V_{bus}} + \frac{1}{2}\right)$$

$$P_{MISN} = \frac{1}{2\pi}\int_0^{2\pi} p_{MISN}\, d\omega t = \frac{\sqrt{2}I_L}{\pi}(\sqrt{2}\pi U_A - 2V_{bus})$$

- **In the curve**

  $P_{MISN} = 0$, Power balance

- **Above the curve**

  $P_{MISN} > 0$, Charging mode

- **Below the curve**

  $P_{MISN} < 0$, Discharging mode

Utilized for MISN voltage Control

Current Distortion due to the Limited Bandwidth of Current Loop

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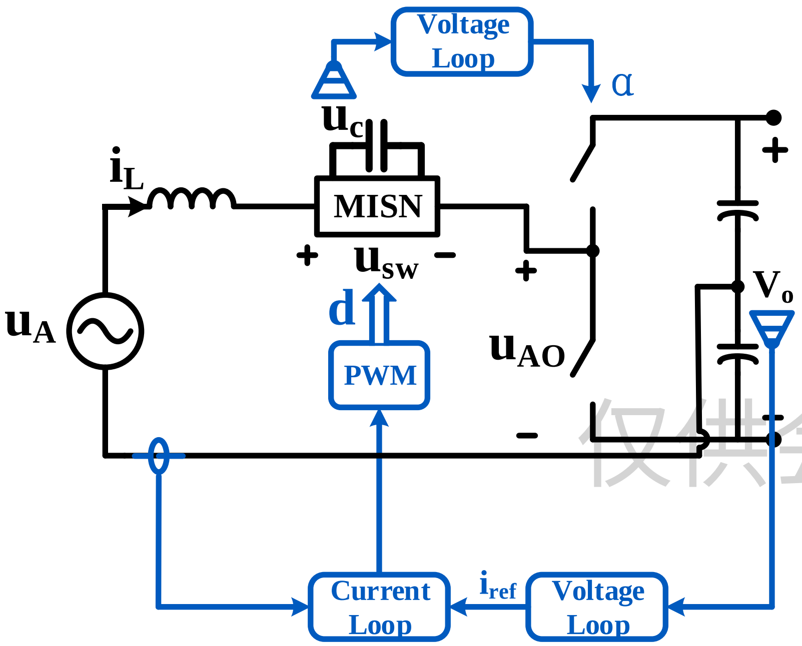
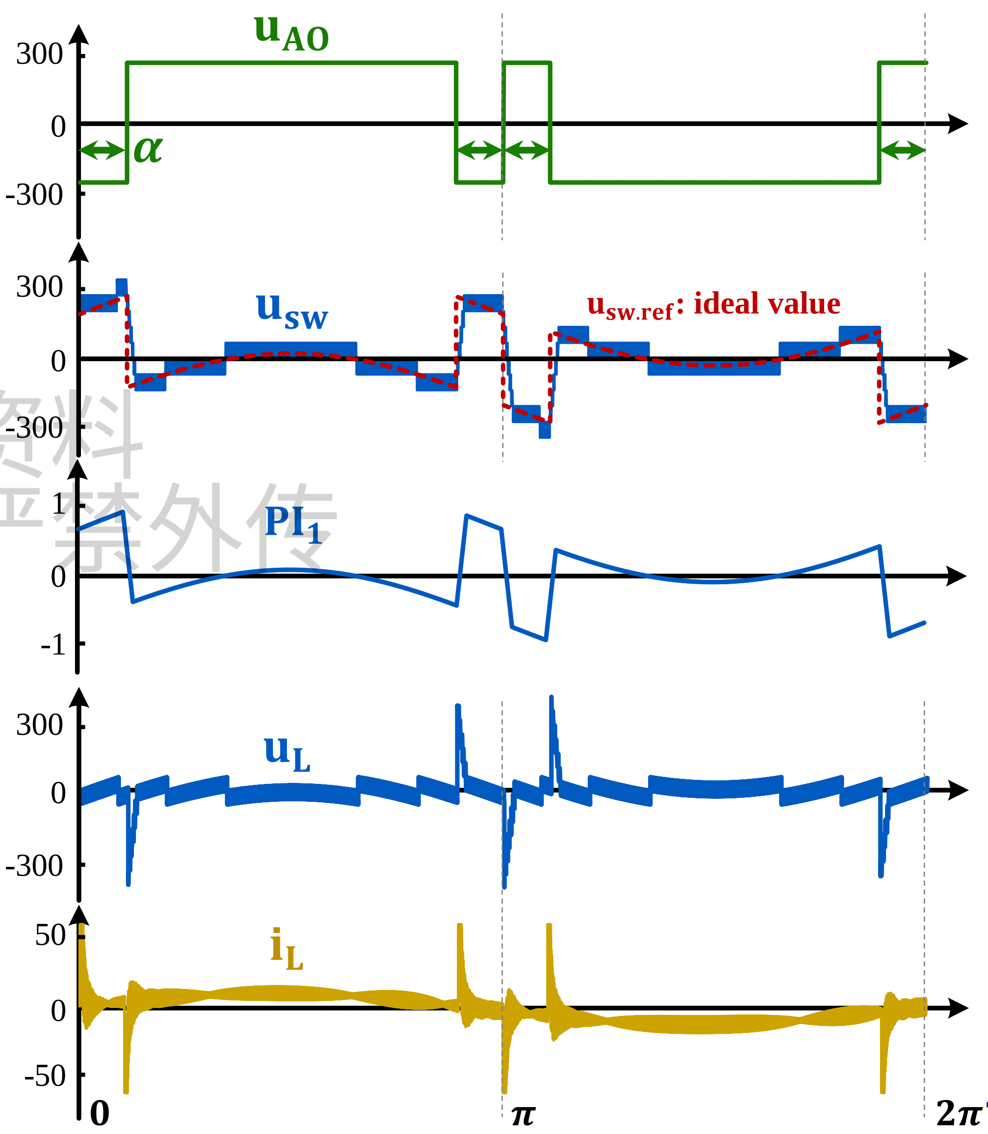
➢ **The Control Strategy of Phase-A**





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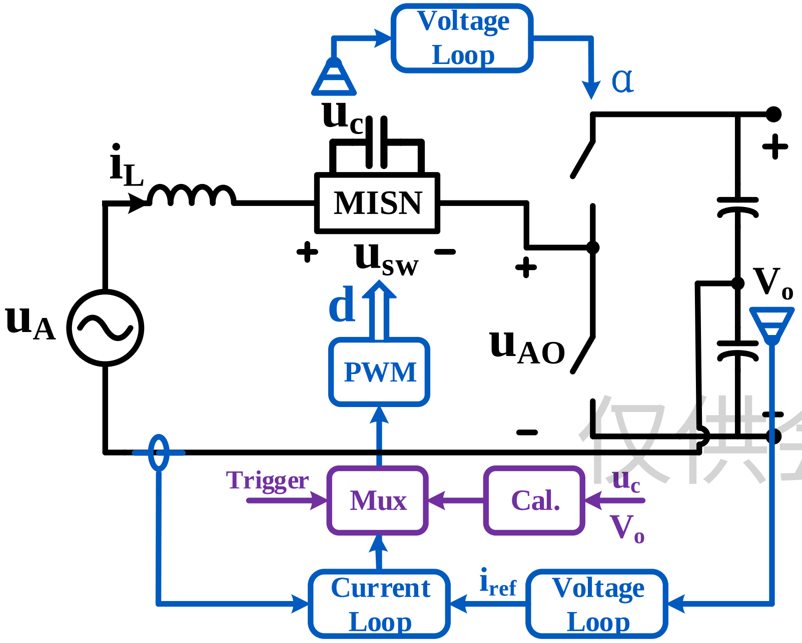
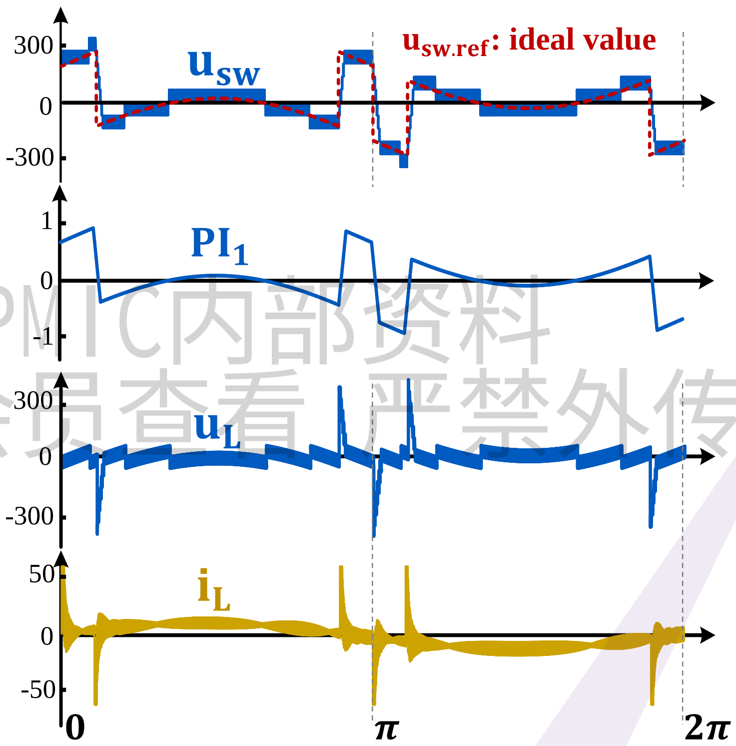
Improved Current Quality with Transient Compensation

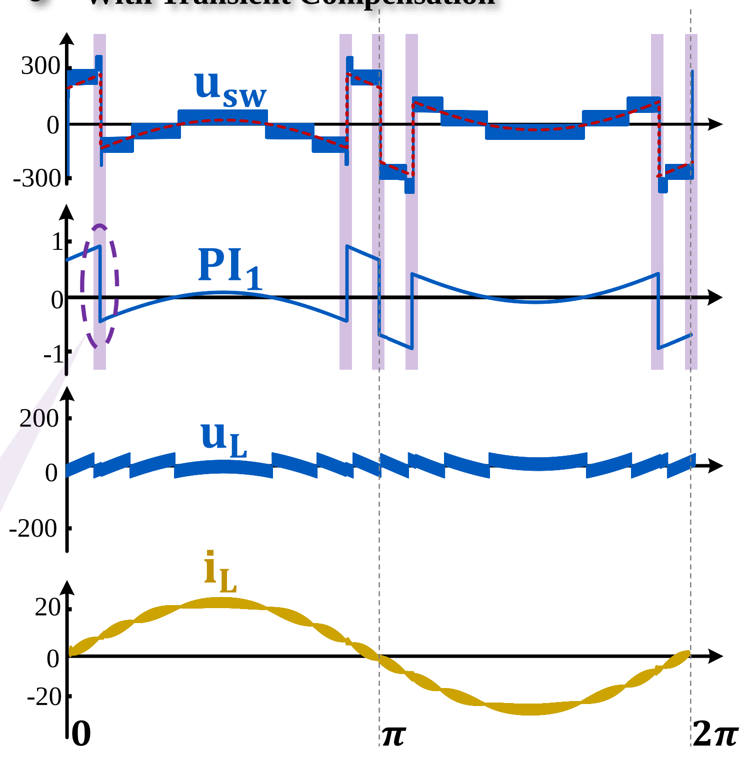
➢ **The Control Strategy of Phase-A**



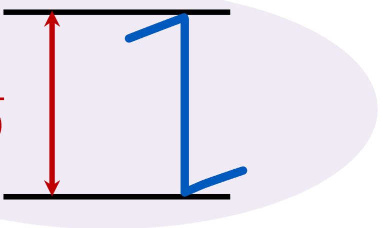
- **Without Transient Compensation**



- **With Transient Compensation**



$$\Delta PI(t) = \frac{v_o(t)}{2u_{c.total}(t)}$$



The Steady State Operation at 10kW

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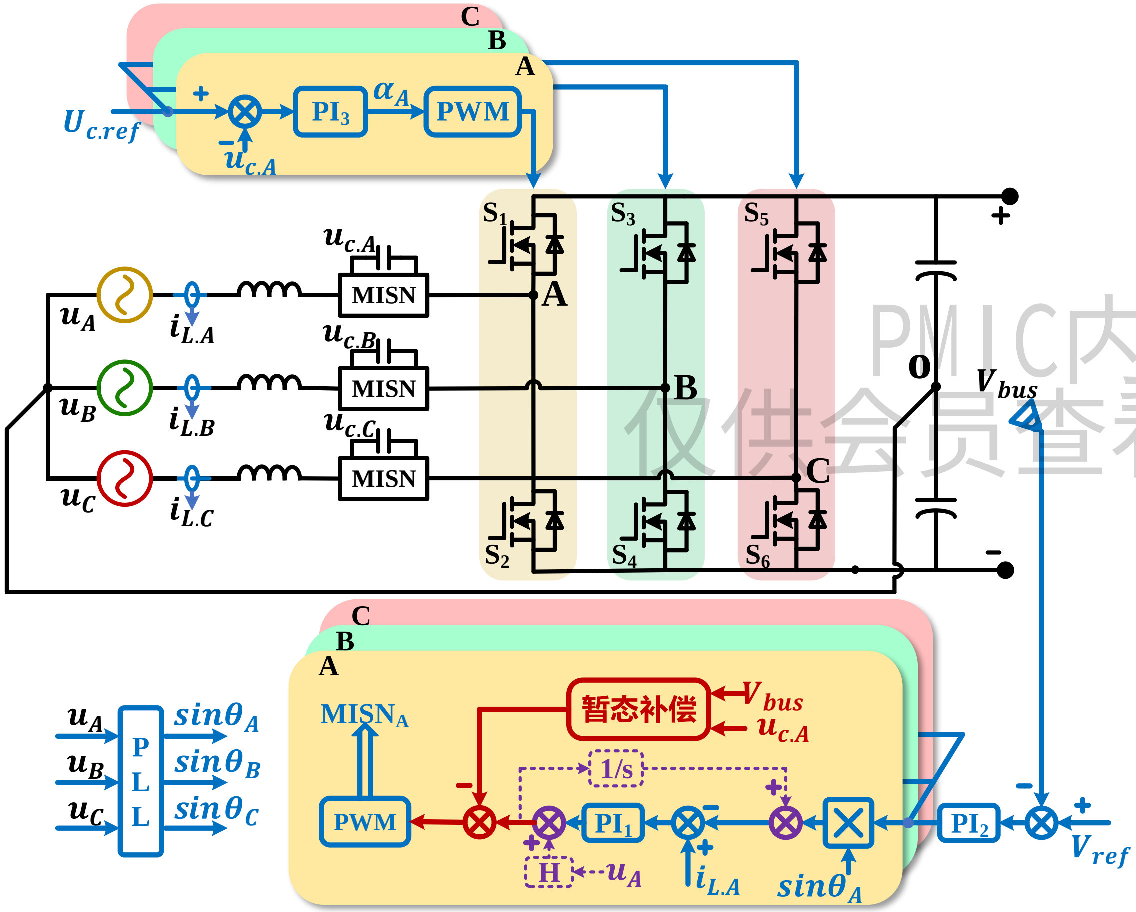
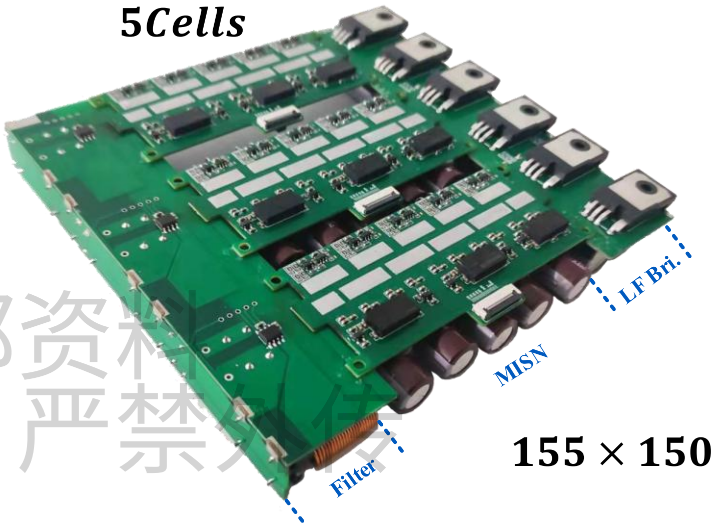
- Control Strategy of 3phase MISN-PFC converter



- 10kW Hardware Implementation



$155 \times 150 \times 22\ mm$

Power Density: $330W/in^3$

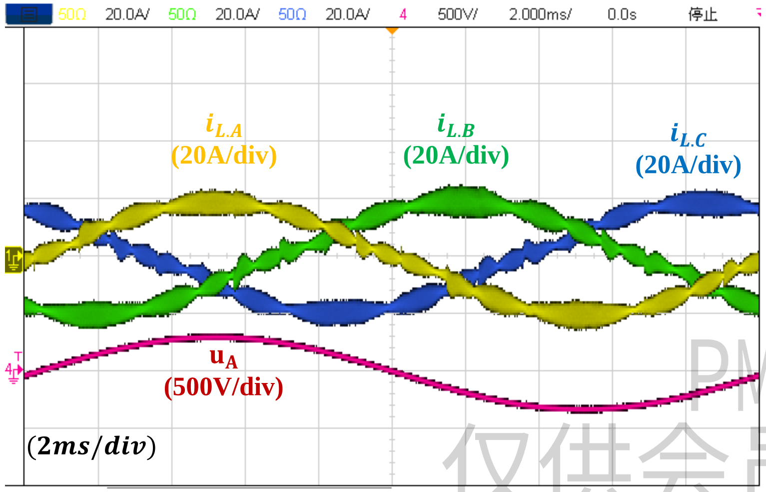
Input Phase Voltage: $220V_{ac} \pm 10\%$

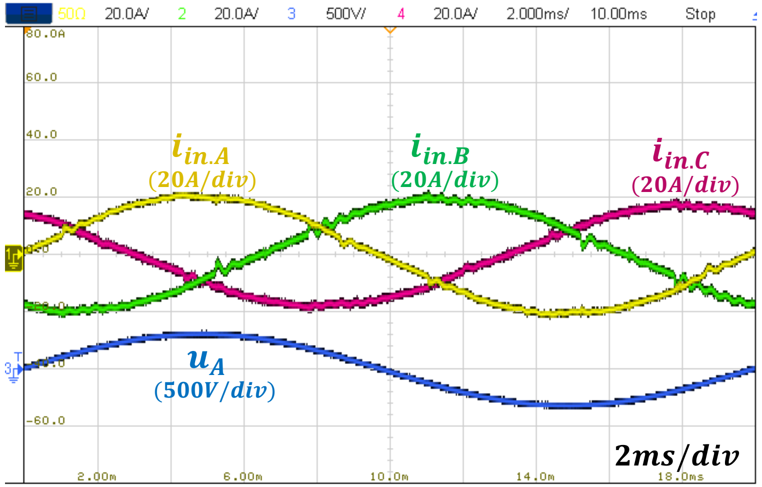
DC Bus Voltage: $550V$

Rated Power: $10kW$

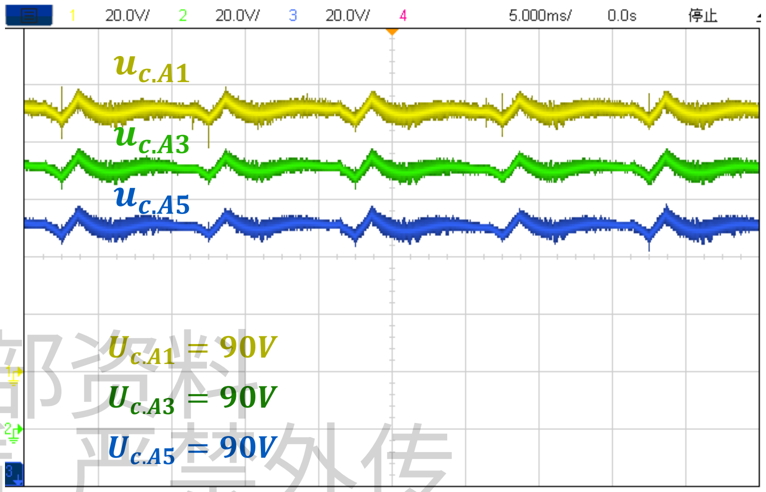
The Experimental Results of Prototype

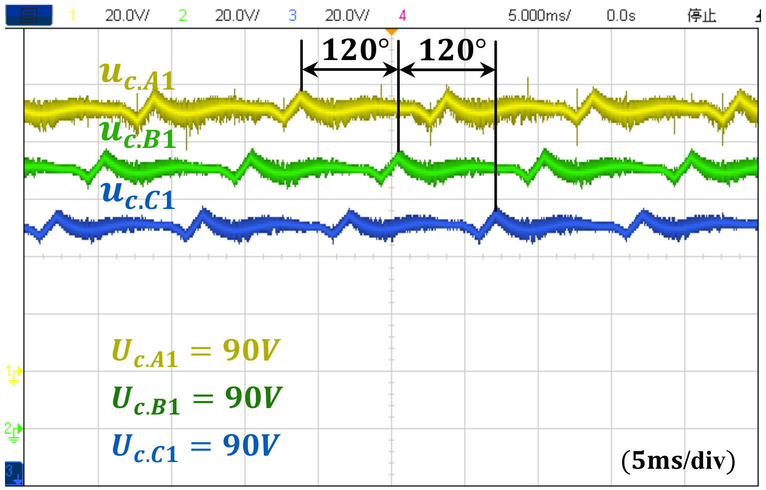
➢ 3-phase Currents





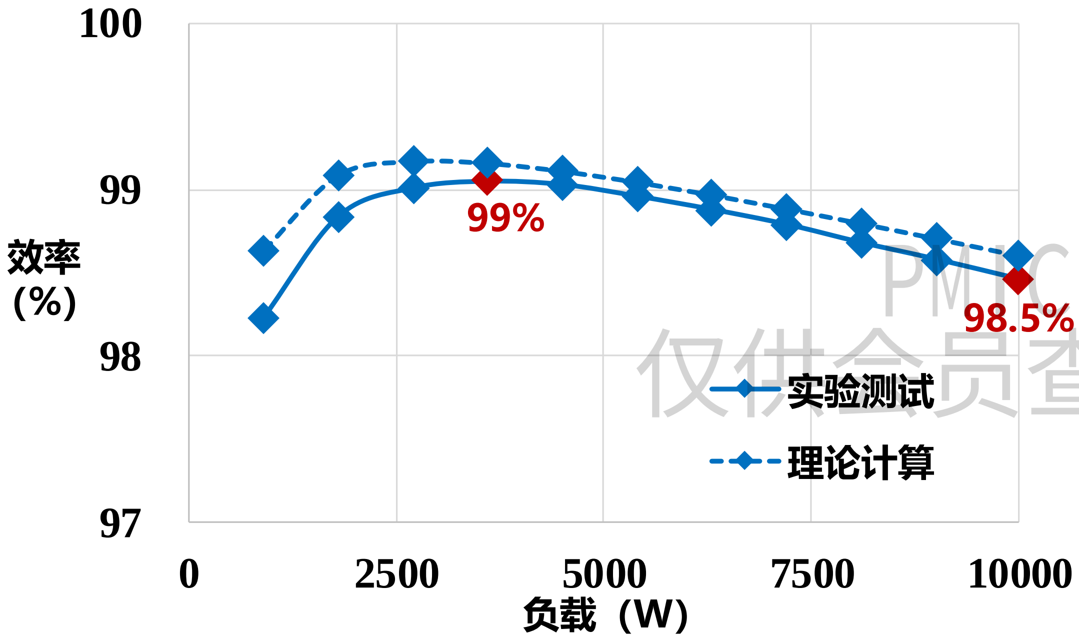
➢ 3-phase MISN Capacitors' Voltages



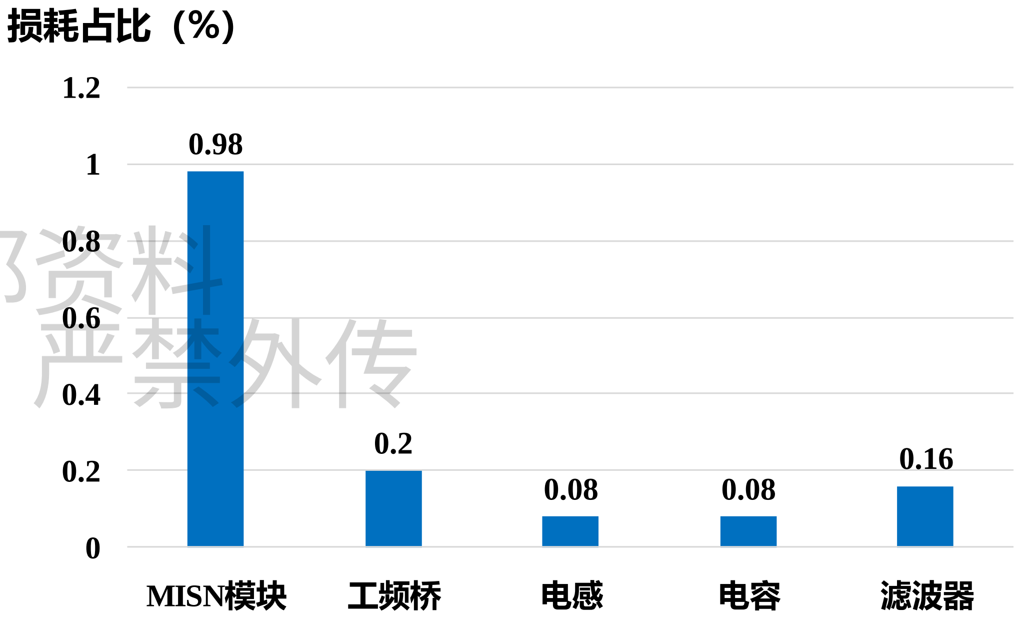


Efficiency Test and Loss Breakdown

➢ Efficiency under different load



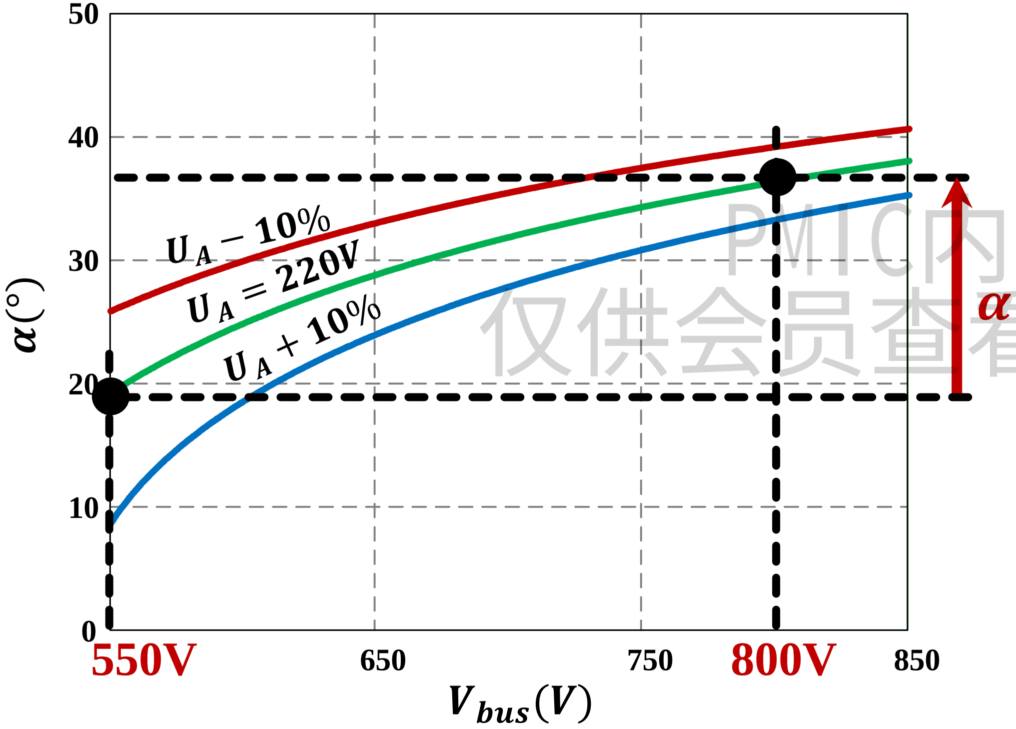
➢ Loss breakdown under full load



Catalogue

Wide Operating Range for Wide DC Bus Voltage

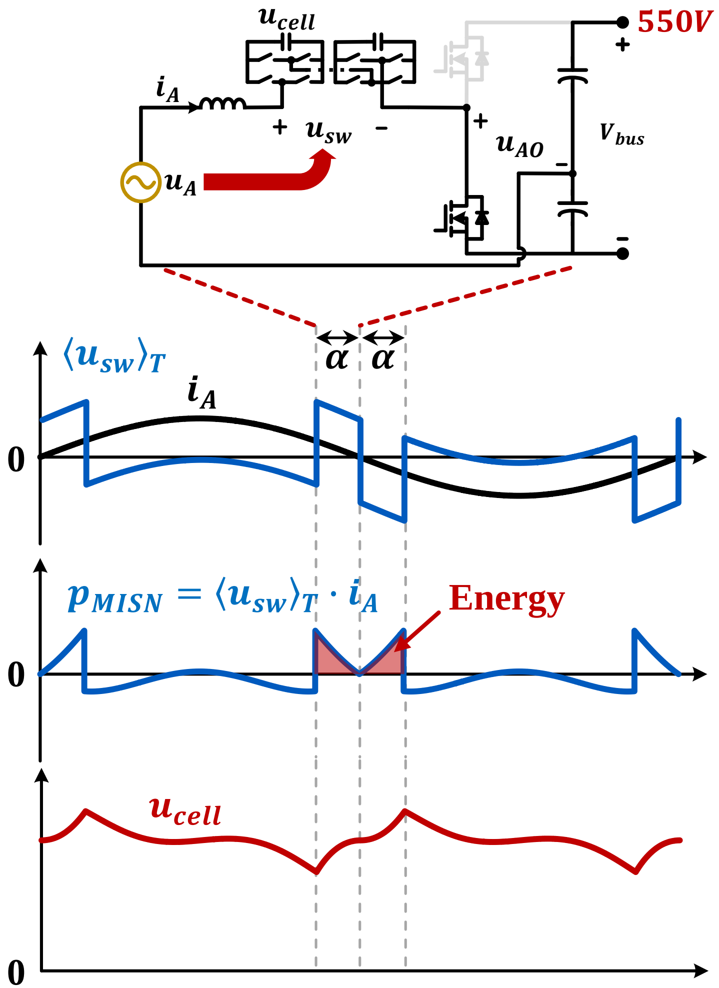
$$\alpha = arccos\left(\frac{\sqrt{2}\pi U_A}{4V_{bus}} + \frac{1}{2}\right)$$

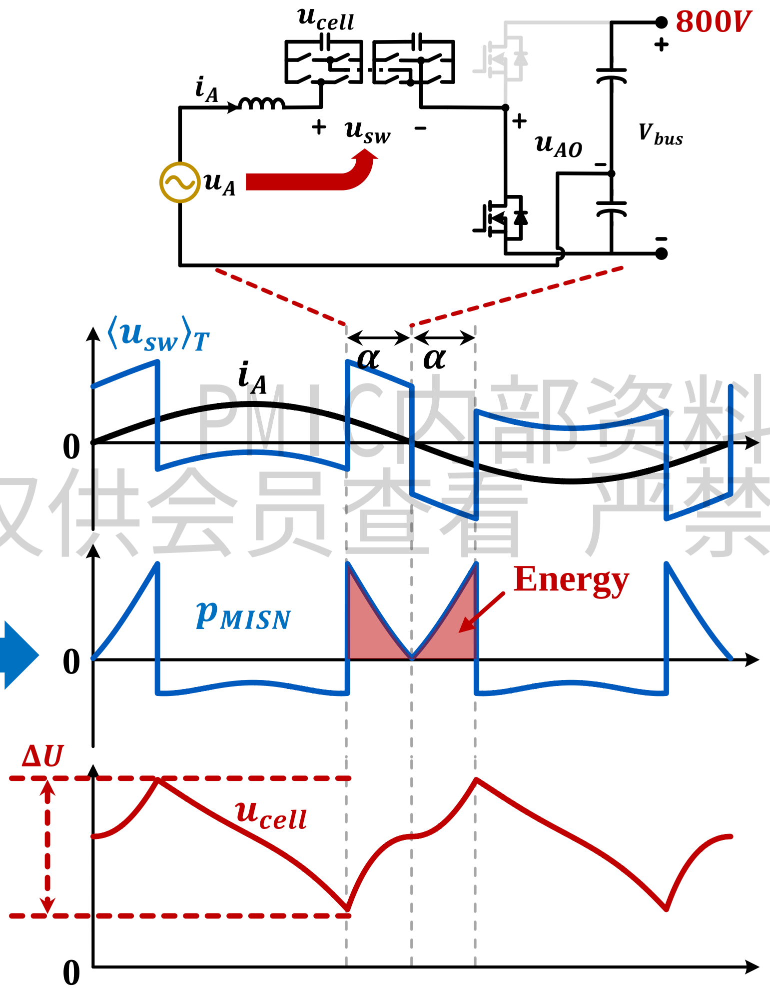


Large DC Bus Voltage Leads to Large Operating Value of α

The Increased MISN Capacitors' Volume due to Large Output Voltage Range

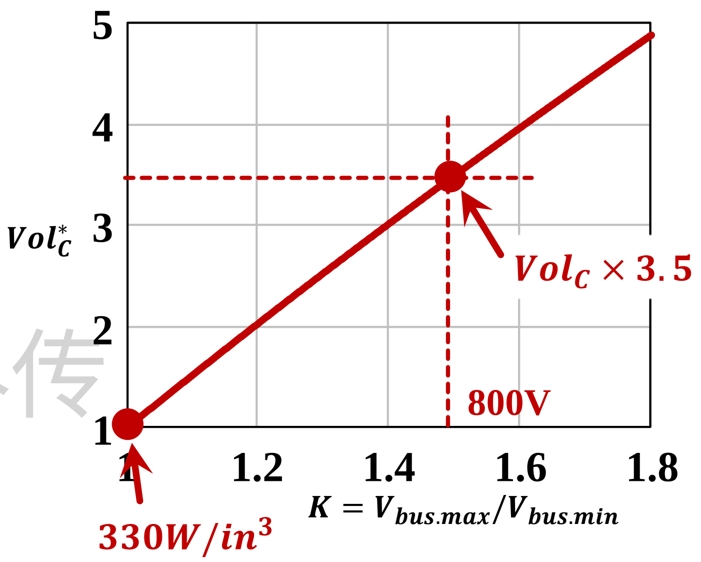
- Charing Mode of MISN Module





Larger capacitance is required

- Mathematical model for MISN Capacitor Volume



$$Vol_C^*(K) = \frac{Vol_C(K \cdot V_{bus.min})}{Vol_C(V_{bus.min})}$$

$$Vol_C = \frac{2P}{\omega E_D \Delta U}\left(2\alpha - \sin(2\alpha) - \frac{\pi(\cos\alpha - 1)}{2\cos\alpha - 1}\right)$$

$$\alpha(K) = acos\left(\frac{\sqrt{2}\pi U_A}{4K \cdot V_{bus.min}} + \frac{1}{2}\right)$$

$$\Delta U = 20\%$$

Reduce Volt-second of MISN Module by 3-level LF-bridge

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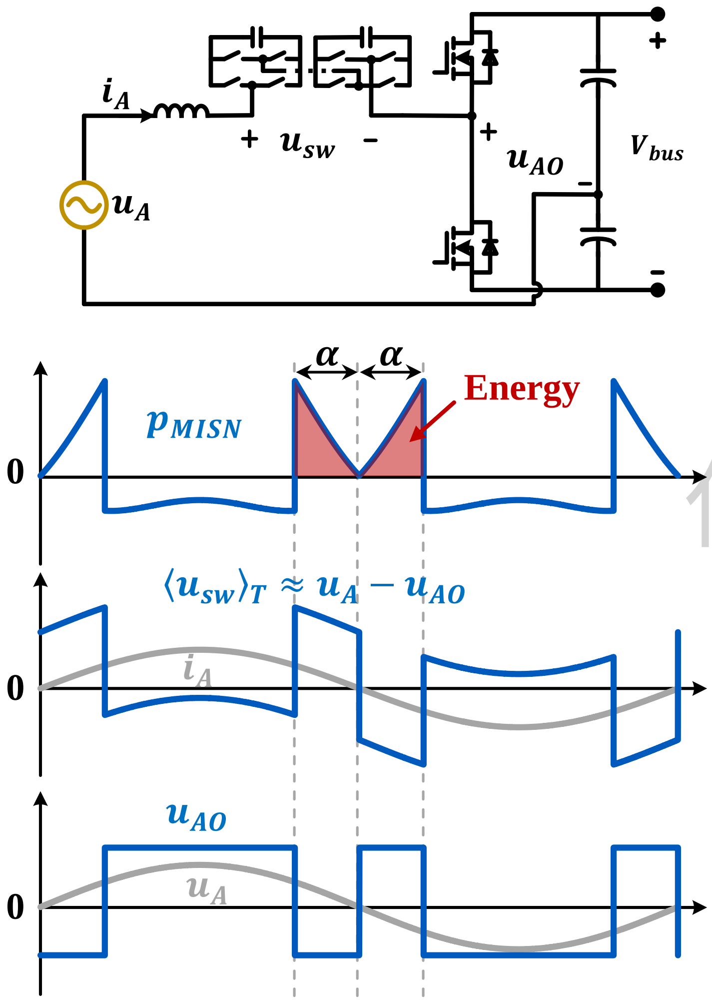
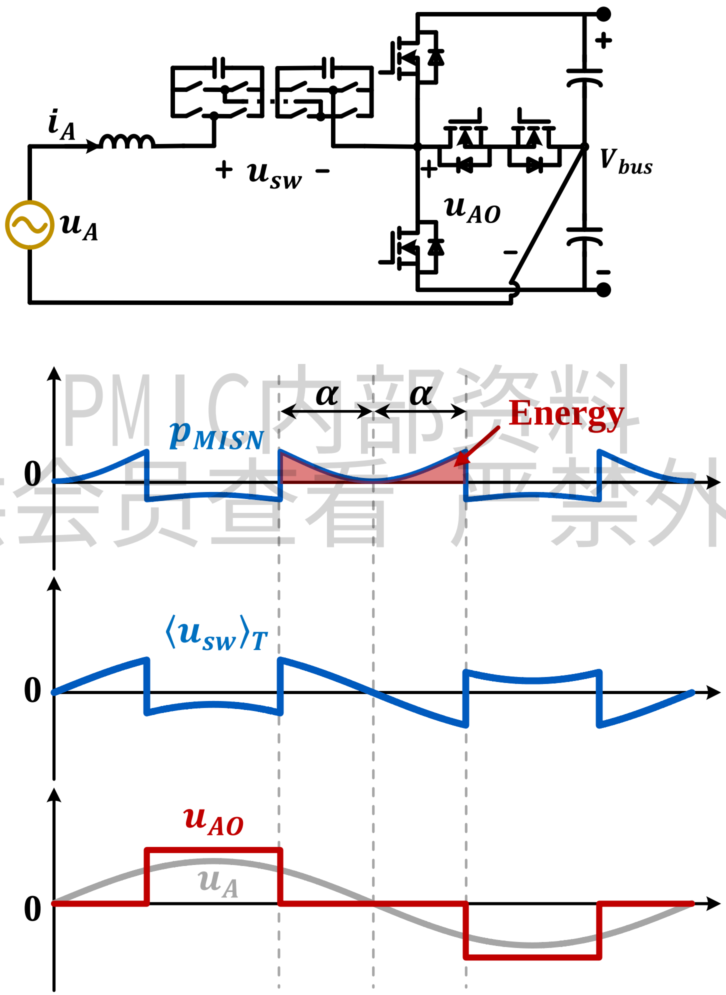
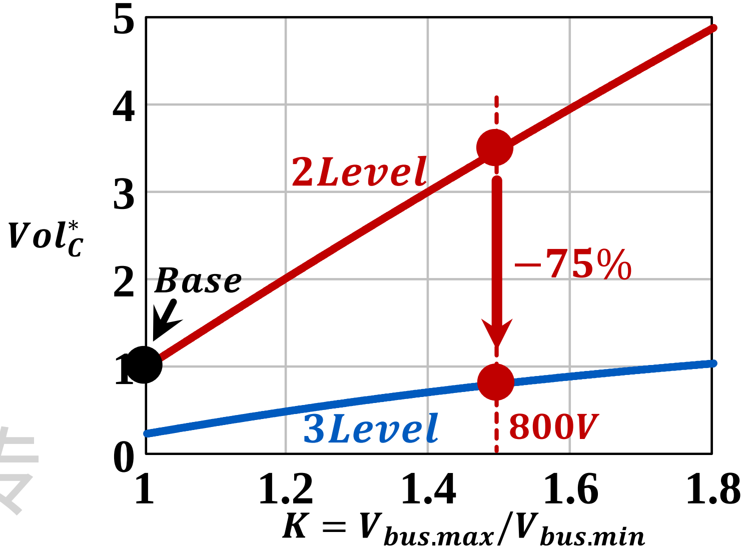
- 2-level LF-bridge



- T-type 3-level LF-bridge





$$Vol^*_{C.2level} = \frac{Vol_{C.2level}(K\cdot V_{bus.min})}{Vol_{C.2level}(V_{bus.min})}$$

$$Vol^*_{C.3level} = \frac{Vol_{C.3level}(K\cdot V_{bus.min})}{Vol_{C.2level}(V_{bus.min})}$$

T-type 3-level LF-bridge is adopted

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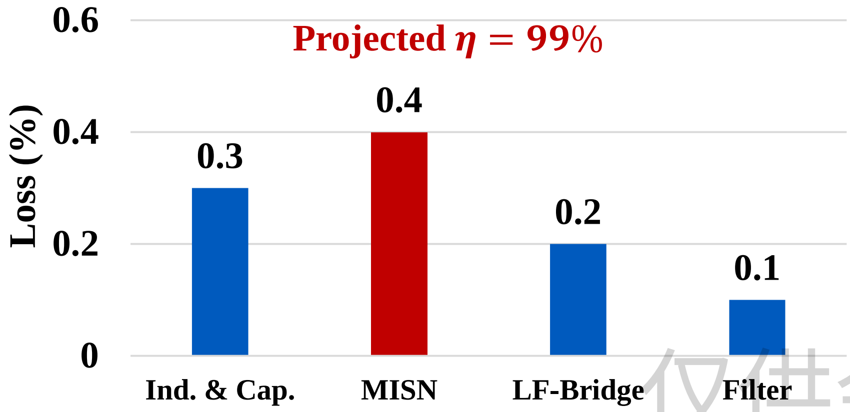
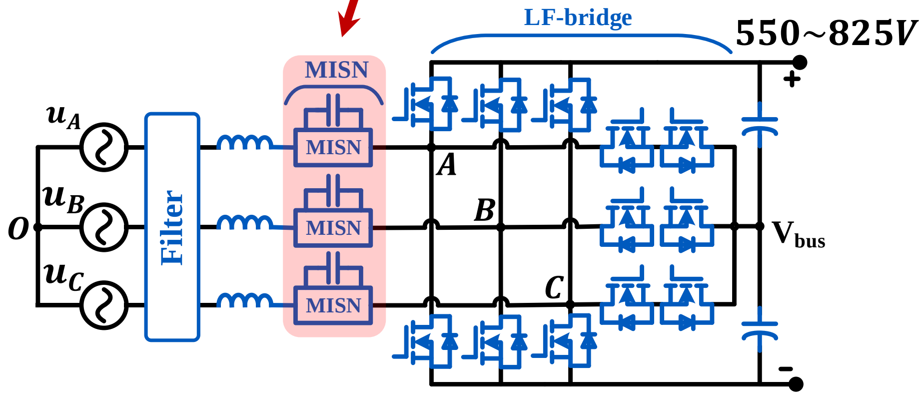
Loss Model for MISN Module Considering N_c, f_s, V_{BR}

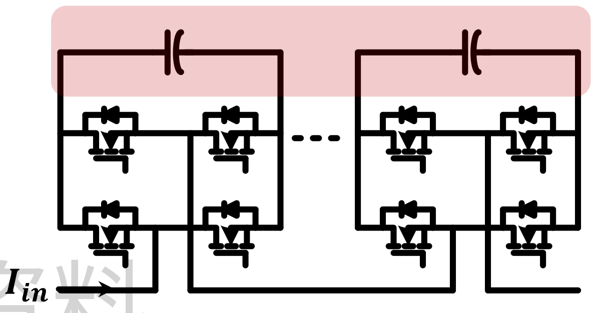
➢ The Loss Distribution at 10kW 800V_{dc}





➢ Minimum Loss Model of MISN Module (GaN)

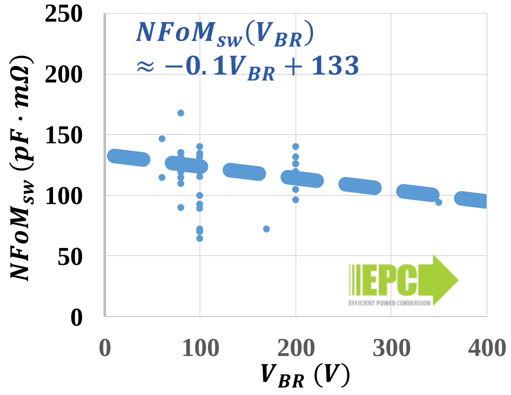
$U_{c.total} \rightarrow 0.7 N_c V_{BR}$

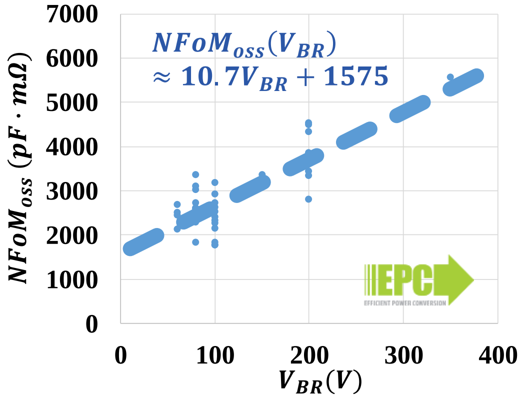


$$P_{Loss.min}(N_c, f_s, V_{BR})$$

$$= 4(U_{c.total})\, I_{in} \sqrt{k_{temp} k_{dyn} (k_{sw} I_{in} NFoM_{sw} + NFoM_{oss}) f_s}$$

$$= 4(0.7 V_{BR} N_c)\, I_{in} \sqrt{k_{temp} k_{dyn} (k_{sw} I_{in} NFoM_{sw}(V_{BR}) + NFoM_{oss}(V_{BR})) f_s}$$





- J. Wu, X. Wu , et al., "A Unified Switch Loss Model and Design Consideration for Multilevel Boost PFC -", TPEA 2021.

The Limitation for f_s based on the Projected Loss

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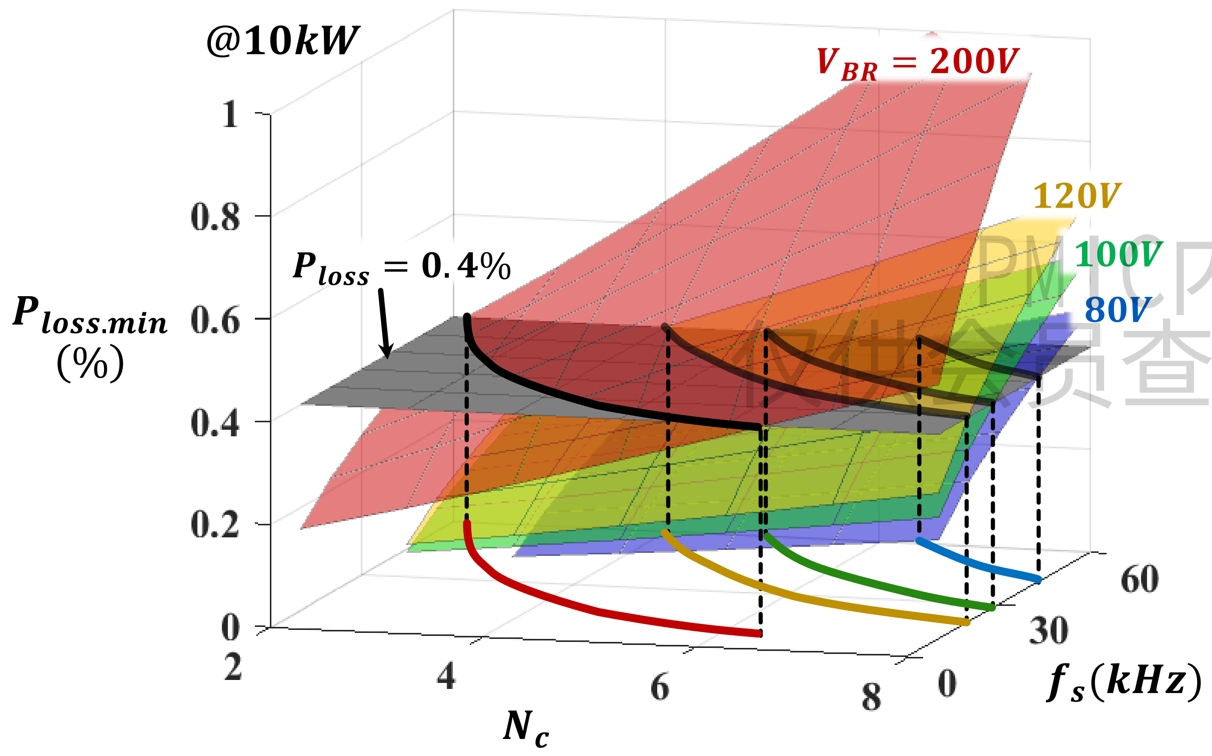
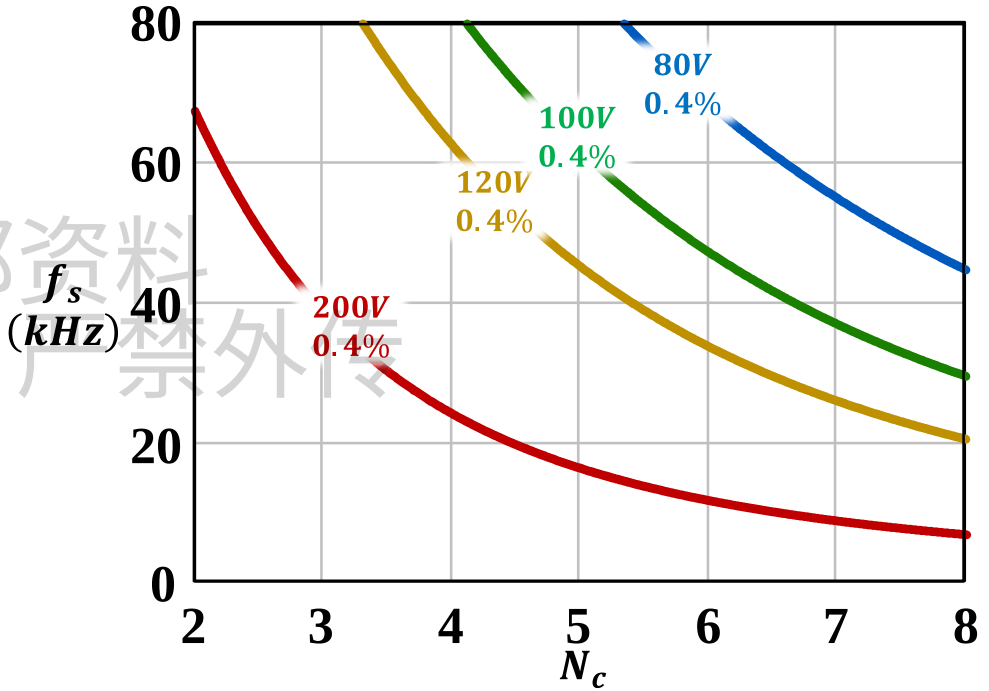
- $P_{Loss.min} = f(N_c, f_s, V_{BR})$



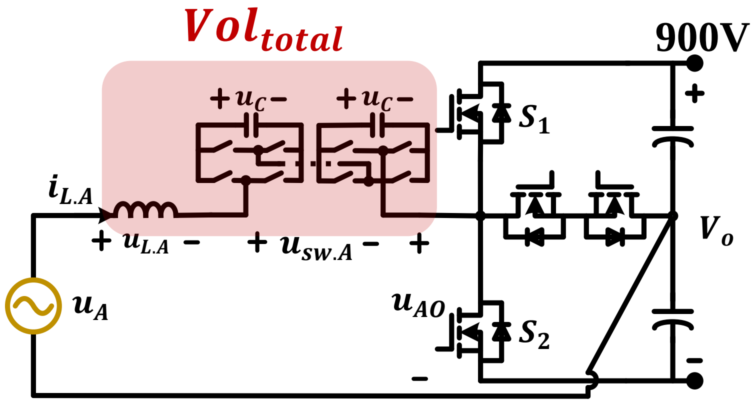
- The Limitation for f_s



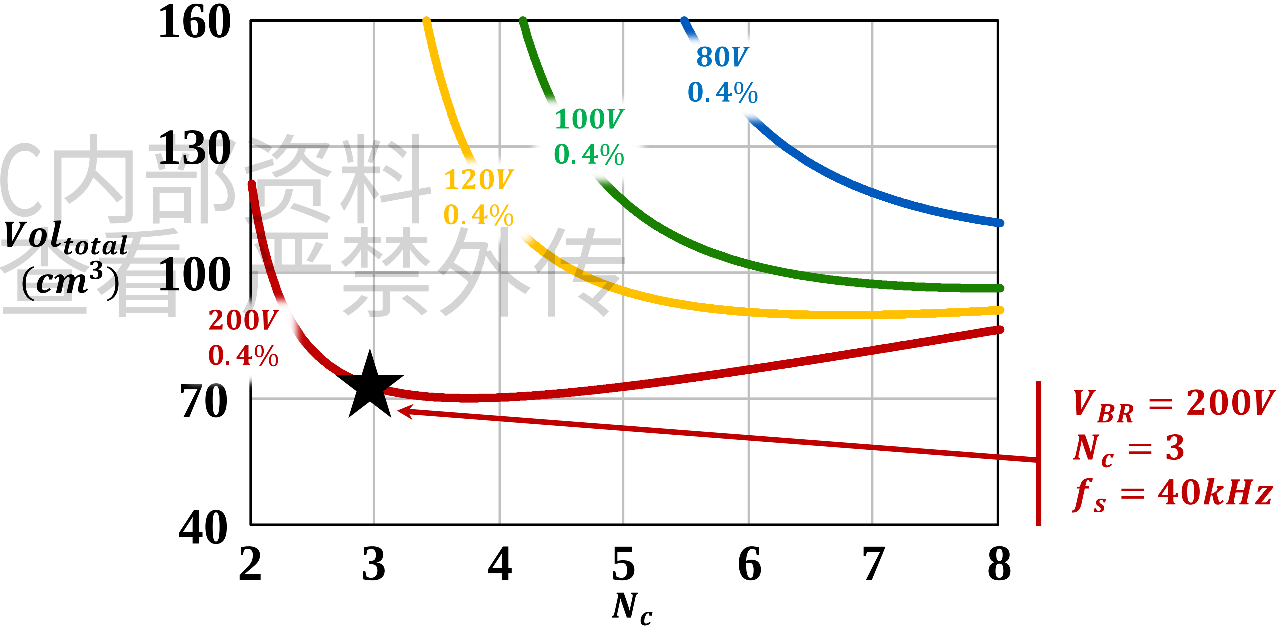
$$f_s(N_c, V_{BR}) = \frac{1}{k_{temp}k_{dyn}(k_{sw}I_{in}NFoM_{sw} + NFoM_{oss})}\left(\frac{P_{loss.exp}}{4U_{c.total}^{avg}I_{in}}\right)^2$$

- $N_c \cdot V_{BR} \geq U_{c.total}^{valley} = \sqrt{2}U_A sin\alpha$

Volume Optimization for 0.4% Loss Limit



$$Vol_{total} = Vol_L + Vol_C + Vol_{cell}$$



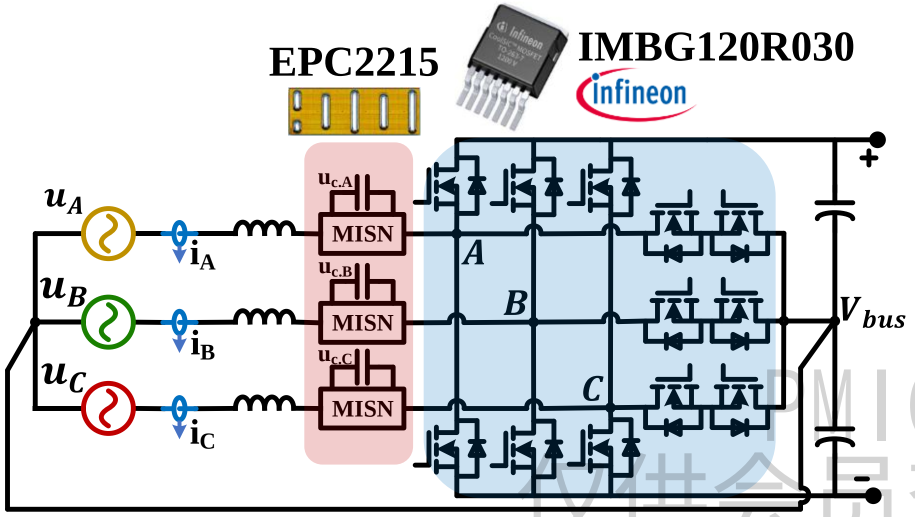
- Inductor Volume: (AP Method)

$$\begin{cases} L(\mathrm{N_c}, \mathrm{f_s}, \mathrm{V_{BR}}) = \dfrac{0.7V_{BR}}{8N_c f_s \Delta \mathrm{i_{pp}}} \\ Vol_L = k_L \left(\dfrac{LI_{peak}I_{RMS}}{k_w J B_m}\right)^{\frac{3}{4}} \end{cases}$$

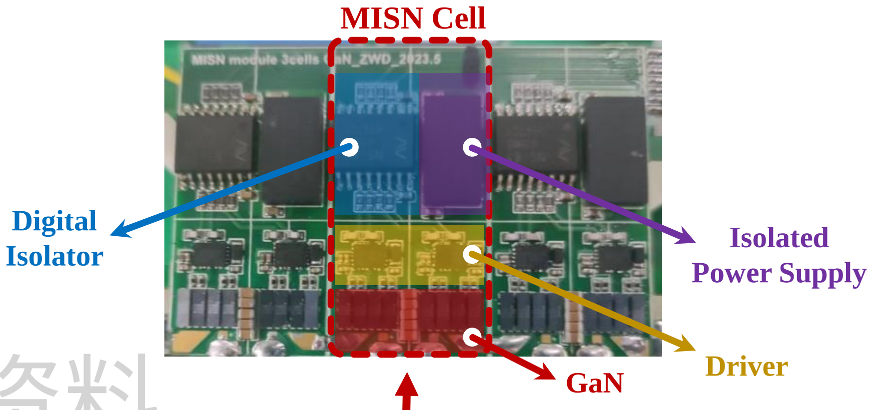
- Capacitor Volume: $Vol_C(N_c, V_{BR}) = \dfrac{\frac{1}{2}(1.2C_{eq.min})(V_{BR})^2}{E_D} N_c$

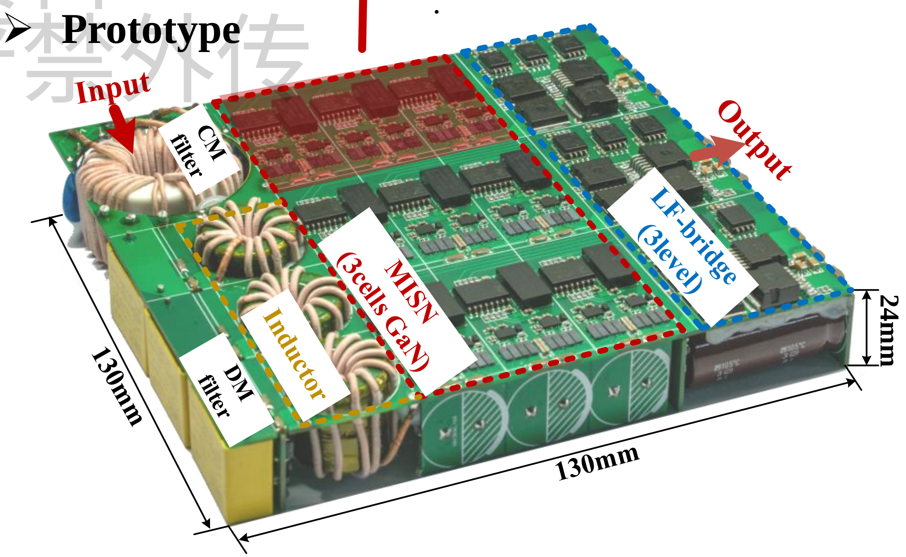
- MISN Cell Volume: $Vol_{Cell} = K \cdot N_c$

Hardware Implementation



Parameter	Value
Power	10kW
Input Phase Voltage	$220V_{RMS} \pm 10\%$
Output Voltage	$550V \sim 900V$
MISN Voltage	$3 \times 120V$
Frequency (MISN)	$40kHz$





Power Density: $400W/in^3$

Efficiency for the Designed MISN Converter

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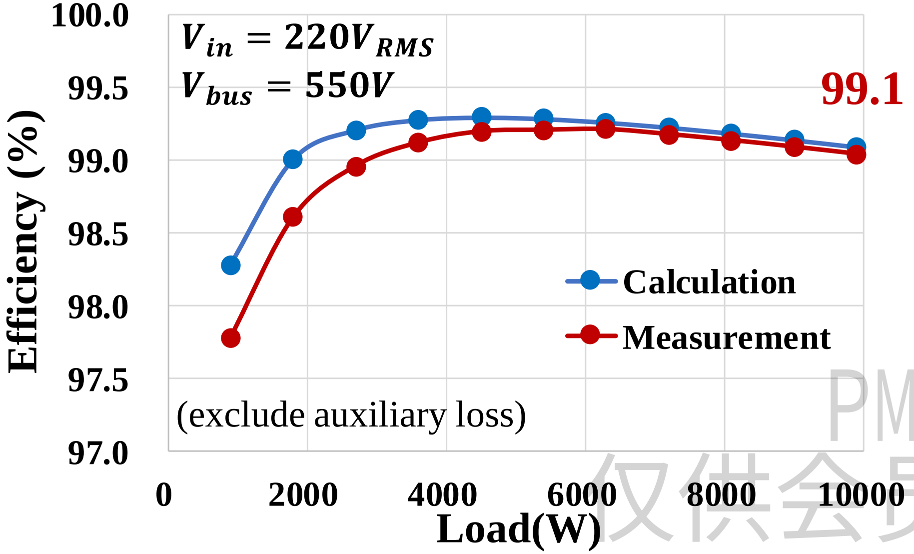
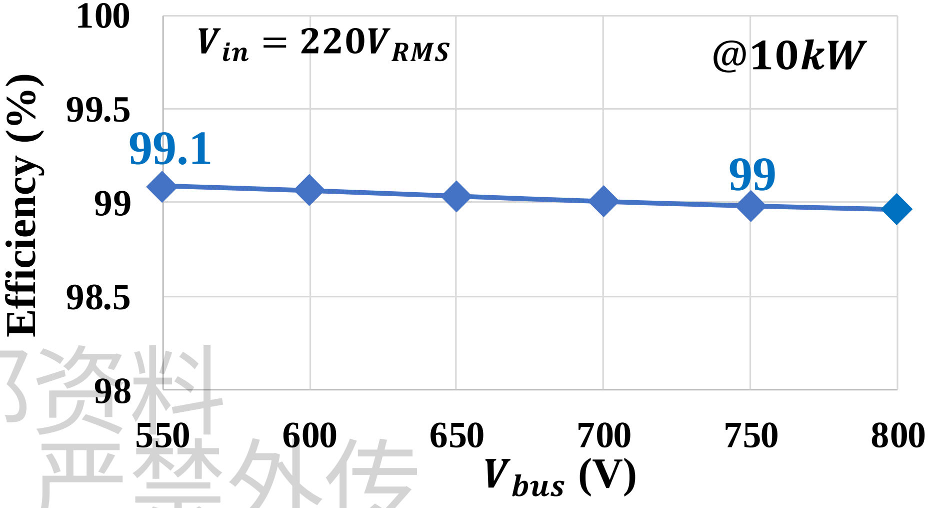
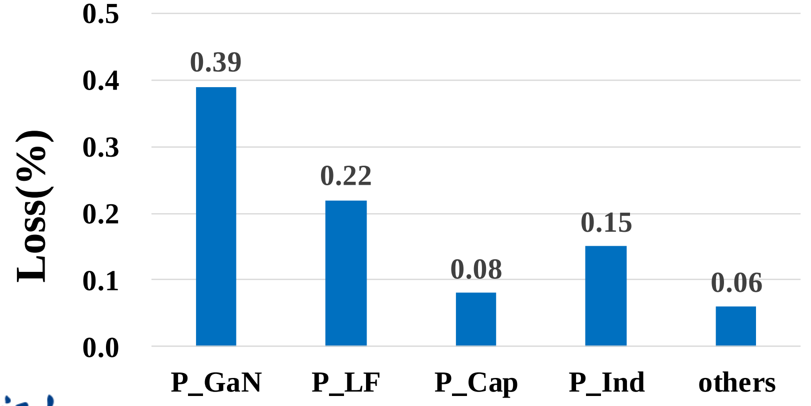
- Test condition: 5min/point

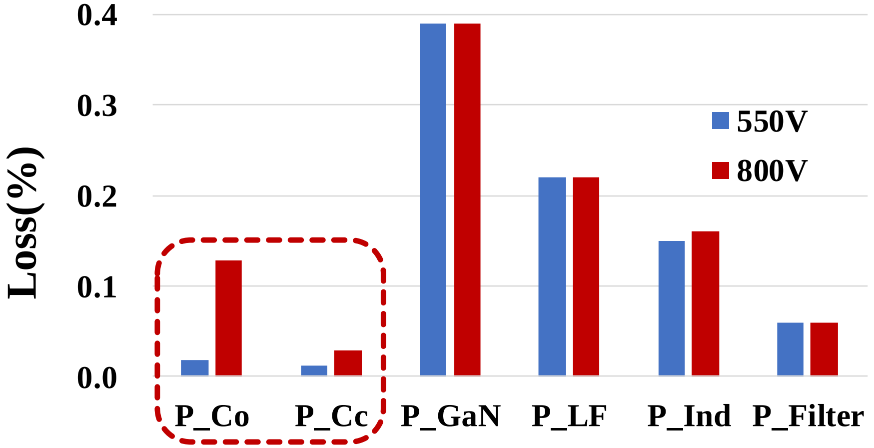




- Loss breakdown for 10kW



- Loss breakdown for 10kW



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Catalogue

Oscillation Phenomenon When α Close to 90°

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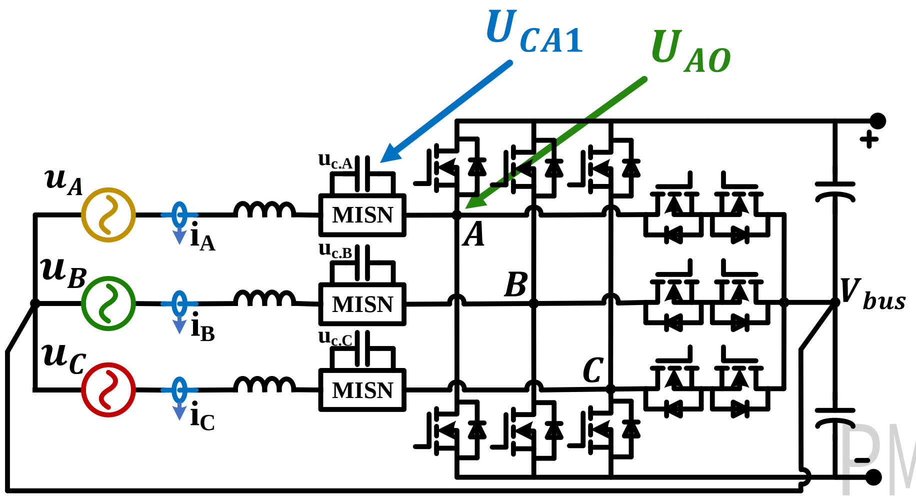
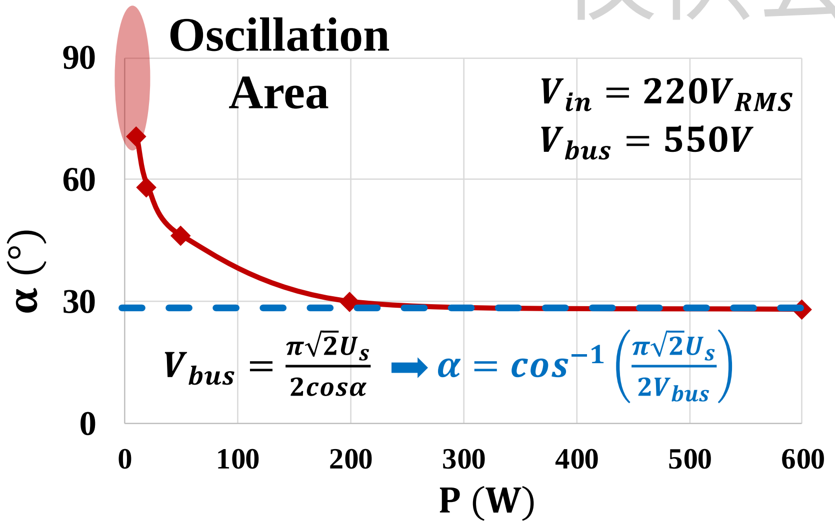
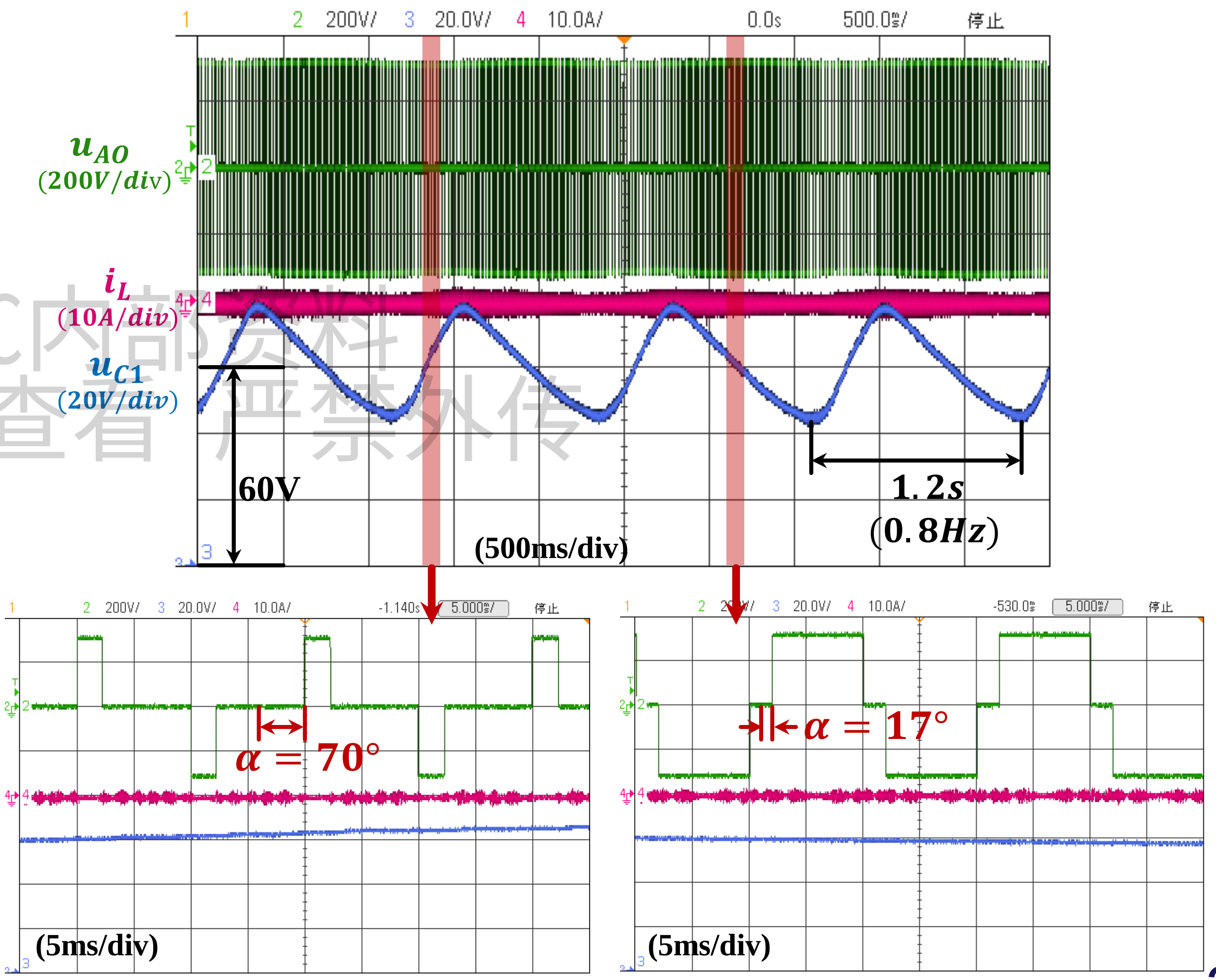
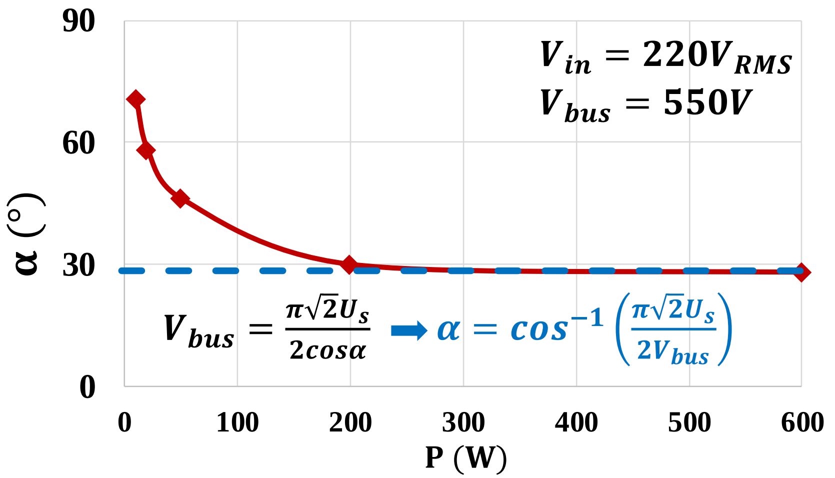




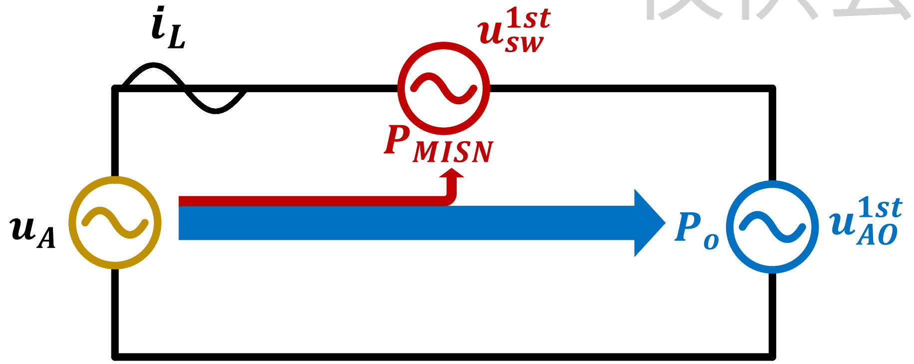
- **The Oscillating of MISN Voltage Loop at No Load**



The Fundamental Voltage U_{AO}^{1st} is Reduced at Light Load



- Fundamental Equivalent Circuit

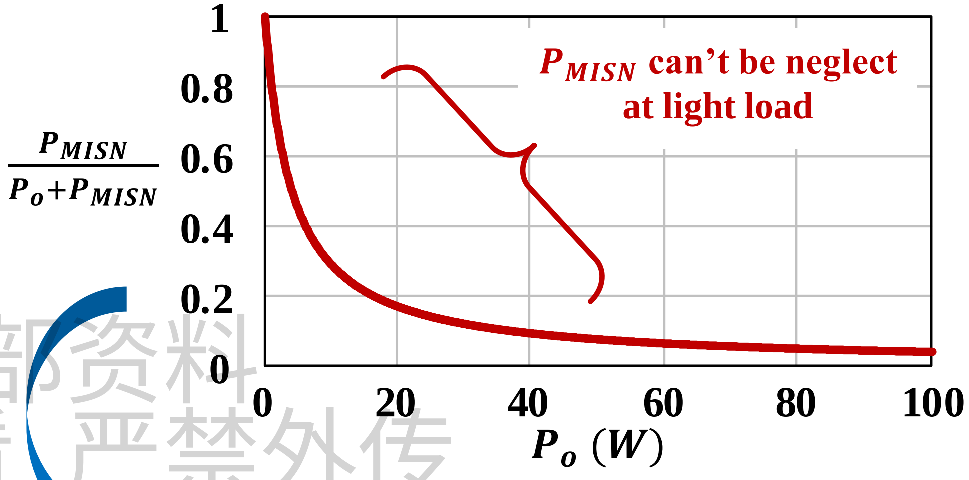


Assume $P_{MISN} \approx 0$ ➡ $u_{AO}^{1st} = u_A$ ➡ $V_{bus} = \frac{\pi\sqrt{2}U_A}{2cos\alpha}$

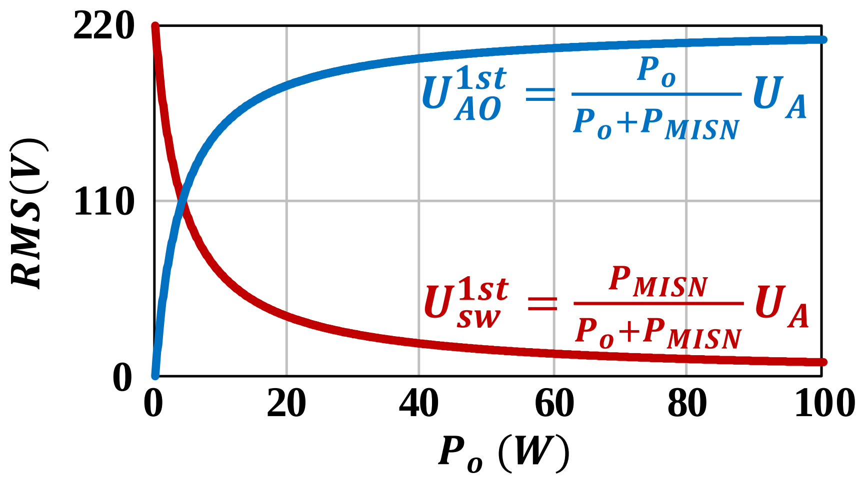
$\alpha = cos^{-1}\left(\frac{\pi\sqrt{2}U_s}{2V_{bus}}\right)$

$$\frac{P_{MISN}}{P_o} = \frac{U_{sw}^{1st}}{U_{AO}^{1st}}$$

- The Proportion of P_{MISN} $(P_{MISN} \approx P_{GaN} + P_{cap})$



- The Proportion of Voltage $(U_{AO}^{1st} + U_{sw}^{1st} = U_A)$



The Increase Proportion of P_{MISN} at Light Load Resulting in the Increase of α

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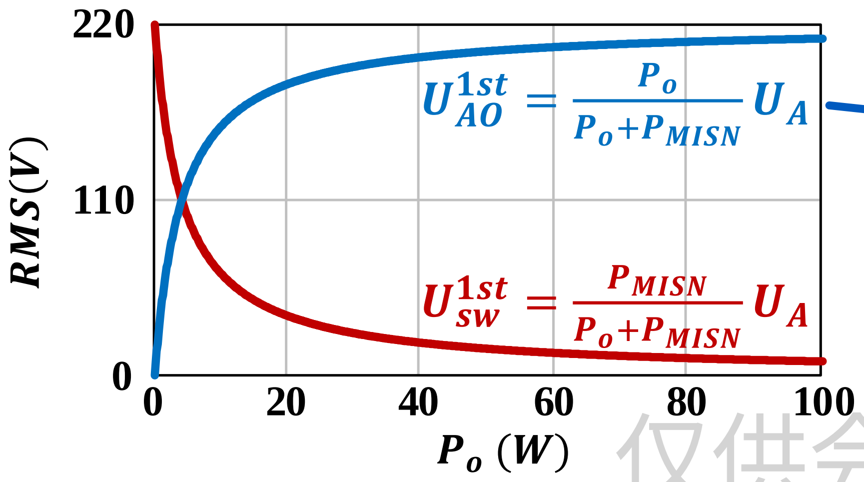
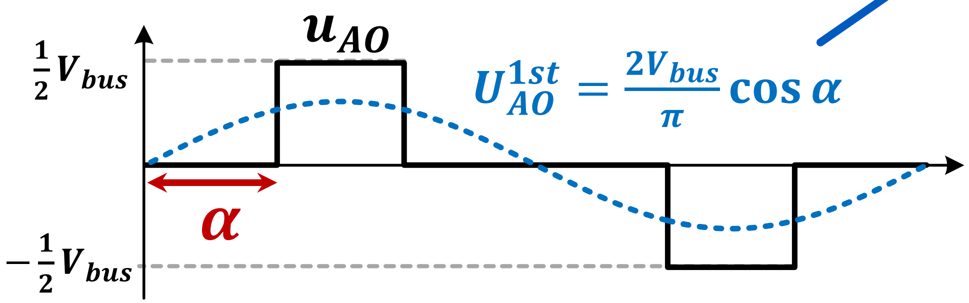
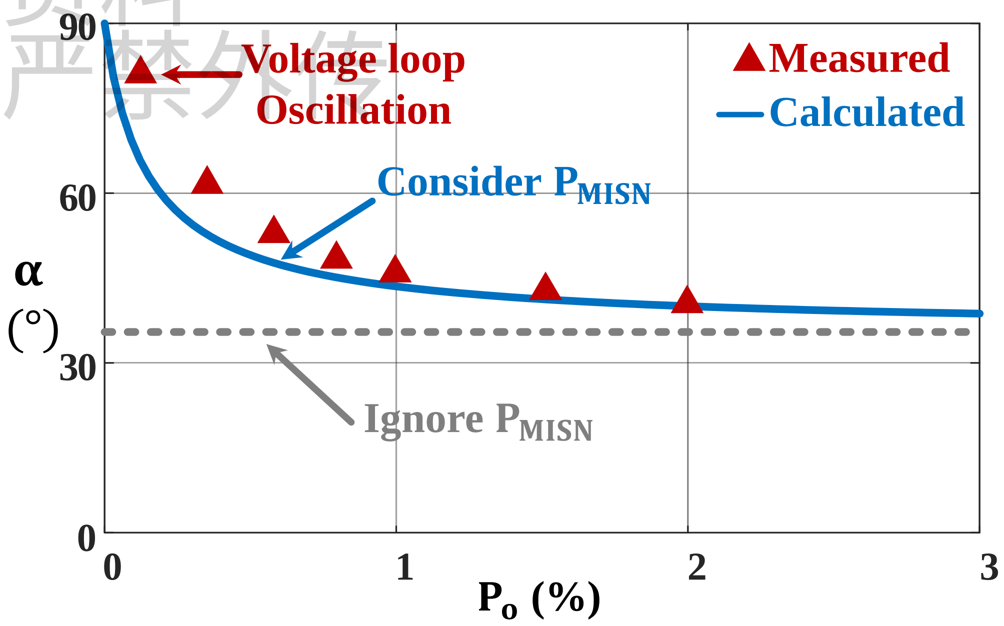
➢ The Proportion of Voltage



$$\alpha = cos^{-1}\left(\frac{\pi\sqrt{2}U_A}{2V_{bus}} \cdot \frac{P_o}{P_o+P_{MISN}}\right)$$

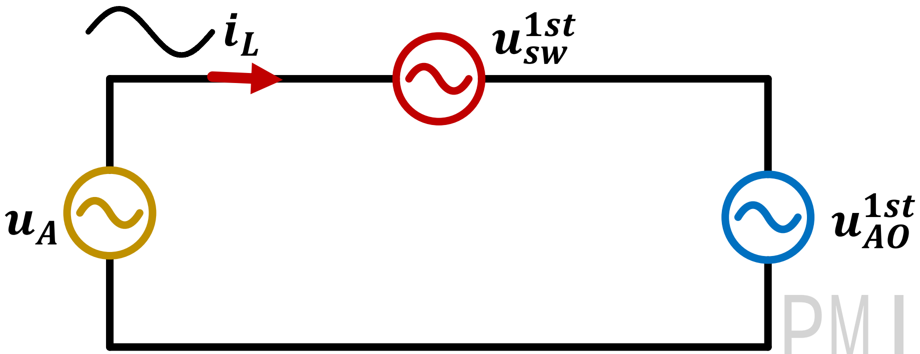


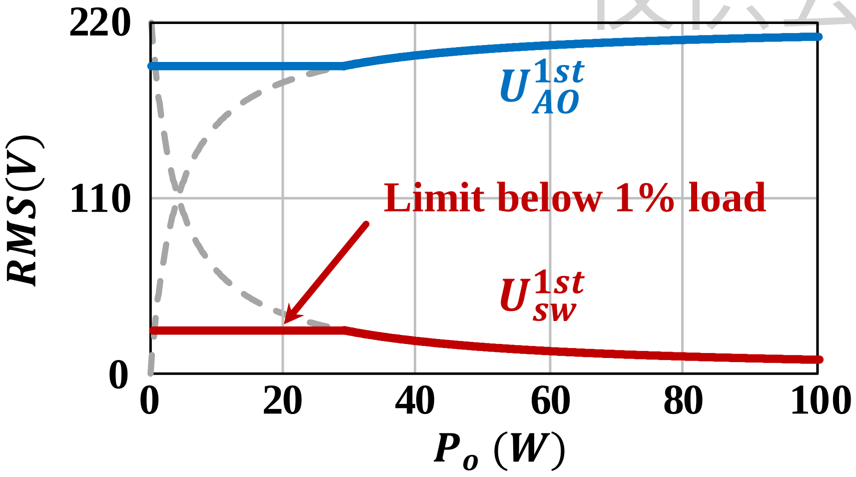
$U_{AO}^{1st} \downarrow \Rightarrow \alpha \uparrow$



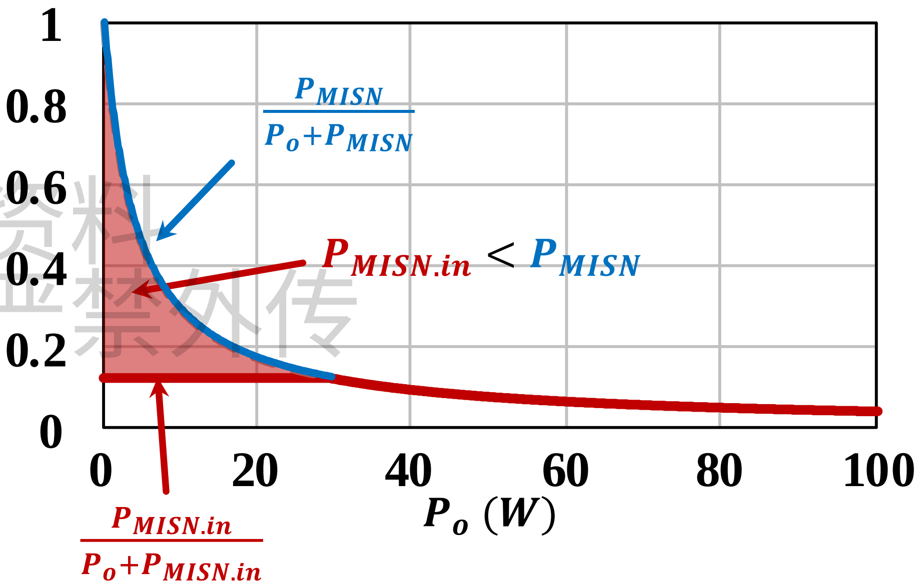
The Input Power $P_{MISN.in}$ can't Meet with Power Consumption P_{MISN} when α is Limited

➢ **Fundamental Equivalent Circuit**





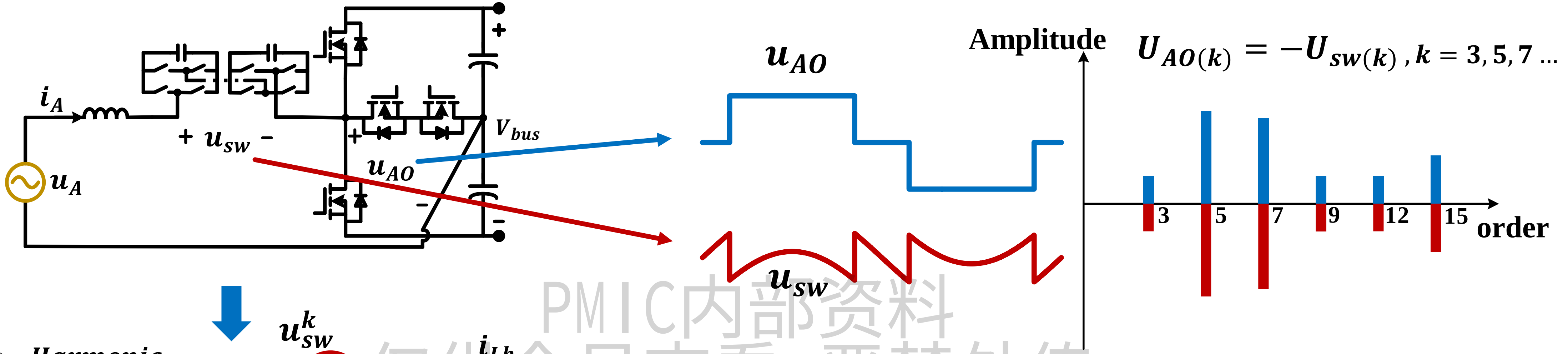
➢ **The Proportion of P_{MISN}**

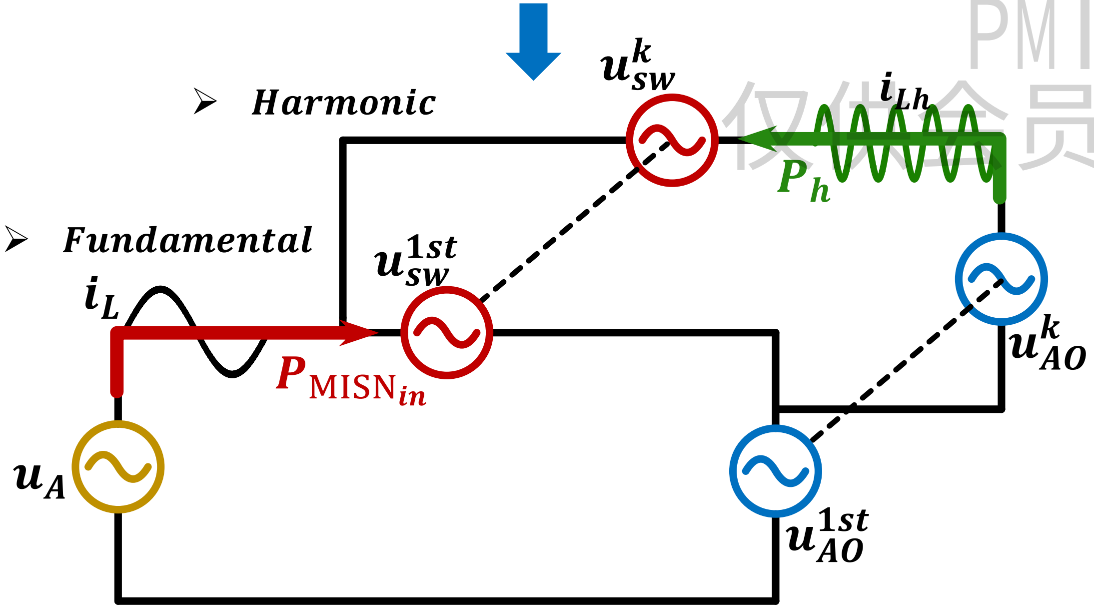


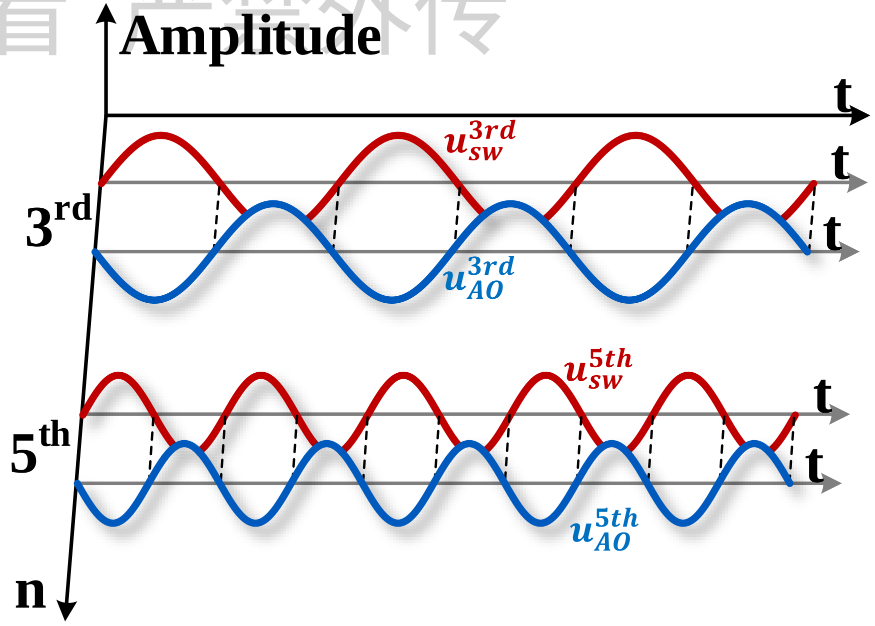
$$P_{MISN} \approx P_{GaN} + P_{cap}$$

$$P_{MISN.in} \approx U_{sw}^{1st} \cdot I_L$$

Power Compensation based o the Harmonic Current Injection

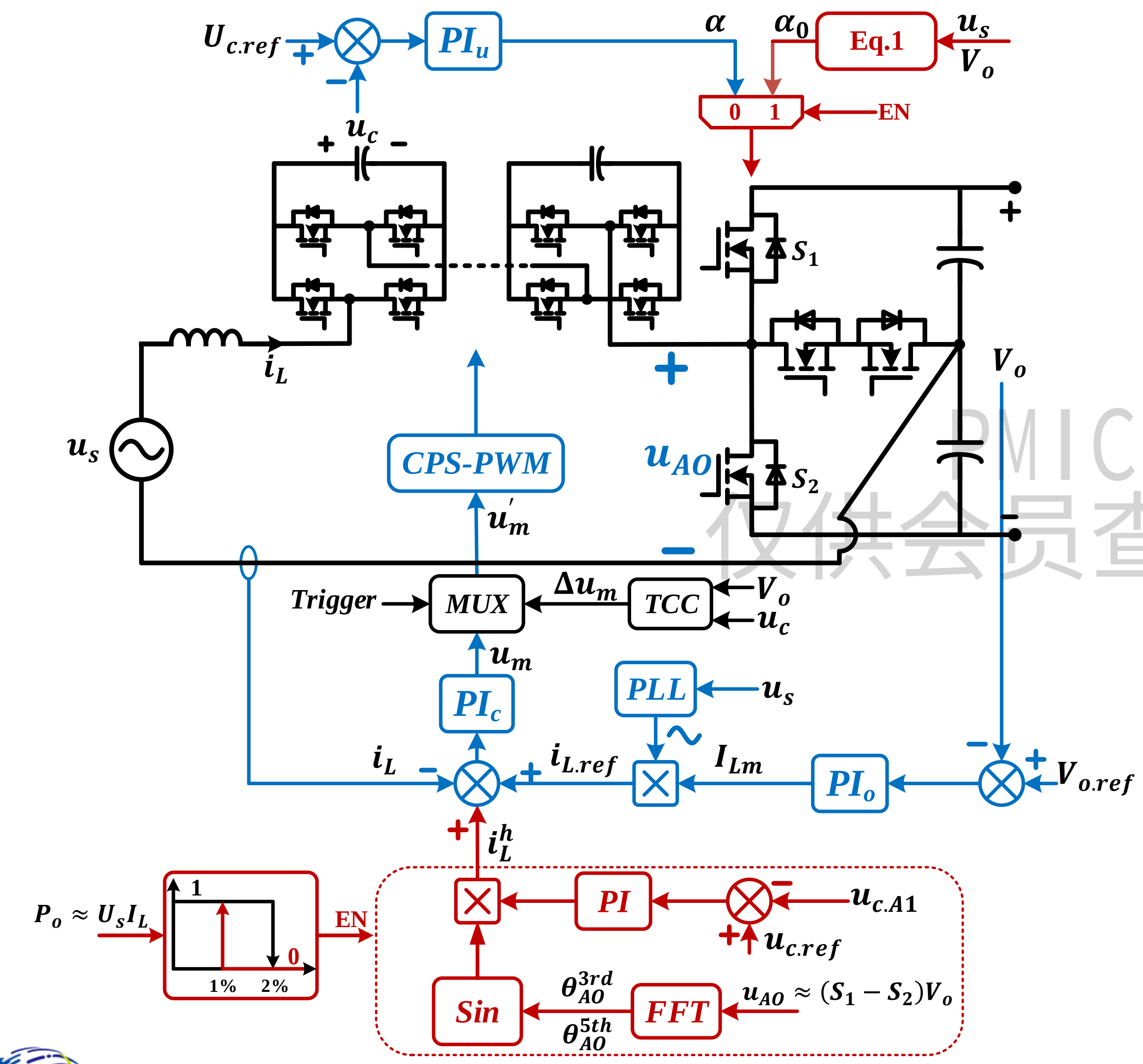




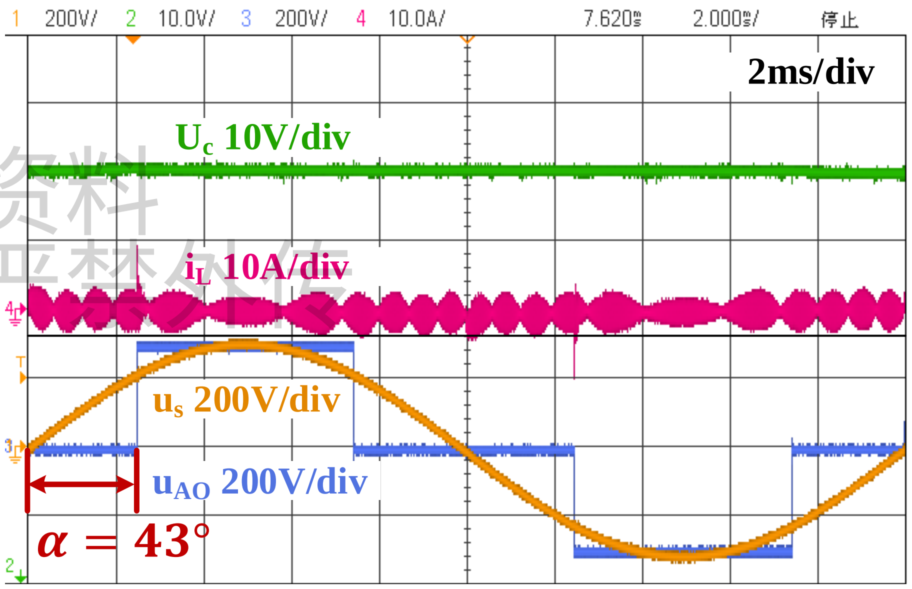


$$P_{MISN.in} + P_h = P_{MISN}$$

The Light Load Control Strategy of MISN-PFC Converter Based on the Harmonic Power Compensation



➢ **No Load Operating**



$\alpha_0 = 35°$

- $Eq.1\!: \ \alpha_0 = K\alpha = arccos\left(\frac{\sqrt{2}\pi U_S}{4V_o}\right)$

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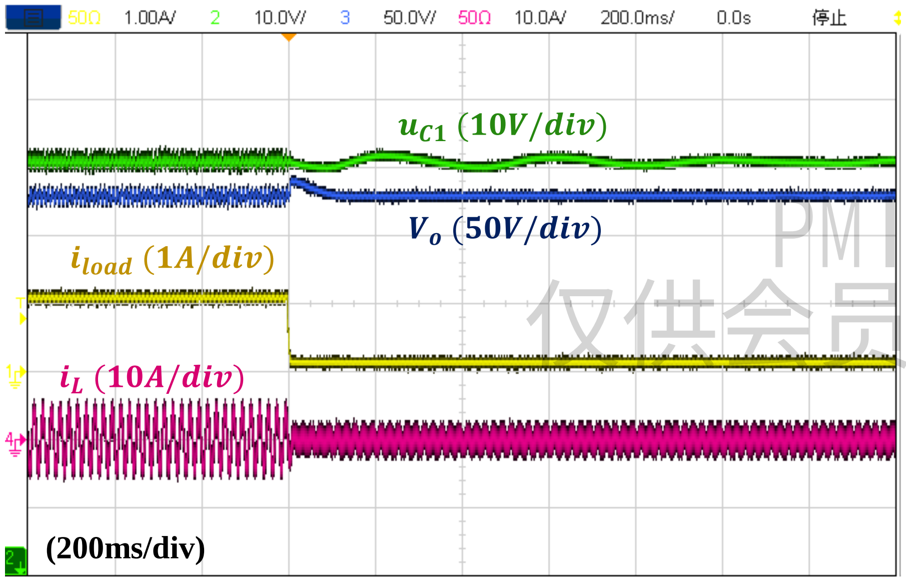
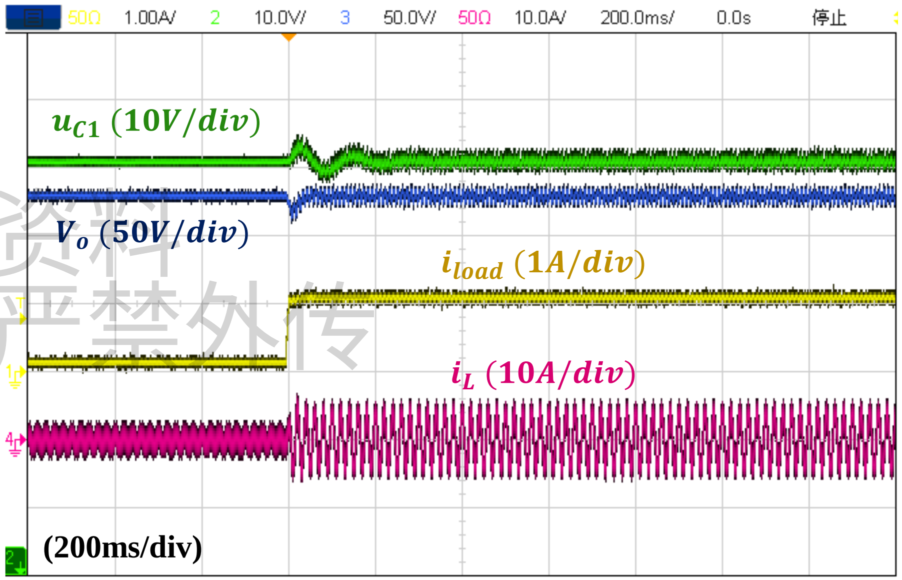
The Dynamic Verification for Control Strategy Switching

- **From 10% load to No load**



- **From No load to 10% load**



Summary

创新点一
暂态补偿控制策略

- 针对现有模块化的多电平PFC拓扑多母线导致系统架构复杂且母线电容体积大的问题，提出一种新型的模块化感性开关网络PFC变换器和相应的控制策略，大幅减小电感伏秒，提升变换器功率密度，并实现高度模块化多电平单元以及单直流母线结构。

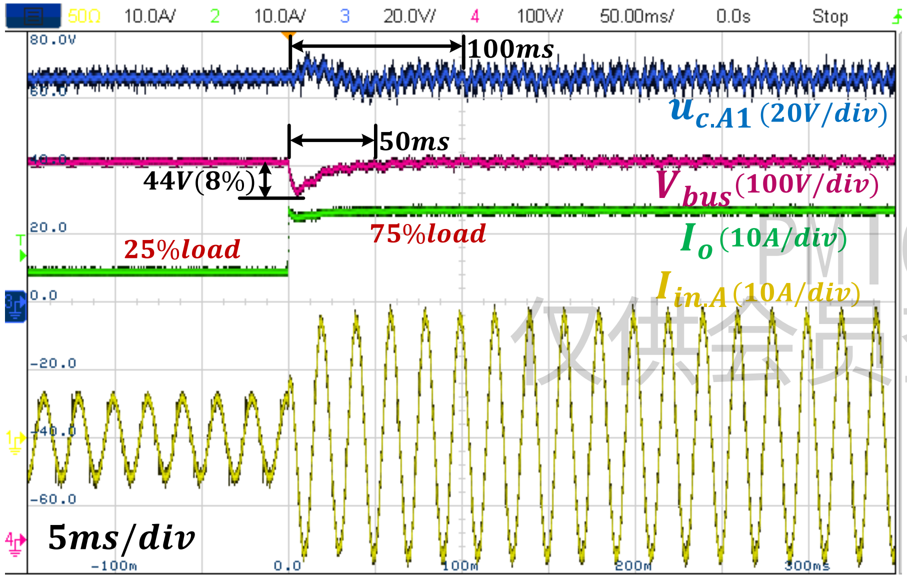
创新点二
多变量优化设计方法

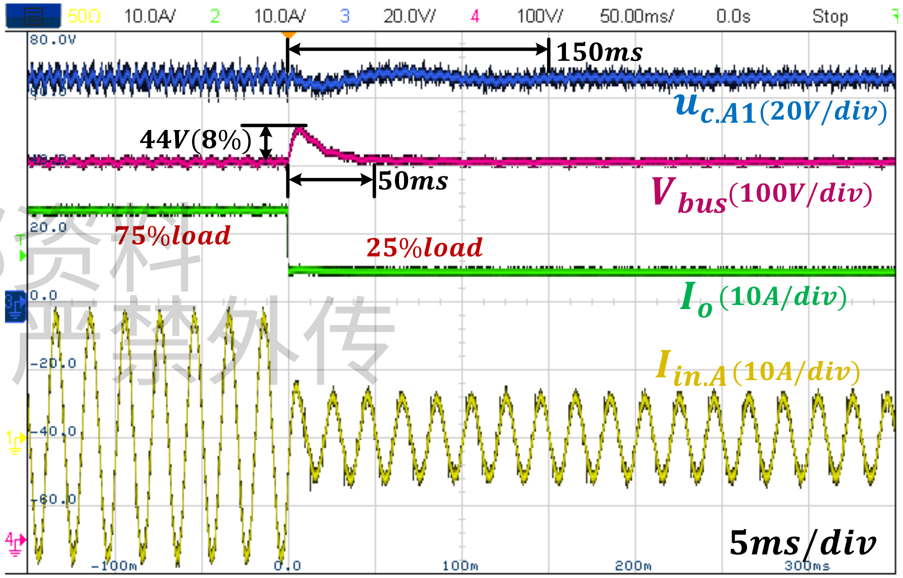
- 针对多电平PFC变换器电路缺乏系统性设计方法的问题，本文提出一种创新的优化设计策略，全面考虑MISN-PFC变换器的损耗以及体积，高效地根据效率目标确定变换器最优功率密度所需电路参数，设计方法的指标预测误差小于10%。

创新点三
极轻载控制策略

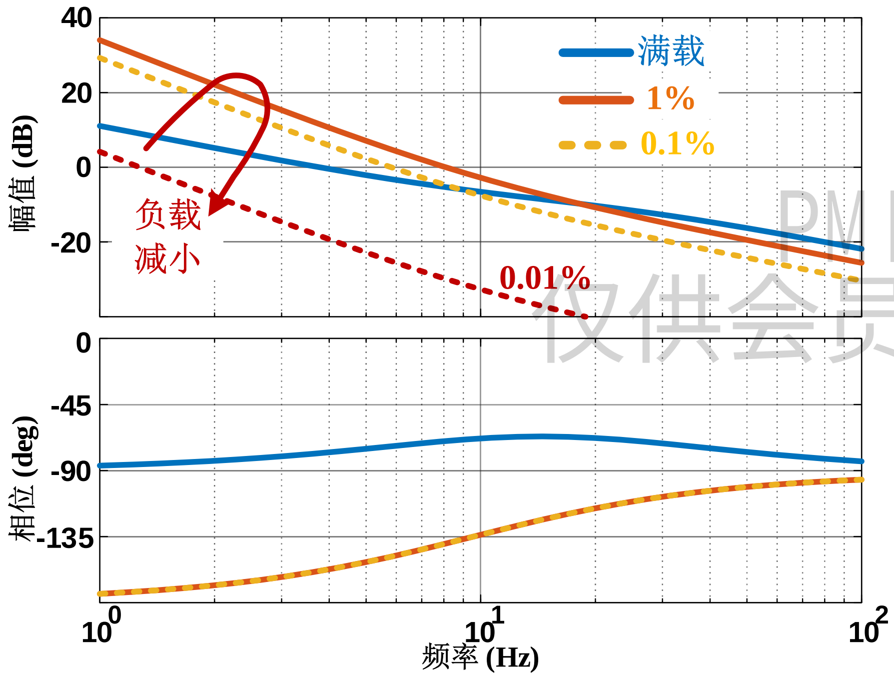
- 针对MISN-PFC在极轻载工况下工频整流桥斩波角趋于饱和导致电压环路震荡的问题，本文建模分析工频频率下变换器的功率传输路径，揭示极轻载下MISN模块损耗导致斩波角增大的原理，在此基础上提出一种基于谐波功率补偿的极轻载控制策略，通过谐波频段维持MISN模块功率平衡，实现电压环路稳定。

1. 当输入电压三相不平衡时，如何处理？当输入电压掉电再恢复时，如何能够快速锁相并保证驱动时序的正确性？如果母线电容中点不接功率管，可以吗？
2. 请问可否使用磁集成磁心？
3. 怎么实现均流控制？
4. 请问功率因数可提高多少？

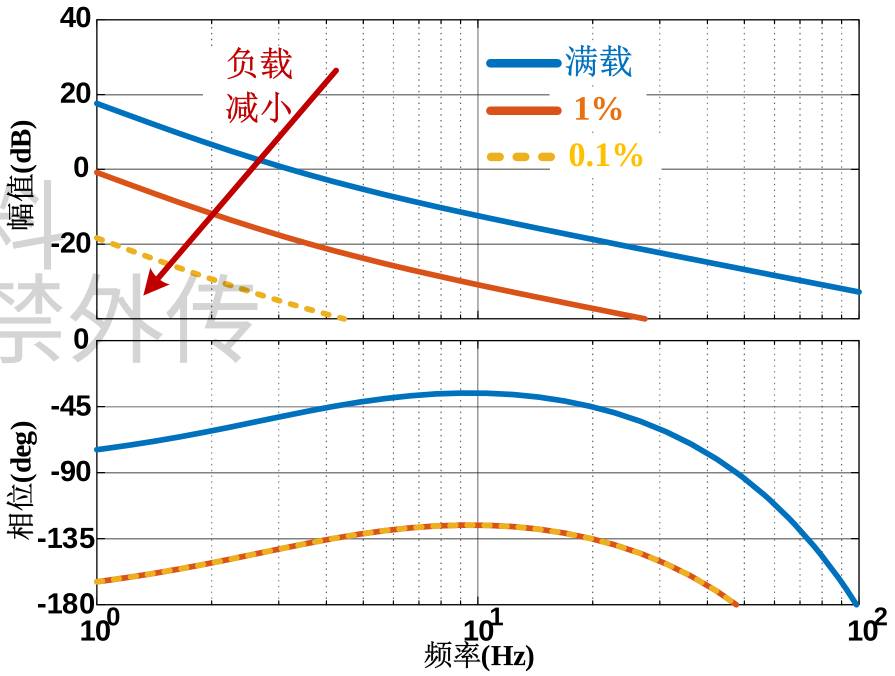

10.0A/
10.0A/
20.0V/
100V/
50.00ms/
0.0s
Stop
100ms
$u_{c.A1}$ (20V/div)
50ms
44V(8%)
V_{bus}(100V/div)
25%load
75%load
I_o(10A/div)
$I_{in.A}$(10A/div)
5ms/div

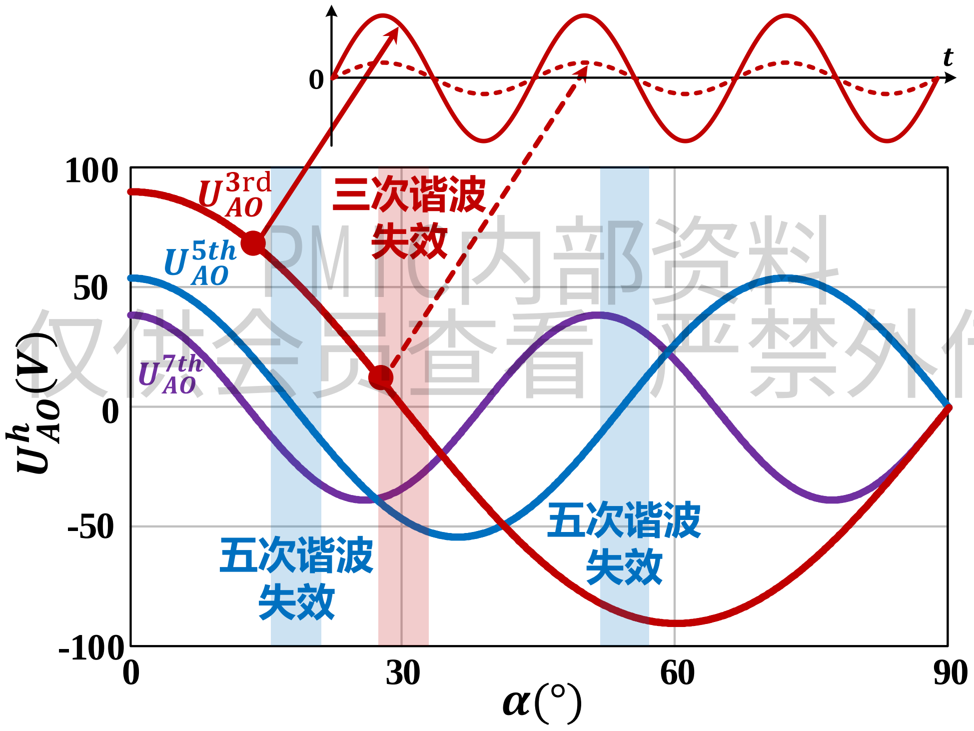

10.0A/
10.0A/
20.0V/
100V/
50.00ms/
0.0s
Stop
150ms
$u_{c.A1}$(20V/div)
44V(8%)
50ms
V_{bus}(100V/div)
75%load
25%load
I_o(10A/div)
$I_{in.A}$(10A/div)
5ms/div

- Bode diagram for DC bus voltage loop



- Bode diagram for MISN voltage loop




0
t
100
50
0
-50
-100
U_{AO}^{3rd}
U_{AO}^{5th}
U_{AO}^{7th}
三次谐波
失效
五次谐波
失效
五次谐波
失效
$U_{AO}^{h}(V)$
0
30
60
90
$\alpha(°)$

Comparison for Basic Multilevel Topology

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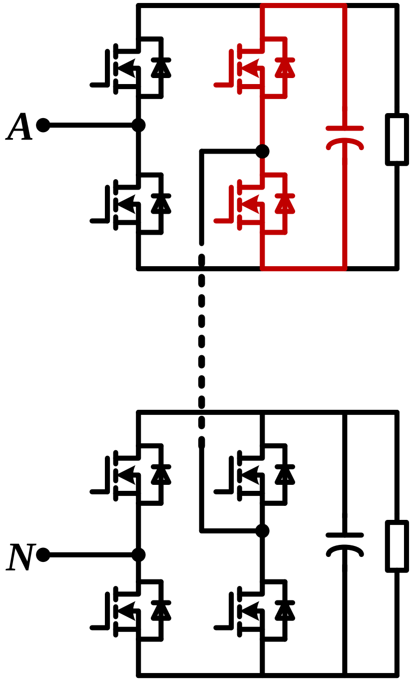
- CHB

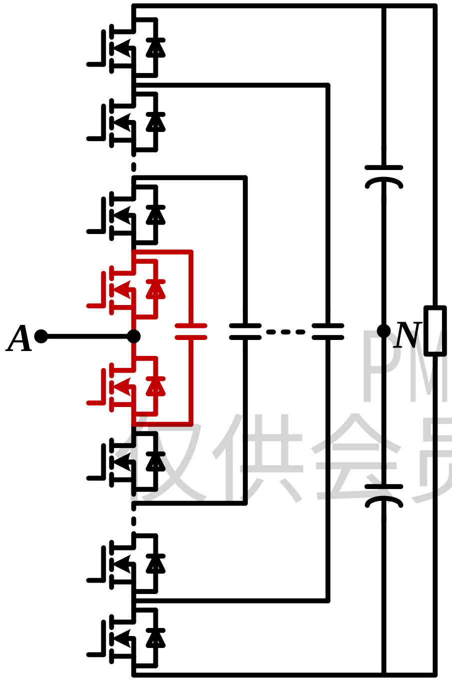


✓ Good Modularity

! Multiple DC Bus

Complicated structure
Bulky Capacitor

- FC

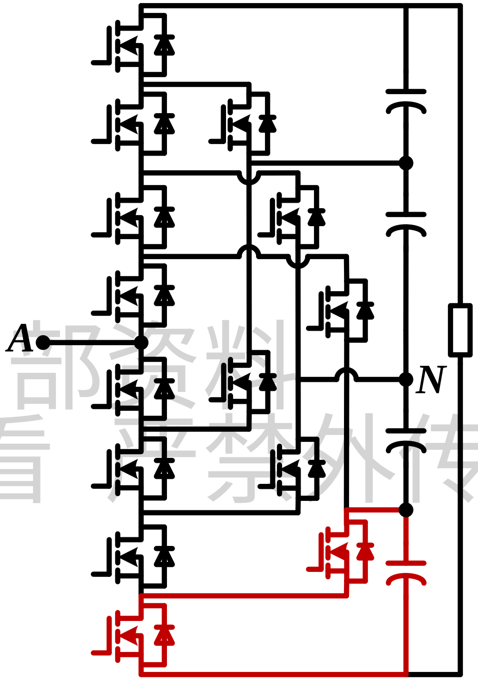


✓ Single DC Bus

! Bad Modularity

Short fault protect
Redundancy

- ANPC



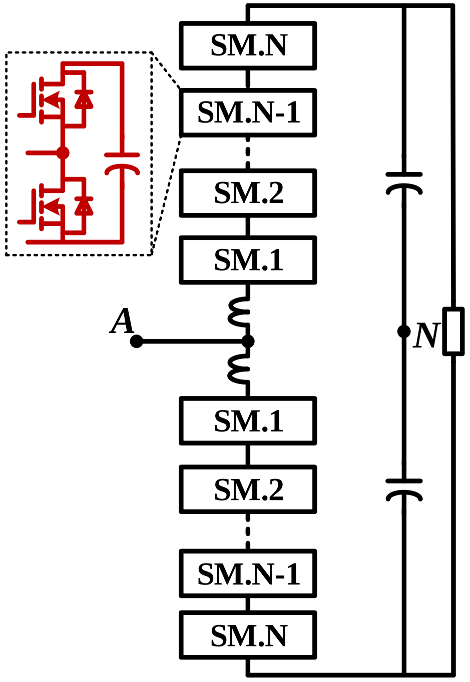
✓ Single DC Bus

! Bad Modularity

Redundancy

! More switches

- MMC



✓ Single DC Bus

✓ Good Modularity

! More switches

! More Capacitors

Larger capacitance

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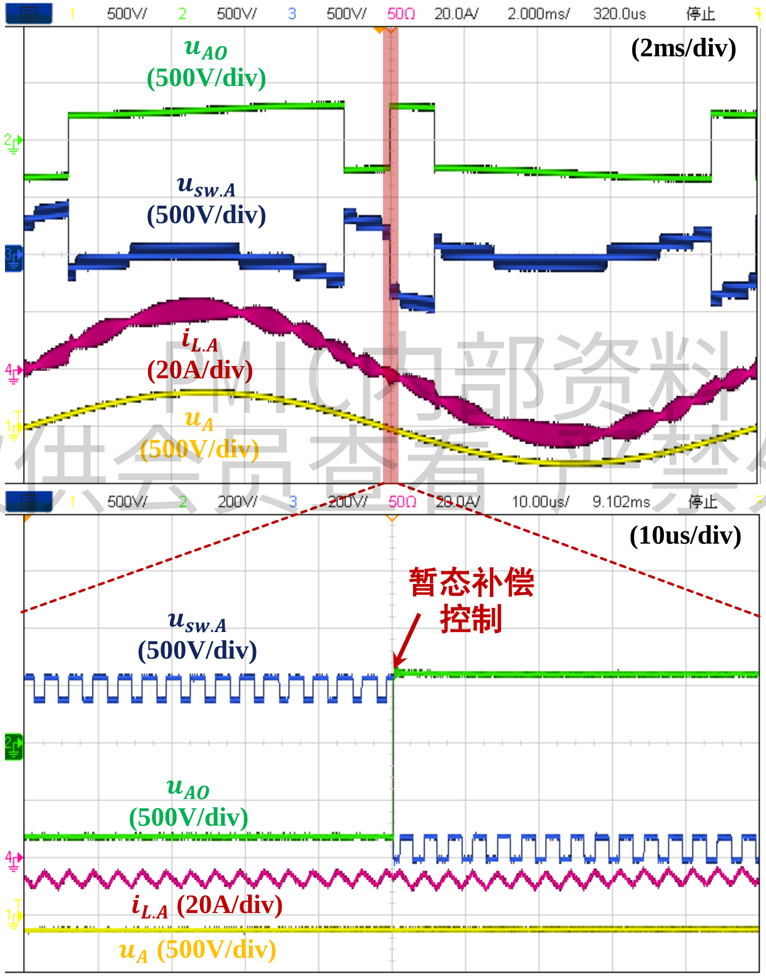
500V/ 500V/ 500V/ 50Ω 20.0A/ 2.000ms/ 320.0us 停止
u_{AO} (500V/div)
(2ms/div)
$u_{sw.A}$ (500V/div)
$i_{L.A}$ (20A/div)
u_A (500V/div)
500V/ 200V/ 200V/ 50Ω 20.0A/ 10.00us/ 9.102ms 停止
(10us/div)
暂态补偿
控制
$u_{sw.A}$ (500V/div)
u_{AO} (500V/div)
$i_{L.A}$ (20A/div)
u_A (500V/div)