High Efficiency and High Power Density Three-phase MISN-PFC with Wide DC Bus

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

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2004 — 12V PSU

2012 — Gen1: 12V POL

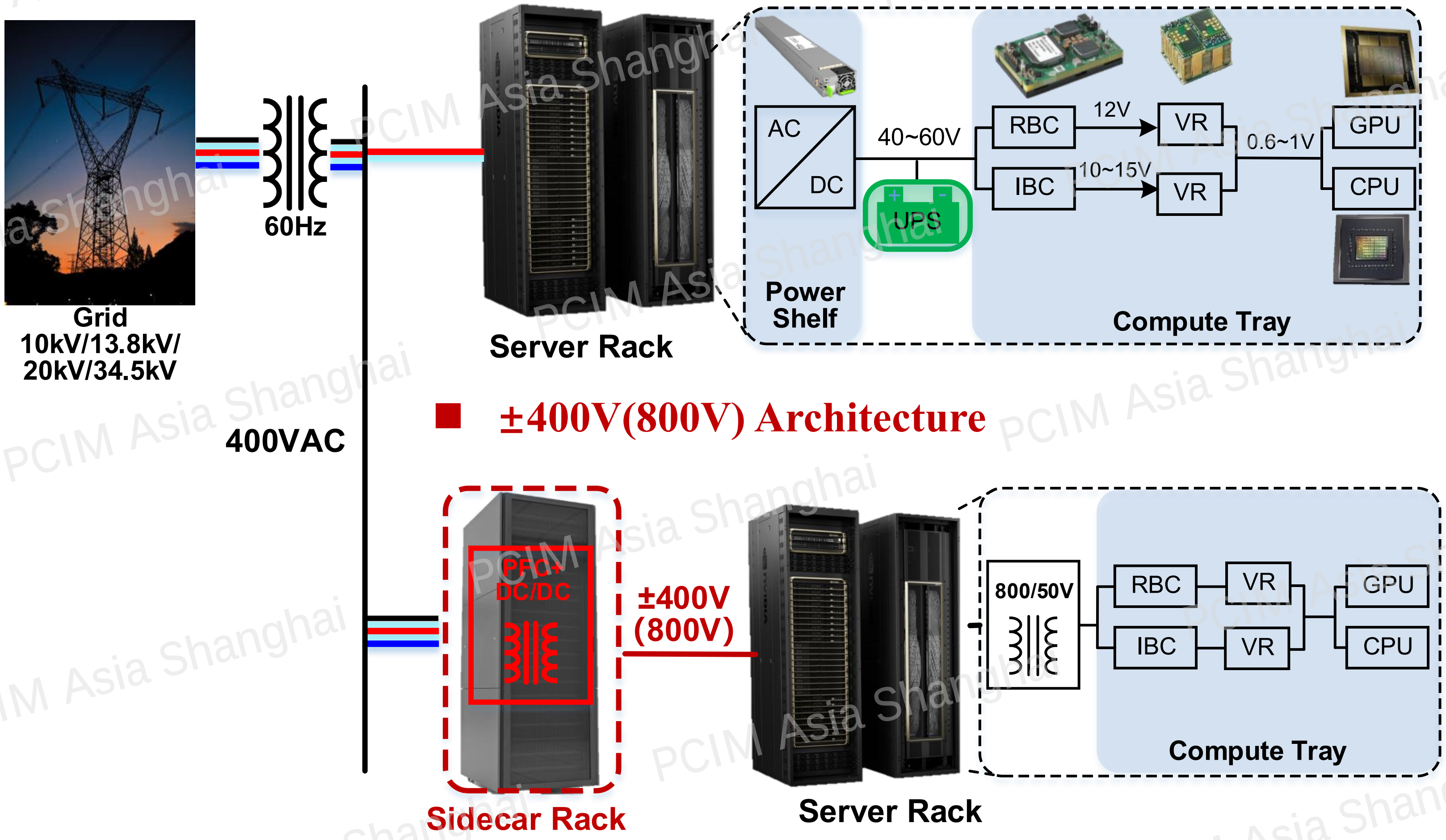
2013 — Gen2: 48V Rack&UPS

2015 — Multi48VtoPoL solutions

2017 — Open Rack V2.0 48V through OCP

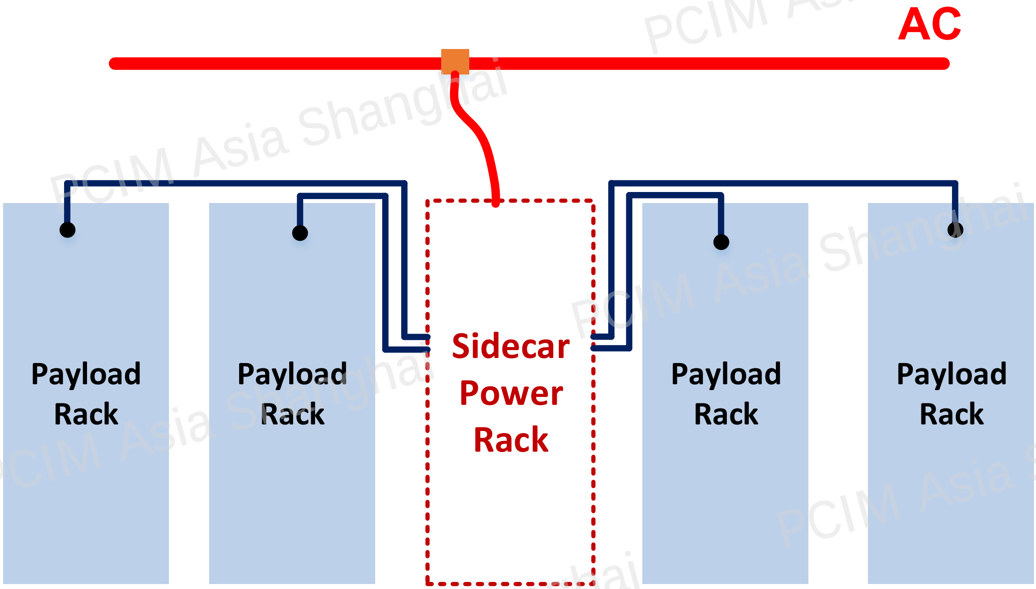
2024.10 — OCP ±400Vdc(800V) Power supply

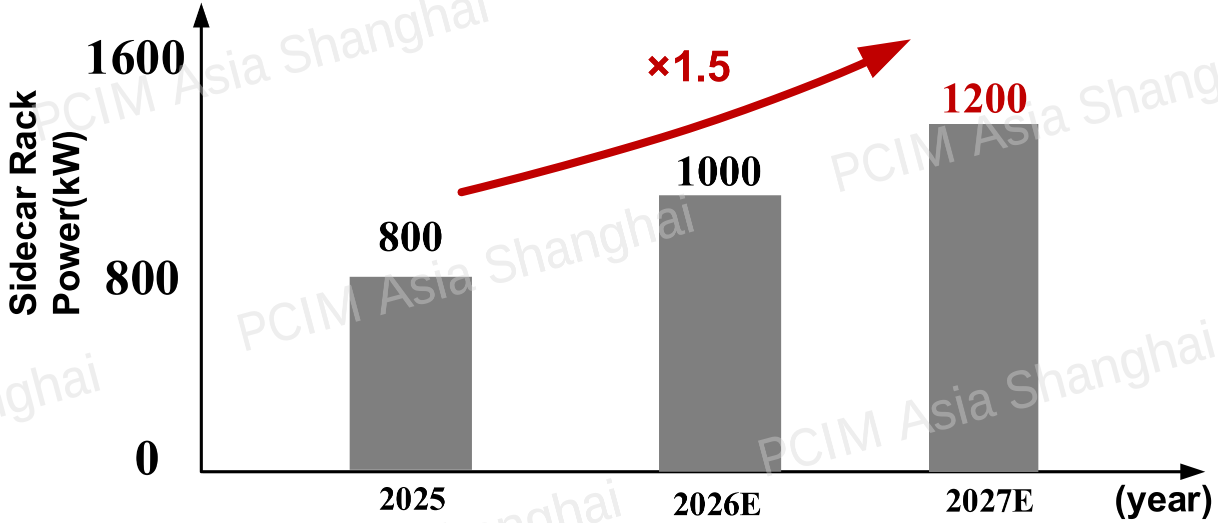
(year)



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

Trend of Sidecar Rack Power



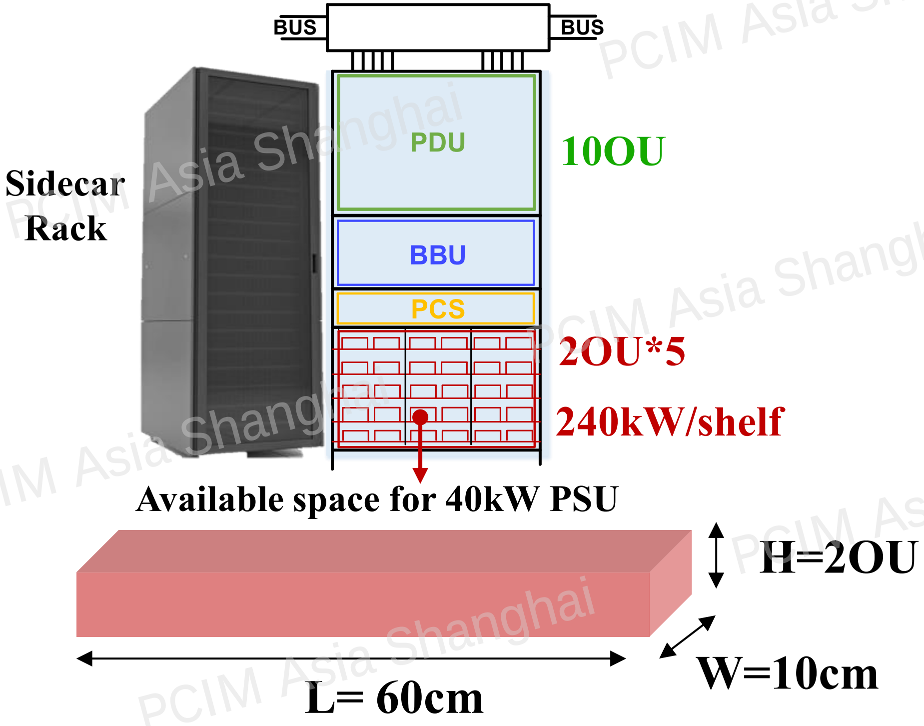


The power of server rack has been rapidly increasing

- OCP Global Summit 2024 - Google

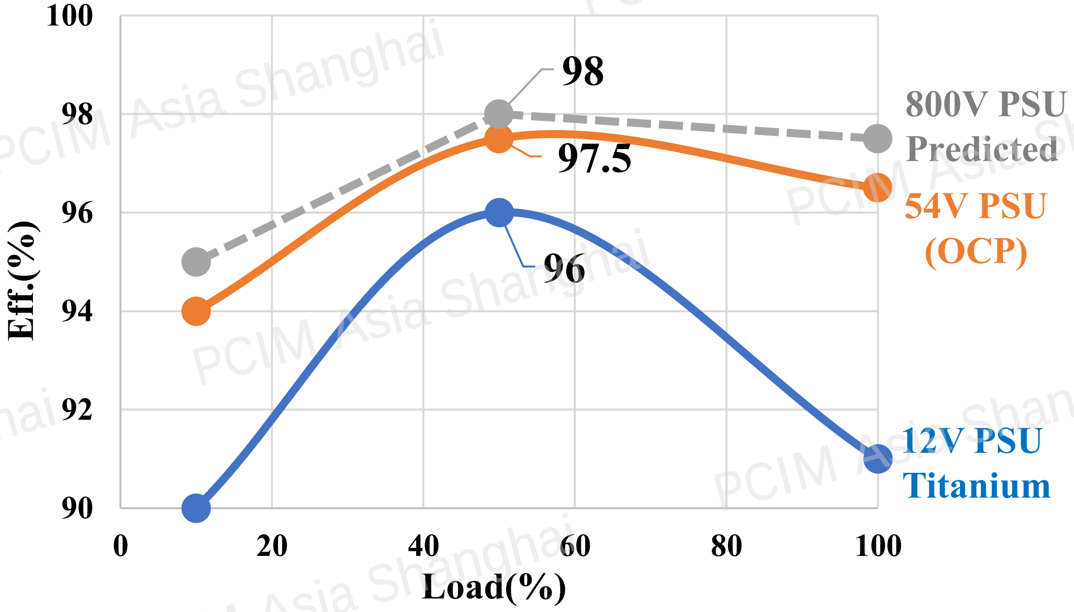
High Efficiency High Density for Server PSU

➢ **High Power Density**



Power Density: >150W/in^3

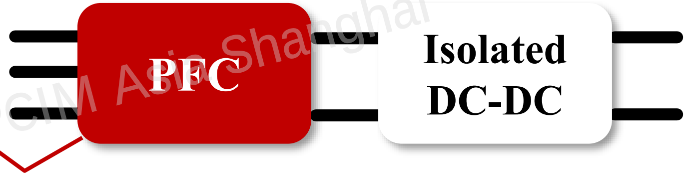
➢ **High Efficiency**

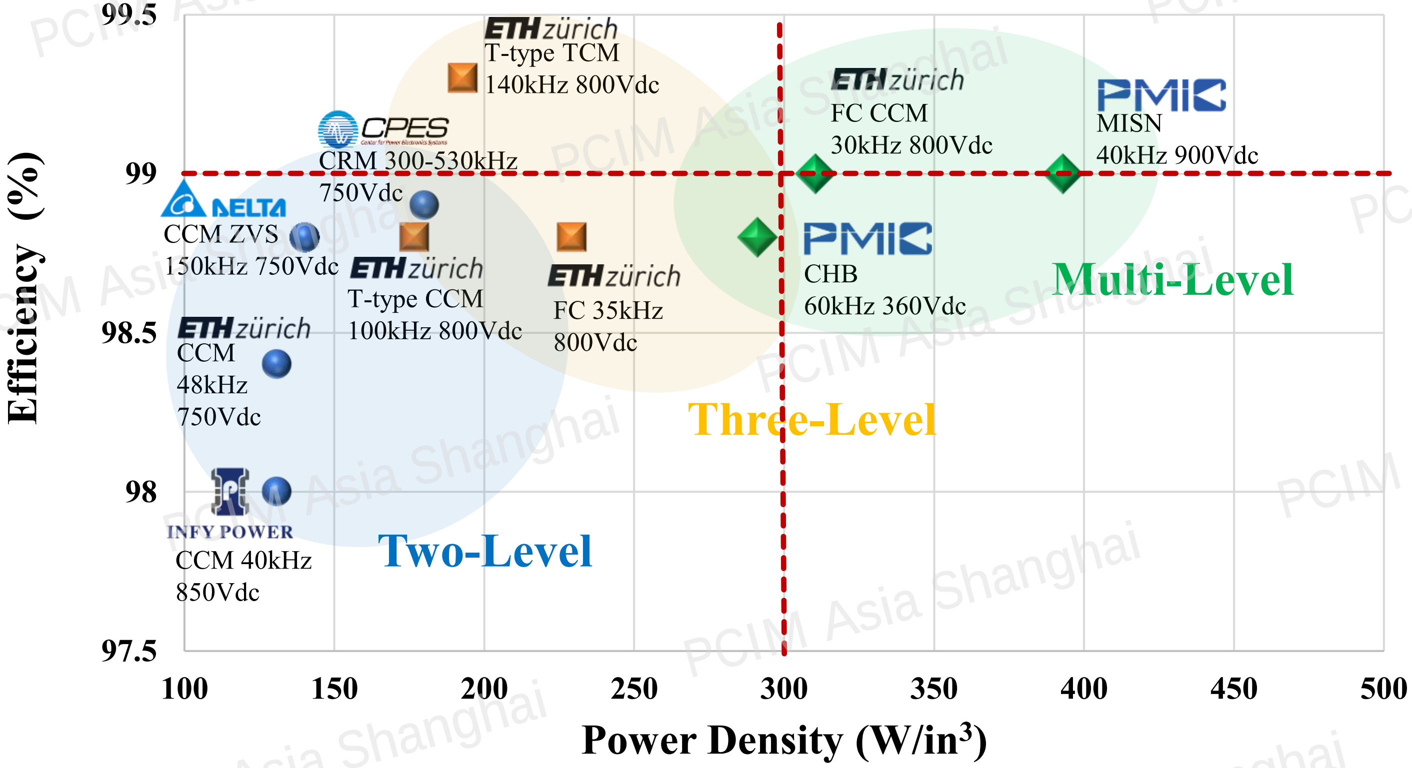


Efficiency: >98%

Comparison the Different Multilevel Topologies

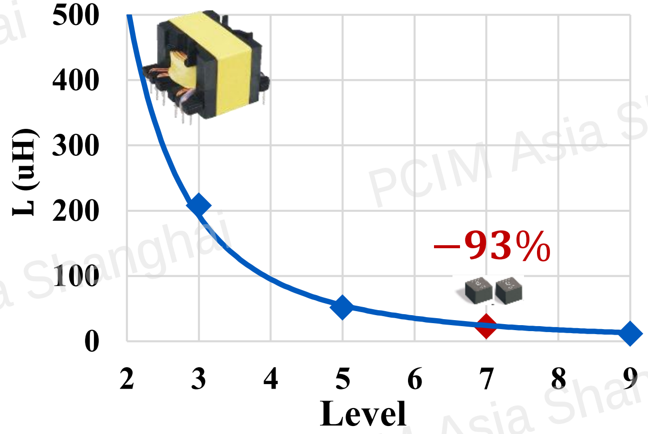
Power density: > 300W/in^3
Efficiency: > 99%



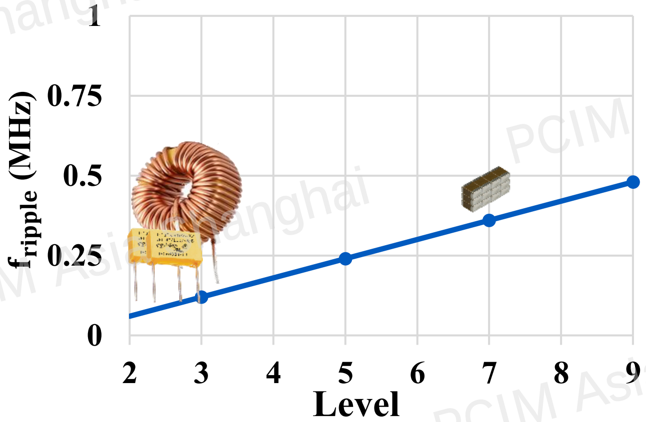


➢ The Influence of Multilevel Converter

- **Lower Volt-second**

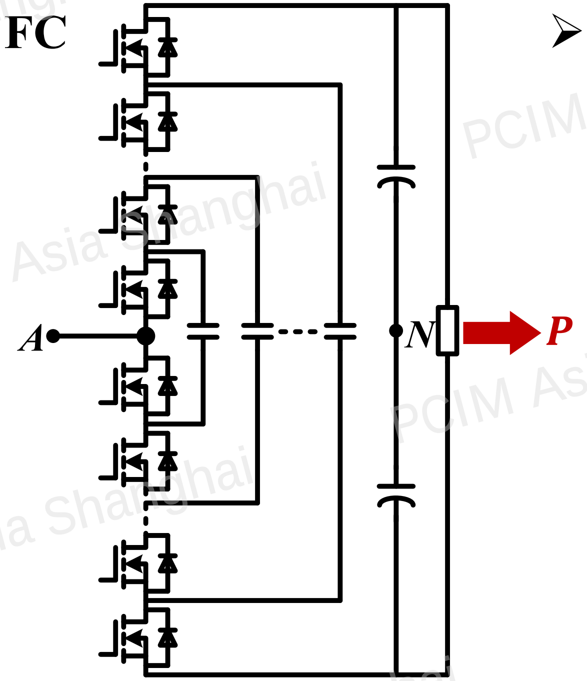


- **Higher Frequency**



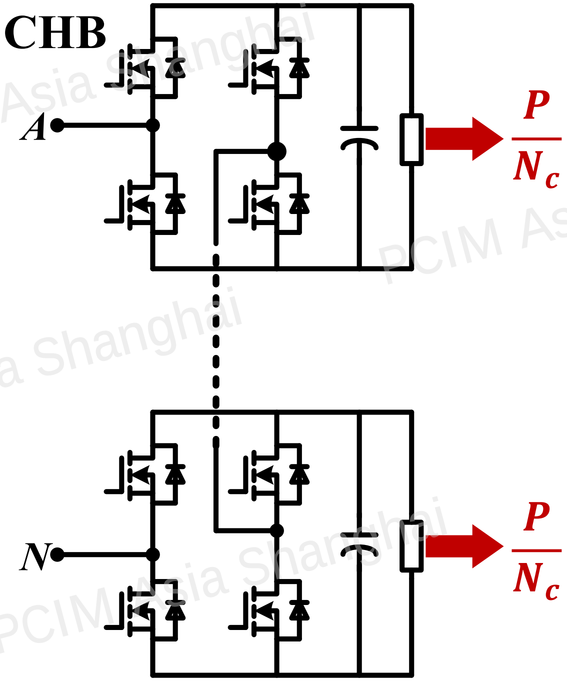
Comparison the Different Multilevel Topologies

- FC



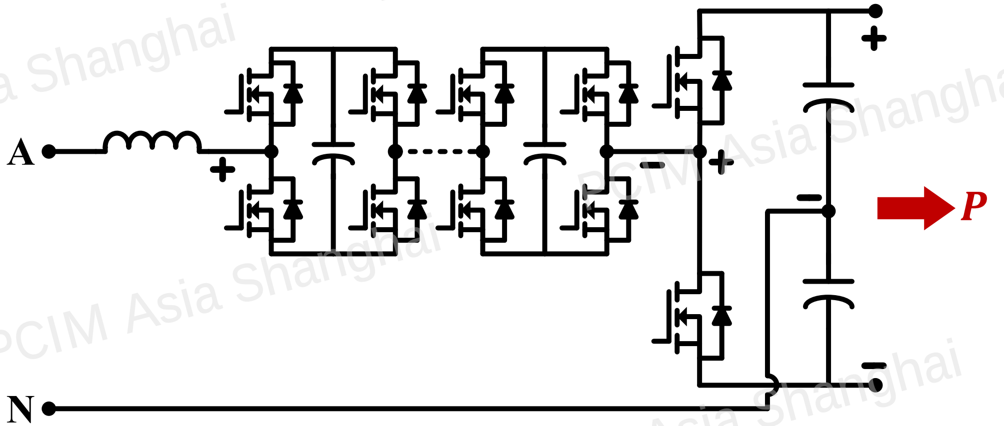
- ✓ Single DC Bus
- × Bad Modularity
  - Short fault protect
  - Redundancy

- CHB



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

- MISN (Modular Inductive Switching Network)

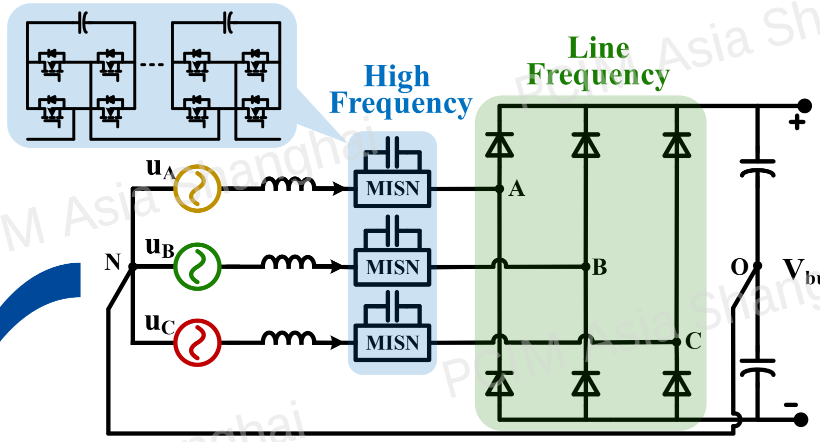


- ✓ Single DC Bus
- ✓ Good Modularity
- × Line-frequency Bridge

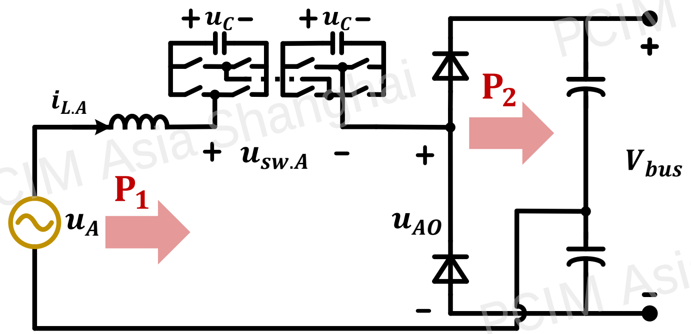
- Zhao, W., T. Huang and X. Wu, Three Phase PFC Converter With Multilevel Inductive Switching Network. TPEL, 2023.
- Zhao, W., T. Huang and X. Wu, Control Strategies and Design Guideline for Single Phase MISN PFC Converter. TIE, 2025.

Operating Principle of Diode-Based MISN Converter (Unregulated)

➢ **Diode-Based MISN-PFC Converter**

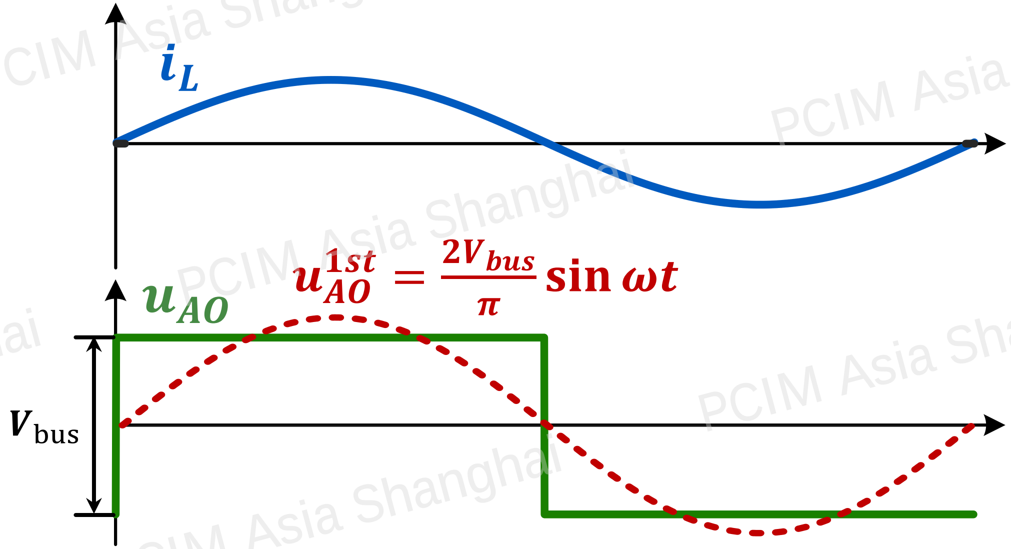


➢ **Equivalent Circuit of Phase-A**



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

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

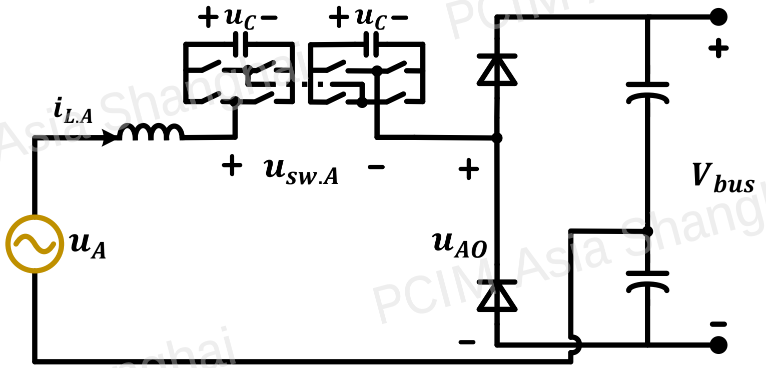


$$V_{bus} = \frac{\pi}{\sqrt{2}} U_A$$

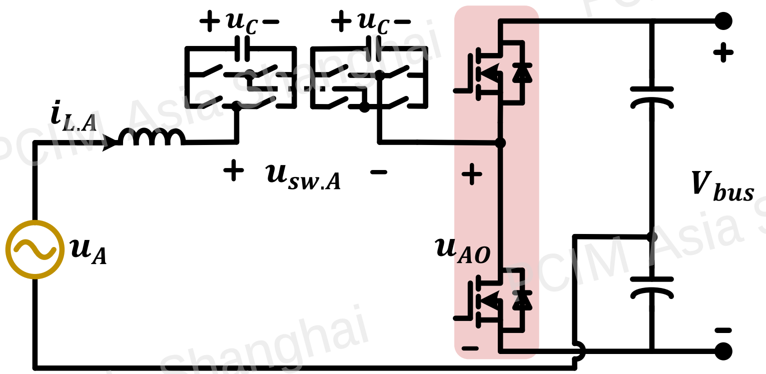
- MISN: Modular Inductive Switching Network

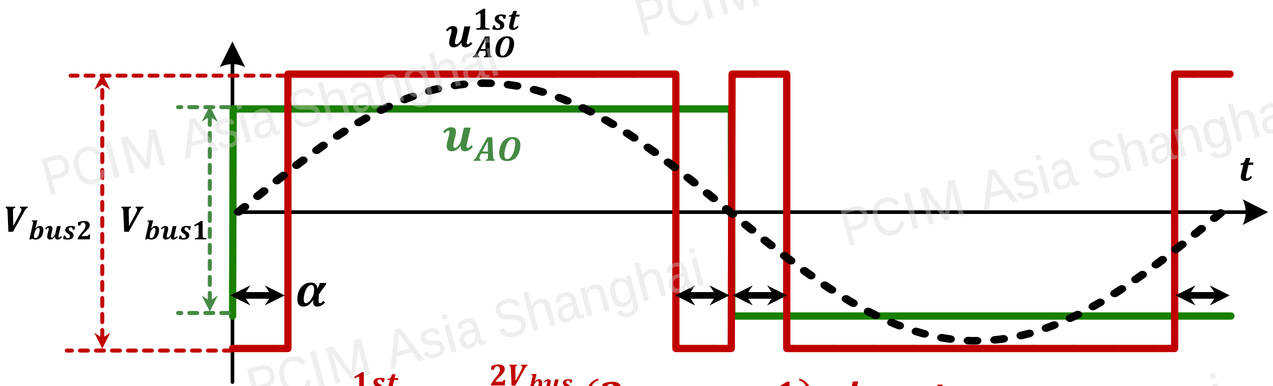
Regulated DC Bus Voltage for MISN Converter

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



- **Switch Based**



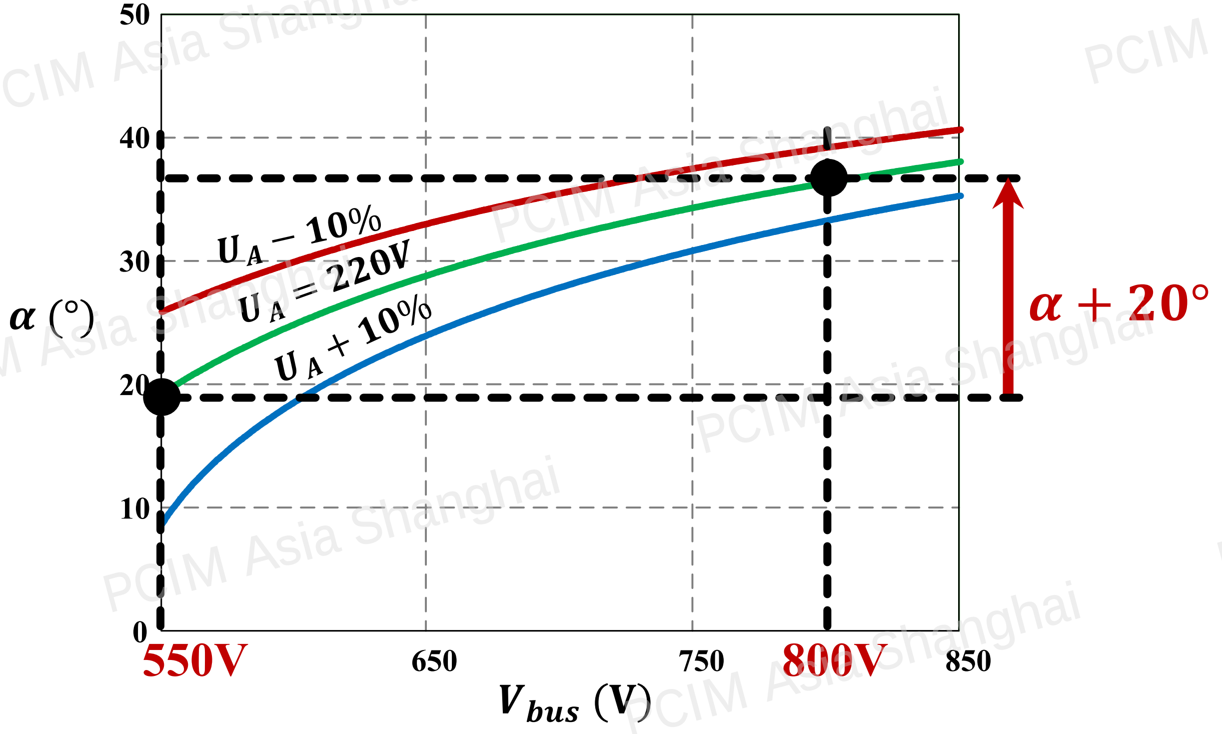


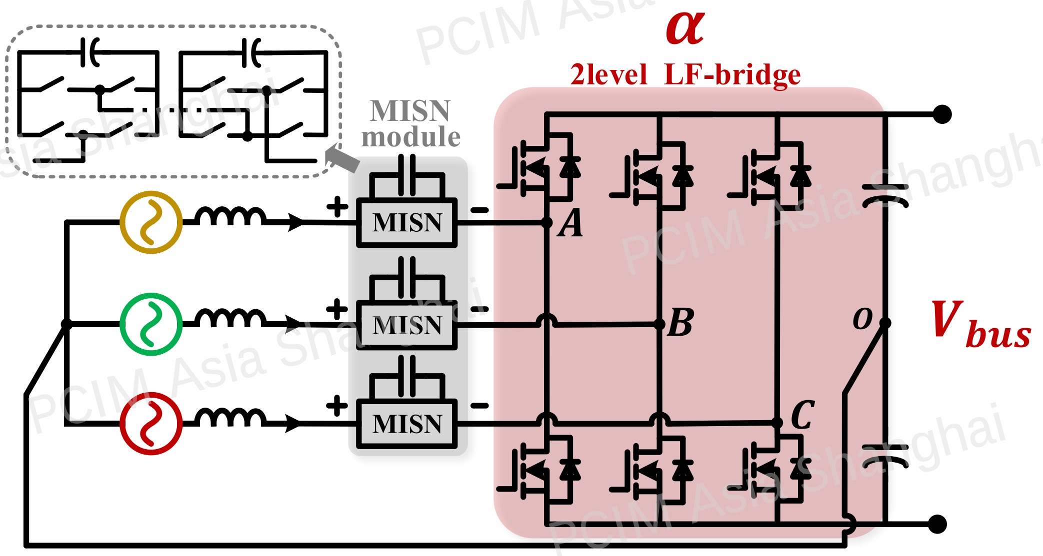
$$u_{AO.\alpha}^{1st} = \frac{2V_{bus}}{\pi}(2\cos\alpha - 1)\sin\omega t$$

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

The DC Bus Voltage is Positively Correlated with α

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





What is the impact of the increased α?

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

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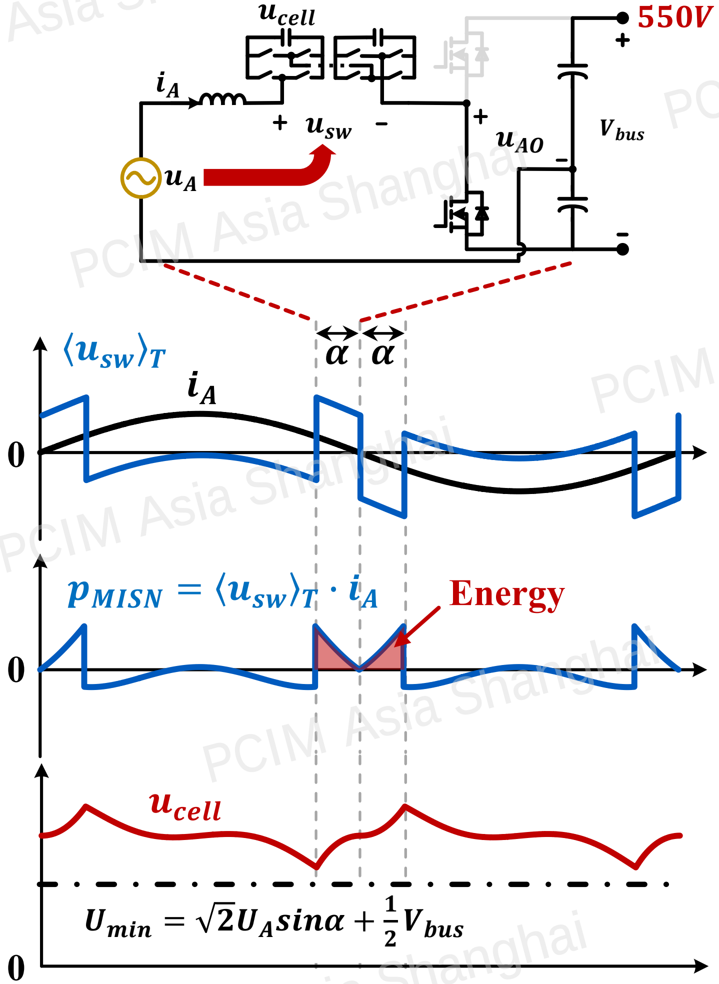
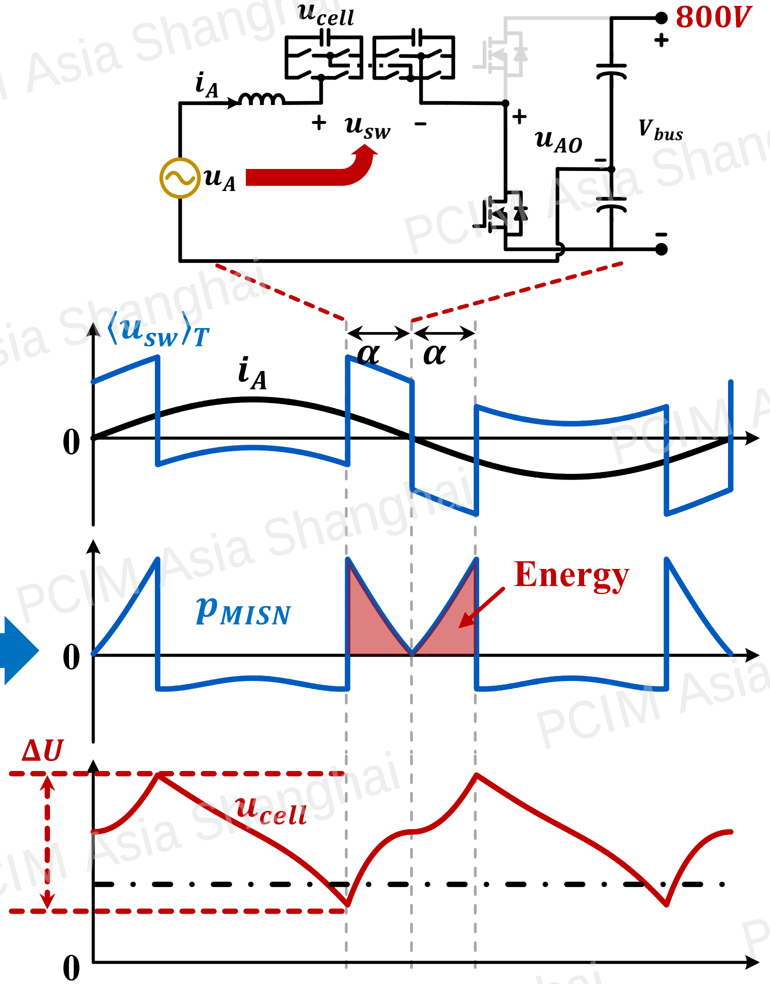
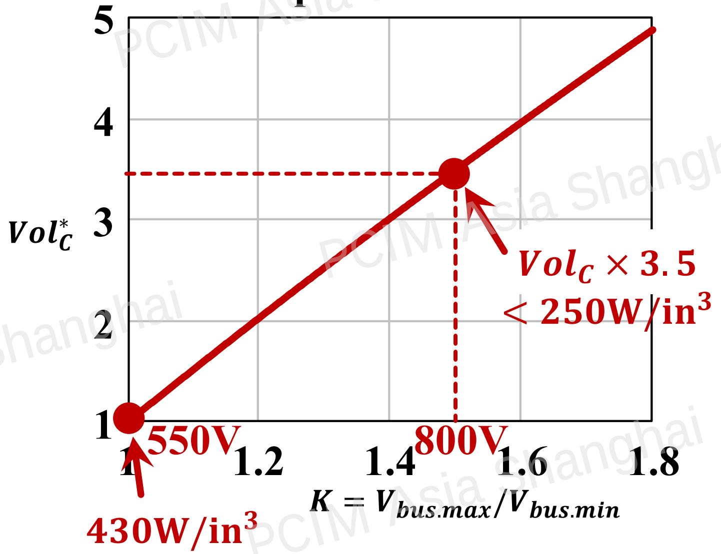
- Charing Mode of MISN Module





Larger capacitance is required

- Mathematical model for MISN Capacitor Volume



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

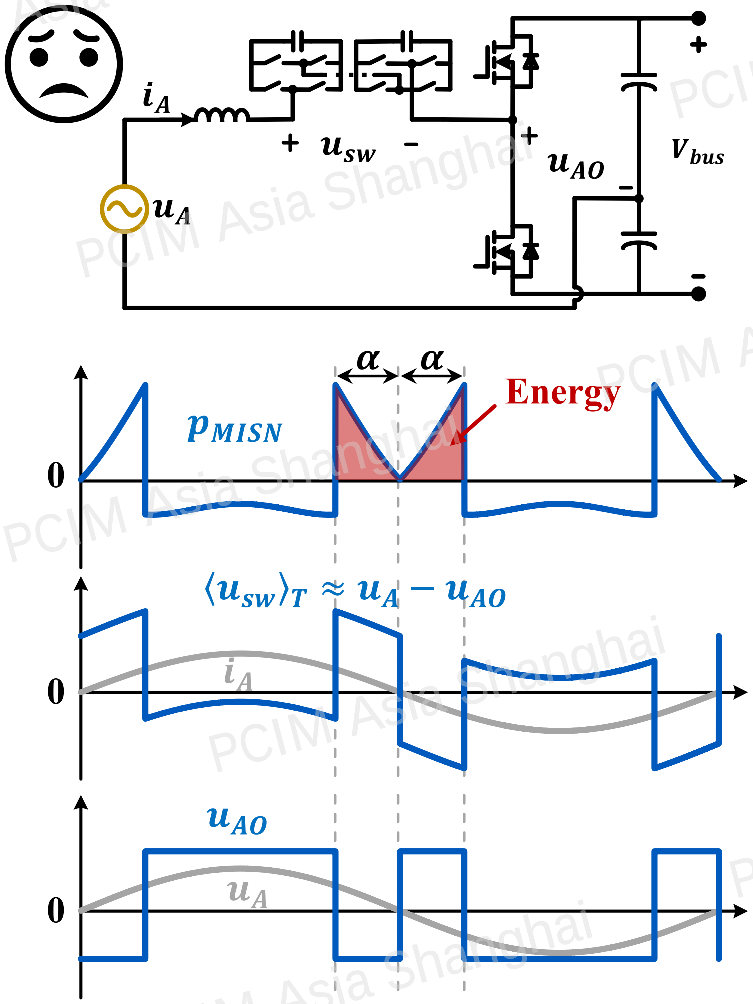
$$Vol_C = \frac{2P}{\omega E_D \Delta U}\left(2\alpha - \sin(2\alpha) - \frac{\pi(\cos\alpha - 1)}{2\cos\alpha - 1}\right)$$

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

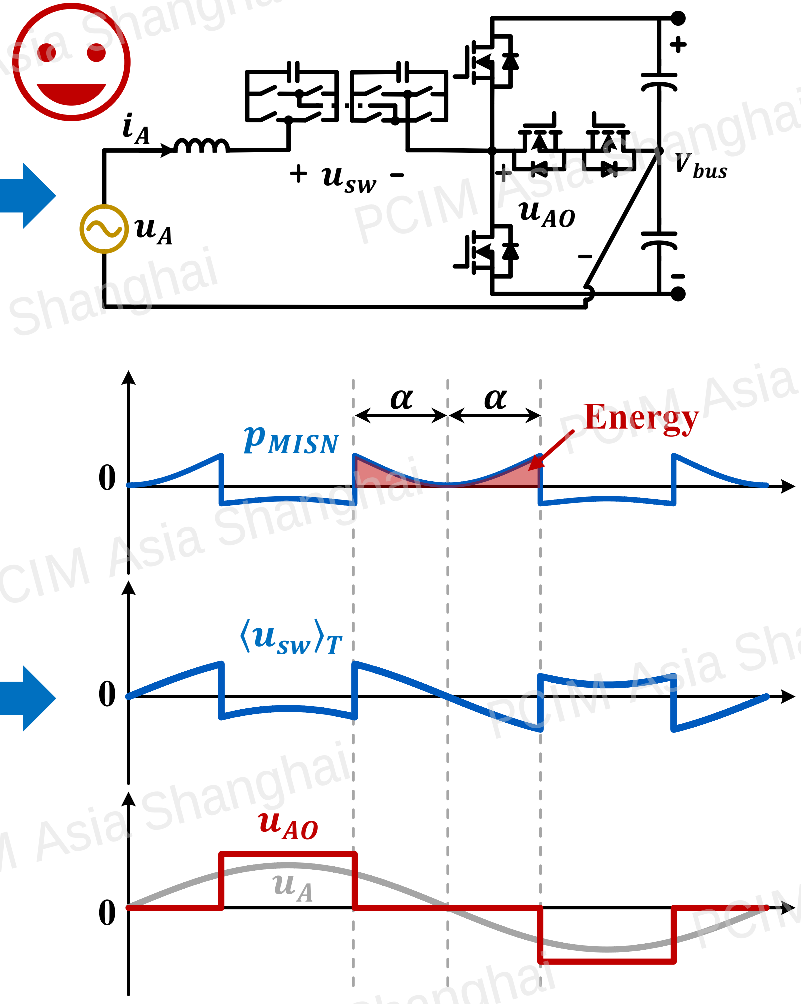
$$\Delta U = 20\%$$

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

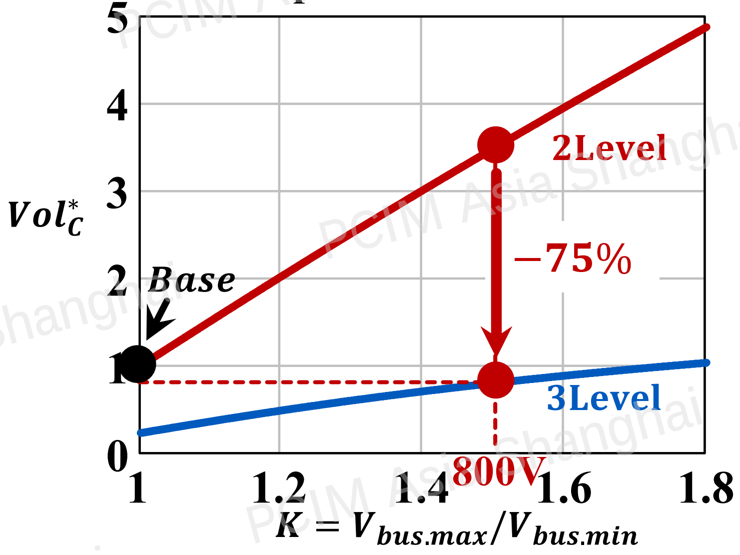
- 2-level LF-bridge



- T-type 3-level LF-bridge



- Mathematical model for MISN Capacitor Volume



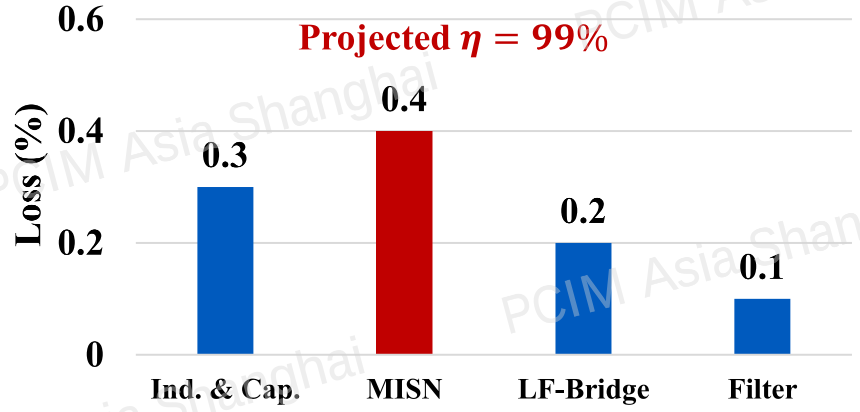
$$Vol^*_{C.2level} = \frac{Vol_{C.2level}(K \cdot V_{bus.min})}{Vol_{C.2level}(V_{bus.min})}$$

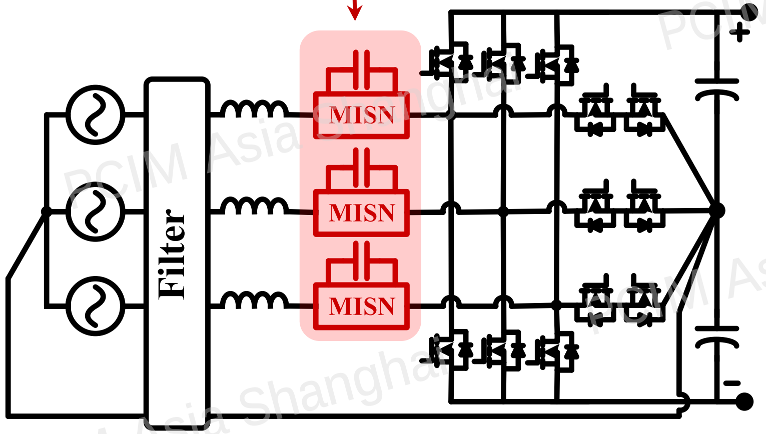
$$Vol^*_{C.3level} = \frac{Vol_{C.3level}(K \cdot V_{bus.min})}{Vol_{C.2level}(V_{bus.min})}$$

T-type 3-level LF-bridge is adopted

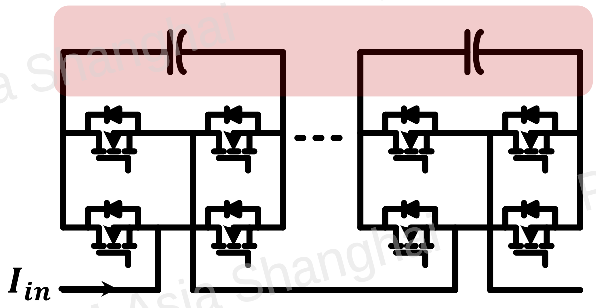
Loss Model for MISN Module (Parameters: N_c, f_s, V_{BR})

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

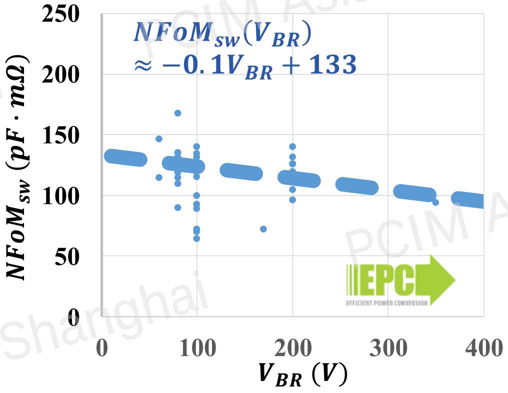


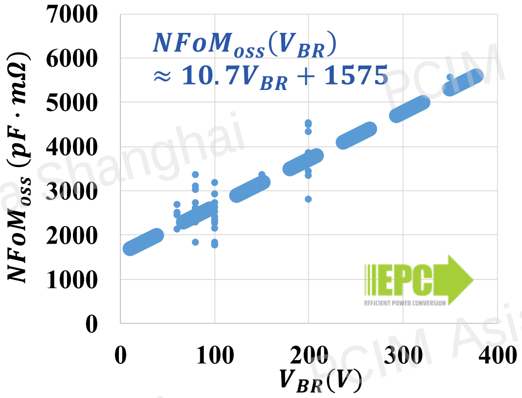


- Minimum Loss Model of MISN Module (GaN)



$$P_{Loss.min}(N_c, f_s, V_{BR})$$
$$= 4(U_{c.total})\, I_{in}\sqrt{k_{temp}k_{dyn}(k_{sw}I_{in}NFoM_{sw} + NFoM_{oss})f_s}$$
$$= 4(0.7V_{BR}N_c)\, I_{in}\sqrt{k_{temp}k_{dyn}(k_{sw}I_{in}NFoM_{sw}(V_{BR}) + NFoM_{oss}(V_{BR}))f_s}$$

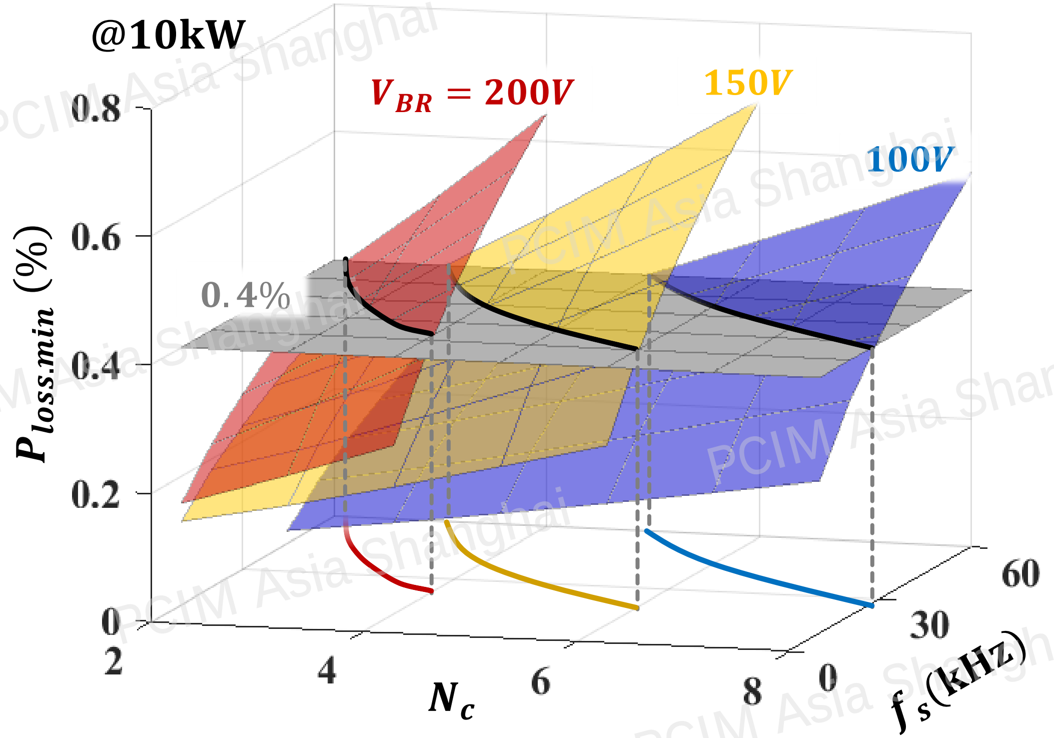




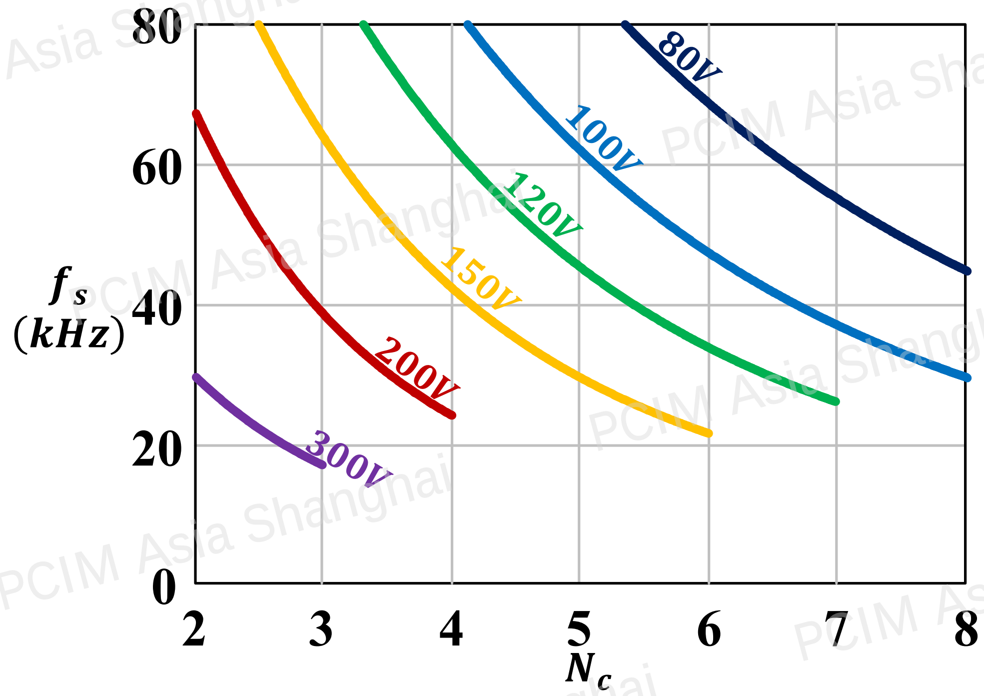
- J. Wu, X. Wu , et al., “A Unified Switch Loss Model and Design Consideration for Multilevel Boost PFC -”, TPEA 2021.

The Limitation for f_s based on the Projected Loss

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



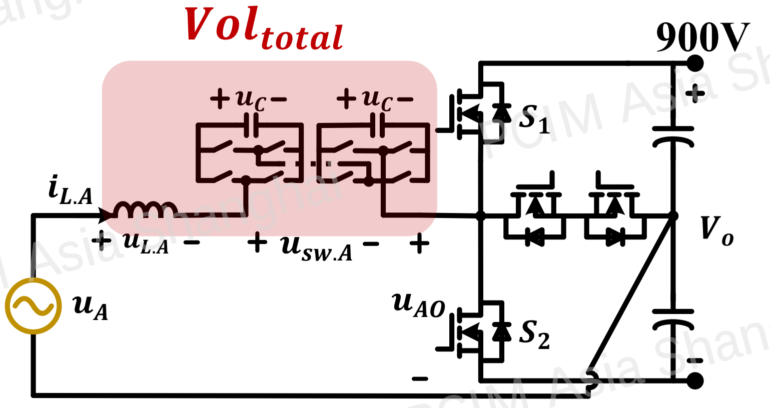
- The Limitation for f_s



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

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

Volume Optimization for 0.4% Loss Limit

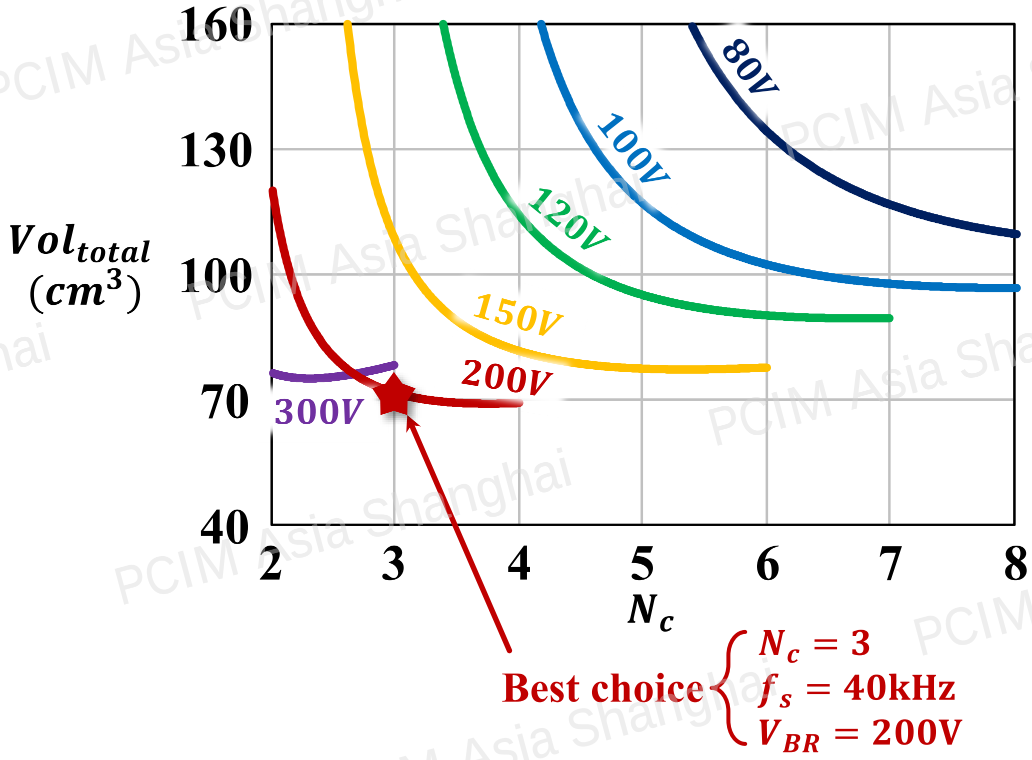


$$Vol_{total} = Vol_L + Vol_C + Vol_{cell}$$

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

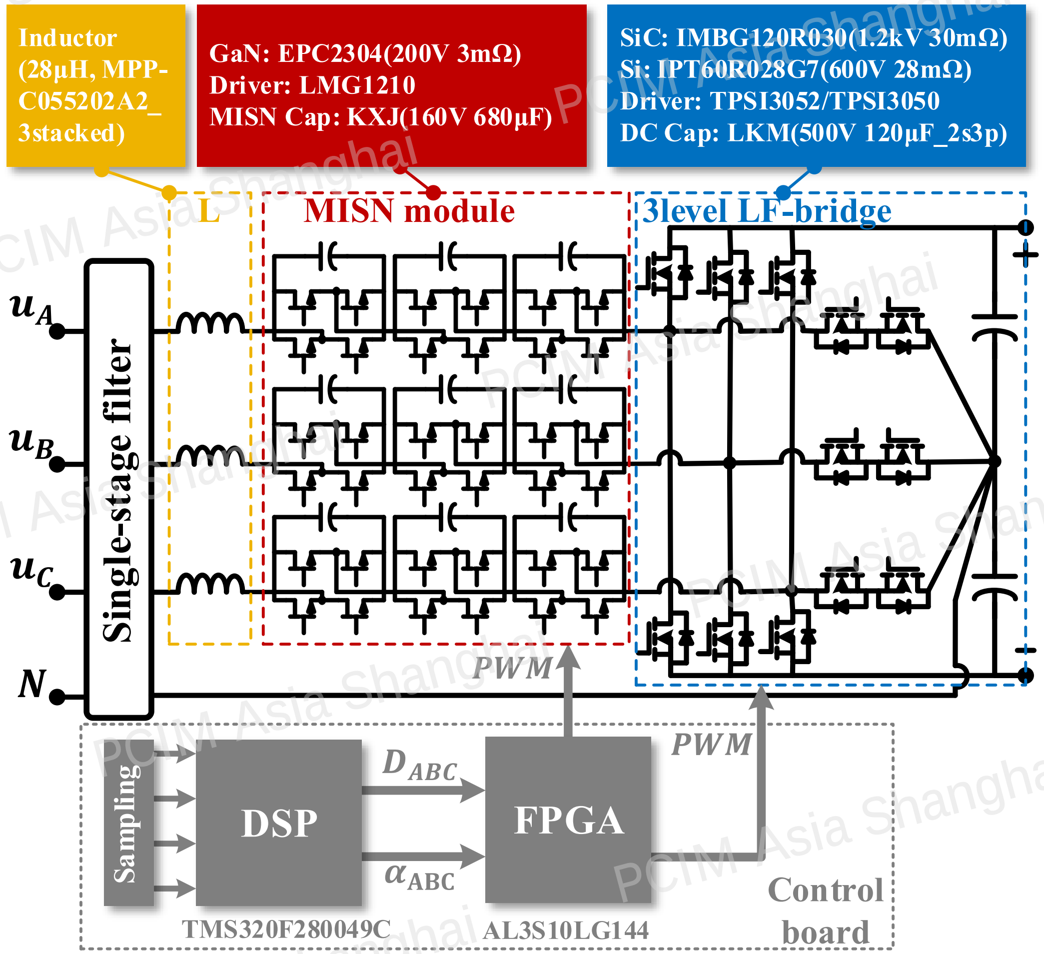
- **Capacitor Volume:** $Vol_C(N_c, V_{BR}) = \dfrac{\frac{1}{2}(1.2C_{eq.min})(V_{BR})^2}{E_D}N_c$

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

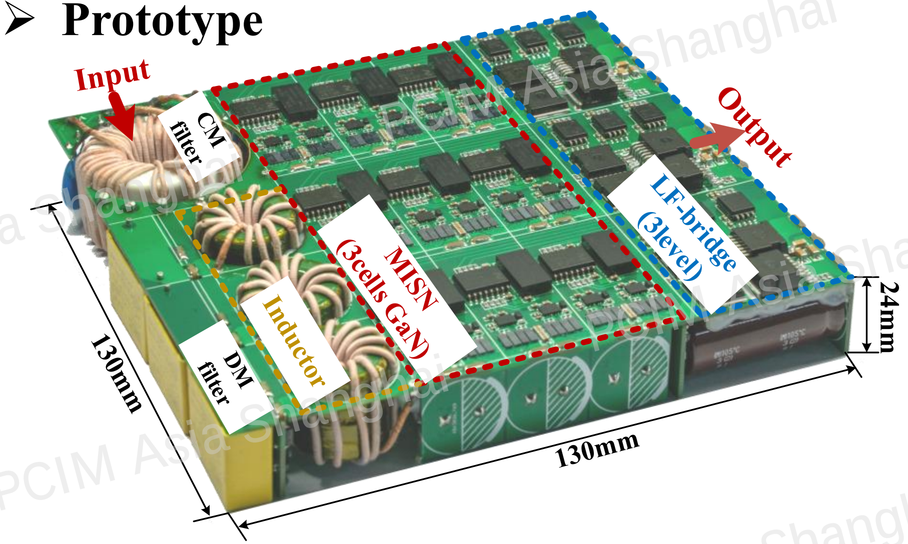


Hardware Implementation

➢ **Schematic Diagram**



➢ **Prototype**



Power Density: 400W/in^3 (~25kW/L)

Parameter	Value
Power	10kW
Input Phase Voltage	$220V_{RMS} \pm 10\%$
DC Bus Voltage	Typical: 800V 550V~900V
MISN Voltage	$3 \times 120V$
Frequency (MISN)	40kHz

Sponsor: Infineon, POCO MAGNETIC, NIPPON CHEMI-CON, Coilcraft, PMIC

The Waveforms of Currents at Full-load

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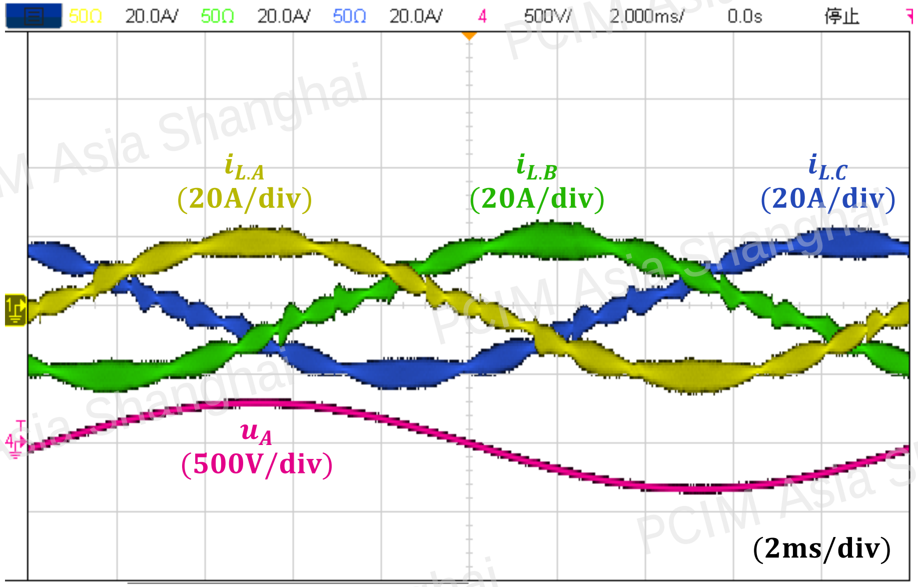
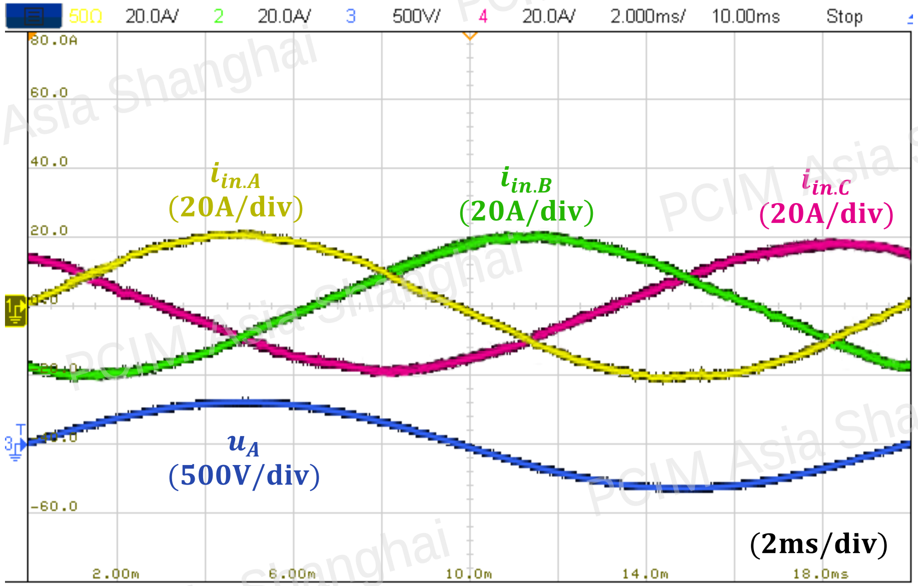
➢ **Three−phase Inductor Currents**

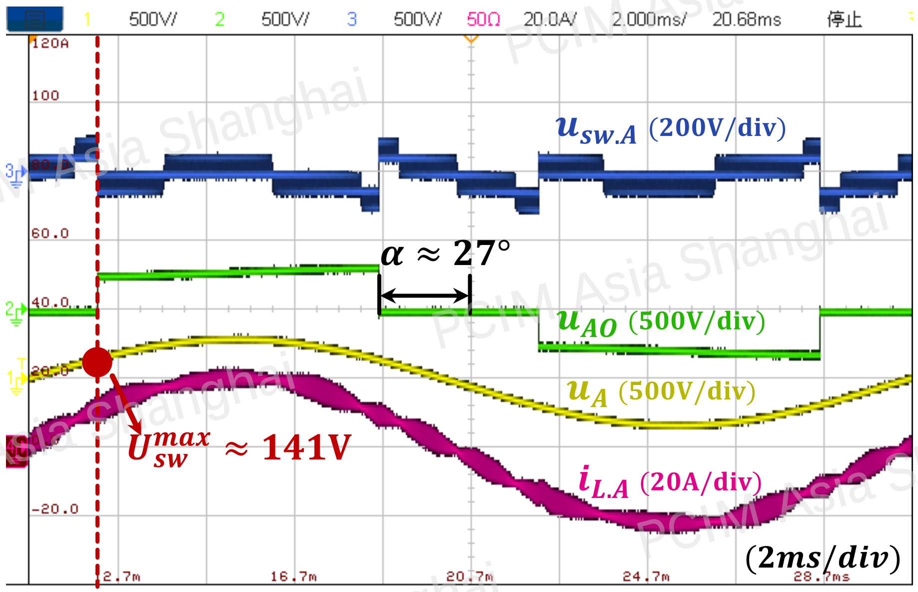


➢ **Three−phase Input Currents**

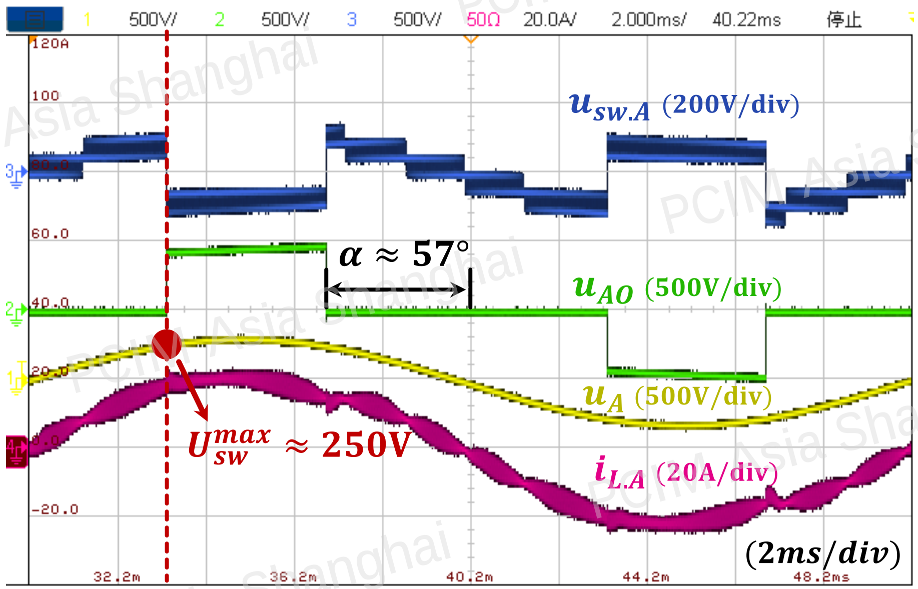


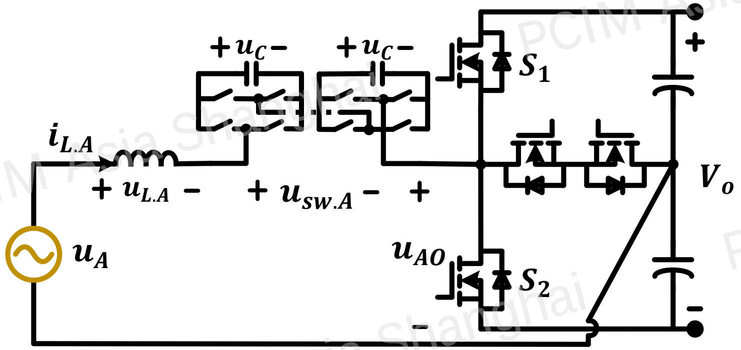
The Waveforms of AC-side Voltages and MISN Voltage Stress

- $V_{bus} = 550V$

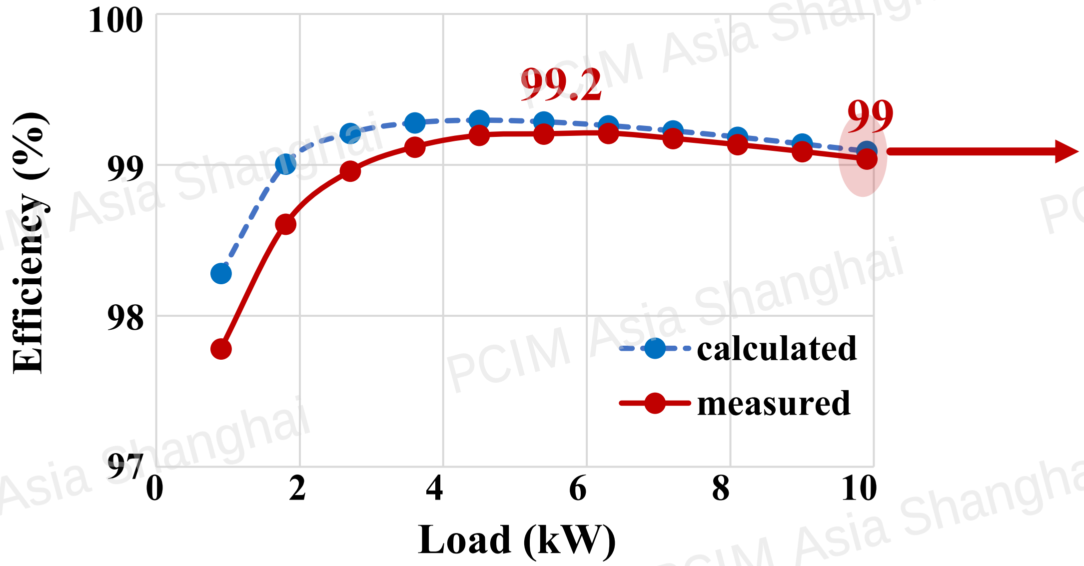


- $V_{bus} = 800V$



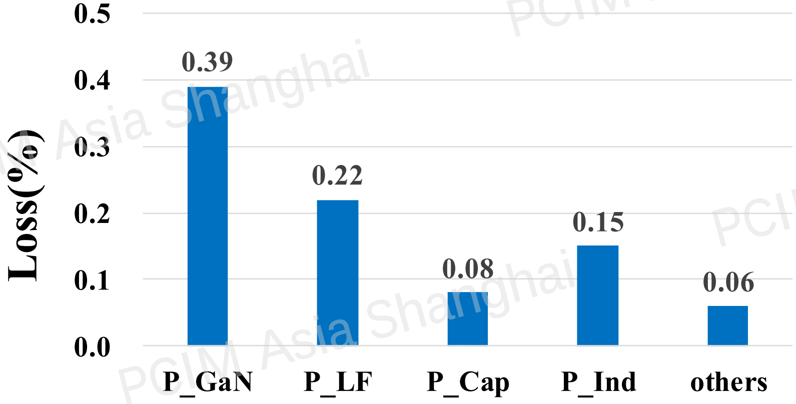


Efficiency for the Designed MISN Converter

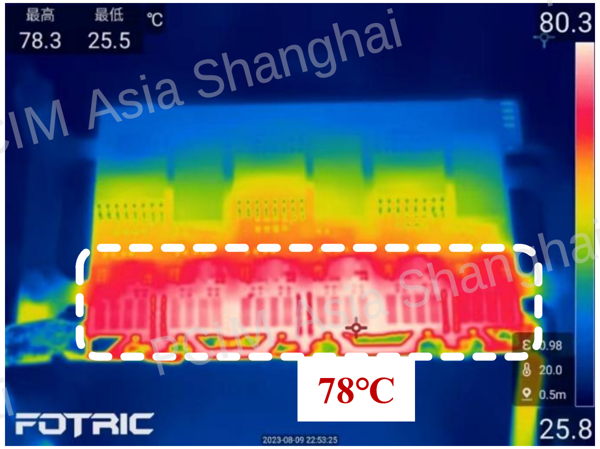


- $380V_{RMS} \rightarrow 800V_{dc}$
- Test condition: 5min/point
- exclude auxiliary loss

➢ **Loss breakdown for 10kW**



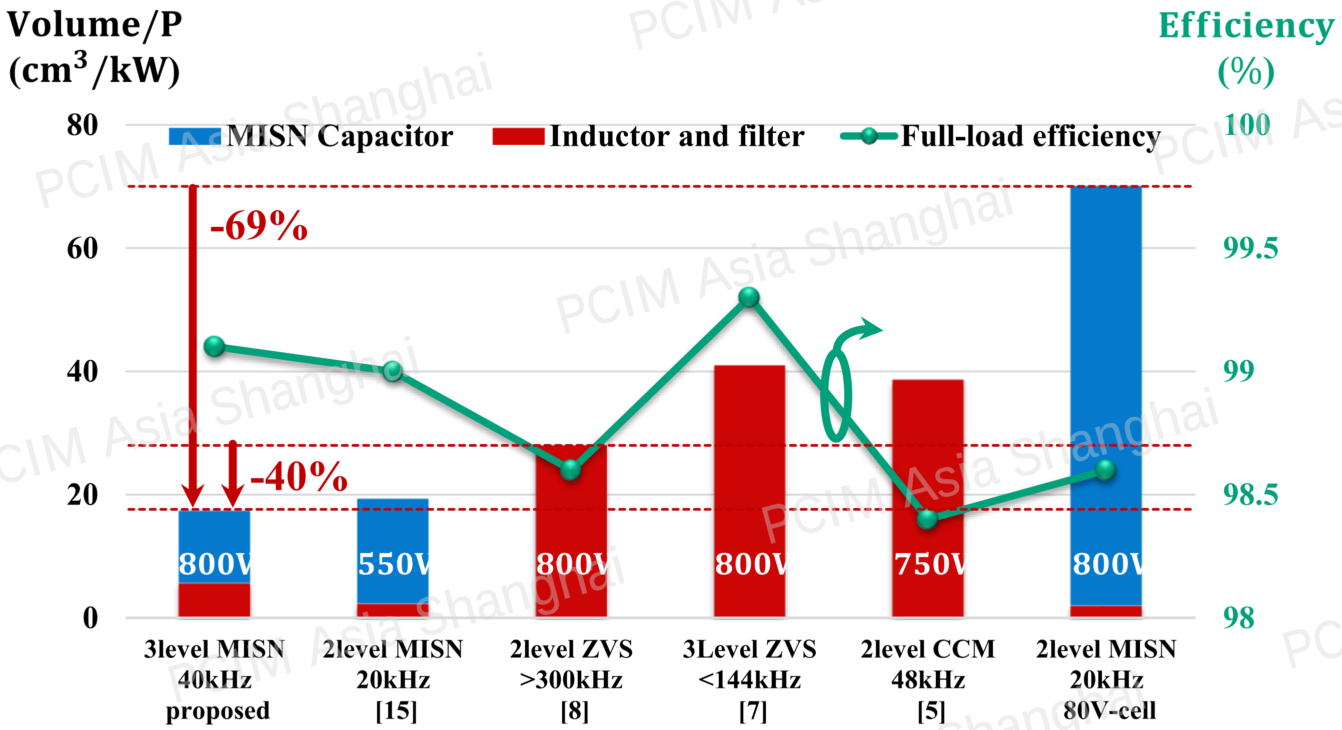
➢ **The Temperature at Full Load**



GaN & Driver

wind speed: ~3m/s

Comparison for different schematics in the aspects of components' volumes and full load efficiencies.



Ref	Type	Spec.	fs	THD	Eff	kW/L	Cost
[5]	2LB6 CCM	22kW 650~750V	48kHz	3.2%	98.4%	8	Low
[8]	2LB6 CRM	25kW 650~800V	300~530k Hz	2%	98.9%	11	Mid
[7]	T-type TCM	6kW 650~800V	140kHz	-	99.3%	11.8	Mid
[15]	MISN 2level LF	10kW 550V	20kHz	2.5%	99%	26	High
This	MISN 3level LF	10kW 550V	40kHz	3%	99%	25	High

- **Passive components' volumes are reduced more than 40%**
- **More than 99% Efficiency is achieved**

Summary

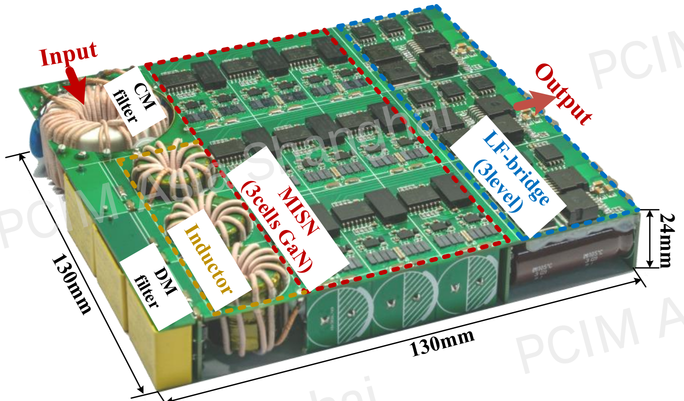
- To address the issue of reduced power density in three-phase MISN converters under a high DC bus voltage, the impact of bus voltage on the buffer energy of the MISN was modeled and analyzed. **This revealed the critical influence of the line-frequency rectifier bridge on the MISN capacitor size**.

- A topology optimization method was proposed using a T-type three-level line-frequency rectifier bridge. Compared to a two-level design, **this reduced the required MISN capacitor volume by 75% at a 800V bus voltage**.

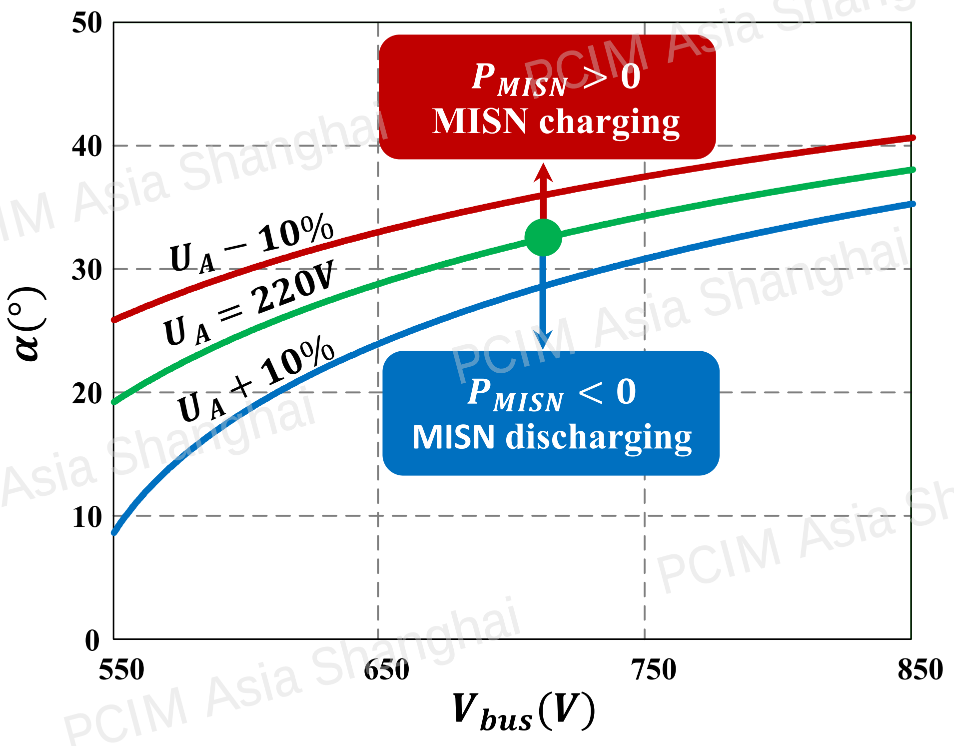
- For the multi-variable optimization challenge of the MISN converter, **a minimum loss model and a volume model for key components were established**. A hierarchical optimization design method was subsequently proposed to fully exploit the potential for efficiency and power density.

- A prototype was built and tested with 800V DC bus. It achieved a **power density of 400W/in^3** and a **peak efficiency of 99.2%**.

Thanks!



The Principle for MISN Voltage Control



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

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

- **In the curve**

  $P_{MISN} = 0$, Power balance

- **Above the curve**

  $P_{MISN} > 0$, Charging mode

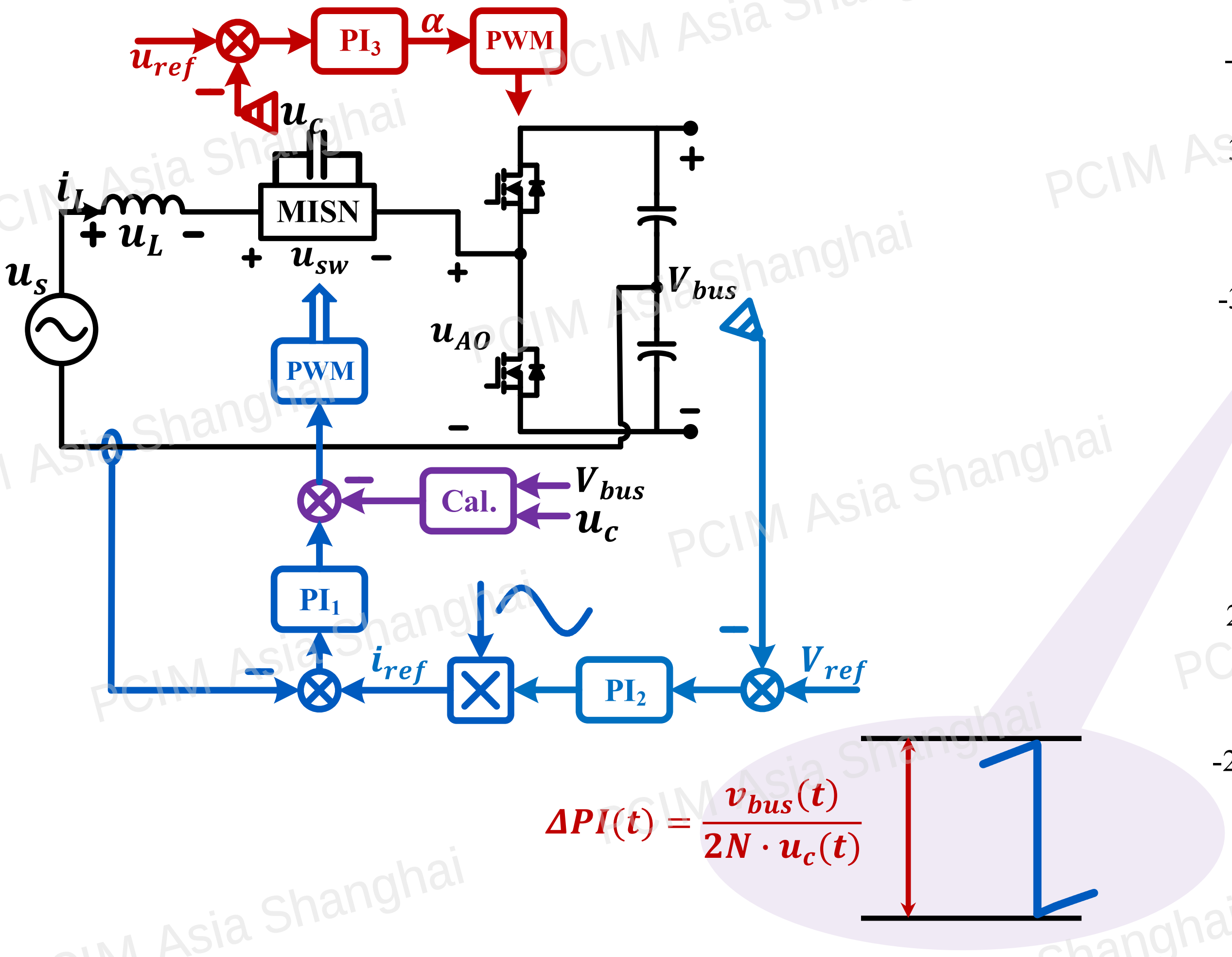
- **Below the curve**

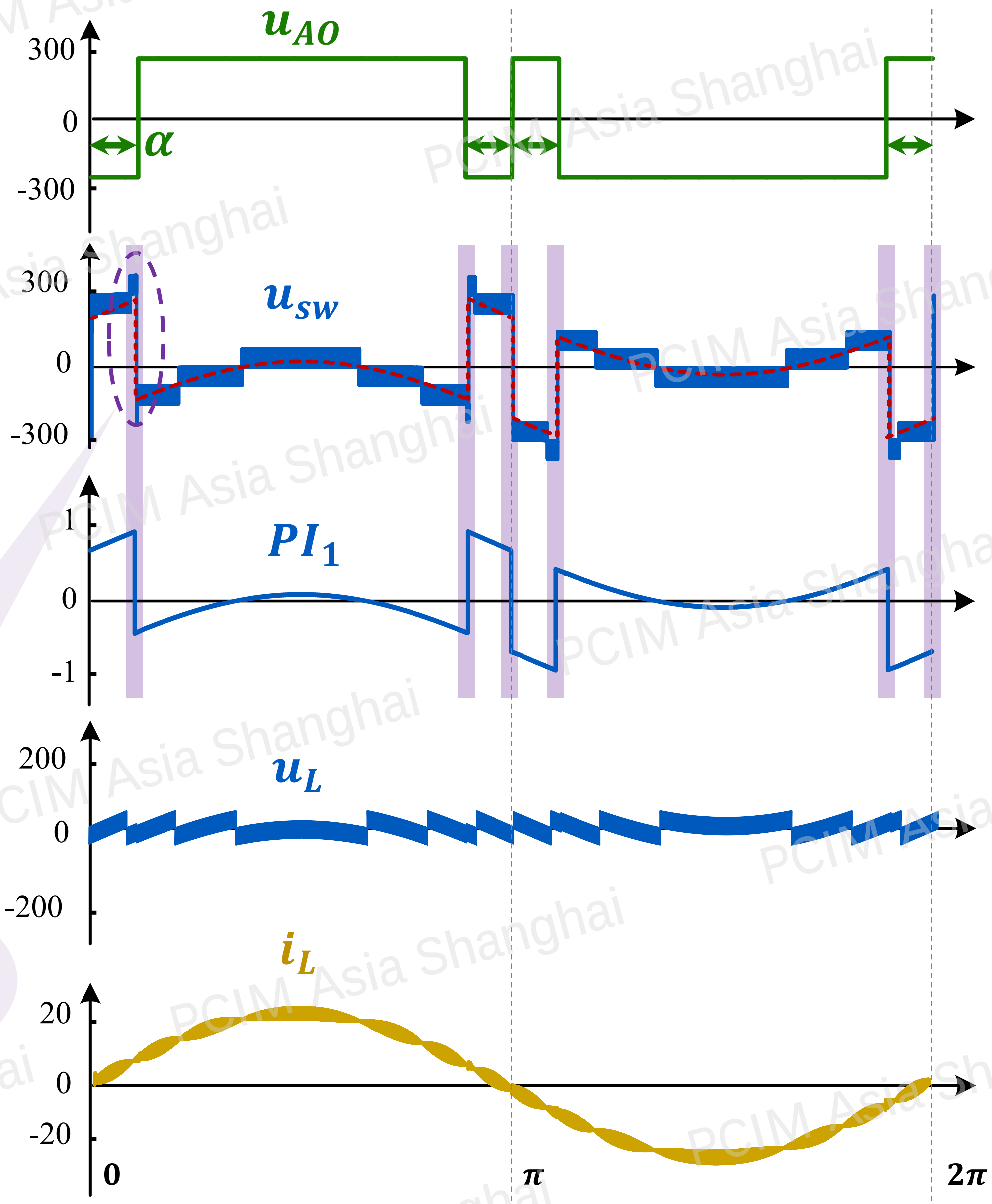
  $P_{MISN} < 0$, Discharging mode

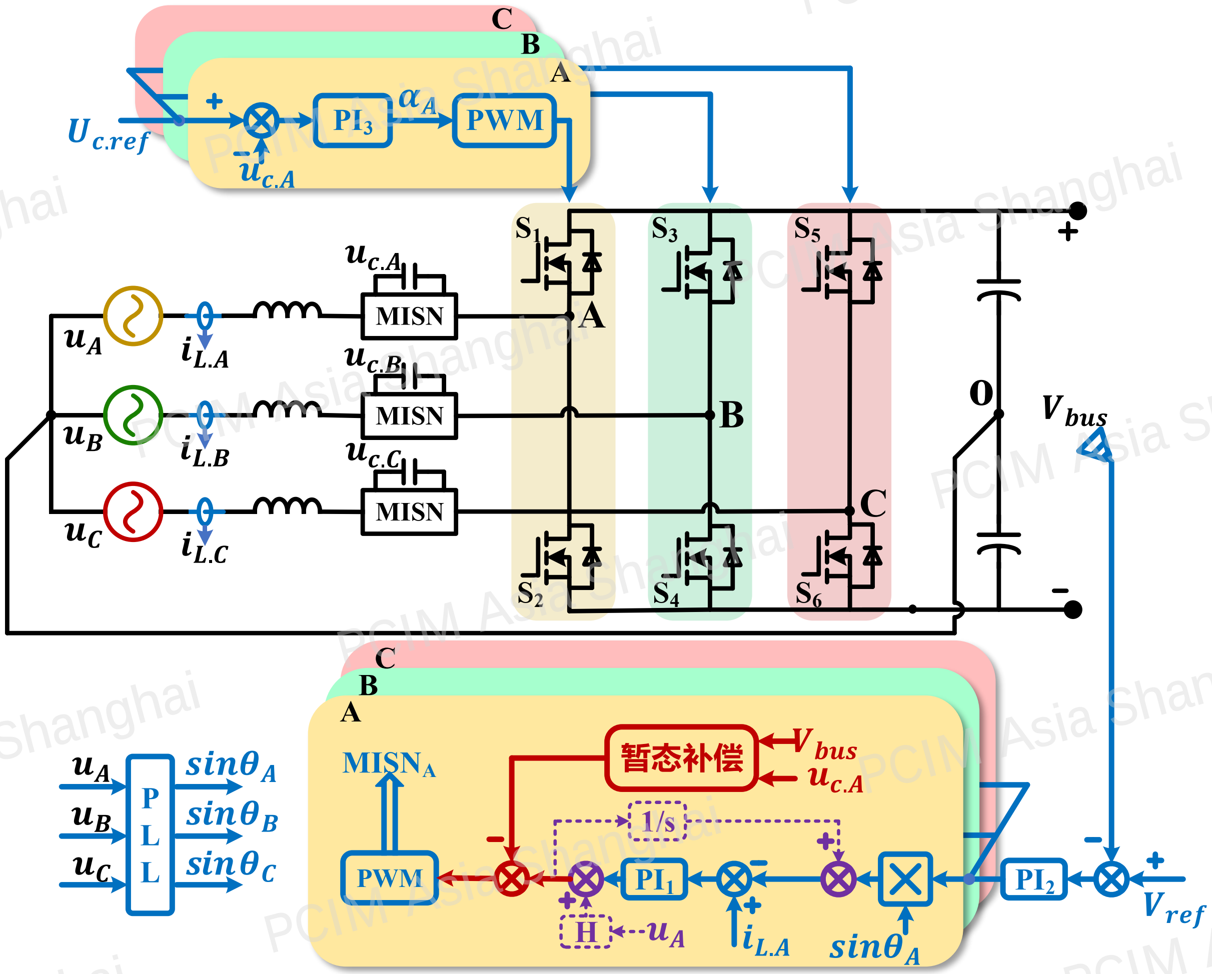
Utilized for MISN voltage Control

Three-loop Control Strategy for MISN-PFC

➤ **The Control Strategy of Phase-A**






C
B
A
$U_{c.ref}$
+
-
$u_{c.A}$
PI3
α_A
PWM
S1
S3
S5
S2
S4
S6
$u_{c.A}$
$u_{c.B}$
$u_{c.C}$
MISN
MISN
MISN
u_A
u_B
u_C
$i_{L.A}$
$i_{L.B}$
$i_{L.C}$
A
B
C
O
+
-
V_{bus}
暂态补偿
V_{bus}
$u_{c.A}$
$MISN_A$
PWM
1/s
H
u_A
PI1
$i_{L.A}$
$sin\theta_A$
PI2
V_{ref}
P
L
L
$sin\theta_A$
$sin\theta_B$
$sin\theta_C$