高频平面变压器绕组与
开关器件的统一损耗模型研究与设计案例

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4.17

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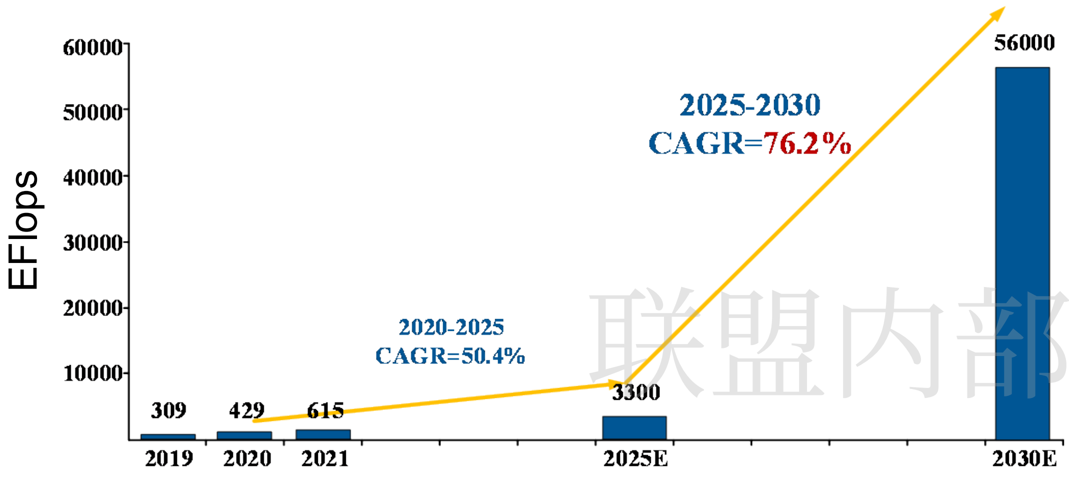
Case 1: High Frequency Transformer for Server Power Supply

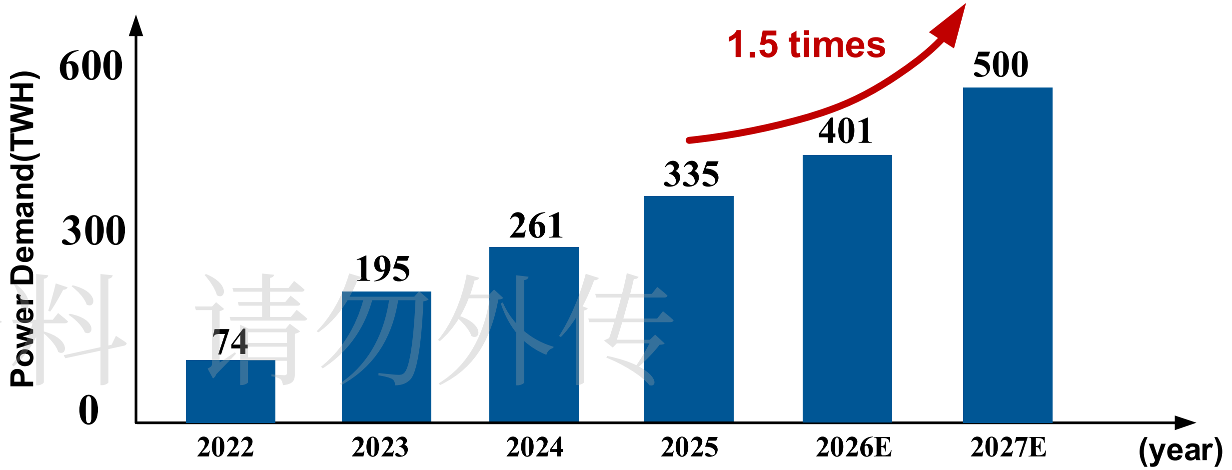
Case 2: MHz Cellular Transformer for Energy Storage System

Power Demand of Data Center

- Trend of increasing computing power (EFlops)[1]



- Predicted Power Demand of AI Data Center[2]



Data center

- By 2027, the electricity demand for AI servers will reach 500×10^8KWh/year

= Half Year power generation power generation of the Three Gorges Dam

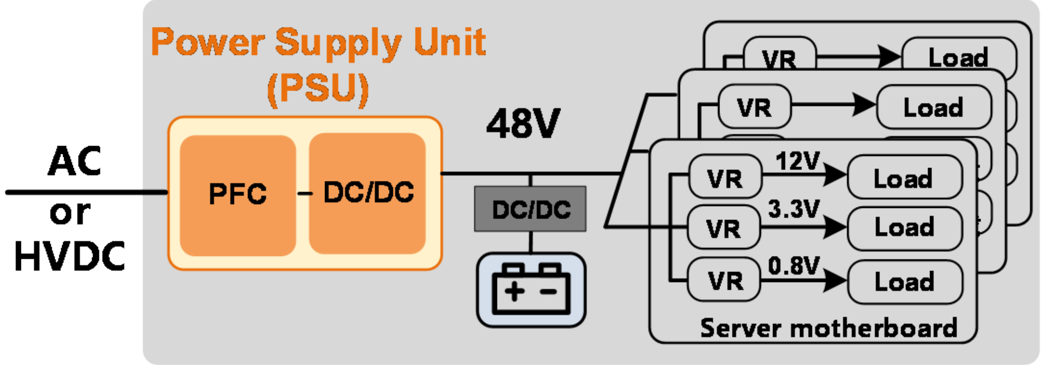
- **High efficiency**

[1]中国信通院《中国算力发展指数白皮书（2022）》
[2]Gartner

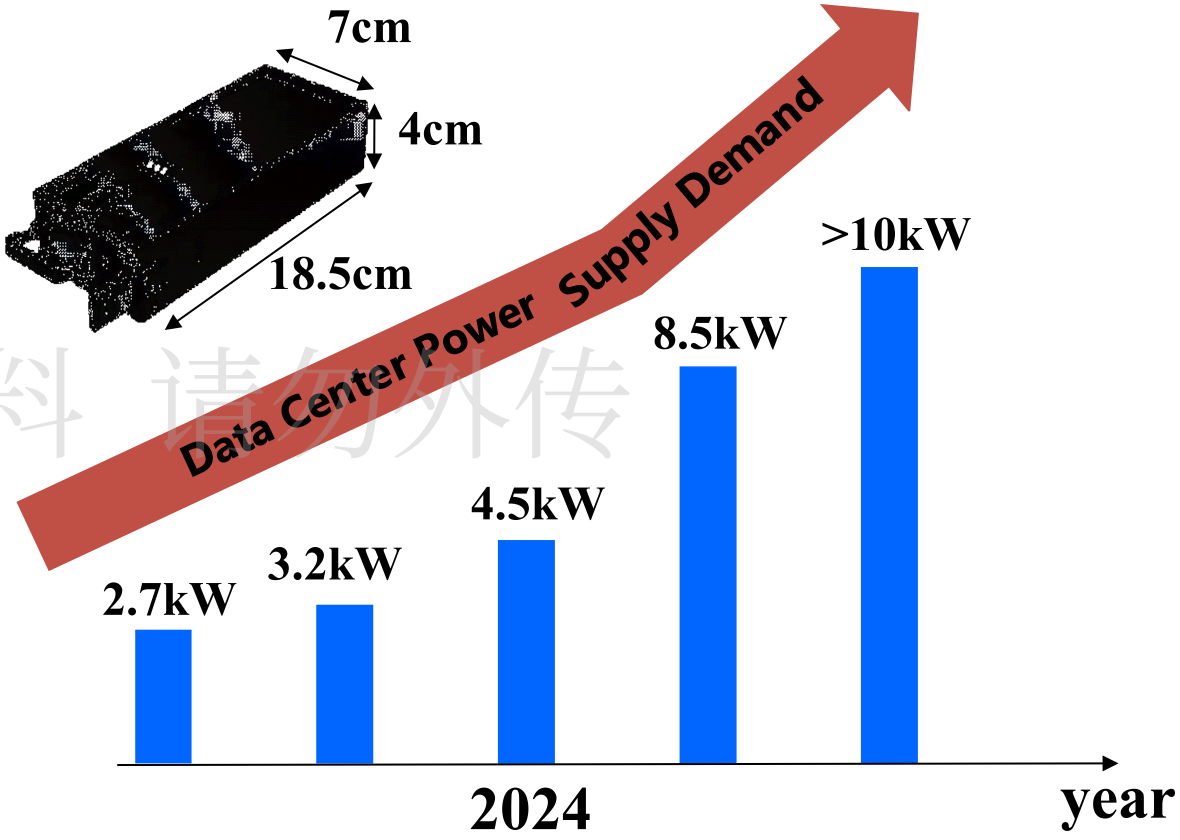
Increased Power Demand for Server Power Supply Unit (PSU)

➢ Server rack Power supply architecture

Server Rack



➢ PSU Power demand requirements:



➢ Higher power density for Server PSU

The Peak Efficiency of Commercial PSUs need Improving

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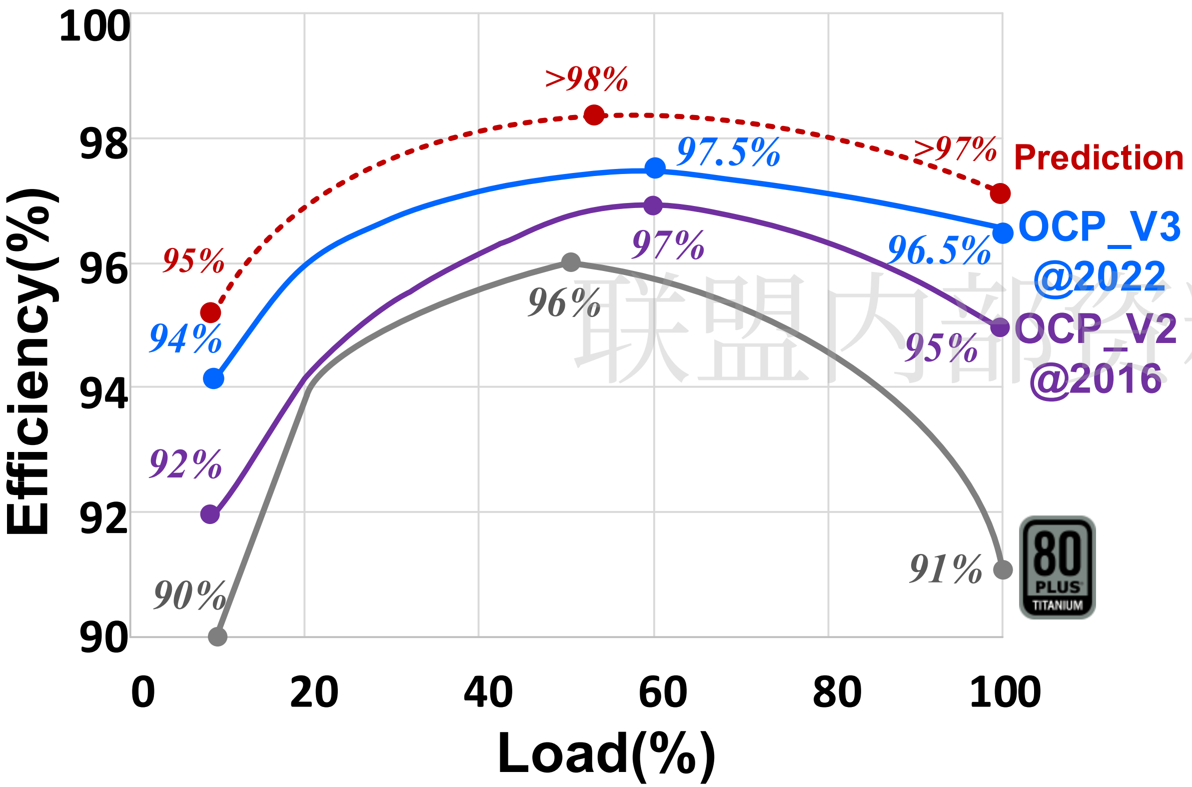
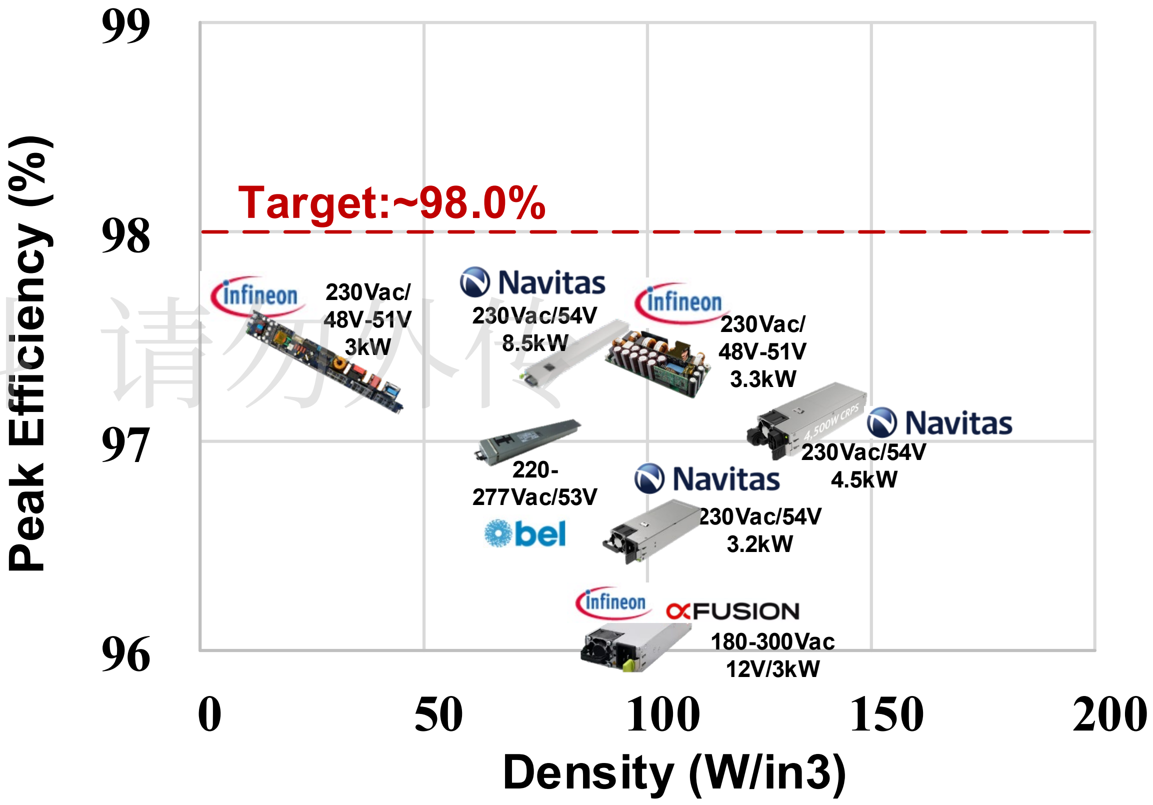
➢ PSU efficiency requirements



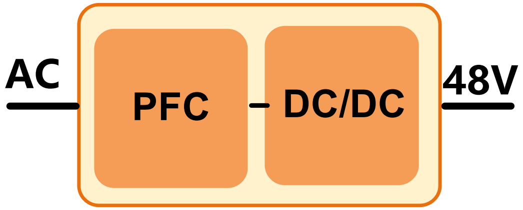
➢ Commercial Server PSU:



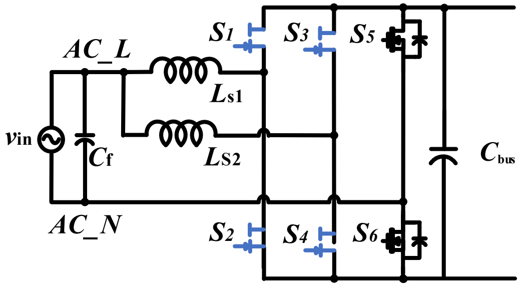
➢ 98% efficiency for the future PSU

PSU efficiency need improving

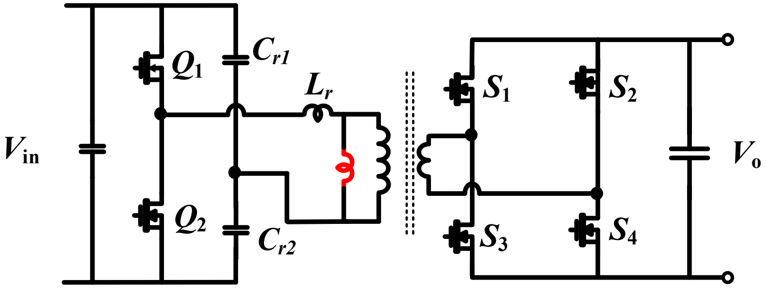
DC/DC Stage Efficiency needs Further Improving



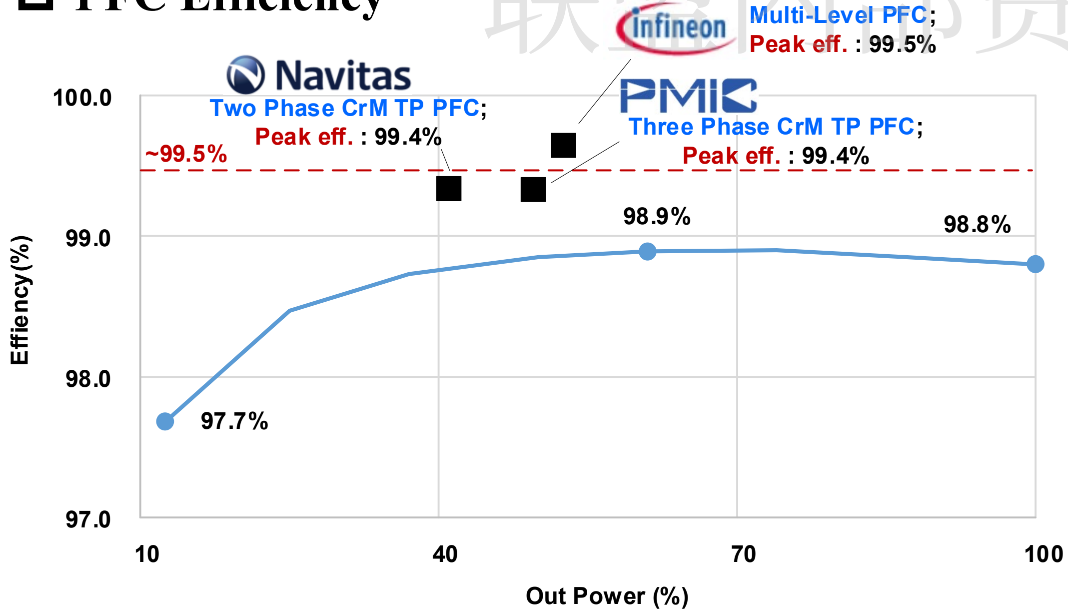
Interleaved TP PFC



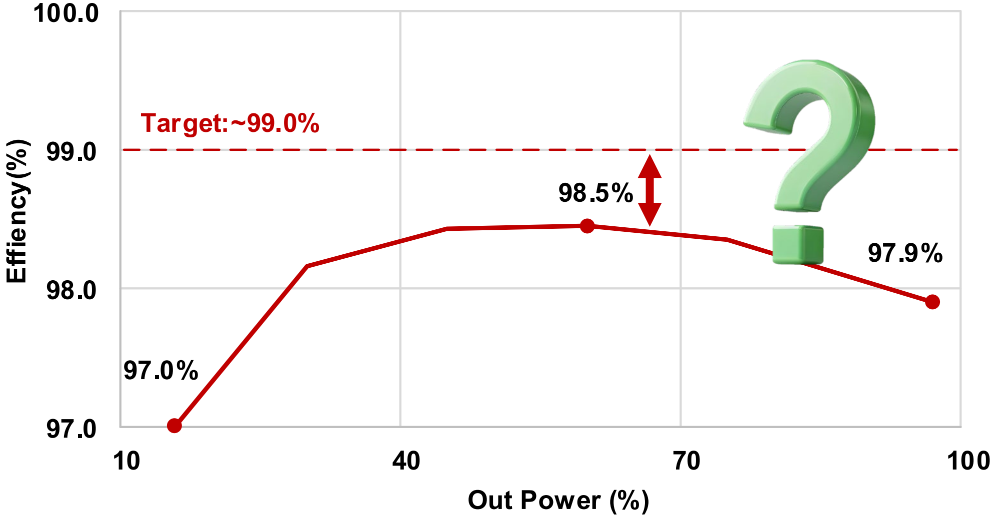
Half Bridge LLC



PFC Efficiency



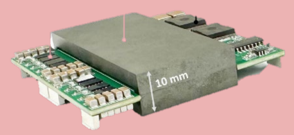
DC/DC Efficiency



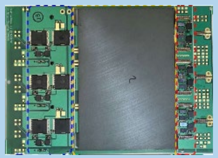
[1] https://www.infineon.com/cms/en/product/promopages/AI-PSU/;

The State-of-the-art Academic LLC Efficiency reaches 99%

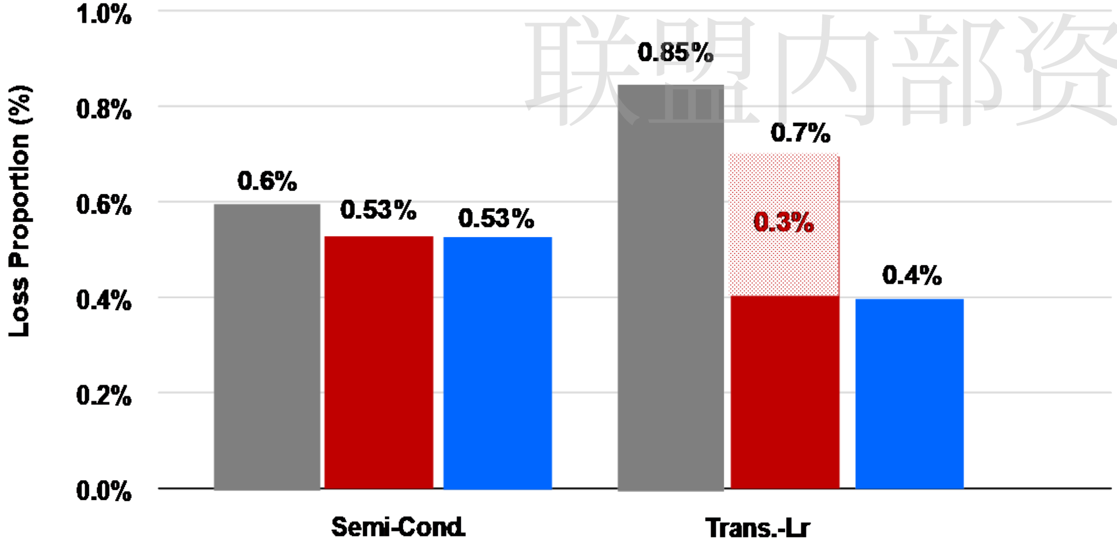
Peak eff.: *~98.5%*



Peak eff.: *~98.7%*

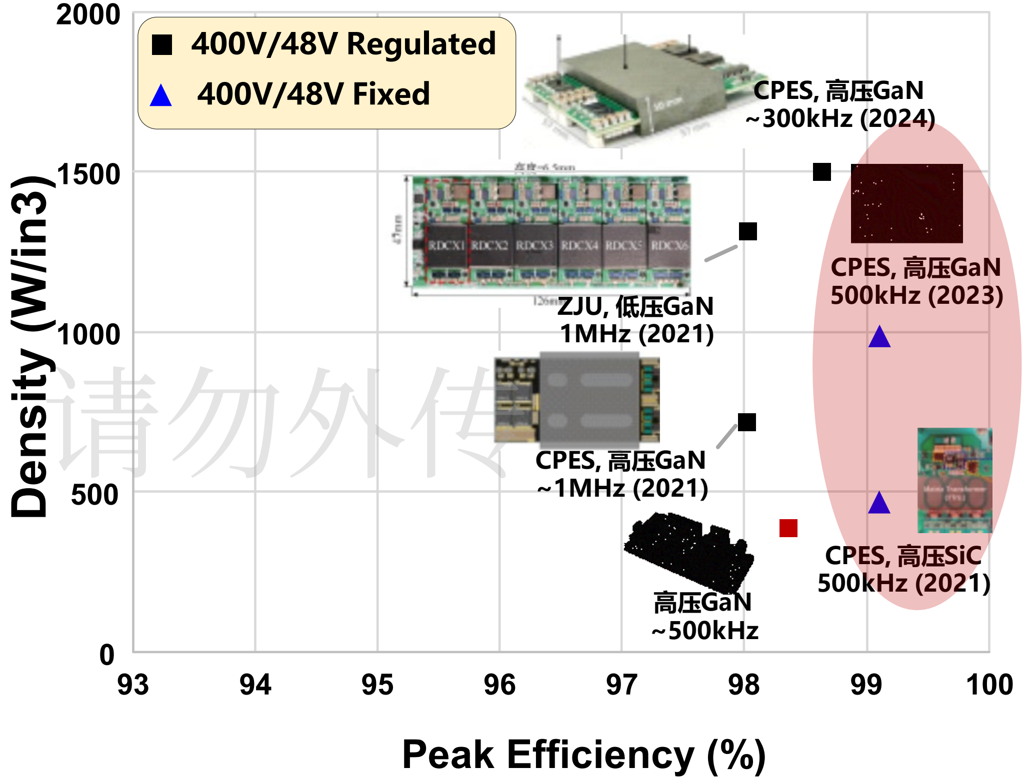


Peak eff.: *~99.1%*



Loss Breakdown @ 1500W

□ The academic DC/DC：

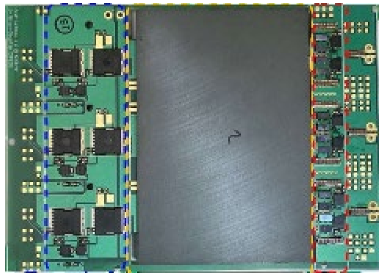


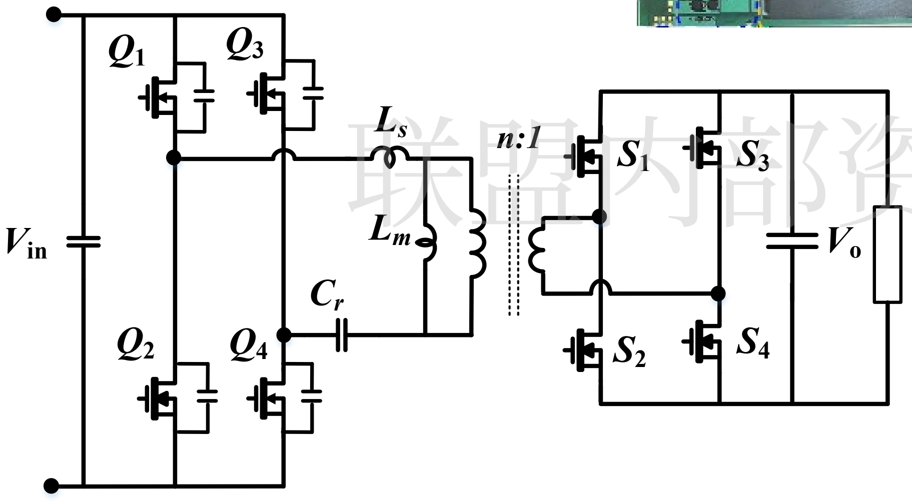
- Minimum magnetizing current;
- Without resonant inductor;

[3] A. Nabih, F. Jin and Q. Li, "Efficient Integrated Transformer–Inductor With High PCB Utilization and Optimized Core," in *IEEE TIE,2024*
[4] R. Gadelrab, A. Nabih, F. C. Lee and Q. Li, "LLC Resonant Converter with 99% Efficiency for Data Center Server," *APEC 2021*
[5] R. Gadelrab and F. C. Lee, "PCB-Based Magnetic Integration and Design Optimization for Three-Phase LLC," in *IEEE TPE 2023*

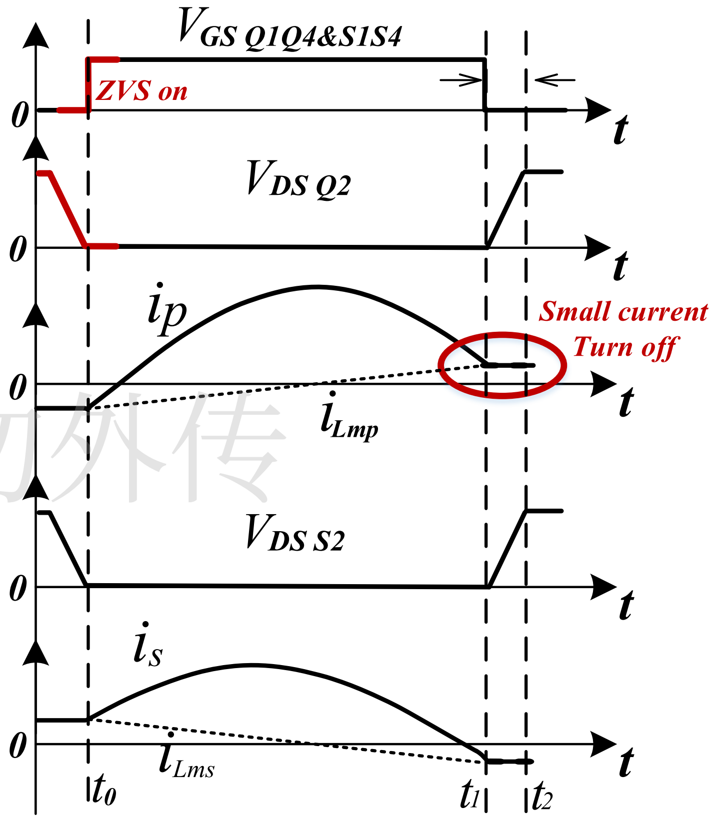
Series resonant Converter (SRC) is suitable for DCX

➢ Series Resonant Converter (SRC)





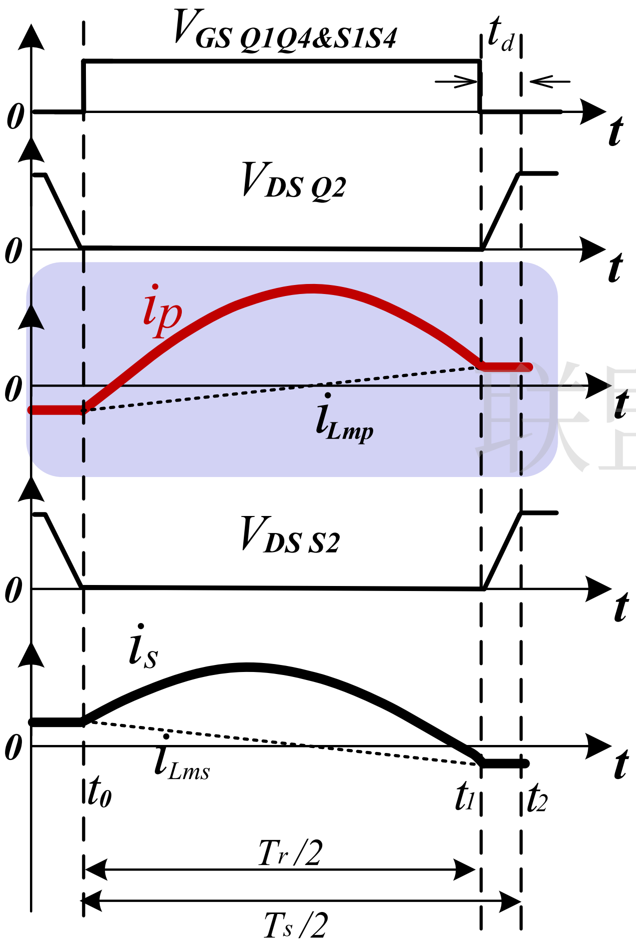
➢ Key Waveform of SRC



- Perfect soft switch characteristics
- Small switching losses at MHz

Device Conduction Loss Model in DCX Circuit

➢ Key Waveform



➢ Pri Device Conduction Loss

$$\begin{cases} i_p(t) = I_p sin\left(\frac{2\pi}{T_r}t - \theta_p\right) \quad t_0 < t < t0 + \frac{T_r}{2} \quad (1) \\ i_p(t_0) = I_p sin(\theta_p) = I_{Lms} = \frac{2C_{otr}V_{in}}{t_d} \quad (2) \\ \frac{P_oT_s}{2} = \int_{t_0}^{t_0+T_r/2} V_o I_p sin\left(\frac{2\pi}{T_r}t - \theta_p\right) dt \quad (3) \\ I_p = \sqrt{(I_p sin\theta_p)^2 + (Ipcos\theta_p)^2} = \sqrt{\left(\frac{2C_{otr}V_{in}}{t_d}\right)^2 + \left(\frac{\pi P_o T_s}{2V_o T_r}\right)^2} \quad (4) \end{cases}$$

Resonant current: Sinusoidal wave

Dead time: $I_p = I_{Lmp}$

$$\theta_p = arcsin\frac{\frac{2C_{otr}V_o}{t_d}}{I_p}$$

$$P_{pri.} = \frac{4V_{in}^2 T_r C_{otr\_p}^2}{t_d^2 T_s} R_{dson\_p} + \frac{\pi^2 P_{in}^2 T_s}{4V_{in}^2 T_r} R_{dson\_p}$$

Xinke Wu. Hongbo Shi. “High Efficiency High Density 1 MHz 380–12 V DCX With Low FoM Devices” IEEE TIE 2020. pp1648-1656

Primary Device Selection according to Loss Model for Server DC/DC

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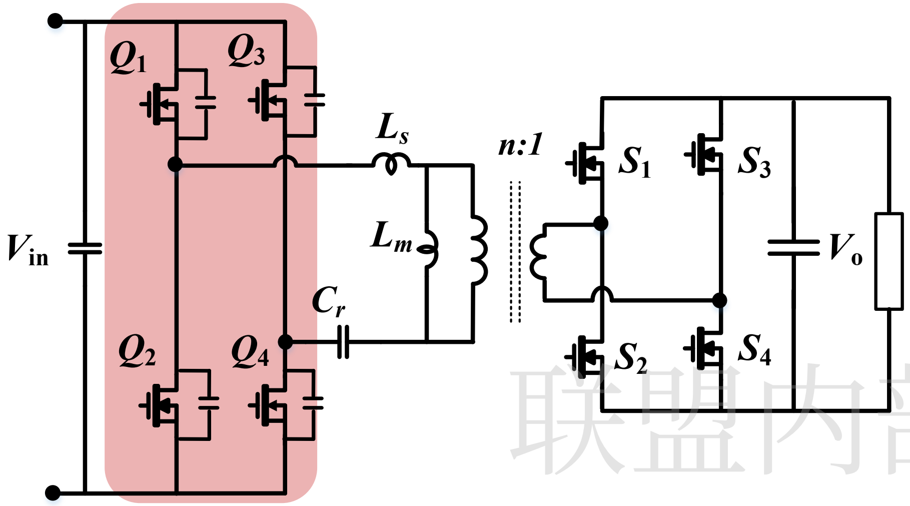
➢Series Resonant Converter (SRC)

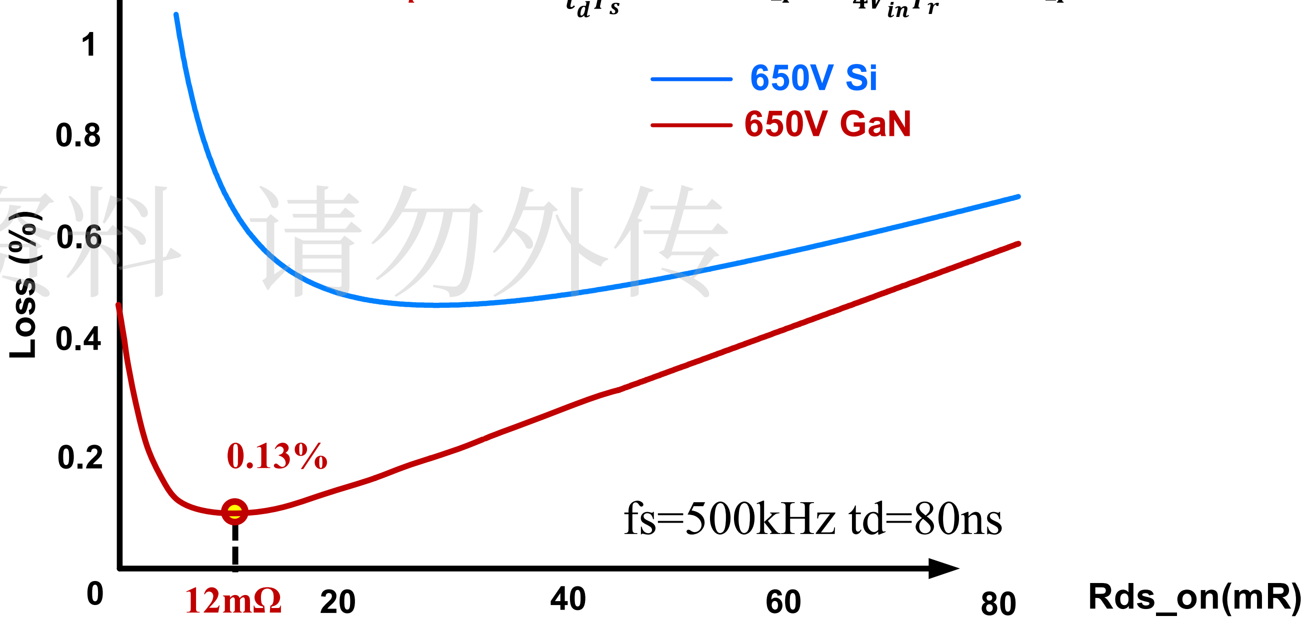


DCX Parameters

Input Voltage	432V
Output Voltage	48V
Output Power	4.5 kW
fs	500kHz
Turn Ratio:	Np:Ns=9:1

➢ Primary Device Loss @half Load 2000W

$$P_{pri.} = \frac{4V_{in}^2 T_r C_{otr\_p}^2}{t_d^2 T_s} R_{dson\_p} + \frac{\pi^2 P_{in}^2 T_s}{4V_{in}^2 T_r} R_{dson\_p}$$

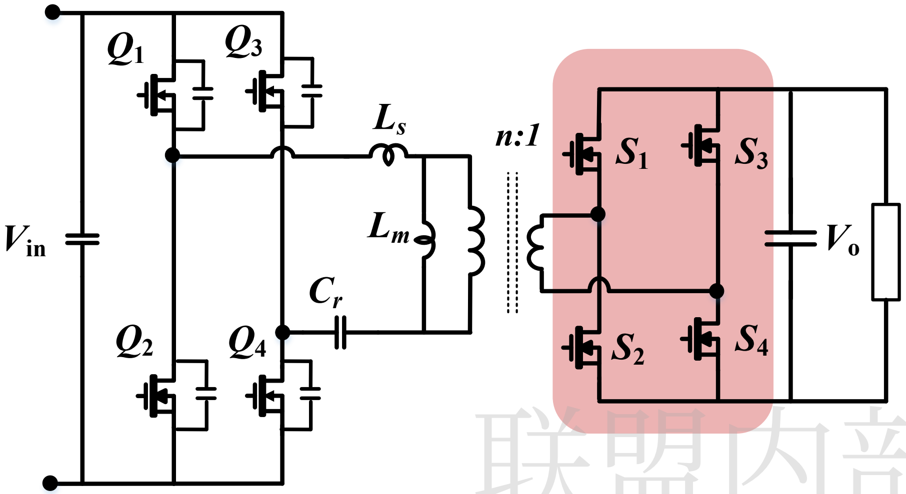


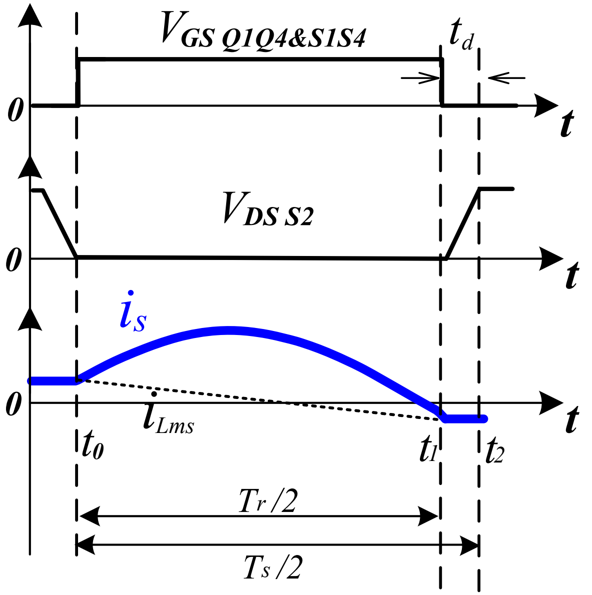
Two 25mΩ GaN parallel
~12.5mΩ

[1] X. Wu and H. Shi, "High Efficiency High Density 1 MHz 380–12 V DCX With Low FoM Devices," in *IEEE Transactions on Industrial Electronics*, vol. 67, no. 2, pp. 1648-1656, Feb. 2020.;

Sec. Device Selection according to Loss Model for 4.5kW Server DC/DC

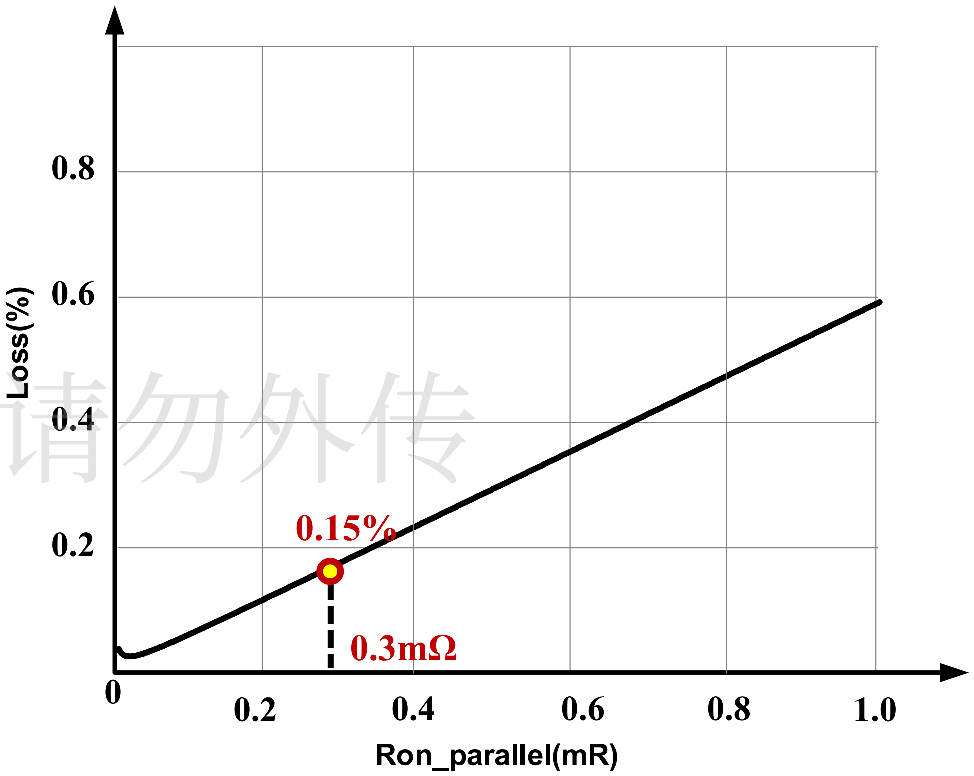
➢Series Resonant Converter (SRC)



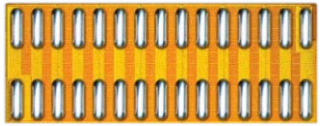


$$P_{sec.} = \frac{4V_o^2 T_r C_{otr\_s}^2}{t_d^2 T_s} R_{dson\_s} + \frac{\pi^2 P_o^2 T_s}{4V_o^2 T_r} R_{dson\_s}$$

➢ Sec Device Loss @half Load



EPC2206
2.2mΩ

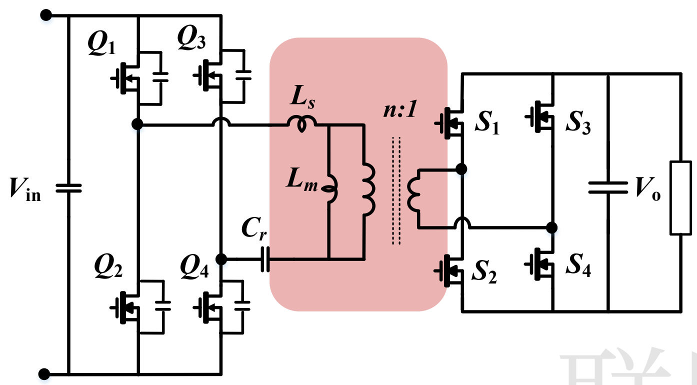


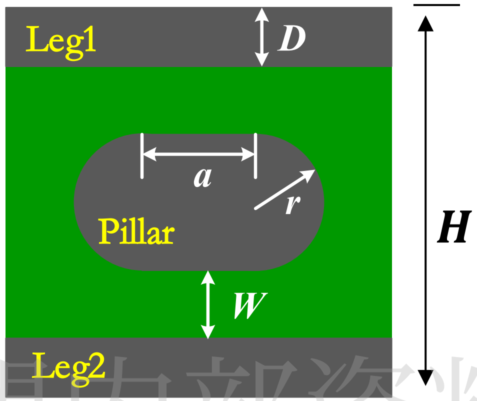
×8

8 devices parallel
~0.28mΩ

Transformer design for 4.5kW server DC/DC

➢ Series Resonant Converter (SRC)



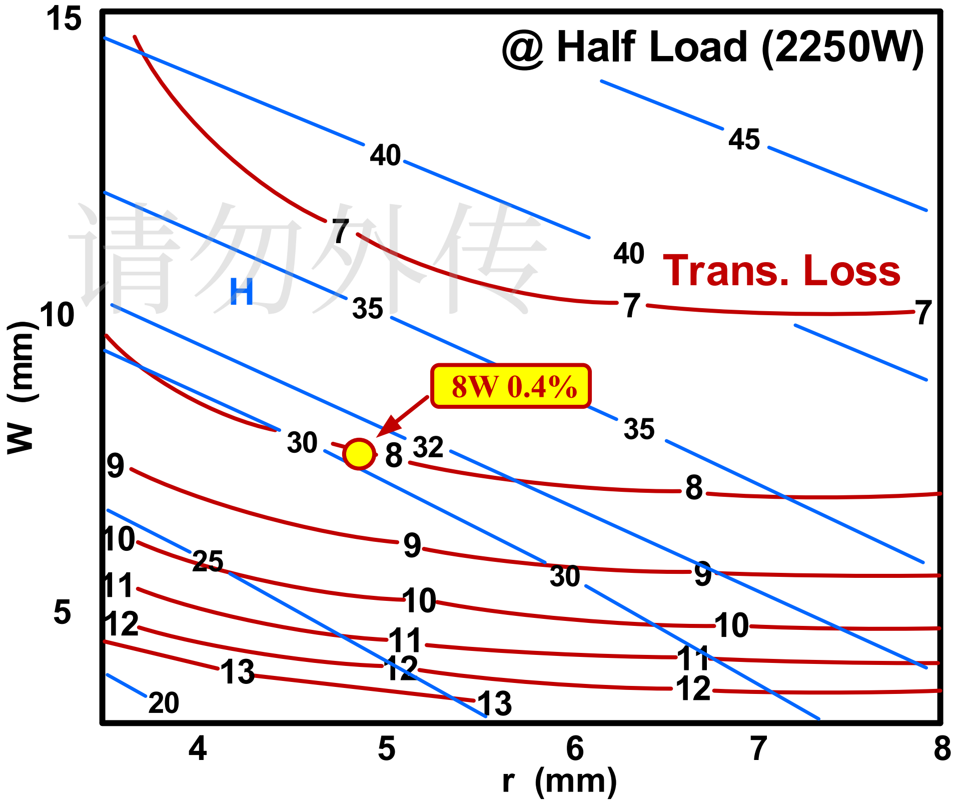


$$D(r,W) = \frac{Ae}{4r^2 + 2ar + 4Wr}$$

Transformer Loss Model:

$$P_{trans} = Pw + Pcore$$

$$H = (D + W + r) \cdot 2 < 32mm$$



r =4.8 W=7 ~0.4% loss @half load

➢ Estimation of winding loss:

$$k_{ac} = 1.5[1]$$

$$P_w = k_{ac}\left[R_{pDC}(r,W) \cdot i_{prms}^2 + R_{sDC}(r,W) \cdot i_{srms}^2\right]$$

➢ Estimation of Core loss:

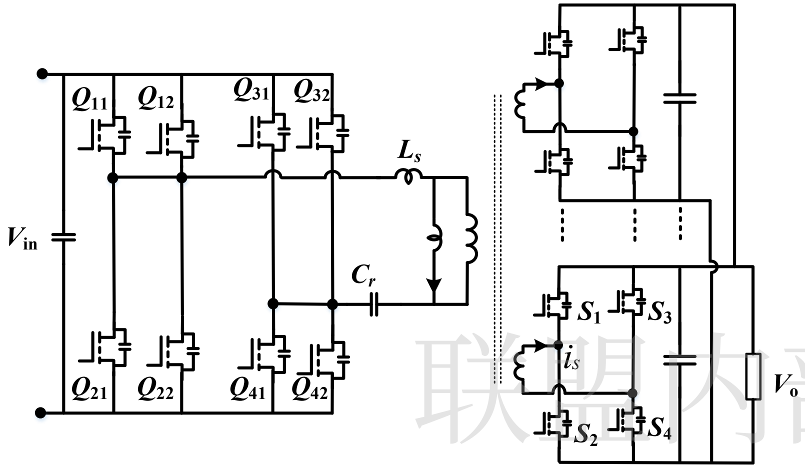
$$P_{core} = P_{cv} \cdot V_e(r,W)$$

[1]Mingkai Mu. Fred C. Lee. "Design and Optimization of a 380–12 V High-Frequency, High-Current LLC Converter With GaN Devices and Planar Matrix Transformers" IEEE JESTPE.2016.2586964

[2] Tianji Liu, Xinke Wu. High-Efficiency High-Density Multi-Module RDCX with Input-Series-Output-Parallel Connection.2022 PMIC Winter Seminar, Hangzhou,2022.;

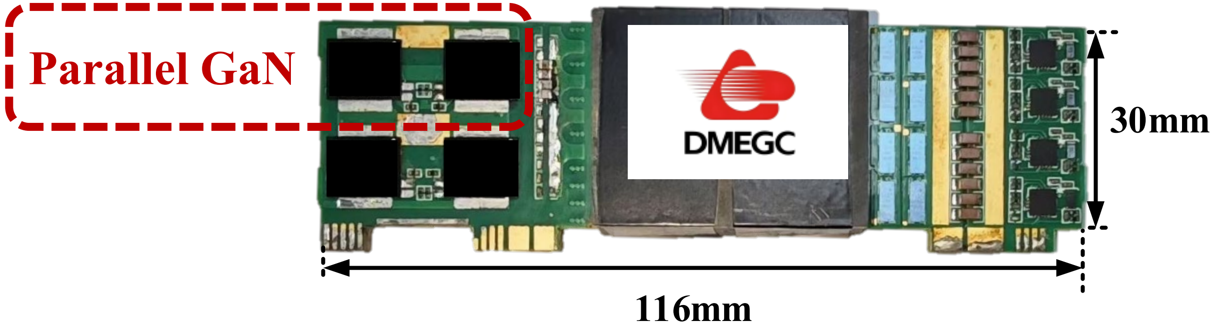
Efficiency of DCX Ver.1 is below 99%

- Topology with parallel device

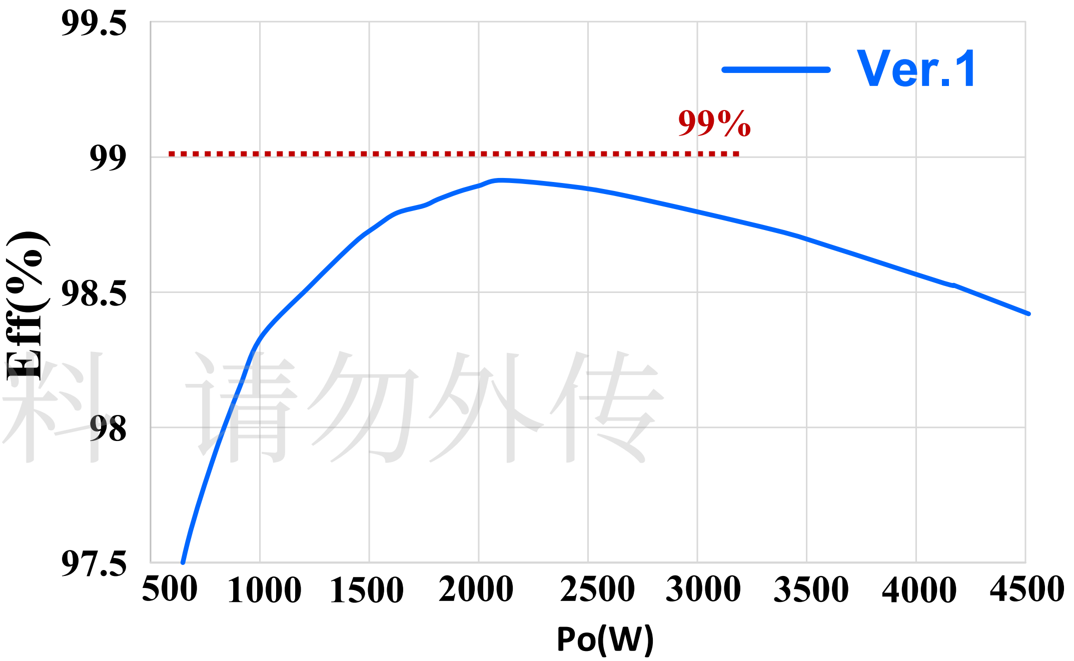


8 rectifiers parallel

Ver.1 Prototype : DCX with parallel GaN:



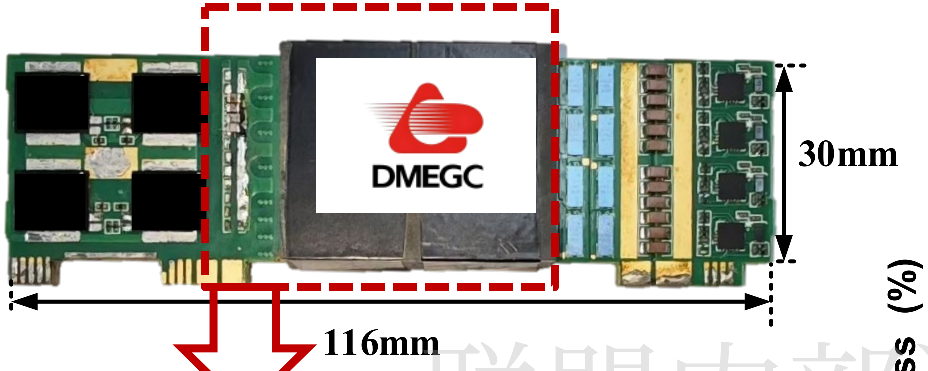
- Efficiency test:

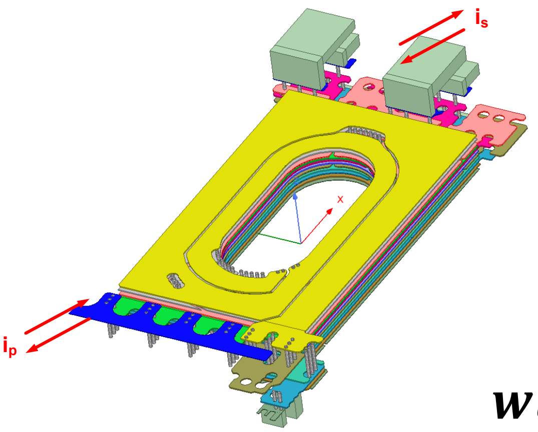


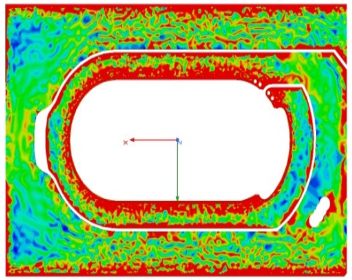
- Efficiency mismatch @half load

Winding Loss Mismatch Leads to Efficiency Mismatch

- Transform model in ANSYS EM

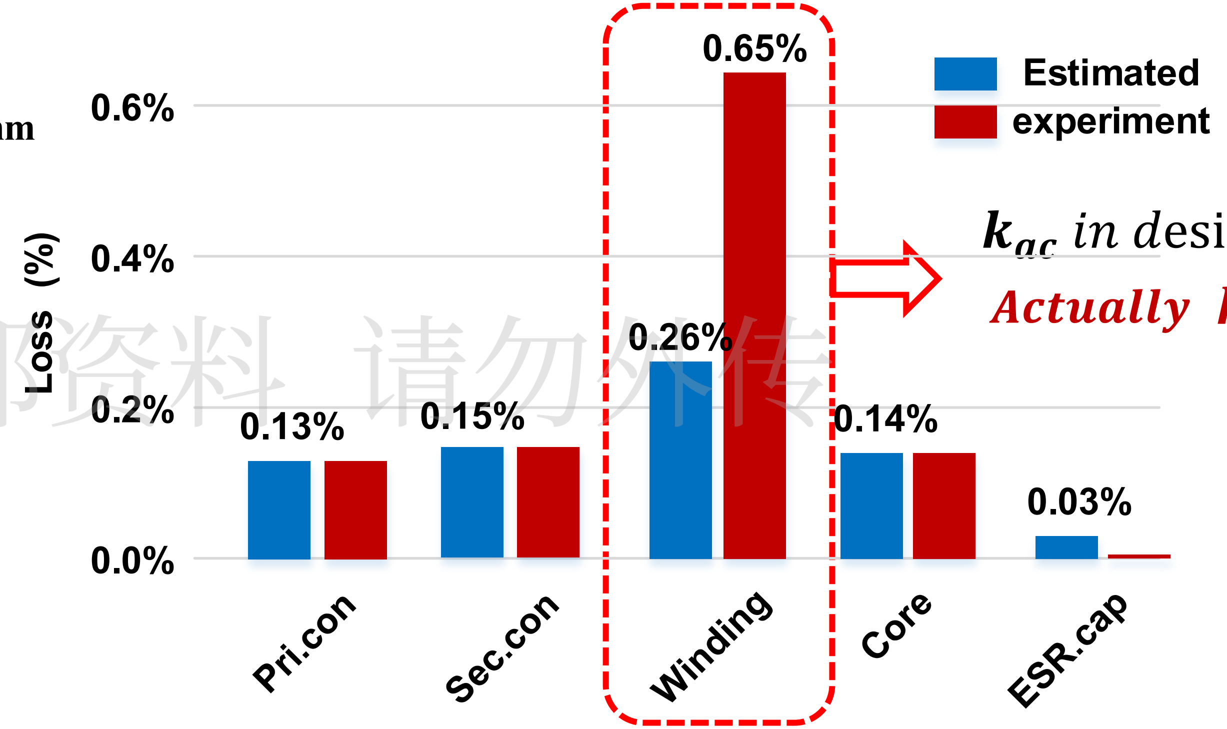






winding loss: ~13W

- Loss Breakdown of DCX



k_{ac} *in design* $= 1.5$

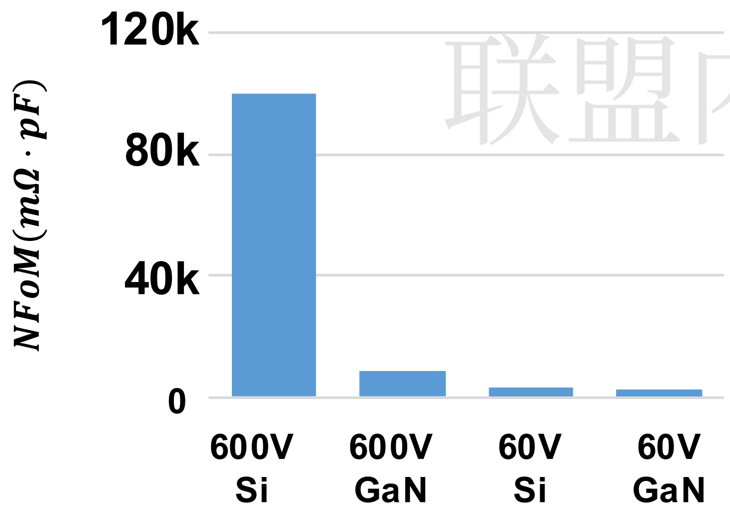
Actually $k_{ac} = 3.8$

- Device loss matches design value
- Kac mismatches with deign

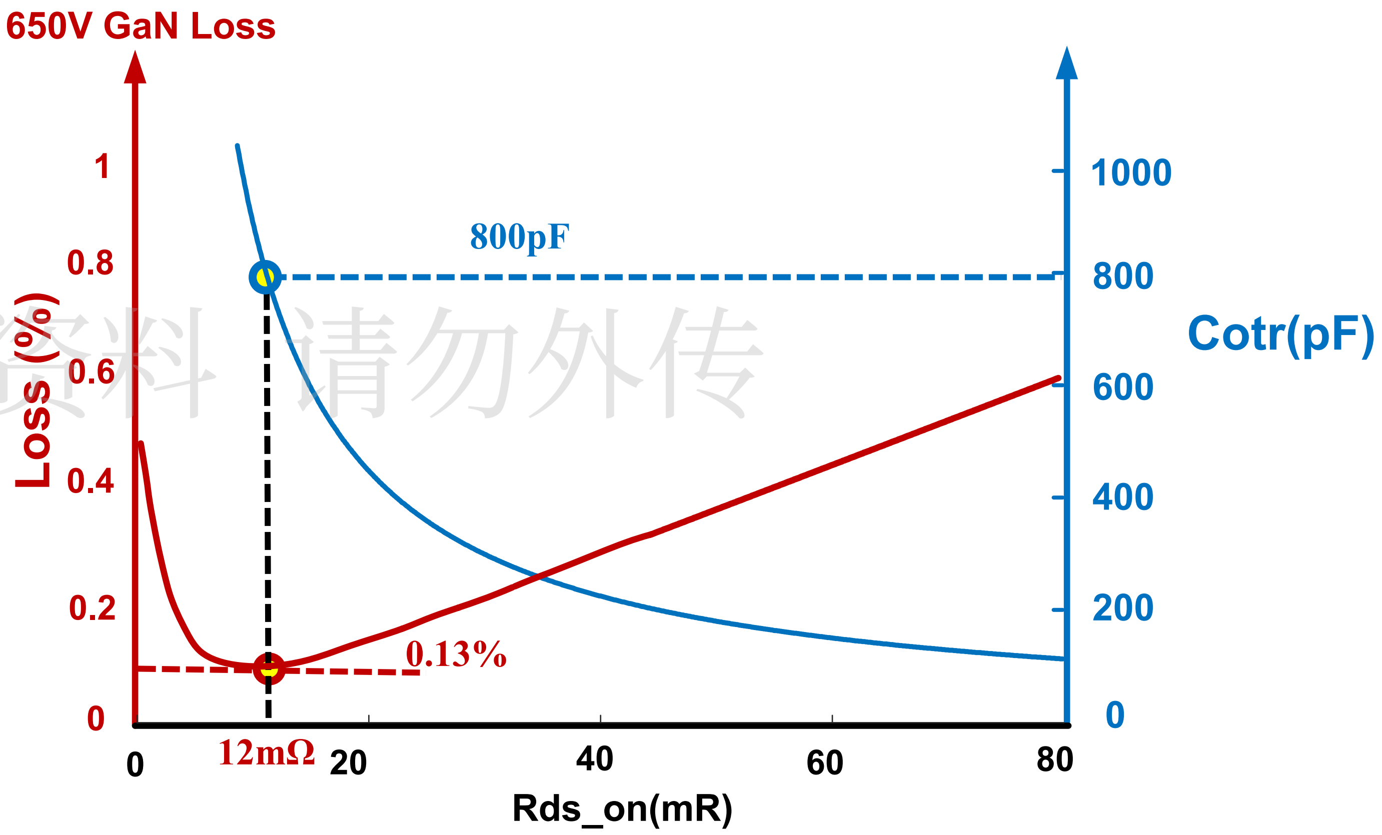
$NFoM = R_{dson} * C_{otr}$ ： Low R_{dson} leads to Large C_{otr}

$NFoM = R_{dson} * C_{otr}$[1]

■ NFoM parameter of device



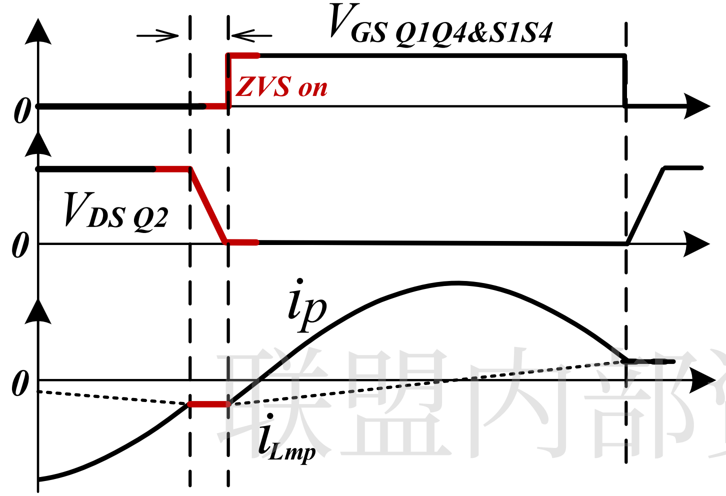
[1] 600V-Si IPB60RxxxC7 Series
[2] 600V-GaN GS665xxx Series
[3] 100V---Si BSCxxxN10LS5 Series
[4]100V-- GaN EPCxxxx

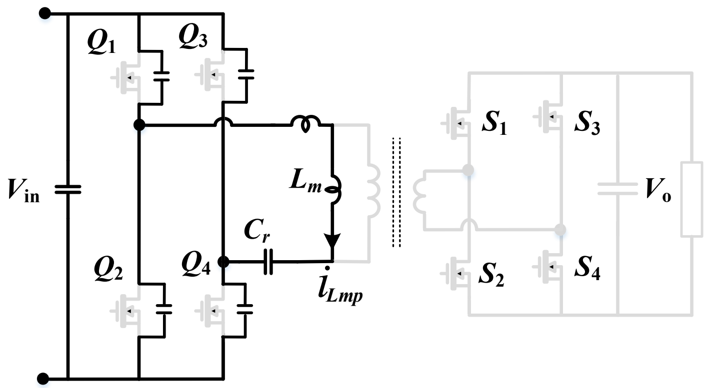


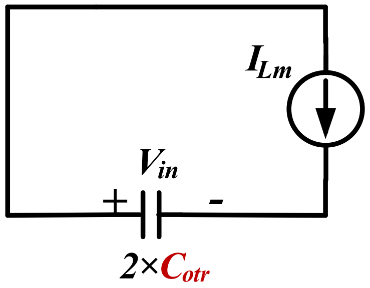
[1]I. J. Kim et al., "New power device figure of merit for high-frequency applications," in Proc. IEEE Int. Symp. Power Semicond. Devices ICS, 1995, pp. 309–314.

Large C_{otr} need Large Magnetizing Current to Achieve Soft Switching

- Soft switching of SRC during dead time (td)

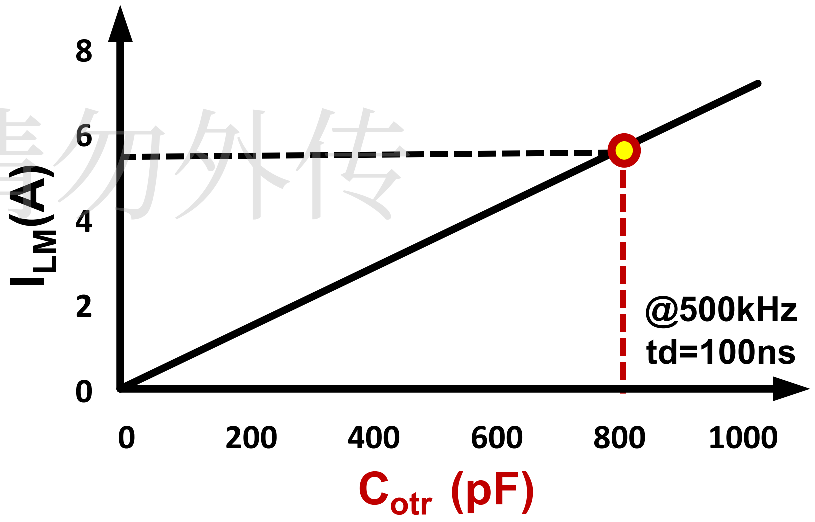






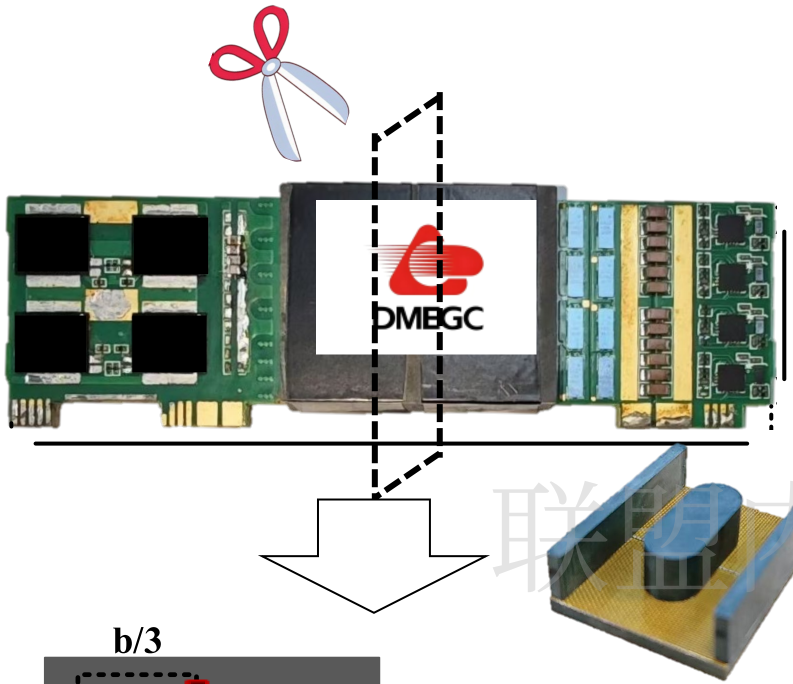
$$I_{Lm} = \frac{2V_{in}C_{otr}}{t_d}$$

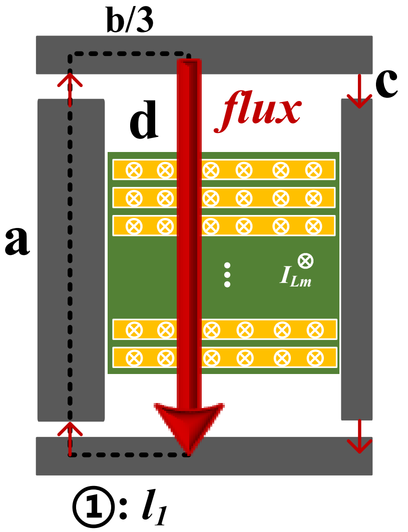
- Magnetizing Current



[1]I. J. Kim et al., “New power device figure of merit for high-frequency applications,” in Proc. IEEE Int. Symp. Power Semicond. Devices ICS, 1995, pp. 309–314.

H-field Enhances As I_{LM} Increases

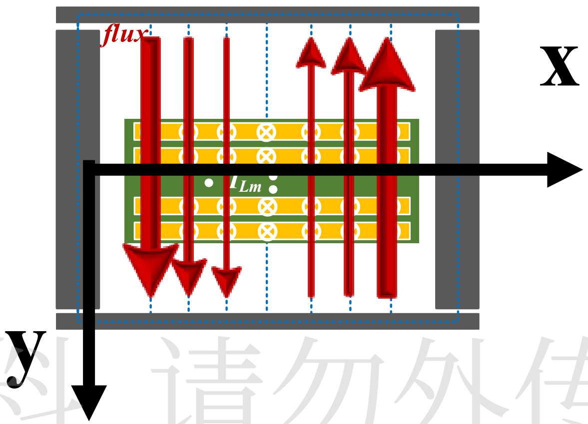


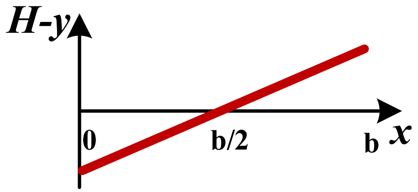


$$\oint Hdl = \sum I_{Lm}$$

Assume:
Ignore horizontal H-field

➢ H-field Distribution

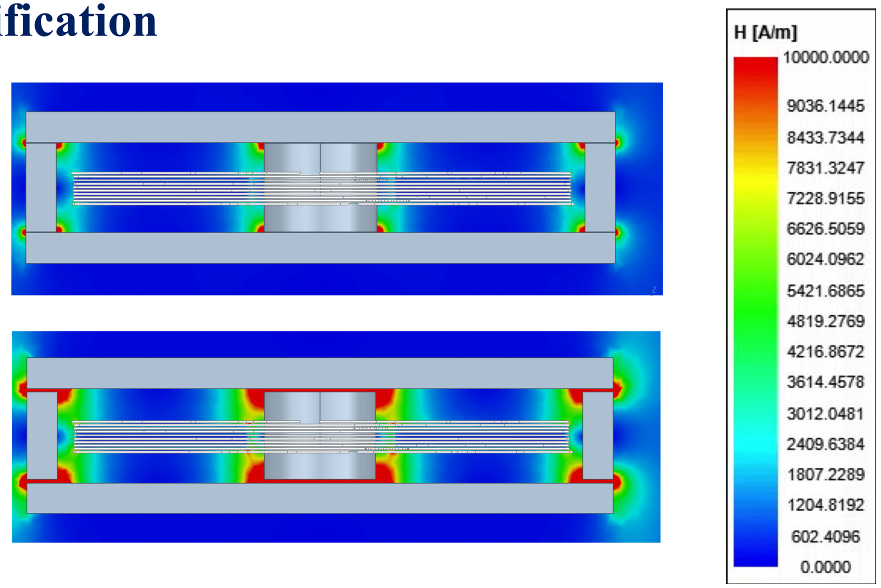




➢ **3D FEA Verification**

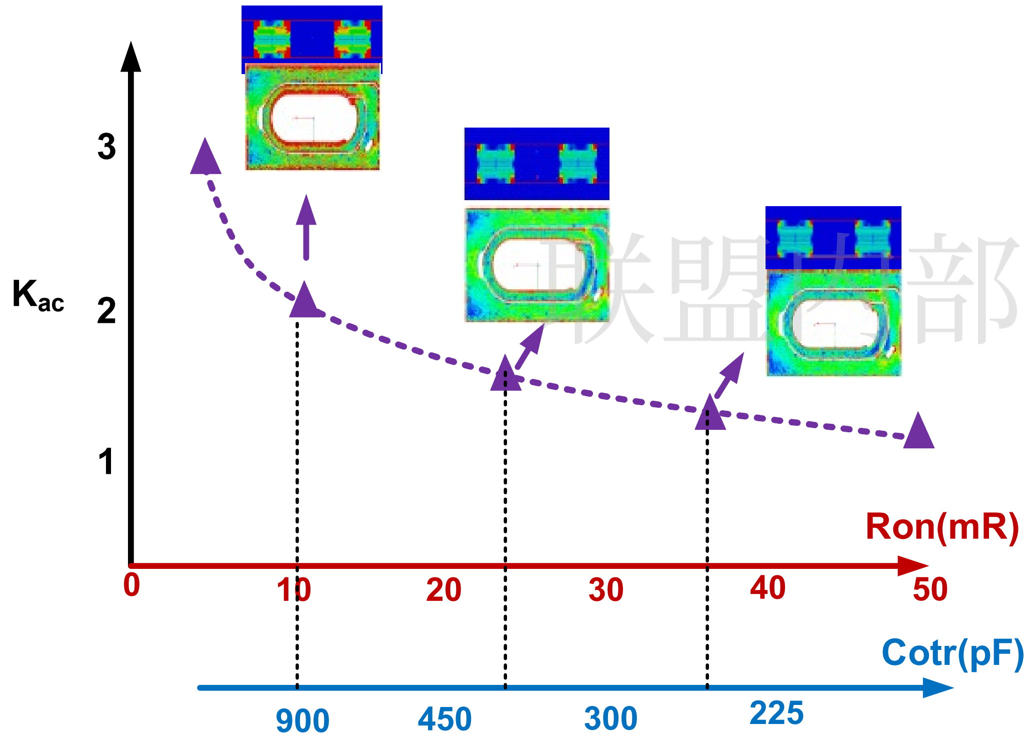
I_{LM}=3.2A

I_{LM}=6.4A

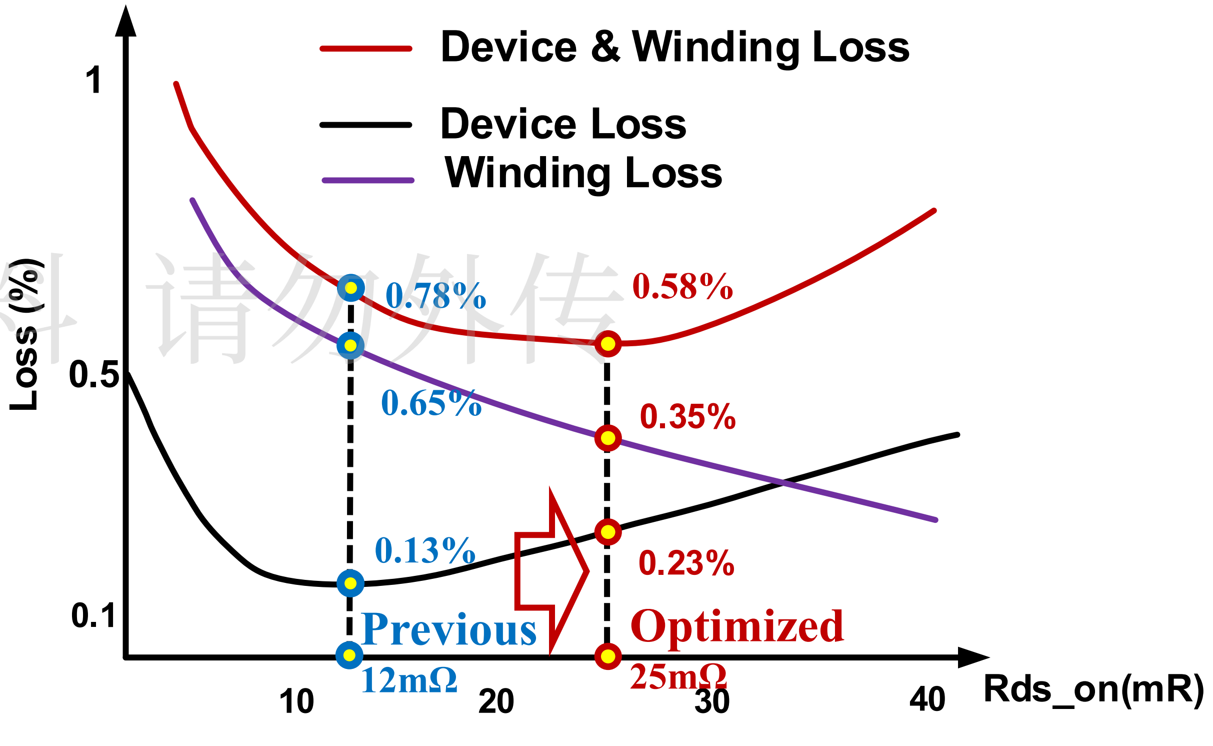


Obtain Loss Model of Combined Winding and Device

➢ kac is a Function of Parasitic Capacitance Cotr



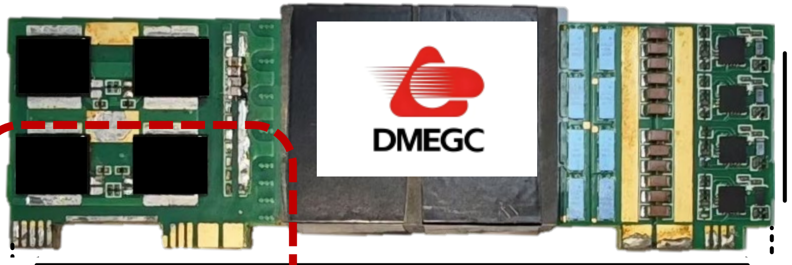
➢ Loss model @2000W 500kHz td=100ns



One 25mΩ device is enough

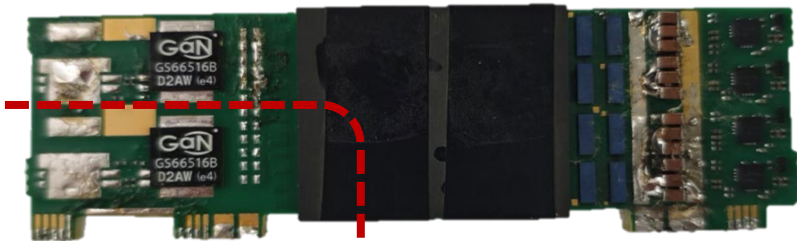
Efficiency comparison between two version

- Prototype Ver.1



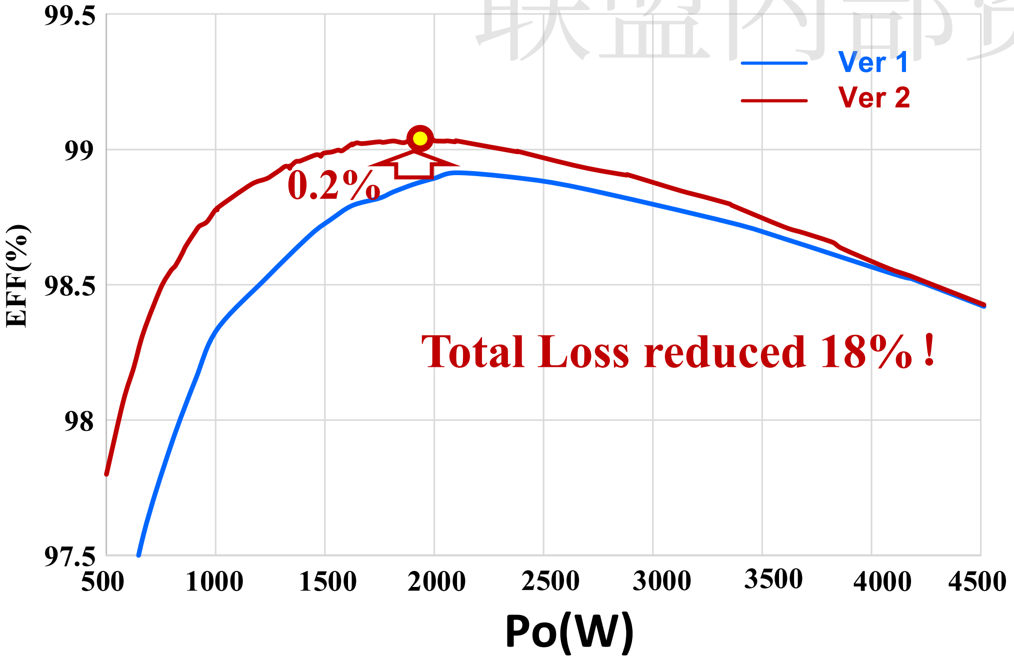
Parallel GaN

- Prototype Ver.2

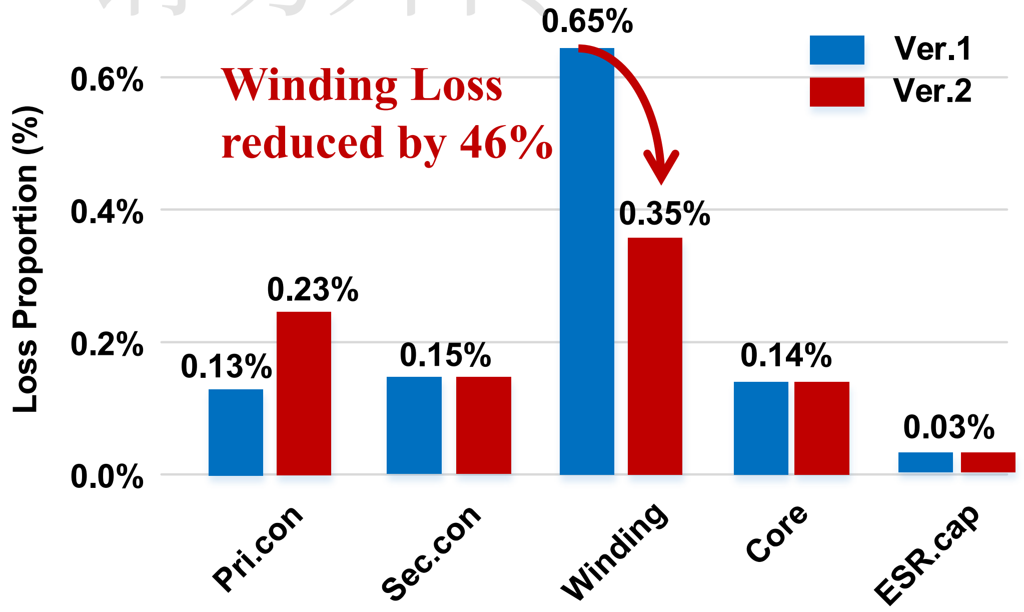


w/o Parallel GaN

- Efficiency test



- Loss Breakdown @2000W



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Case 1: High Frequency Transformer for Server Power Supply

Case 2: MHz Cellular Transformer for Energy Storage System

Efficiency at Full Load is Concerned for Energy Storage System

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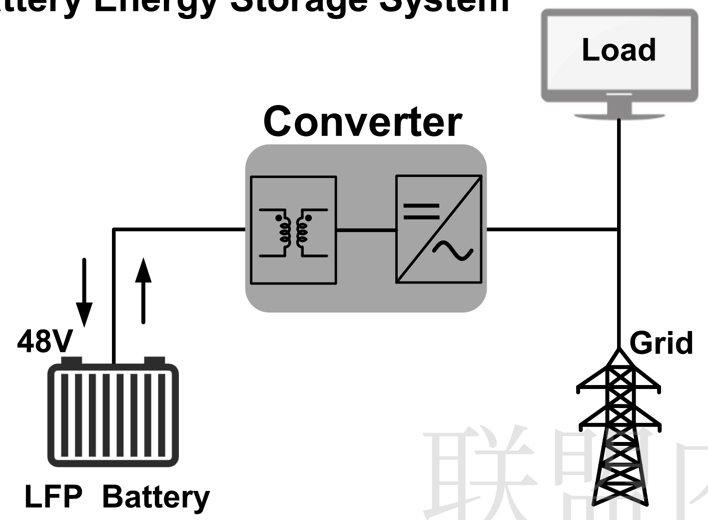
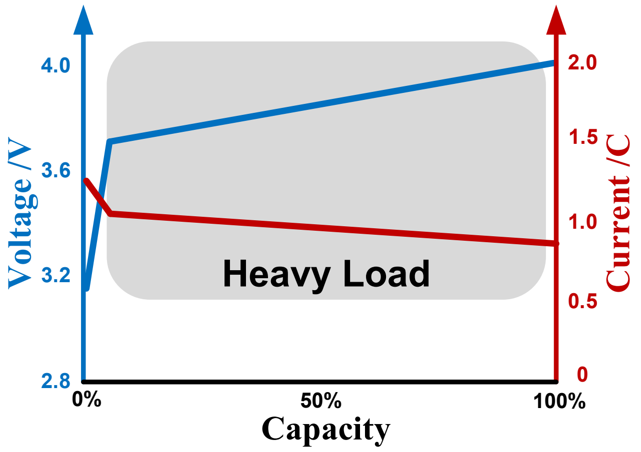
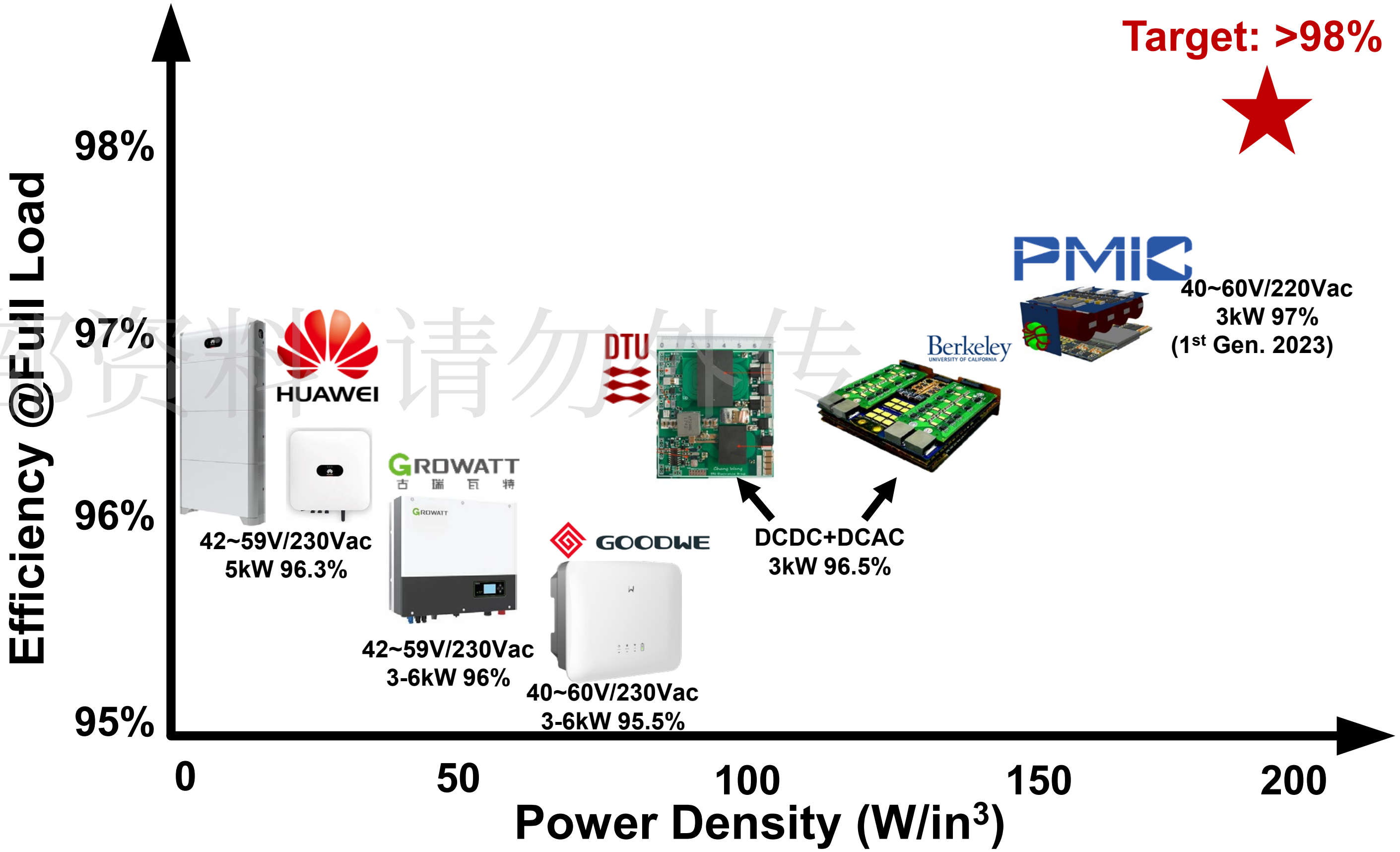
Battery Energy Storage System



LFP Battery Charging/Discharging

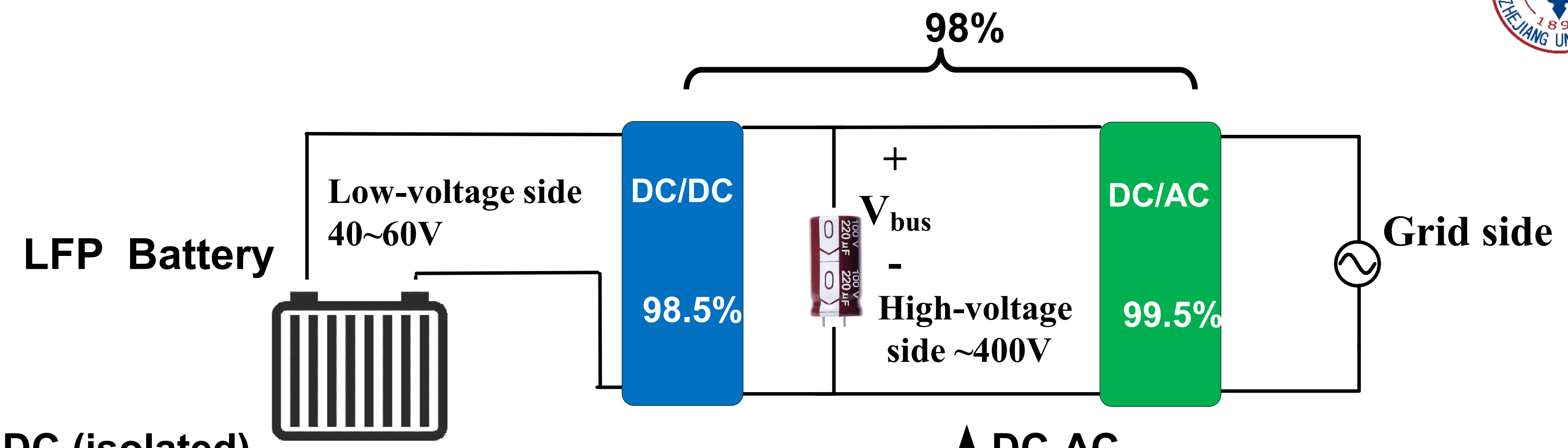


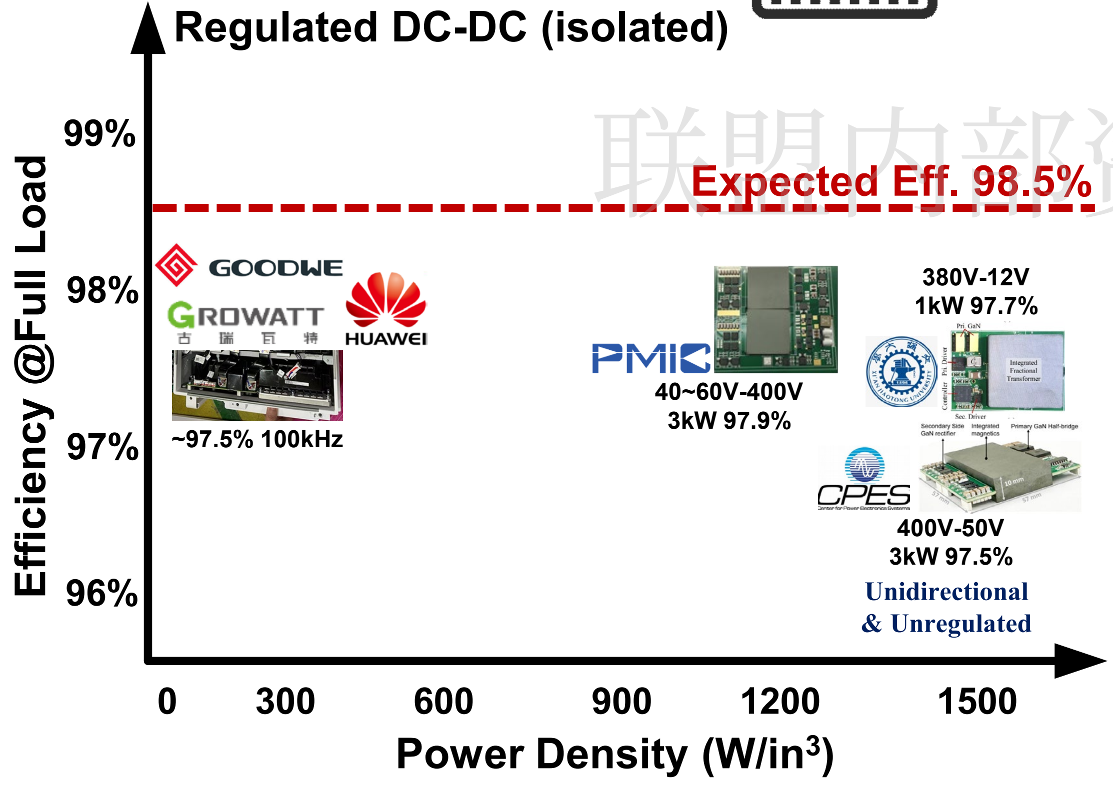


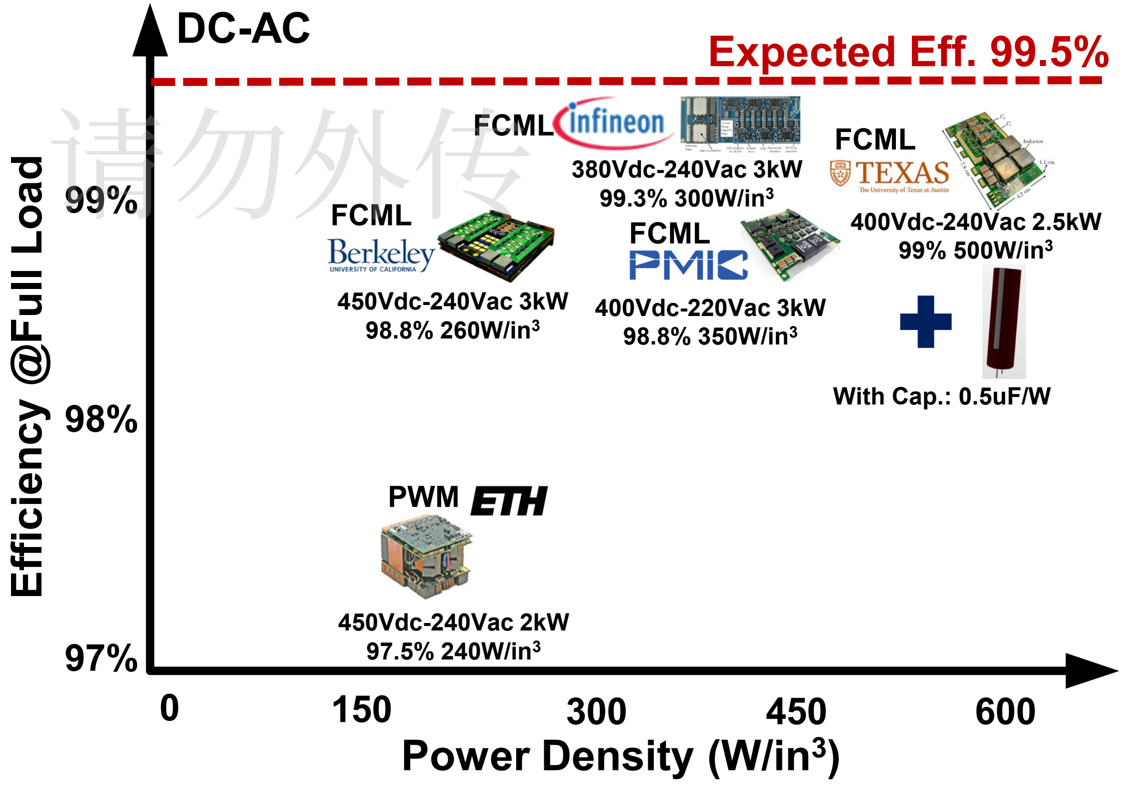
[1] D. Chou et al., “An Interleaved 6-Level GaN …," 2021 IEEE APEC, pp. 1203-1208

[2] C. Wang et al, "Resonant Push–Pull …," IEEE TIE, vol. 68, no. 2, pp. 1178-1187

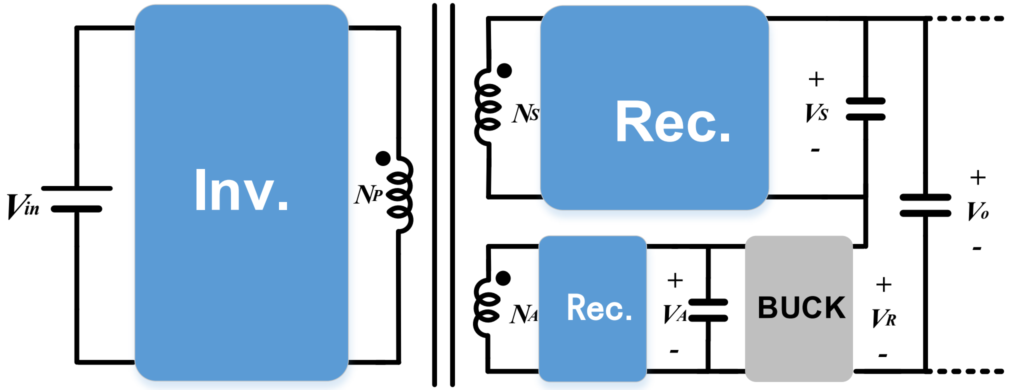
State-of-the-art for Isolated Bidirectional Converter







Low-NFoM Devices Result in Lower Device Conduction Loss

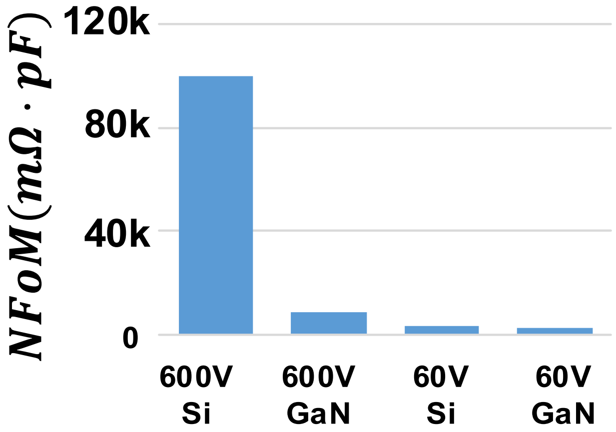


$$P_{con}=\frac{4V_{in}^2T_rC_{otr\_p}^2}{t_d^2T_s}R_{dson}+\frac{\pi^2P_{in}^2T_s}{4V_{in}^2T_r}R_{dson}$$

$$NFoM=R_{dson}*C_{otr}$$

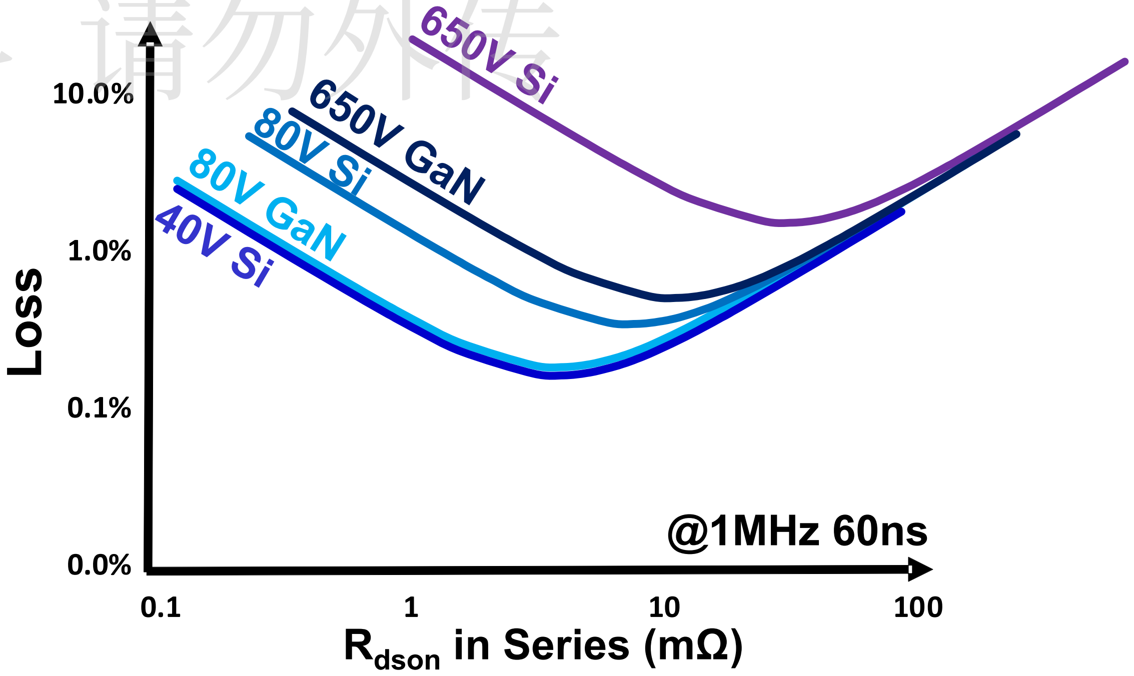
$$P_{con}=\frac{4V_o^2T_rNFoM^2}{t_d^2T_s}\frac{1}{R_{dson\_s}}+\frac{\pi^2P_o^2T_s}{4V_o^2T_r}R_{dson\_s}$$

$$\Rightarrow \frac{P_{conmin}}{P_o}=\frac{2\pi NFoM}{t_d}$$



[1] 600V-Si IPB60RxxxC7 Series
[2] 600V-GaN GS665xxx Series
[3] 60V---Si BSCxxxN06LS5 Series
[4]60V-- GaN EPCxxxx

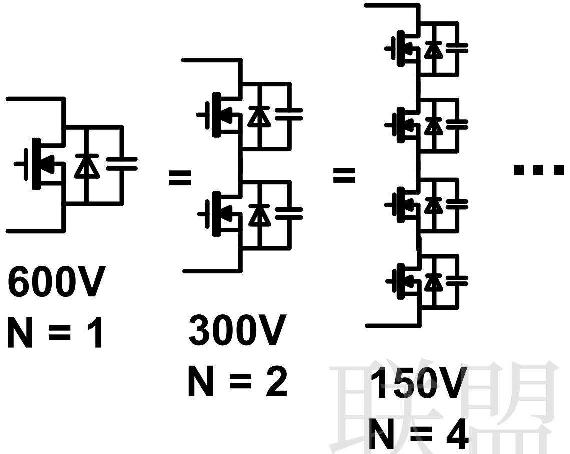
- Conduction Loss



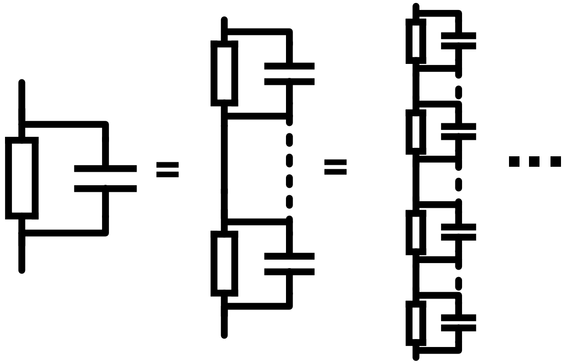
Xinke Wu. Hongbo Shi. "High Efficiency High Density 1 MHz 380–12 V DCX With Low FoM Devices" IEEE TIE 2020. pp1648-1656

Cellular Circuit with Low-Voltage and Low-NFoM Devices

- **Device in Series**

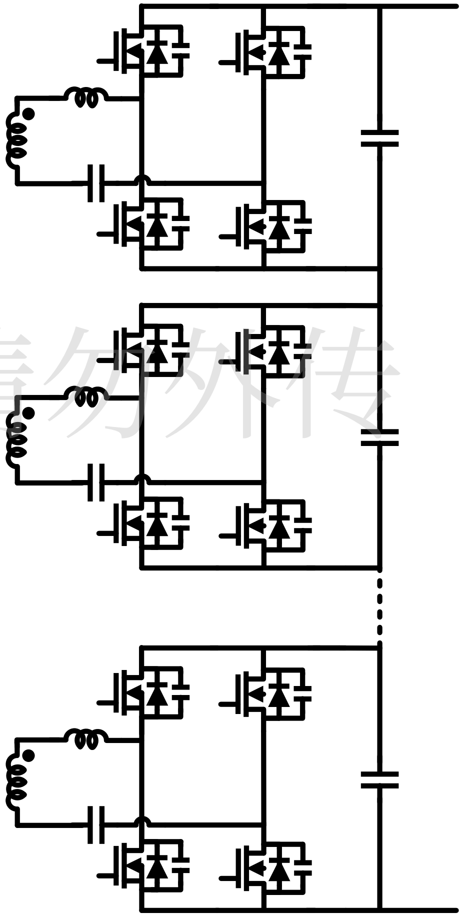


- **Equivalent NFoM**



$$NFoM = \cancel{n}R_{dson} \cdot \frac{C_{otr}}{\cancel{n}}$$

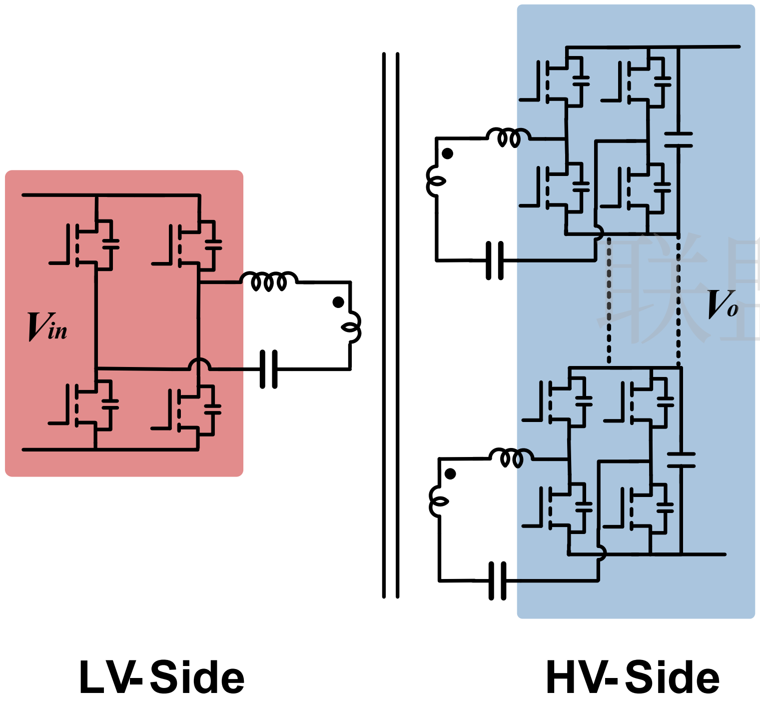
- **Cellular Topology**

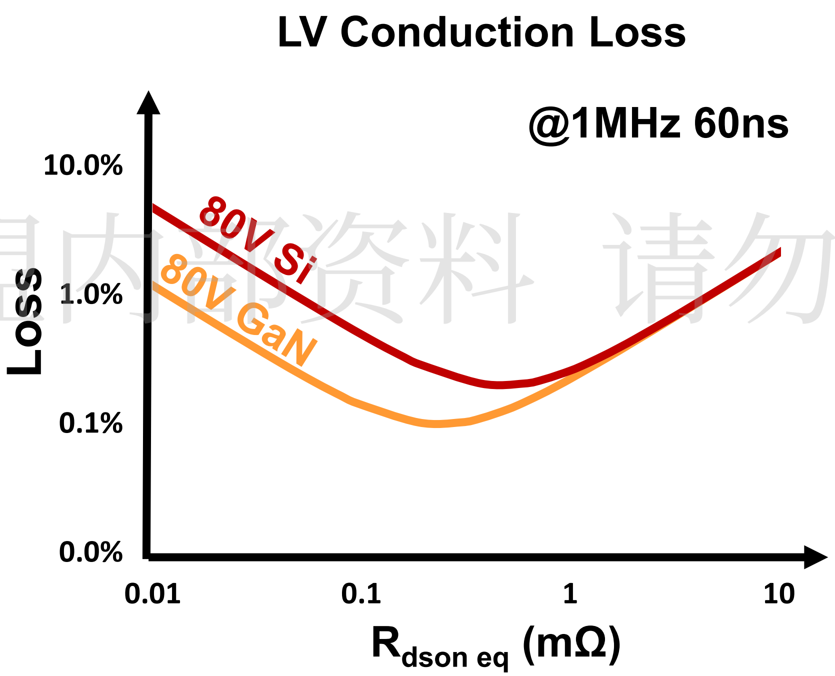


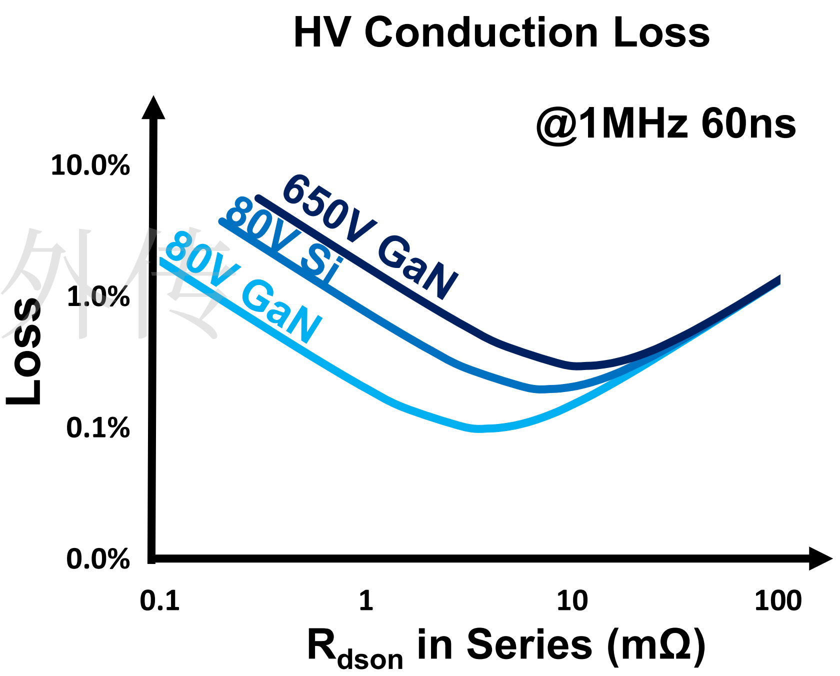
Xinke Wu. Hongbo Shi. "High Efficiency High Density 1 MHz 380–12 V DCX With Low FoM Devices" IEEE TIE 2020. pp1648-1656

80V Device is selected due to low Conduction Loss

- DCX Part V_{in}=48V Fs=1MHz Td=60ns



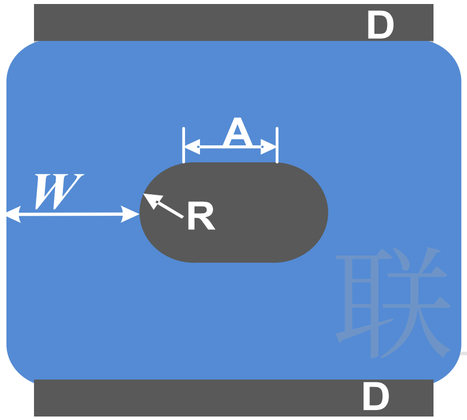




k_{ac} is a Function of C_{otr}

➢ **1MHz Transformer design**

Bmax = 70mT J=25Arms/mm2



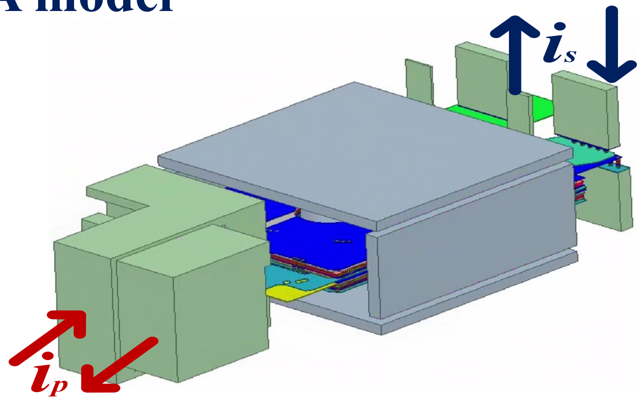
$R = 3.1mm$

$W = 10mm$

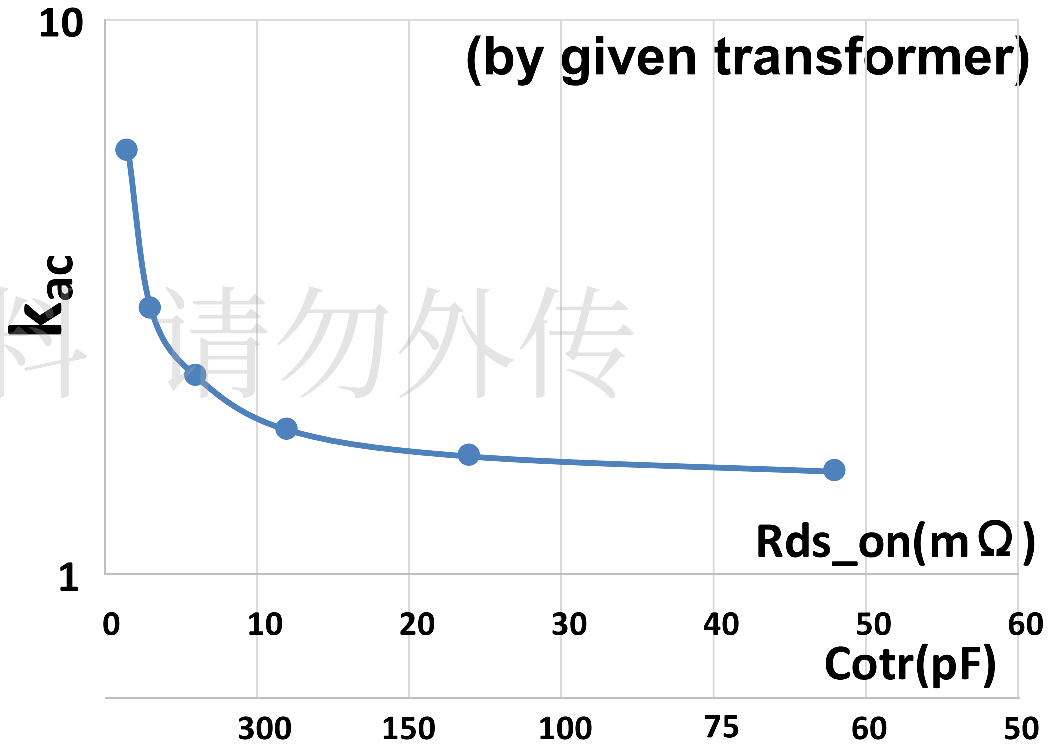
$A = 12mm$

$D = 1.7mm$

➢ **3-D FEA model**

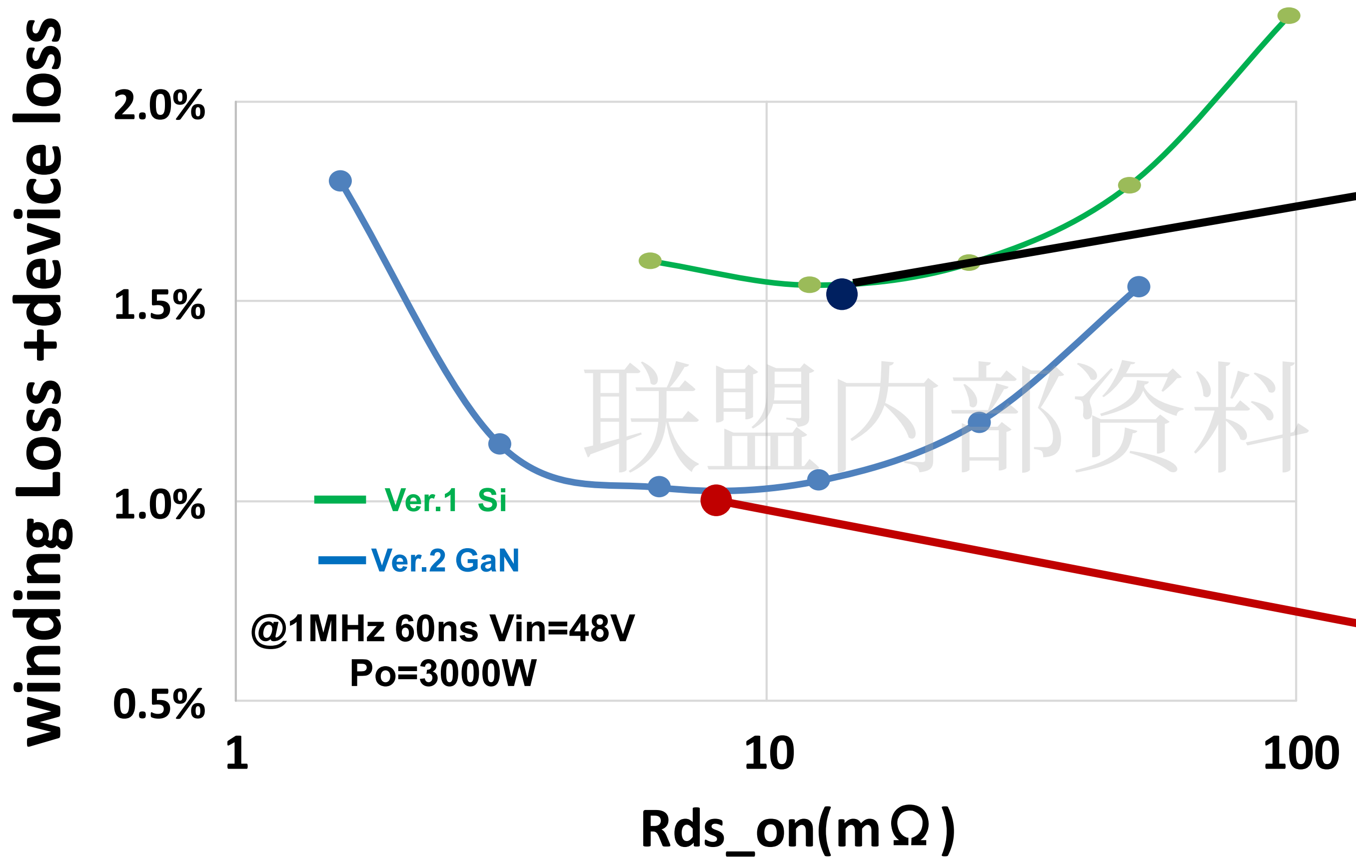


➢ **k_{AC} from 3D FEA in ANSYS EM**

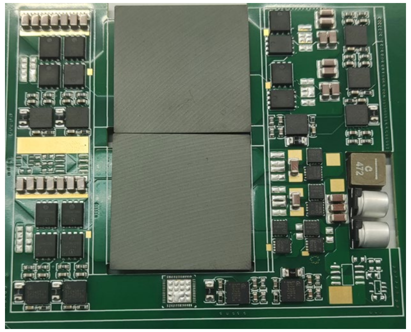


C_{otr} of Device Used As Variable

Prototype Construction based on Combined Loss Model

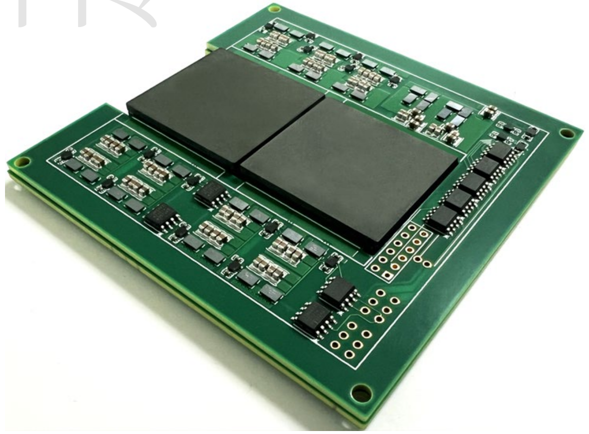


Ver.1



(1MHz&1kW/in³ with 80V Si in 2023)

Ver.2

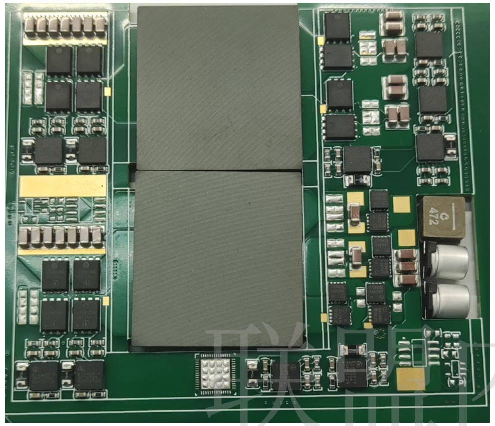


(1MHz&1kW/in³ with 80V GaN in 2024)

Comparison between Two Versions of Prototype

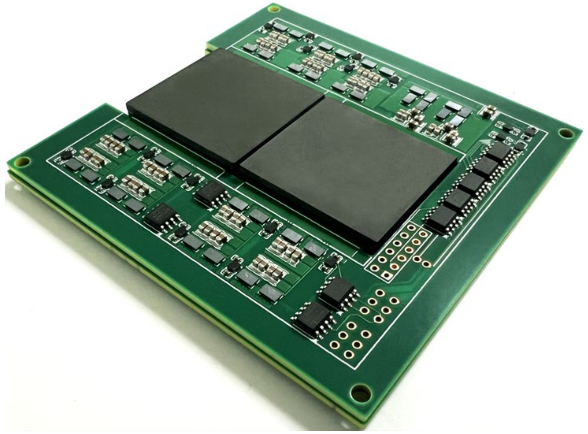
➤ Two Versions of Prototype

Ver.1



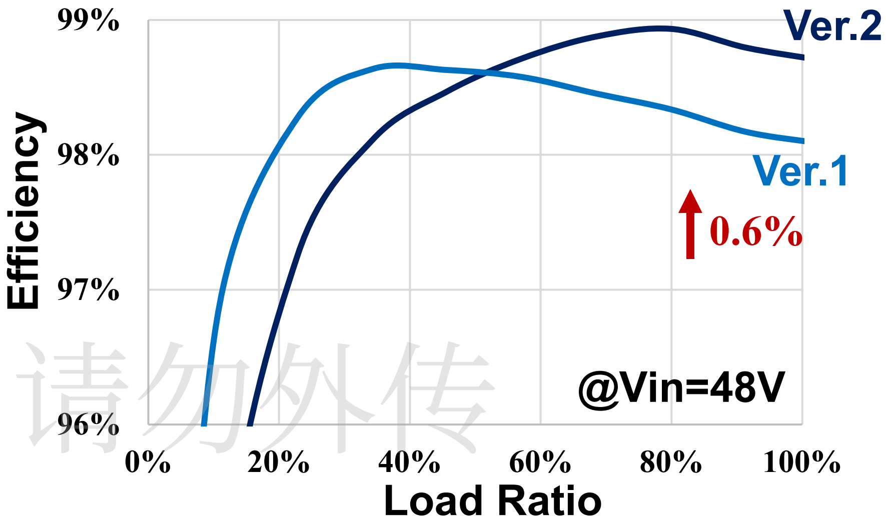
(1MHz&kW/in³ with 80V Si in 2023)

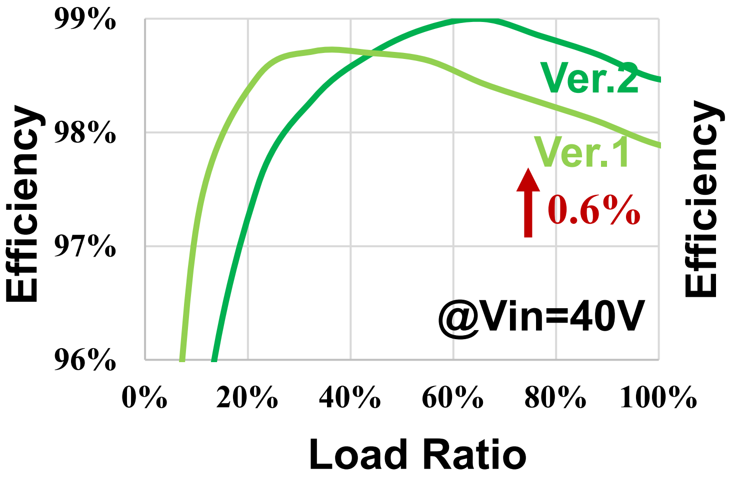
Ver.2

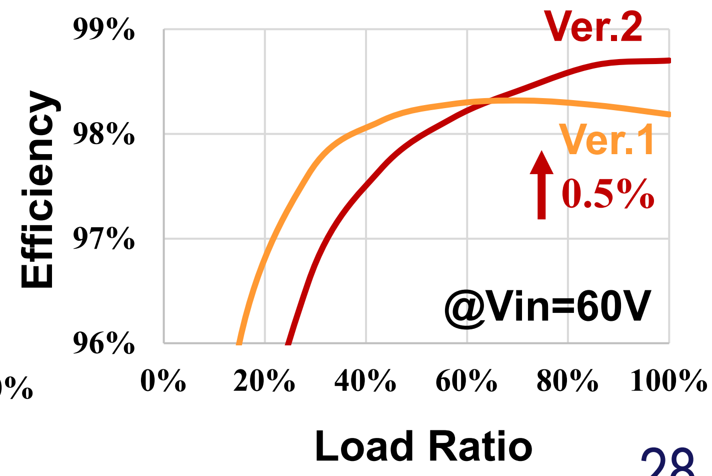


(1MHz&1kW/in³ with 80V GaN in 2024)

➤ DCX Efficiency







Conclusions

1. 揭示了励磁电流对于绕组损耗的影响，利用有限元仿真工具拟合了绕组交流系数kac与励磁电流之间的数学关系，得到了绕组上的导通损耗模型

2. 建立了综合器件损耗和绕组损耗的统一模型，用于指导DCX拓扑中的器件选型和变压器设计

3. 根据统一模型，采用低压器件构造元胞化电路，可实现MHz级开关频率，同时获得高效率和高功率密度

浙江大学杭州国际科创中心
电源管理技术创新联盟

PMIC

Power Management Innovation Consortium

https: pmic.zju.edu.cn

电源管理技术创新联盟(PMIC) 会员- 2024/2025年

PMIC Power Management Innovation Consortium

PMIC 高校主导、行业共建的电源管理技术生态链

器件 → 装置 → 系统

器件

矽力杰半导体
杰华特半导体
铭普光磁
硅动力
横店东磁
希磁科技
英飞凌科技
南芯半导体
铂科新材

装置

深圳英飞源	阳光电源
杰瑞电子	奥海科技
长城电源	麦田能源
富特科技	酷科电子
铂科电子	航嘉驰源
皓文电子	振华微
麦格米特	欣锐科技
晟星和	爱科赛博
七星华创	达峰科技
立讯技术	光宝科技
安世博	军陶科技

系统

OPPO技术
台达电子
中兴通讯
小米科技
安克创新
奇点能源
蔚斯博系统

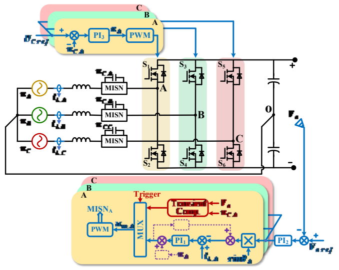
- □ 国内首个
- □ 合作生态
- □ 模式探索
- □ 未来技术

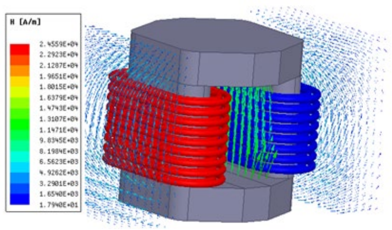
电源管理技术创新联盟-研究方向

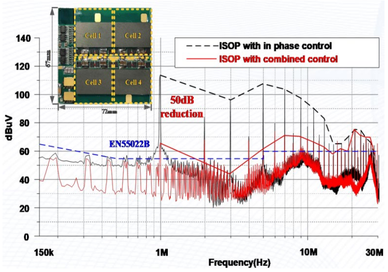
Power Management Innovation Consortium

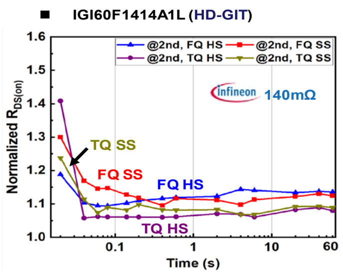
电源管理技术

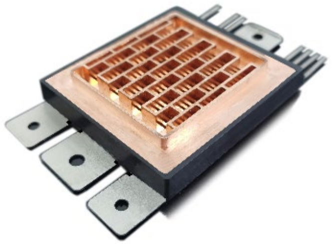
- 电路拓扑
- 磁元件设计
- EMI分析与抑制
- 器件表征
- 先进封装
- 系统集成
- 器件可靠性











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(新百人研究员)

- ◆ 氮化镓芯片及可靠性

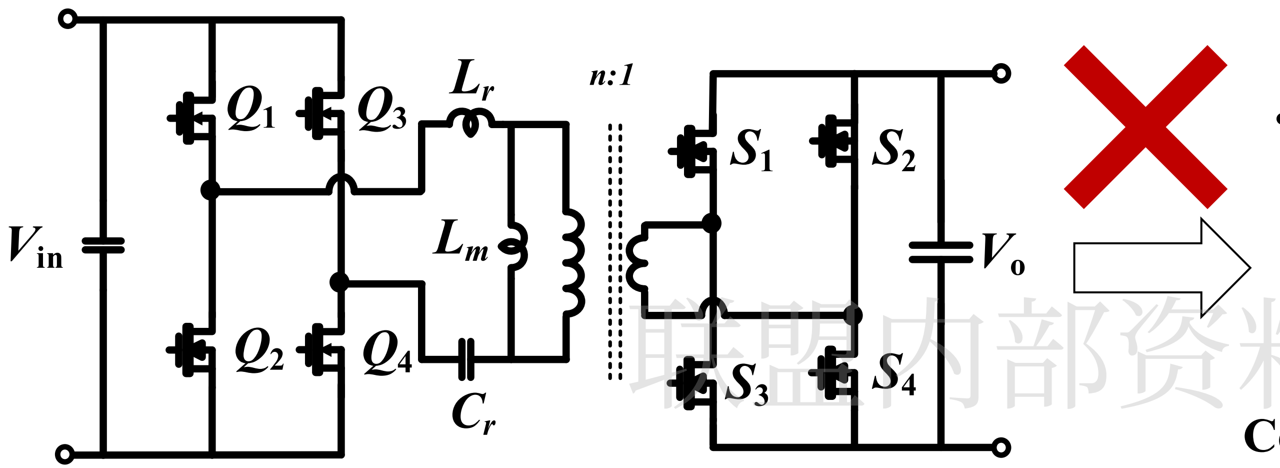
Cinco
浙江 杭州

谢谢！

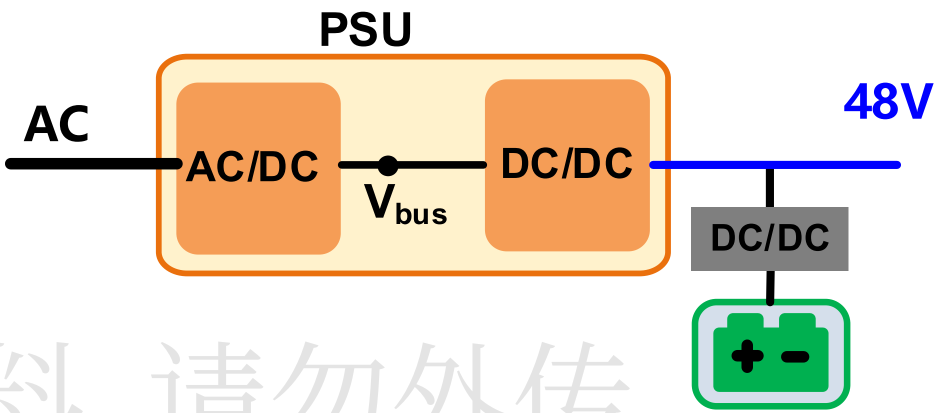
DCX Cannot Be Directly Applied to the DC/DC in Server PSU

Power Management Innovation Consortium

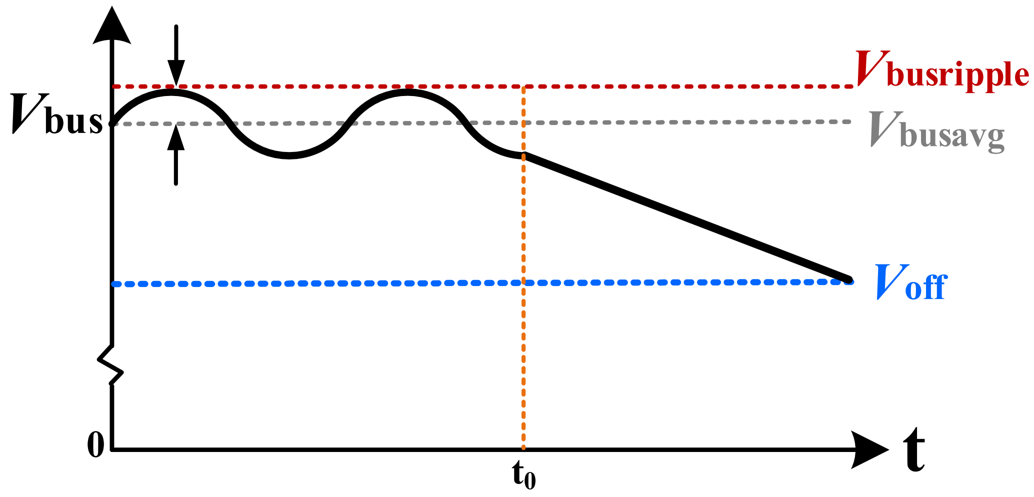
DCX:



400/48V PSU:

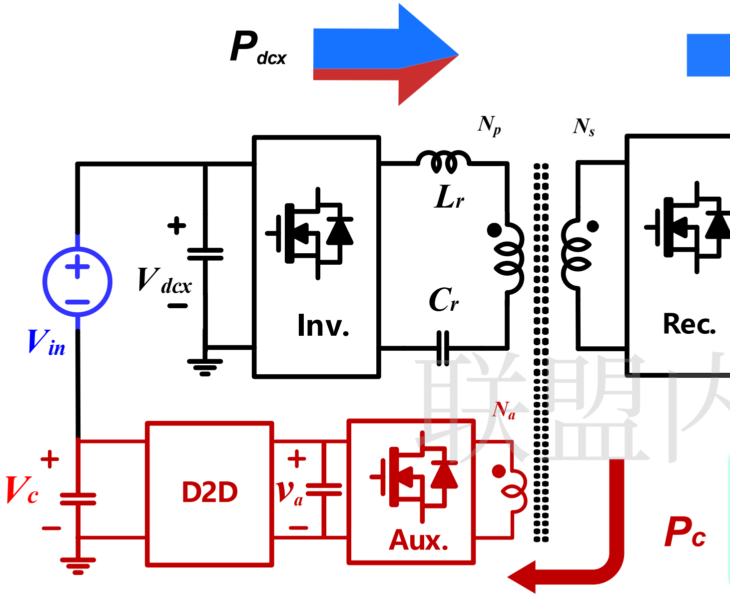


Considering Bus ripple & power-off:



Operation Principle of Regulated DCX (RDCX)

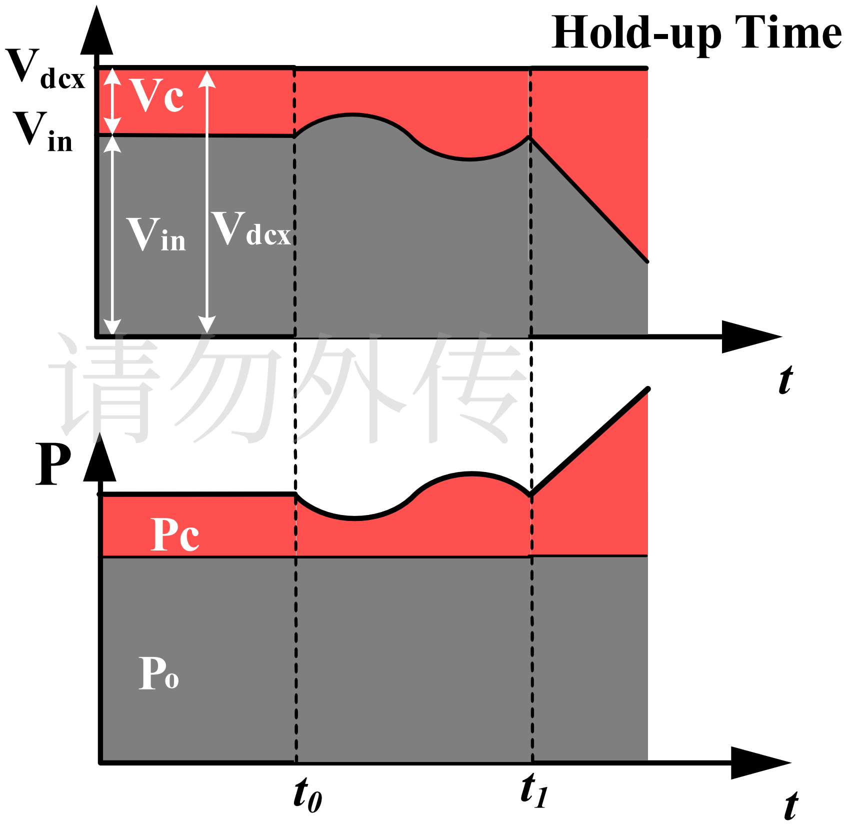
RDCX for 2nd-stage DC/DC:



$$\frac{P_c}{P_{Load}} = \frac{V_c}{V_{in}}$$

- High-frequency high-efficiency DCX;
- Very low P_c @normal operation;
- Simple control strategy

Operation principle:

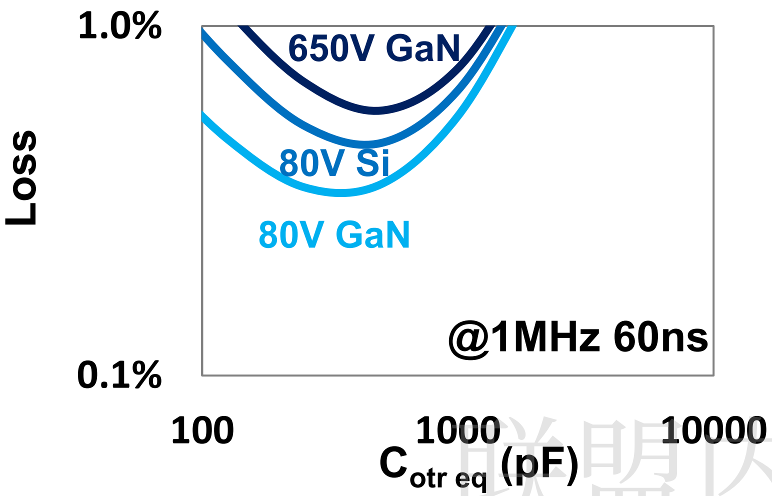


[6] T. Liu, X. Wu and S. Yang, "1 MHz 48–12 V Regulated DCX With Single Transformer," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 1, pp. 38-47, Feb. 2021;

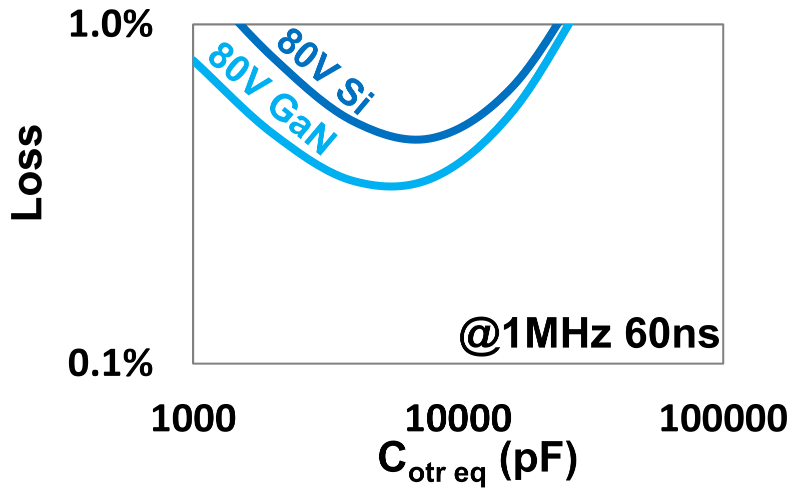
Device Selection Using Combined Conduction Loss Model

Power Management Innovation Consortium

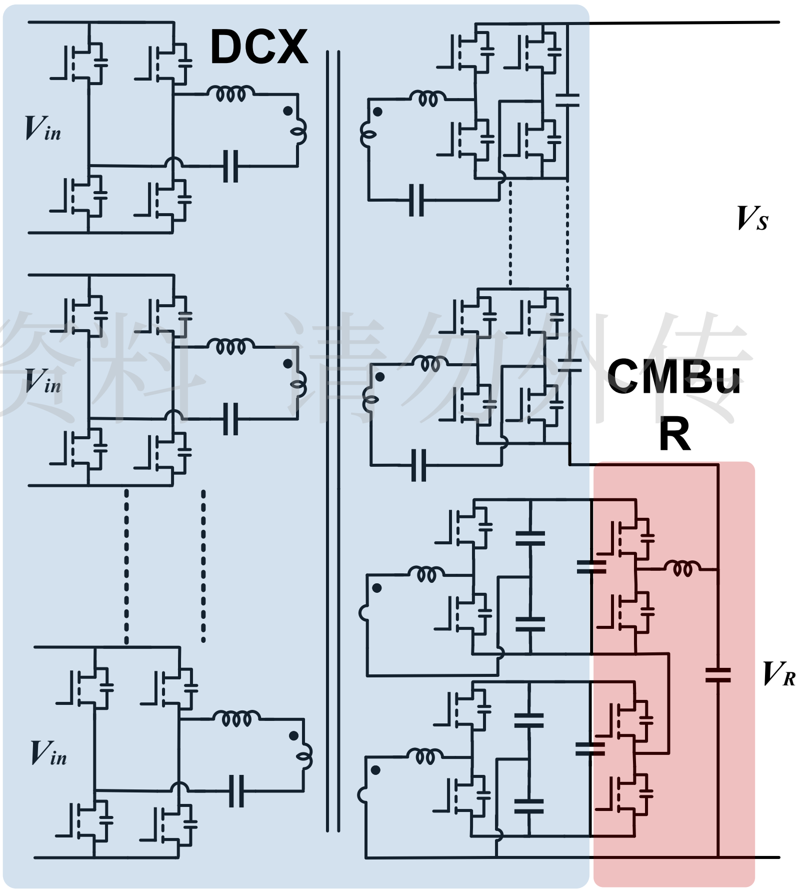
HV Combined Conduction Loss



LV Combined Conduction Loss



- **Cellular RDCX Topology**



Cellular RDCX

Power	3kW
V_{in}	40~60V
V_o	330-420V
Core	DMR51W
Device	EPC2218

Projected Efficiency :
98.8%
@Vin=48V (DCX part)