CPSSC 2021

PCB Based Integrated Magnetics

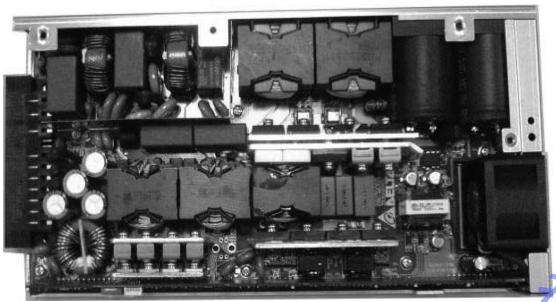
- Benefits and Limitations -

Fred C Lee

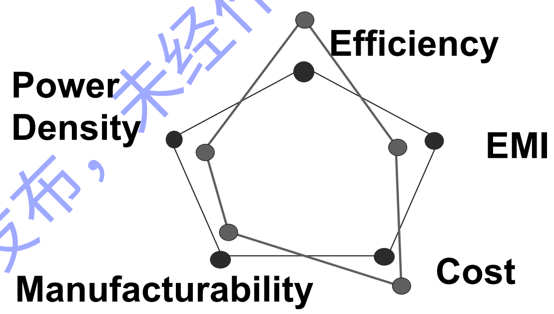
CPES
Virginia Tech

State-of-the-Art Server Power Supplies

SOA silicon based design
has reach a point of maturity in performance optimization



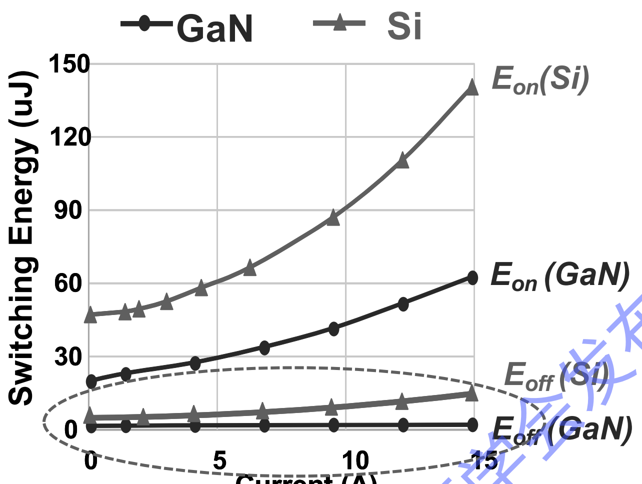
1KW Server power supplies



Trade offs:
efficiency, power density and Cost

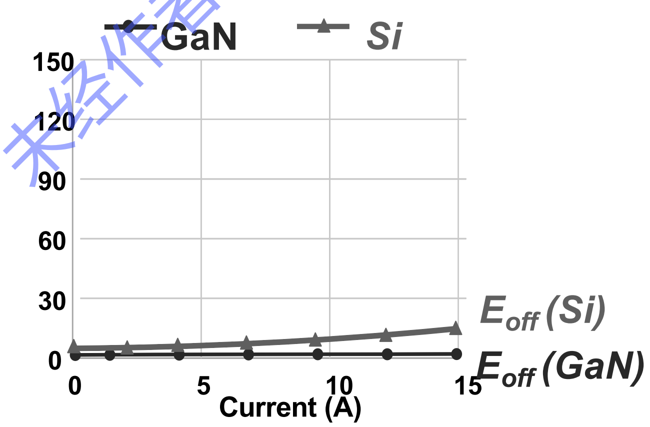
Unsolved Issues: **EMI & Manufacturability**

GaN vs Silicon MOSFET



CaN: 3X better

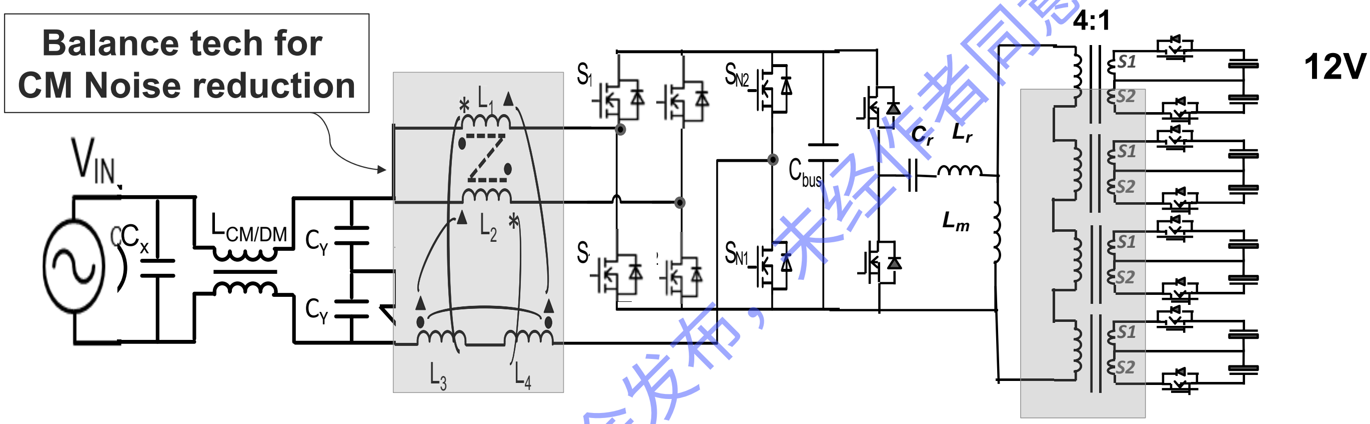
With ZVS



GaN: 10 - 20X better

What would you do if there is no switching related loss??

GaN-Based 1kW Server Power Supplies



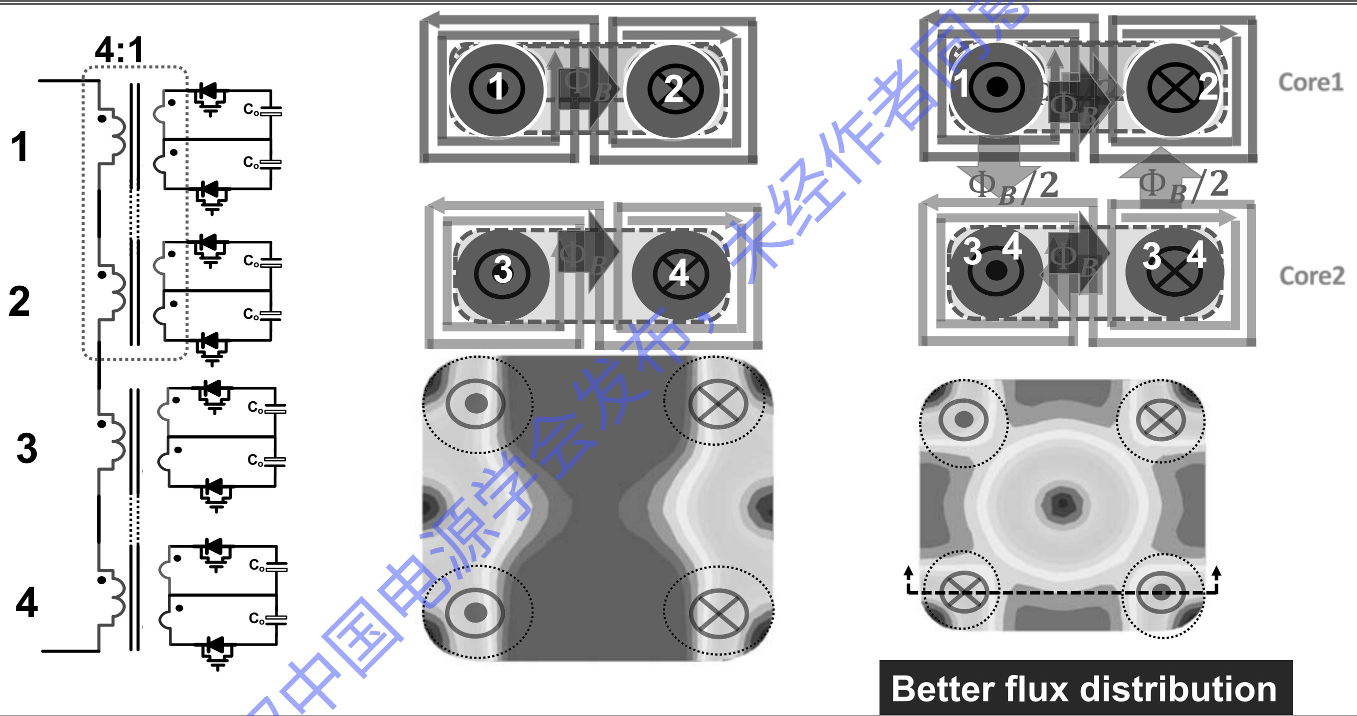
Totem-pole PFC

- > 1MHz
- CRM with ZVS
- PCB Based integrated inducotrs

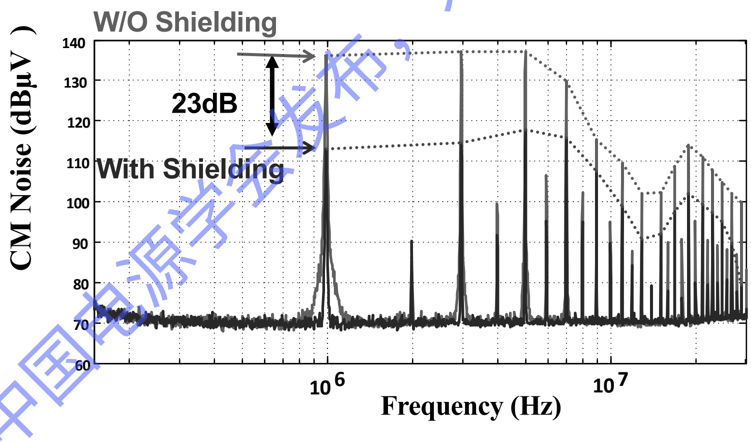
LLC D2D

- > 1MHz
- PCB based integrated L&T

Feature 1: Integrated Transformers in PCB



Feature 2: CM Noise Reduction by Shielding



Yuchen, Yang, D. Huang, F. C. Lee, and Q. Li. "Analysis and reduction of common mode EMI noise for resonant converters" *APEC 2014*, pp. 566-571

Feature 3: Integrated Inductors in PCB

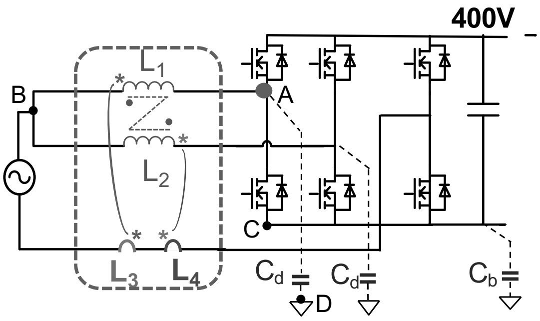
	Winding (W)	Core Loss (W)	Total Loss (W)
PCB Winding	6.7	1.3	8.0
	2.3	2.3	4.6

	Winding(W)	Core Loss (W)	Total Loss (W)
6-Layer with Winding Cut	2.4	1.9	4.3
	2.3	2.3	4.6

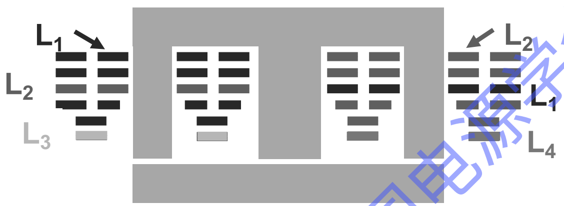
Total loss is smaller than Litz wire inductor

[1] Yuchen Yang's Dissertation, "EMI noise reduction techniques for high frequency power converters", Virginia Tech, Blacksburg, 2018.

Feature 4: Reducing CM Noise by Balance



PCB embedded coupled inductor

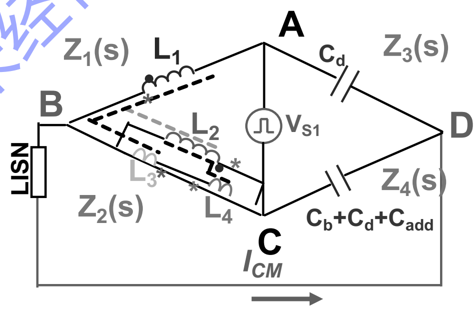


L_3 & L_4 are free gifts

***CM Noise Equivalent Circuit**

Apply superposition to V_{S1}

Wheatstone Bridge

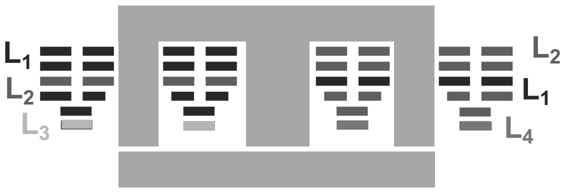


Balance Condition

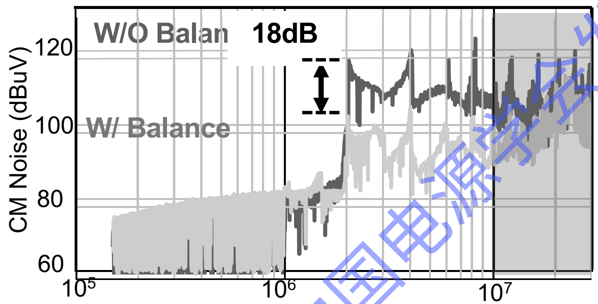
$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4}$$

$I_{CM} = 0$

Further Reduction of CM Noises in High Frequency

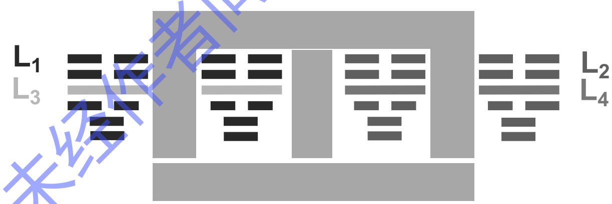


$\alpha_{12} = -0.6$;. $\alpha_{13} = 0.96$

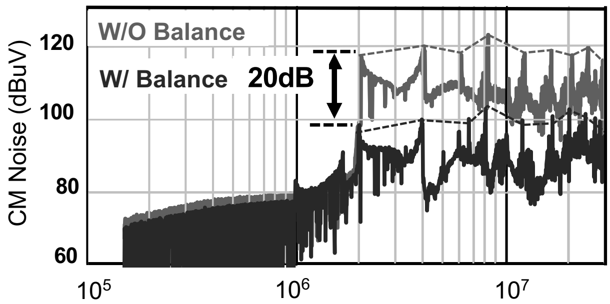


20dB CM noise reduction under 10 MHz

Improved Structure

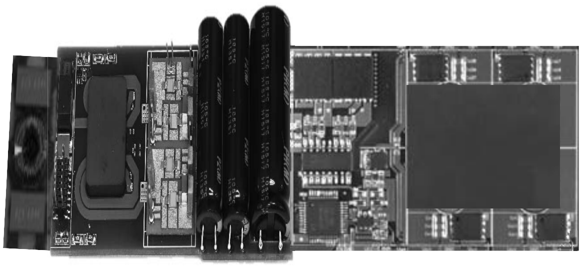


$\alpha_{12} = -0.6$; $\alpha_{13} \approx 1$

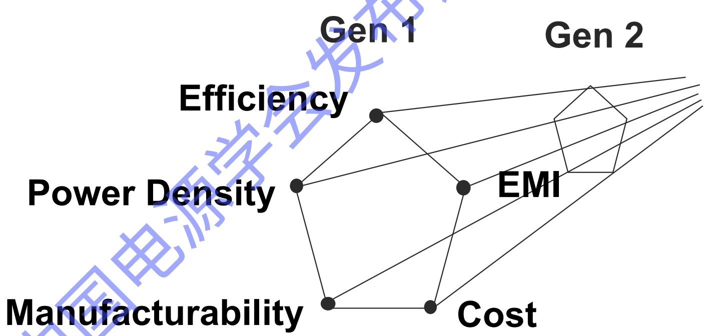


20dB CM noise reduction up to 30 MHz

Is GaN A Game Changer ?



Eff ≈ 98%
Power density $> 5X$
Improved EMI ≈ 20dB
Automated Manufacturing
Low Cost



CPES

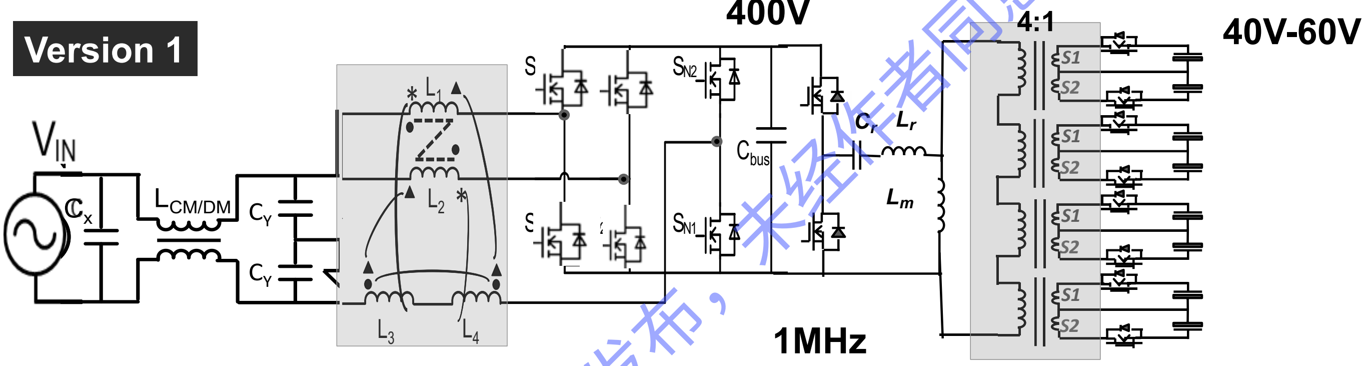
Can we repeat the success of

PCB based Integrated Inductors and Transformers

at Higher Power Level ?

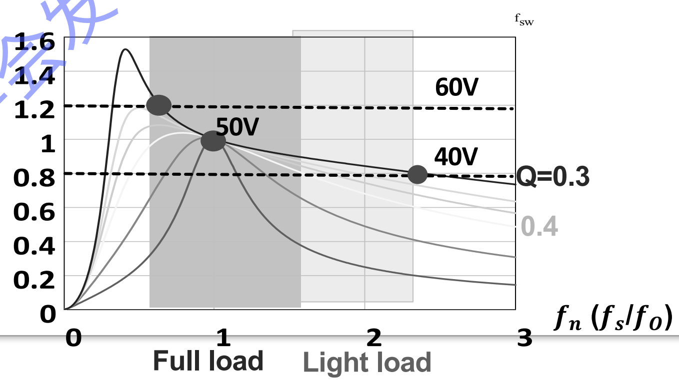
3kW Server Power Supplies

Version 1

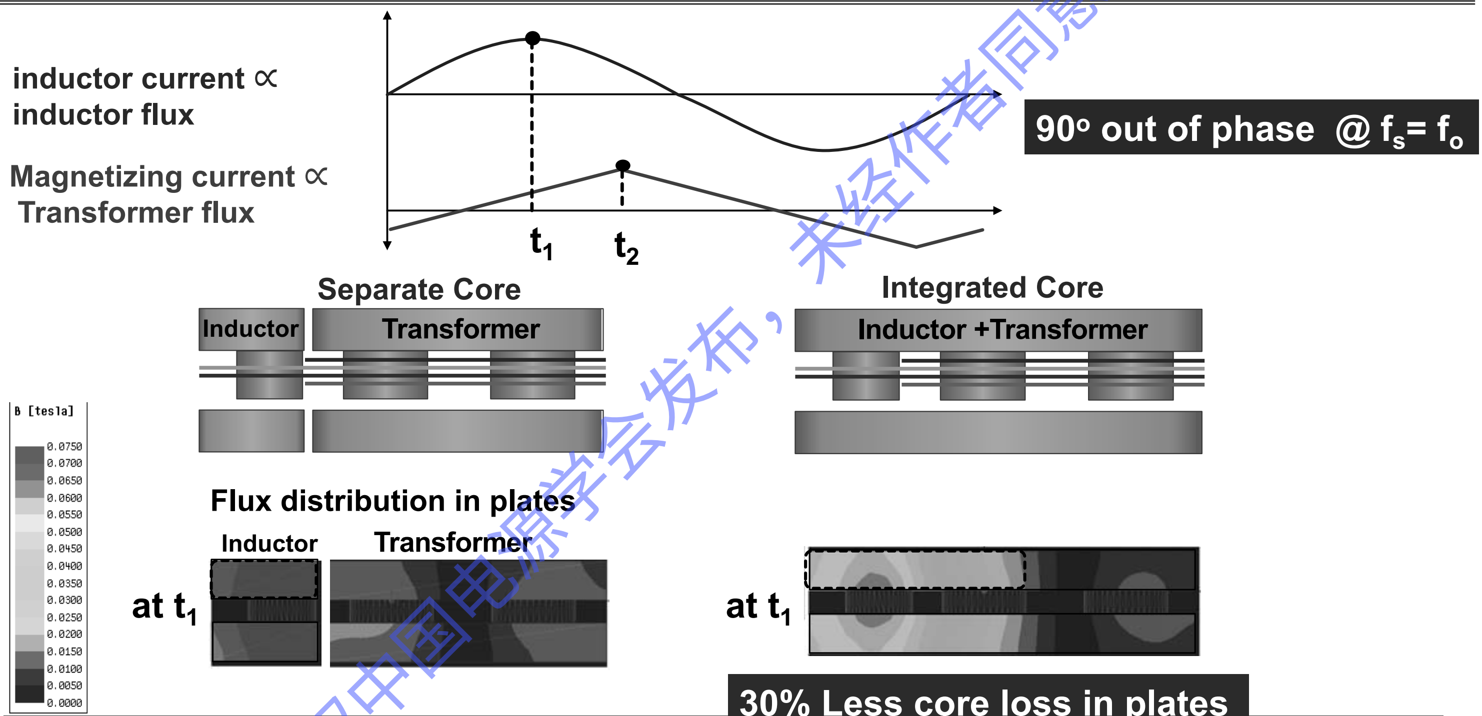


Need gain control

Wide frequency range



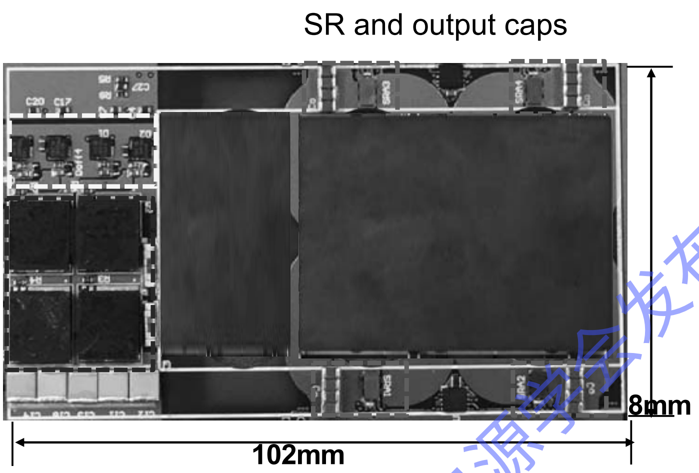
Integration of Inductor and Transformers



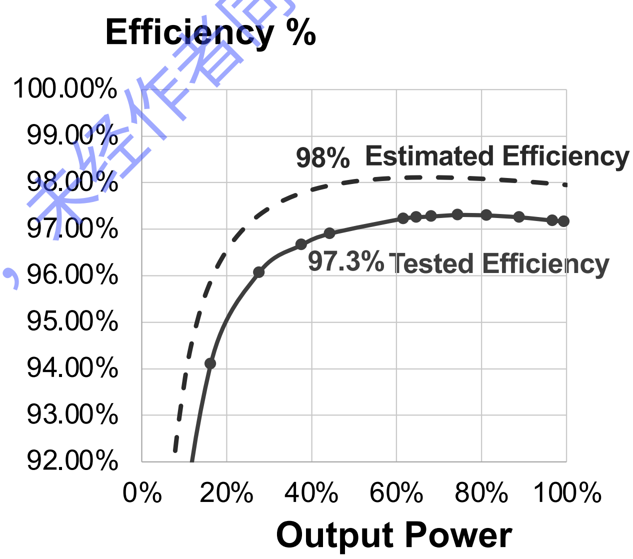
30% Less core loss in plates

Version 1: Hardware Prototype

Fs=1MHz, Lm=16uH, Lr=4uH, Cr=6.2nF, td=65ns

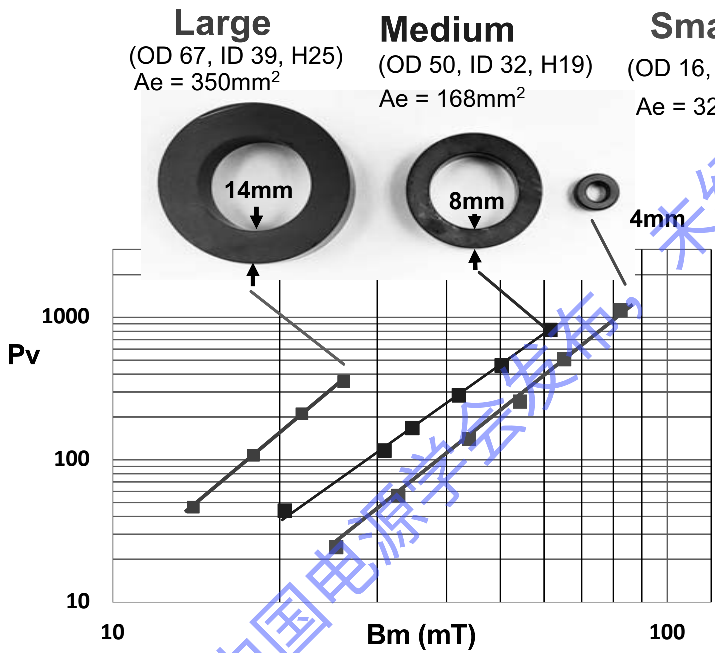


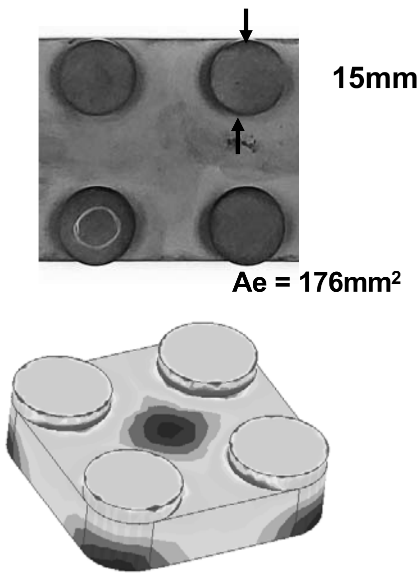
1MHz, 450W/in^3



Significant difference between tested and estimated efficiency

Impact of Core Size on Core Loss

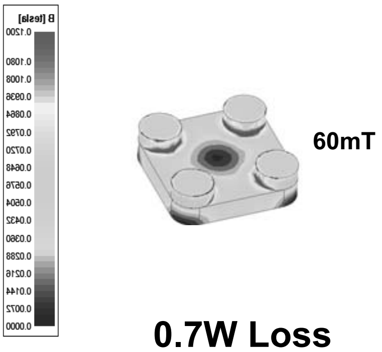




Higher P_v with larger core size

Issues: Eddy Loss and Skin Effect in large Cores

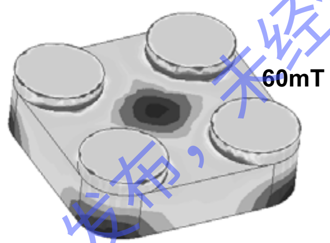
Case 1:
!KW @ 12V & 1MHz



0.7W Loss
(20% Eddy Loss)

4X

Case 2:
3KW @ 48V & !MHz



10W Loss
(60% Eddy Loss)

Eddy Loss density:

$$P_{eddy} = \frac{1}{4}\sigma\pi B_m^2 f^2 A_e$$

$\sigma = material\ conductivity$

$B_m = max\ flux\ density$

$f = frequency$

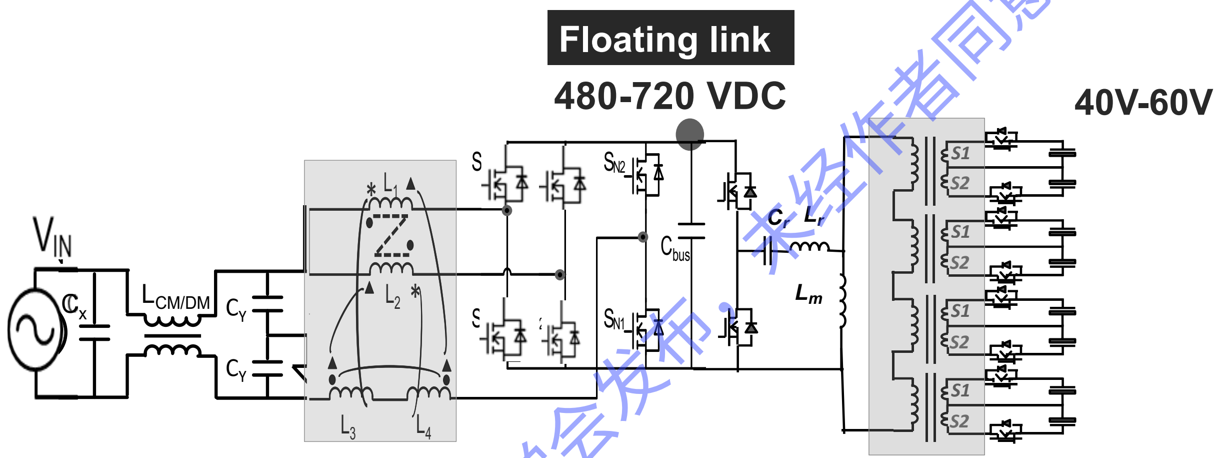
$A_e = cross\ section\ Area$

Core loss density increases disproportionally

About 70-80% core loss is on the plates

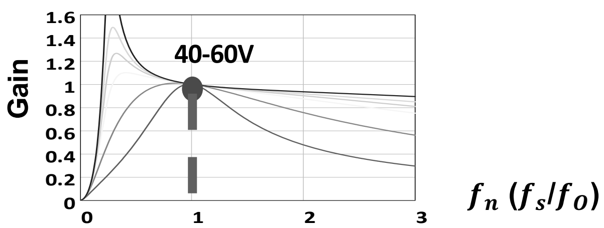
[1] "High-Frequency Dimensional Effects in Ferrite-Core Magnetic Devices" Skutt, Glenn R., Fred Lee, 1996
[2] Jiri Lammeraner and Milos Stafl, Eddy Currents, CRC Press, 1967

Improvement 1 : DCX with Floating Bus Voltage



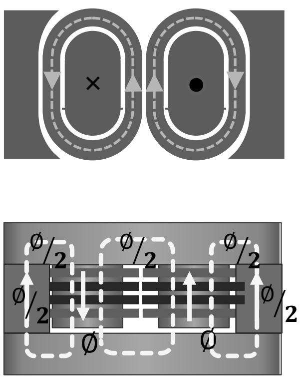
1000V SiC

Fs = 500KHz

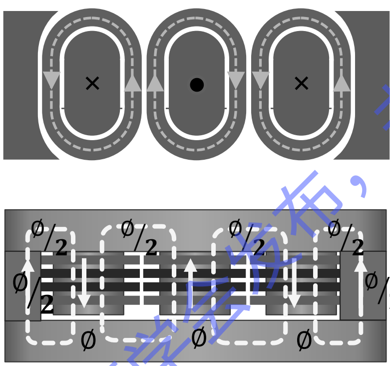


Improvement 2: Planer Magnetic Design

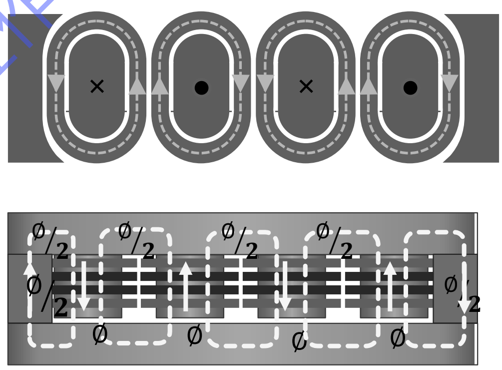
2-Transformers



3-Transfomers

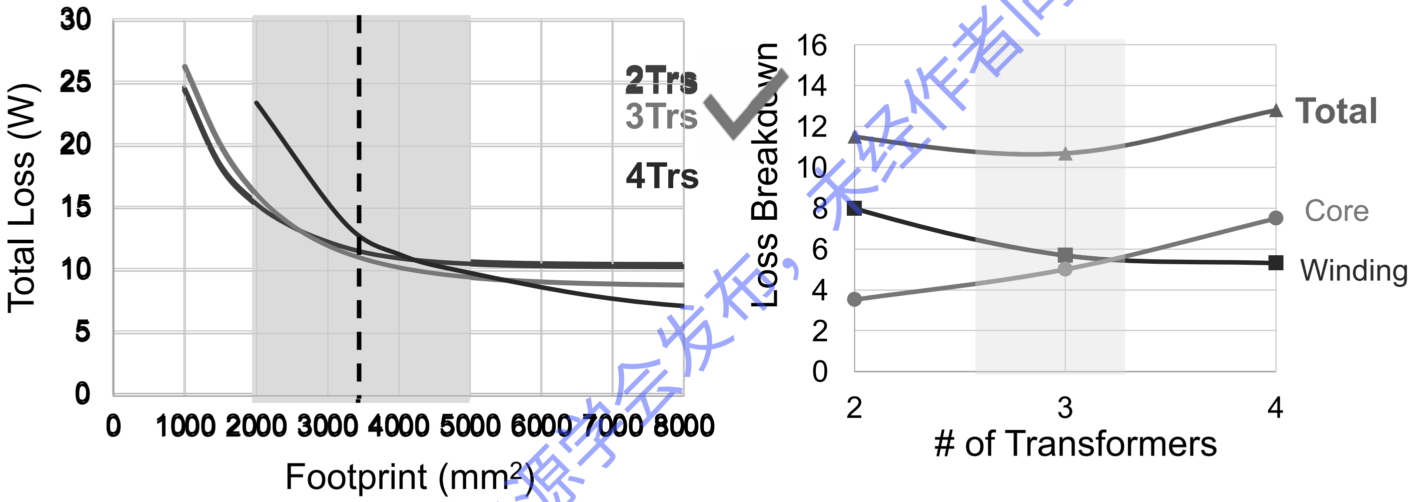


4-Transfomers



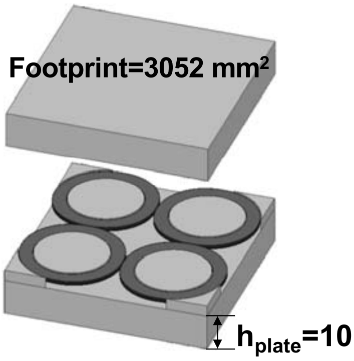
Bm in the plates = 0.5Bm in the posts; thus with reduced eddy loss

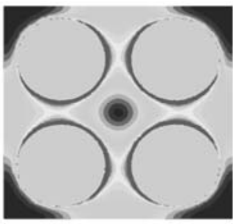
Optimum Number of Transformers



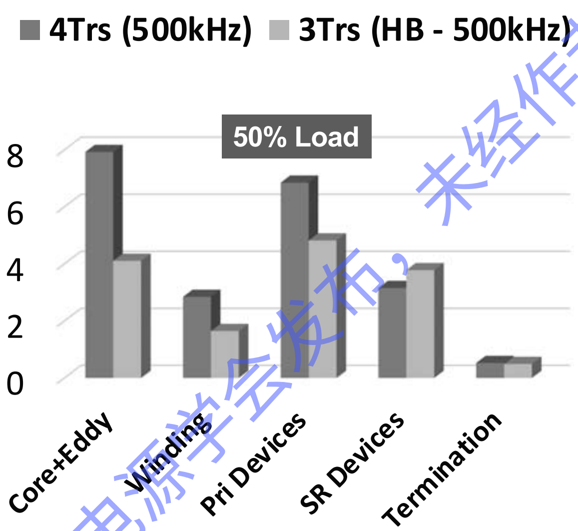
❖ **1-Transfomer per kW is deemed optimal**

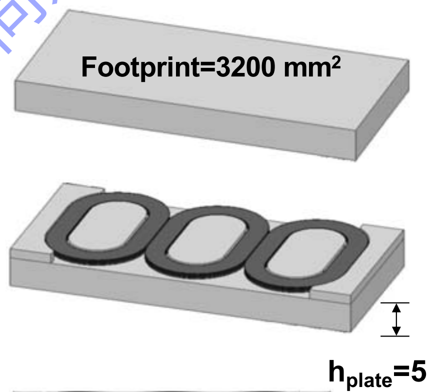
Improvement 2: Transformer Design

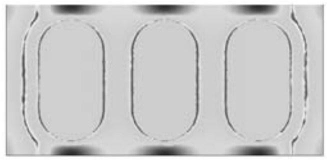




4x 900V SiC MOSFET
16x 80V GaN SR

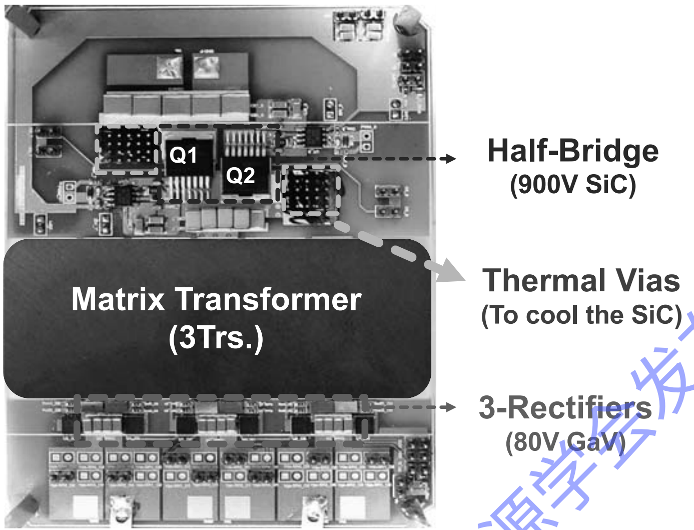


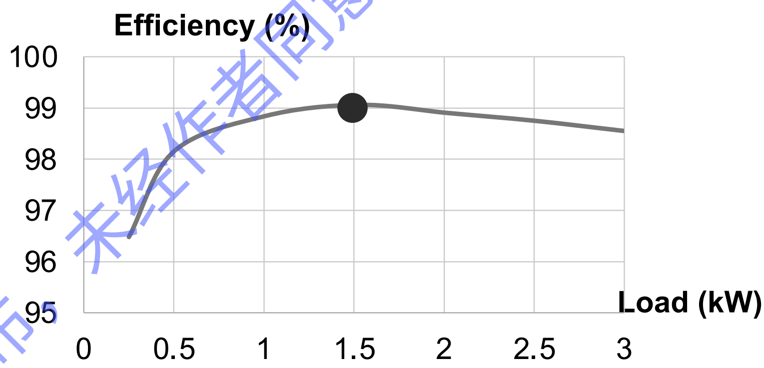


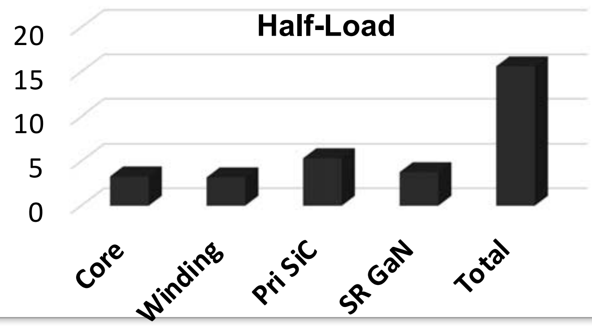


2x 900V SiC MOSFET
12x 80V GaN SR

Hardware Prototype





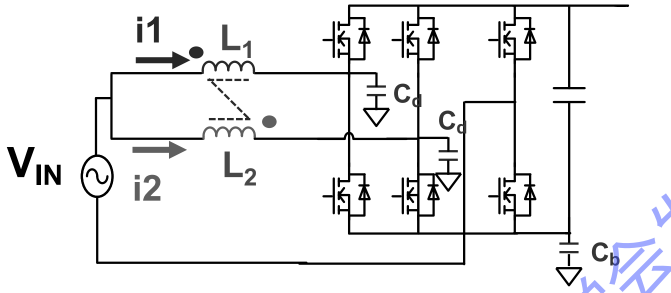


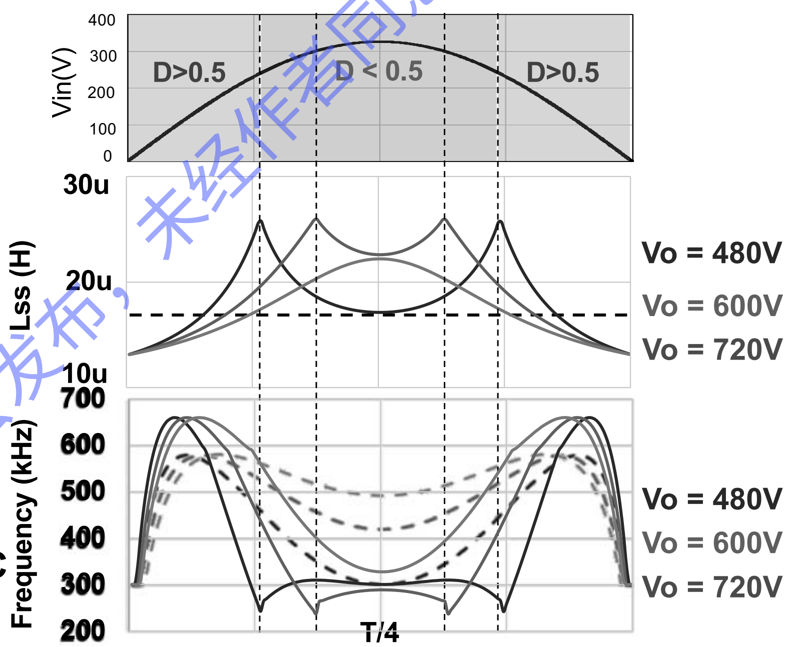
Lm=32 uH   Lk = 0.260 uH   Cr = 420 nF
Fs = 470 kHz Td=85 ns Load = 3 kW (100%)

PFC with Variable Link Voltage

Negative coupling

α = - 0.6





L1 & L2 are positively coupled

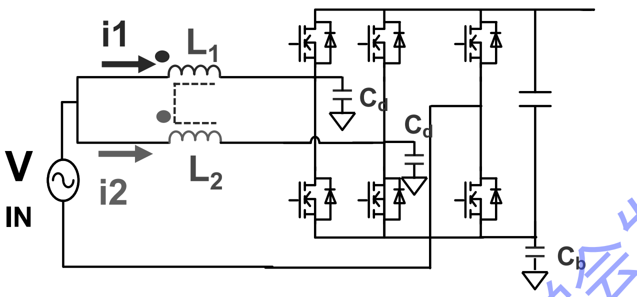
Design is different from 1KW PFC

Negative coupled inductor has larger f_{sw} range than non-coupled inductor

PFC with Variable Link Voltage

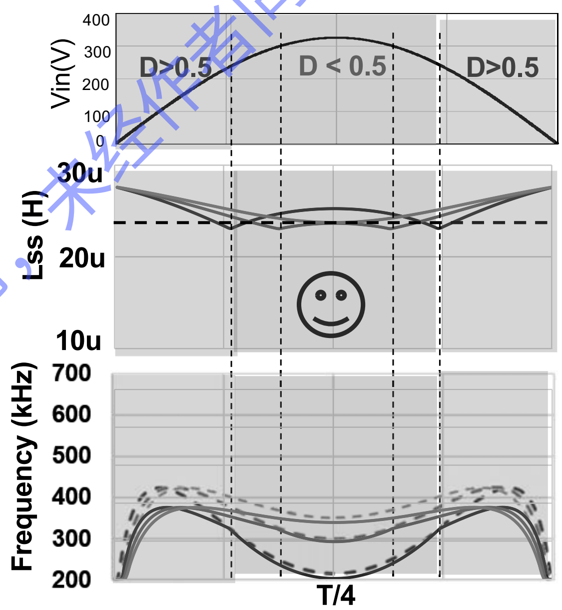
Positive coupling

α = 0.2



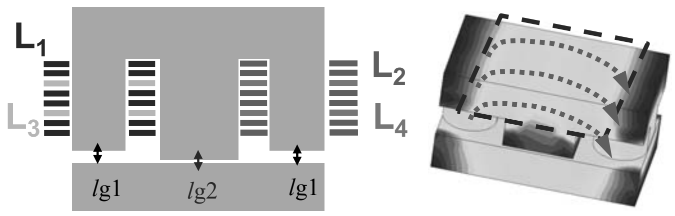
L1 & L2 are positively coupled

Design is different from 1KW PFC



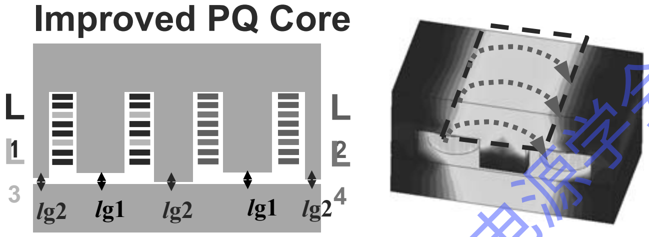
Positive coupling reduces f_{sw} range

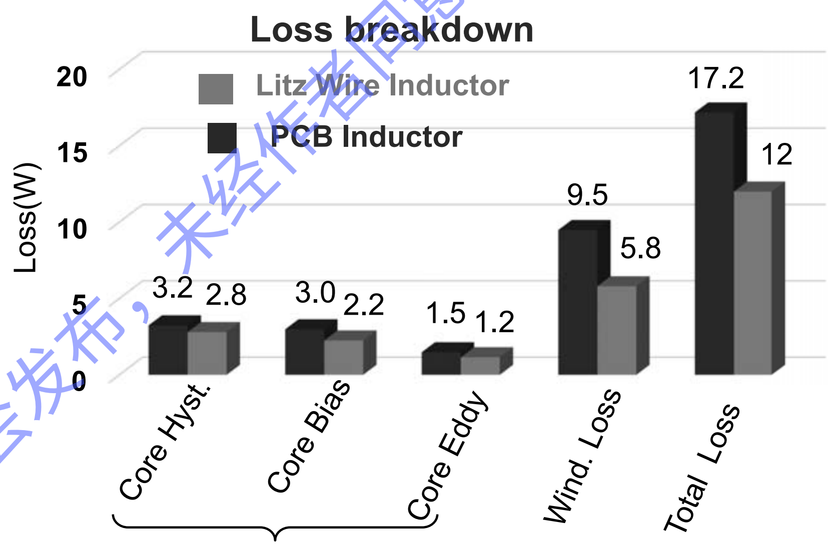
3kW PCB Inductor vs. Litz Wire Inductor



× High core loss

Improved PQ Core





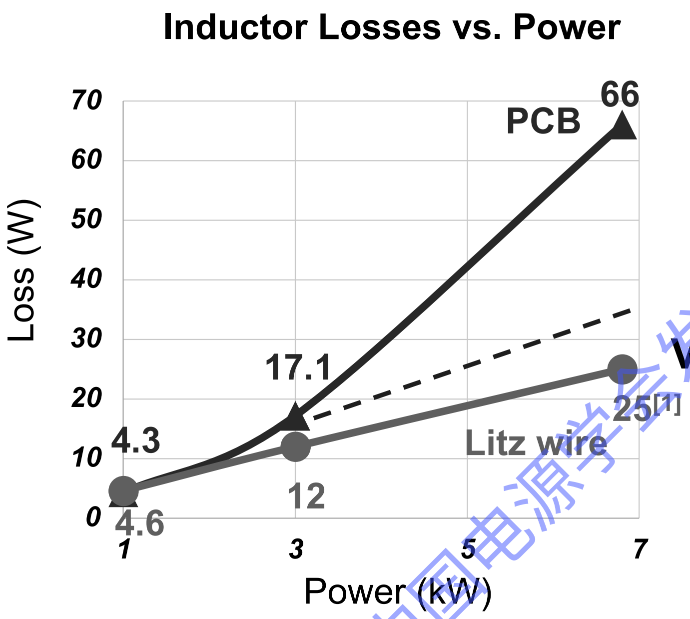
Core loss:
7.7 W vs. 6.2 W

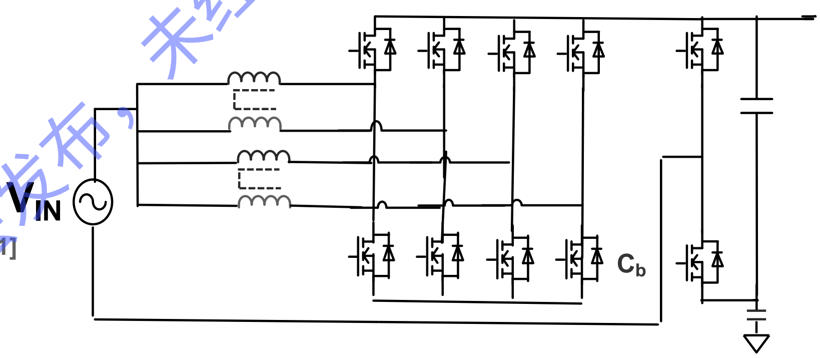
Core loss is reduced by 15%

Limitation: 3KW for PCB Based inductors

CPES

Limitation of PCB based Inductors





Maximum power level at 1 KW per phase

[1] Yuchen Yang's Dissertation, "EMI noise reduction techniques for high frequency power converters", Virginia Tech, Blacksburg, 2018.

Summary

- ❖ PCB Based modular transformer building block @ 1KW
- ❖ PCB Based inductor modular building block @ 1KW

GaN/SiC to Replace Silicon

- ❖ Improvement of Efficiency (incremental)
- ❖ Improvement of Power Density (3-5X)
- ❖ Improvement of EMI/EMC is unique (150KHz- 30MHz)
- ❖ Improvement of Manufacturability - Paradigm shift

Date CPES Proprietary

Acknowledgement

CPES Research Collaborators

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Dr. Mingkai Mu
Mr. Rimon Gadelrab
Mr. Shuo Wang
Dr. Xiucheng Huang
Dr. Yuchen Yang
Dr. Zhengrong Huang
Dr. Zhengyang Liu

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[1] Zengyang Liu, Fred C. Lee, Qiang Li, Yuchen Yang, "Design of GaN-based MHz Totem-pole PFC Rectifier," IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol. 4, No. 3, pp. 799-807, September 2016.

[2] Zhengyang Liu, Zhengrong Huang, Fred C. Lee, Qiang Li, "Digital-Based Interleaving Control for GaN-based MHz CRM Totem-le PFC," IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol. 4, No. 3, pp. 808-814, September 2016.

[3] Yuchen Yang, Mingkai Mu, Zhengyang Liu, Fred Lee, Qiang Li, "Common Mode EMI Reduction Technique for Interleaved MHz Critical Mode PFC Converter with Coupled Inductor," 2015 IEEE Energy Conversion Congress & Expo (ECCE 2015), Montreal, Canada, September 20-24, 2015, pp. 233 - 239.

[4] Yuchen Yang, Zhengyang Liu, Fred C. Lee, Qiang Li, "Analysis and filter design of differential mode EMI noise for GaN-based interleaved MHz critical mode PFC converter", 2014 IEEE Energy Conversion Congress and Exposition (ECCE), Pittsburgh, PA, September 14-18, 2014, pp. 4784 - 4789.

[5] Shuo Wang, Yuchen Yang, Fred C. Lee, Qiang Li, "Single Stage EMI Filter for Server Power Supply", 2020 IEEE Applied Power Electronics Conference & Exposition (APEC 2020), New Orleans, LA, March 15-19, 2020.

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[7] Chao Fei, Fred C. Lee, Qiang Li, "High-efficiency High-power-density LLC Converter with an Integrated Planar Matrix Transformer for High Output Current Applications", IEEE Transactions on Industrial Electronics, Vol. 64, No. 11, pp. 9072-9082, November 2017.

[8] Chao Fei, Yuchen Yang, Qiang Li, Fred C. Lee, "Shielding Technique for Planar Matrix Transformers to Suppress Common-Mode EMI Noise and Improve Efficiency," in IEEE Transactions on Industrial Electronics, Vol. 65, No. 2, February 2018, pp. 1263 – 1272.

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[9] S. Wang, H. Wu, F. C. Lee and Q. Li, "Integrated Matrix Transformer with Optimized PCB Winding for High-Efficiency High-Power-Density LLC Resonant Converter," 2019 IEEE Energy Conversion Congress and Exposition (ECCE)

[10] Zhengyang Liu, Bin Li, Fred C. Lee, Qiang Li, "High-Efficiency High-Density Critical Mode Rectifier/Inverter for WBG Device Based On Board Charger," in IEEE Transactions on Industrial Electronics, Vol. 64, No. 11, pp. 9114-9123, November 2017.

[11] Yuchen Yang, Zhengyang Liu, Fred C. Lee, Qiang Li, "Multi-phase coupled and integrated inductors for critical conduction mode totem-pole PFC converter," 2017 IEEE Applied Power Electronics Conference and Exposition (APEC), Tampa, FL, 2017, pp. 1804-1809.

[12] Bin Li, Qiang Li, Fred C. Lee, Zhengyang Liu, Yuchen Yang, "A High Efficiency High Density Wide-Band-Gap Device Based Bi-Directional On-Board Charger", IEEE Journal of Emerging and Selected Topics in Power Electronics, Vol. 6, No. 3, September 2018, pp. 1627-1636.

[13] Bin Li, Qiang Li, Fred C. Lee, "High Frequency PCB Winding Transformer with Integrated Inductors for a Bi-Directional Resonant Converter," IEEE Transactions on Power Electronics, Vol. 34, No. 7, July 2019, pp. 6123 – 6135.

[14] Bin Li, Qiang Li, Fred C. Lee, Yuchen Yang, "A symmetrical resonant converter and PCB transformer structure for common mode noise reduction," in 2017 IEEE Energy Conversion Congress and Exposition (ECCE), 2017, pp. 5362-5368.