CPSSC 2019

Next Generation of Data Center Power Architecture

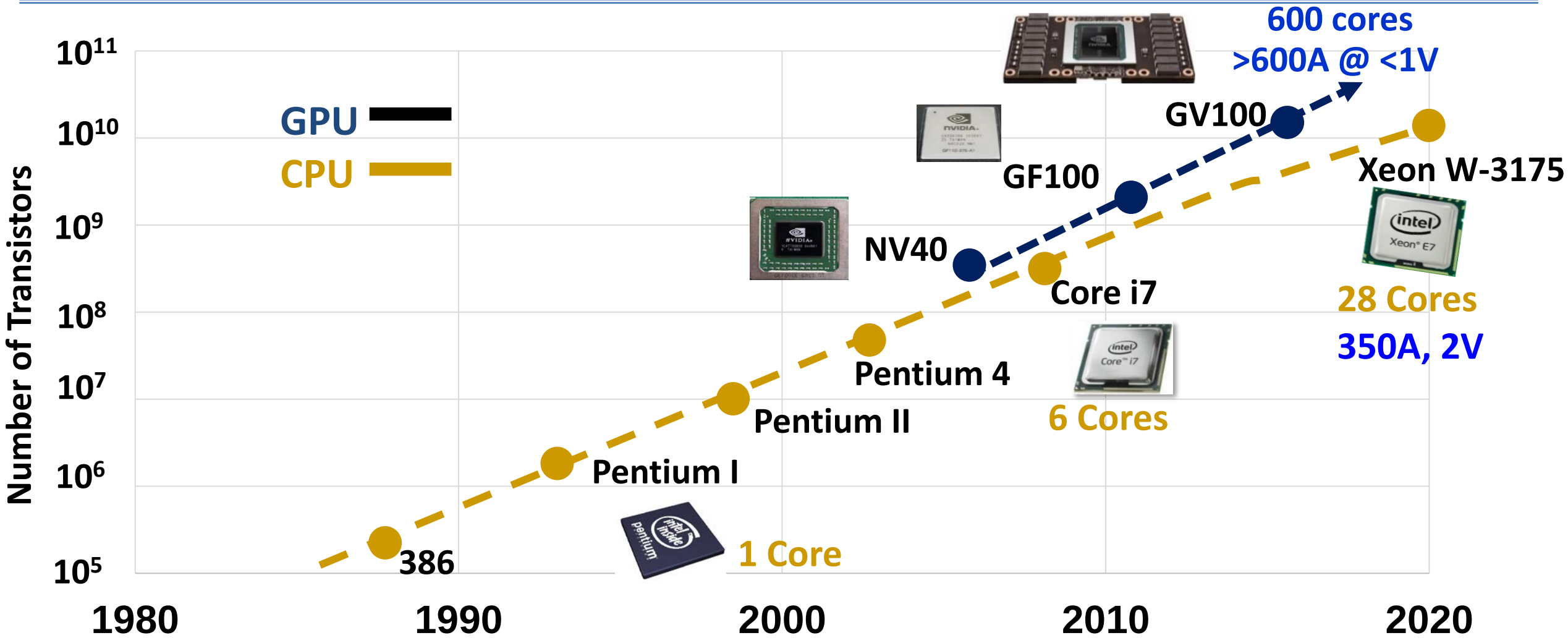
- Opportunities and Challenges

by

Fred C Lee

Virginia Tech

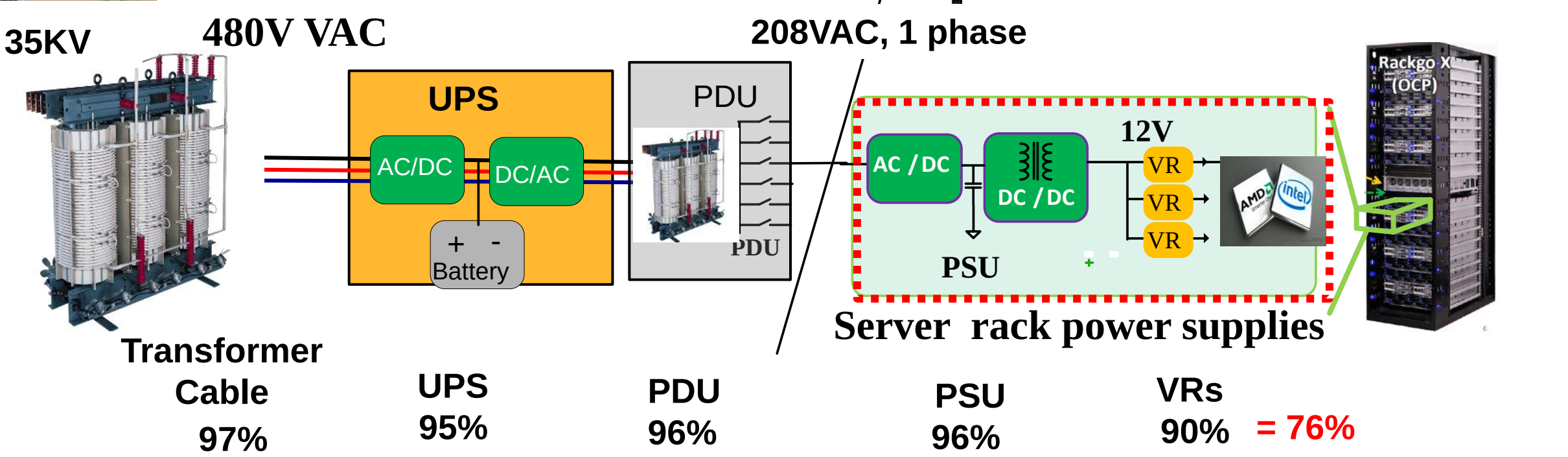
Beyond Moore's Law



Power Per Server Rack > 25 KW | **1V @ 25,000 A**

Significant Challenge for VR Design

Generation 1: Data Center Power Architecture



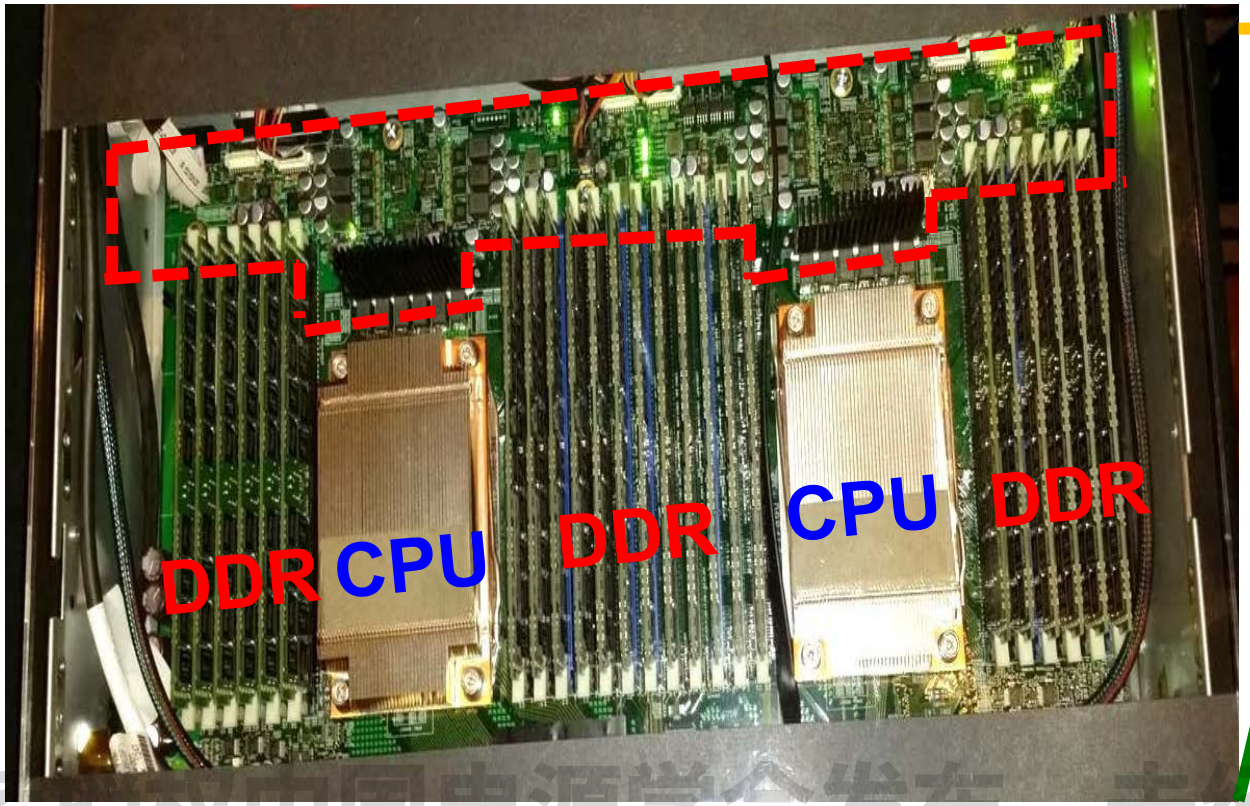
Datacenter will consume 10% of electricity by 2020

1% energy saving → 3 nuclear power plants (each @ 1GW)

Data Center Rack

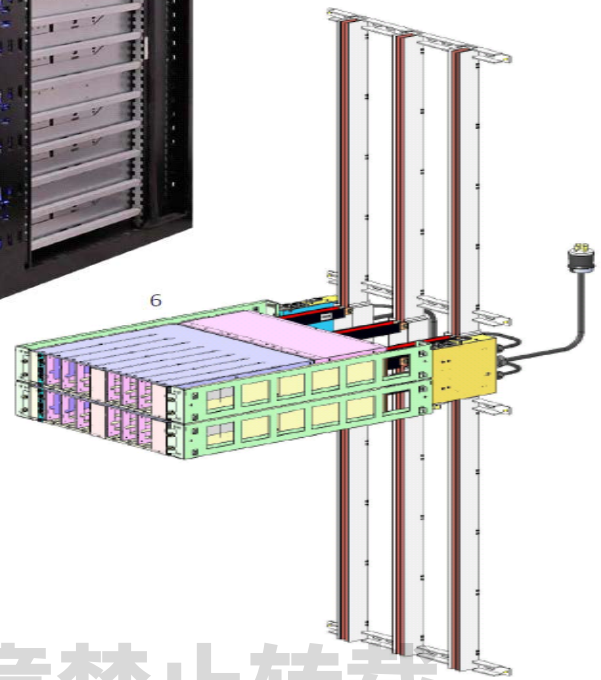
Voltage Regulators

>25,000A @ 1V



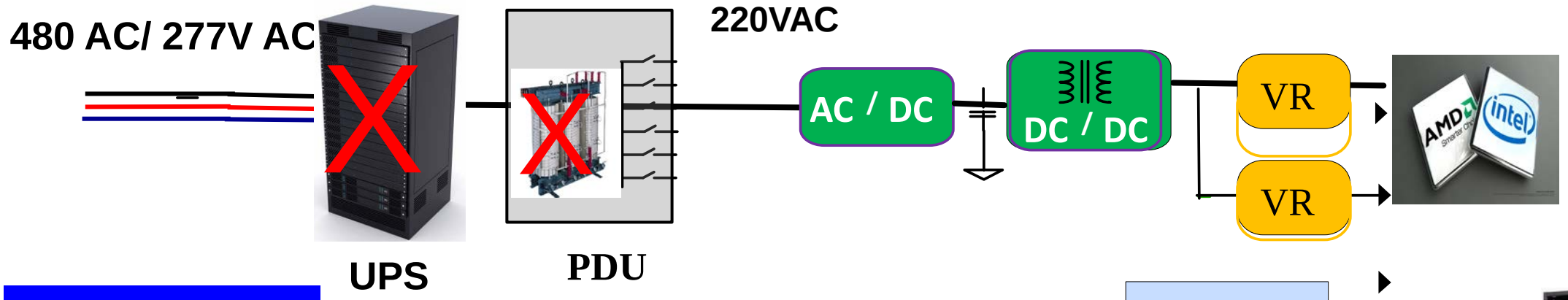
12 V Bus Ba

>2000A

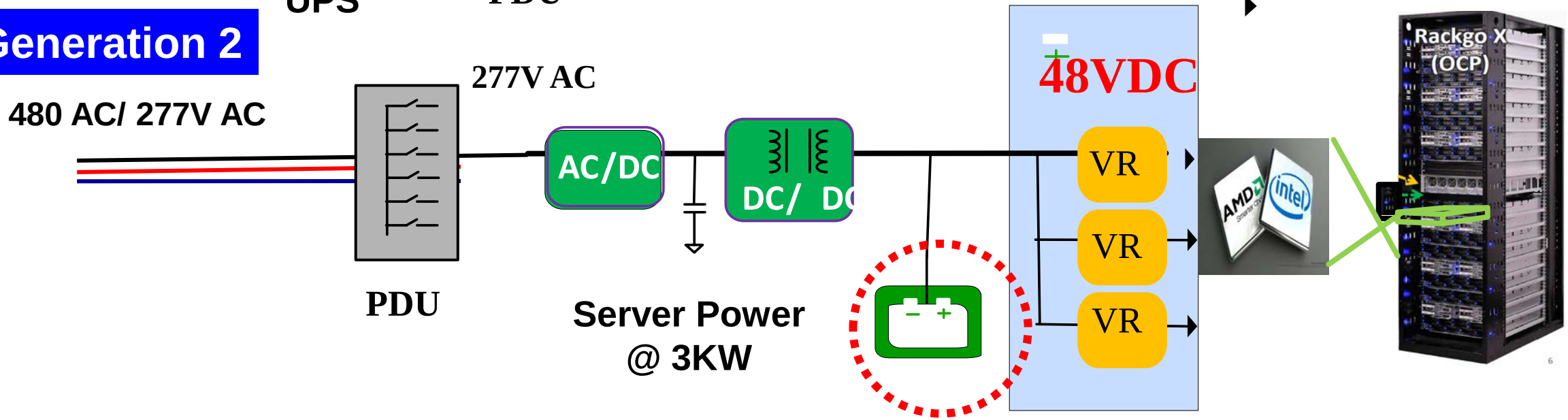


Generation 2: Data Center Power Architecture

Generation 1



Generation 2



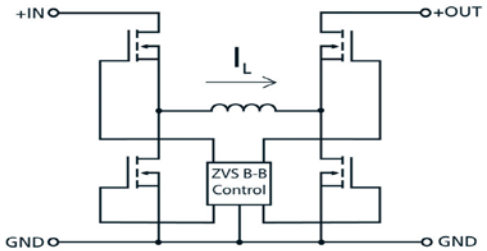
Efficiency 97% 96% 91% = 85%

Energy saving equivalent to 27 nuclear power plants (each @ 1GW) = 2.5 三峡

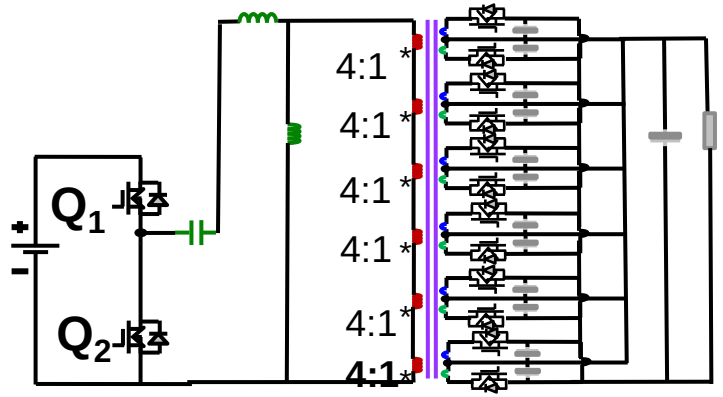
VICOR's Two-Stage (2012)

40-60V → PRM (Regulator) ZVS Buck/Boost → 48V → VTM(Unregulated) ZVS DC/DC → 1.x V

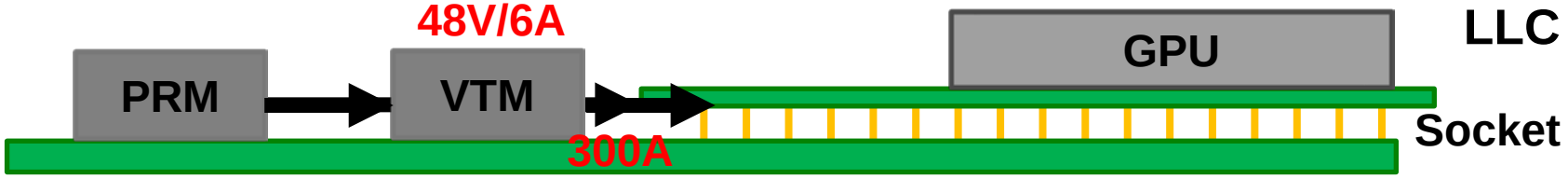
VICOR The Power Behind Performance



Buck/Boost



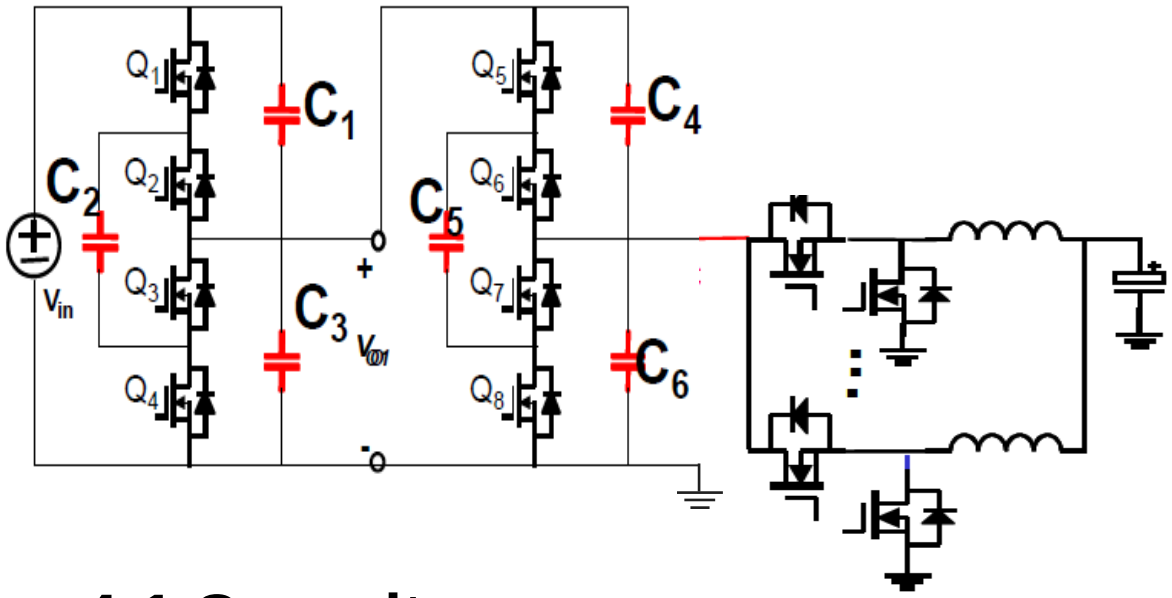
LLC DCX



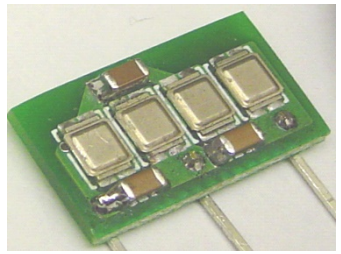
High-Density, High-Efficiency, Not Easily Scalable

M. Salato, "Datacenter power architecture: IBA versus FPA," inINTELEC, International Telecommunications Energy Conference (Proceedings), 2011, pp. 1–4.

CPES Switch Capacitor Voltage Divider (2008)



4:1 Capacitor Voltage Divider



Multi-Phase VR

Eff= 98%

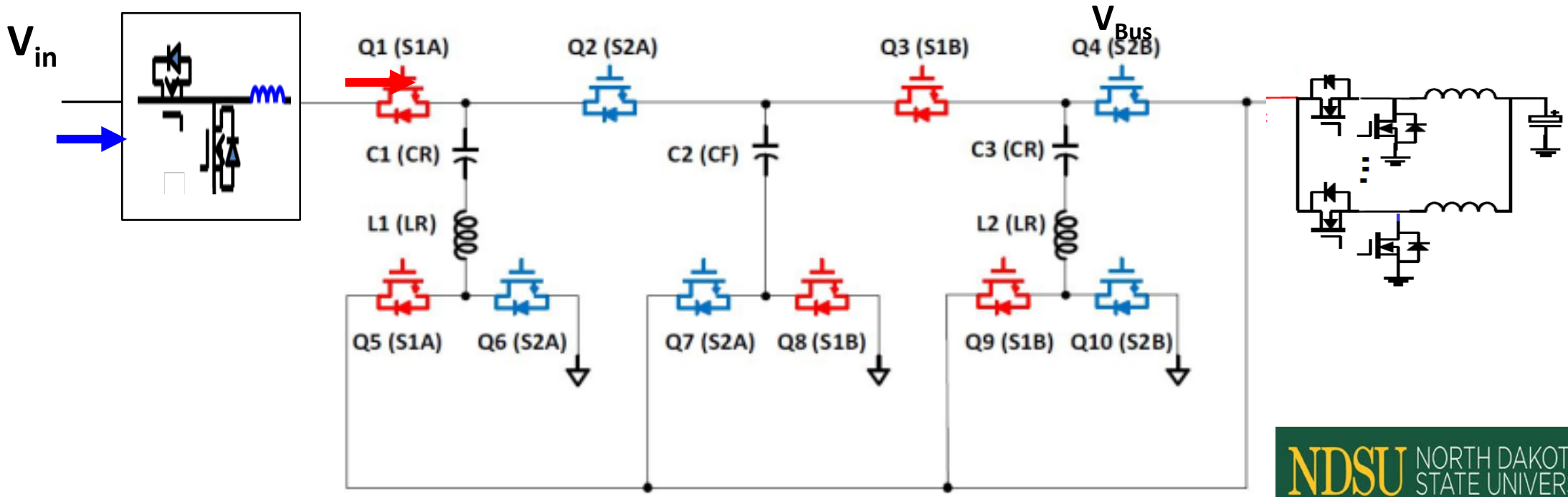
PD = 1050 W/in^3

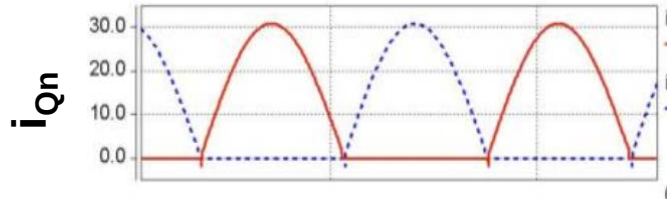
First Stage: High Efficiency and Power Density

Second Stage: Scalable, Low Cost and High BW Control

[6] Julu Sun , “Investigation of Alternative Power Architecture for CPU Voltage Regulators”, PhD Dissertation, Virginia Tech, 2008

Google's STC Two-Stage (2016)





- Zero Current Switching Operati
- Sensitive to component tolerances
- Not easily extendable to lower bus voltage

NDSU NORTH DAKOTA STATE UNIVERSITY

Google

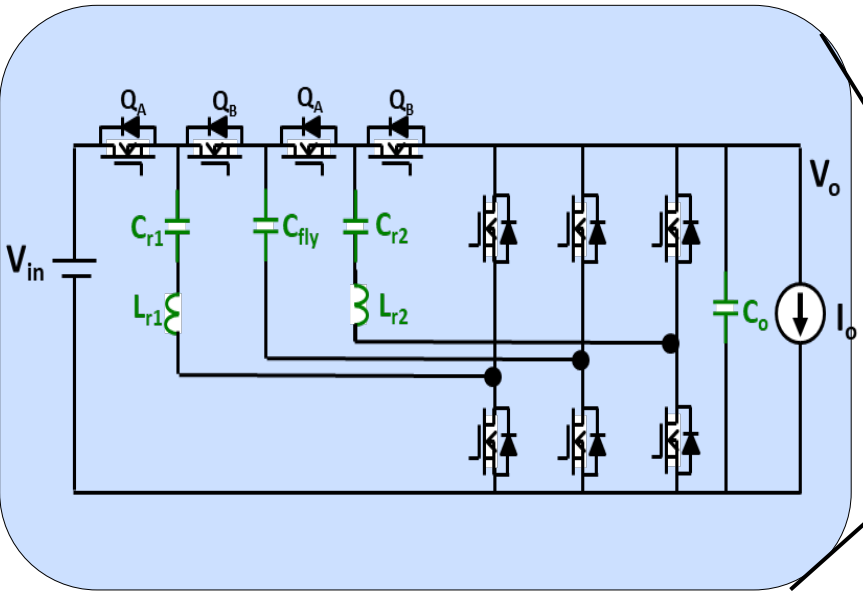
48/12V – 650W

Efficiency = 98.6%

Power Density≈250 W/in²

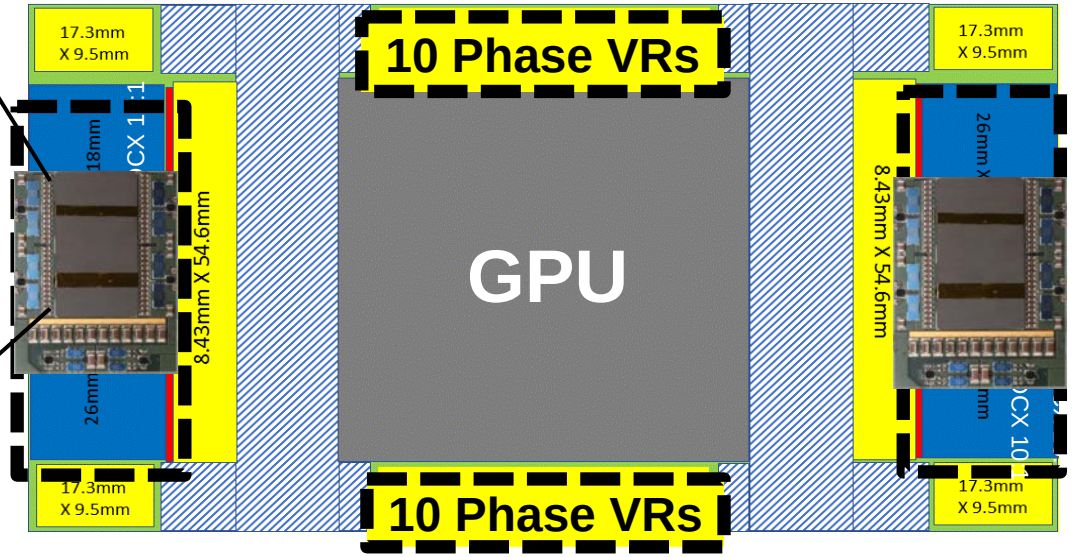
Y. Li, X. Lyu, D. Cao, S. Jiang, and C. Nan, "A High Efficiency Resonant Switched-Capacitor Converter for Data Center" ECCE 2017

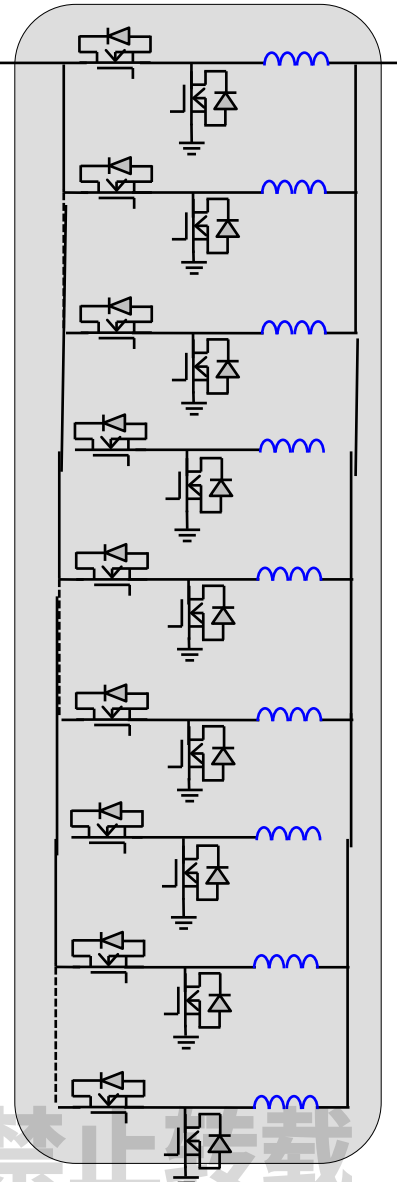
Google Proposed 48V Power Architecture



48V/12V
100KHz

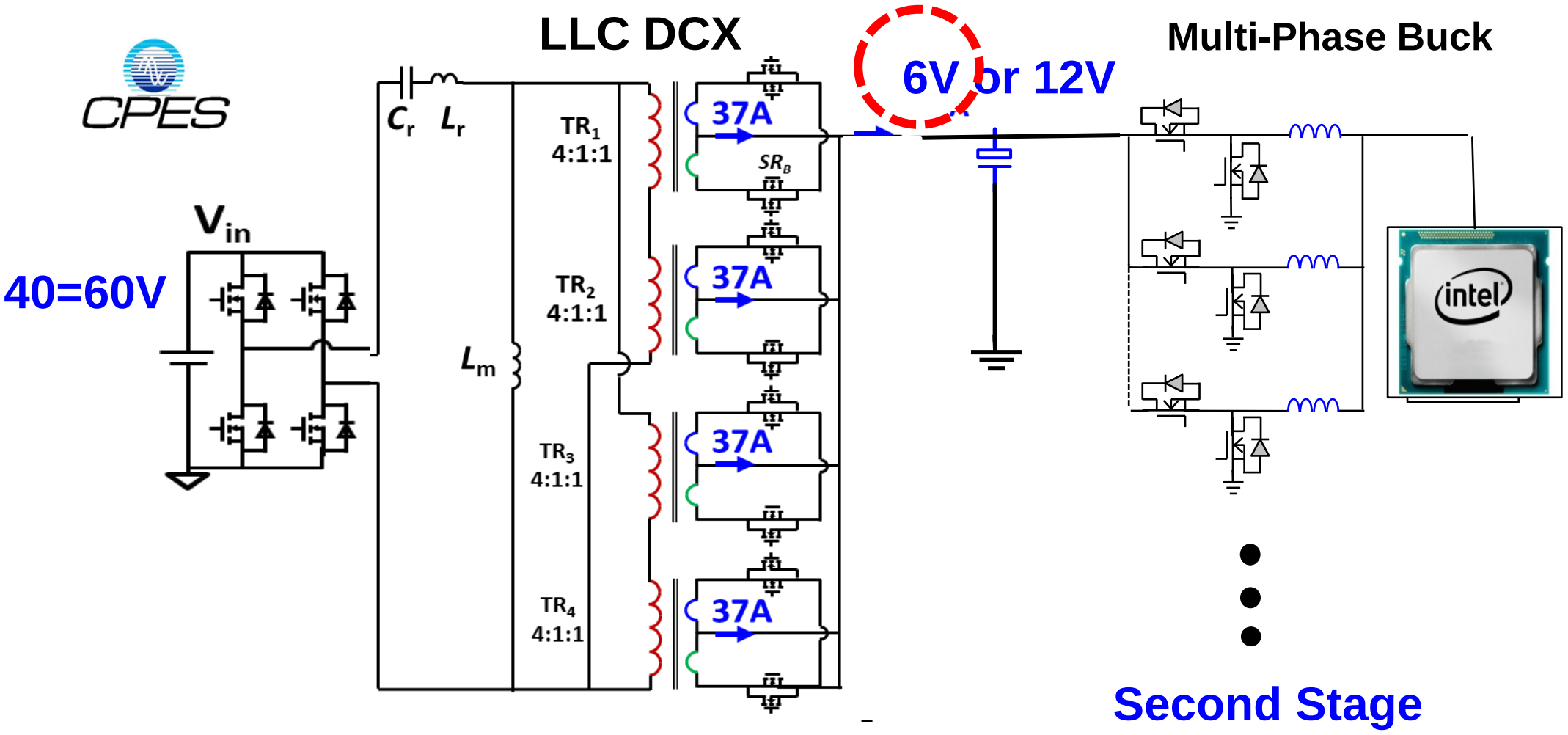
NVidia 48V SXM Card





12V/1V
400-600 KHz

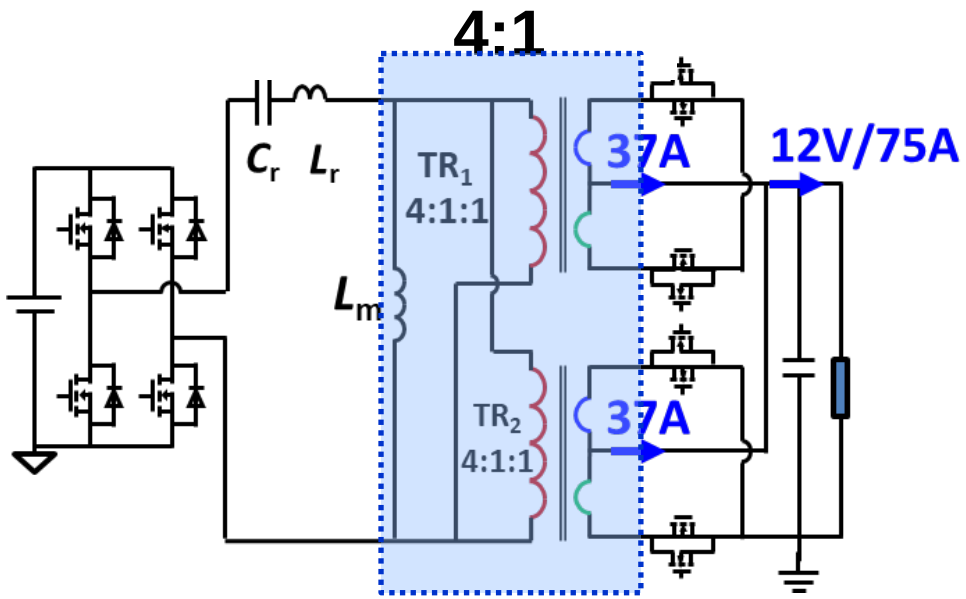
Alternative #1: Two-Stage 48V VRM

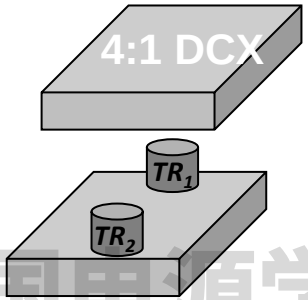


Simple, Scalable, High BW Control

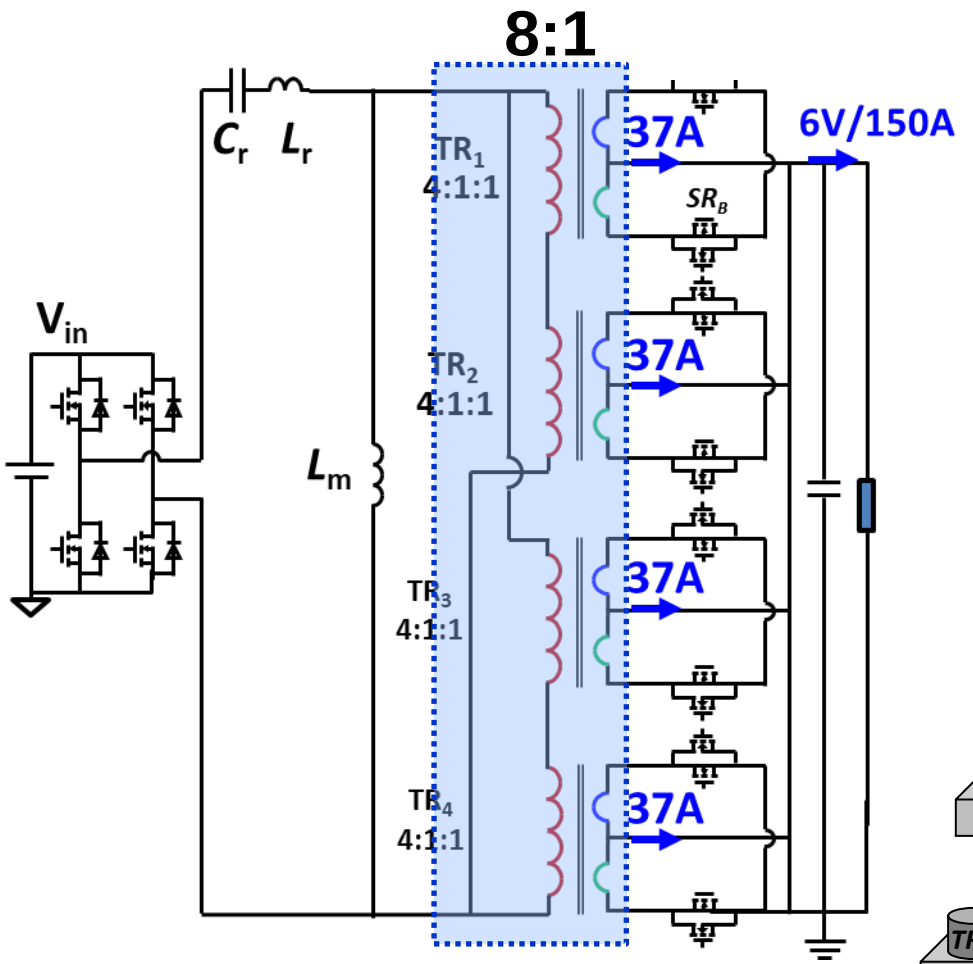
CPES Prototypes for 48V VRs

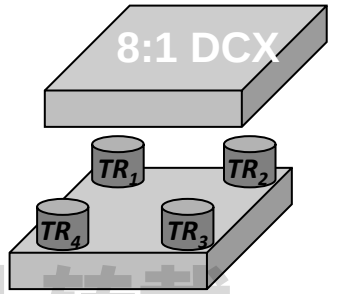
48V/12V -900W





48V/6V - 900W



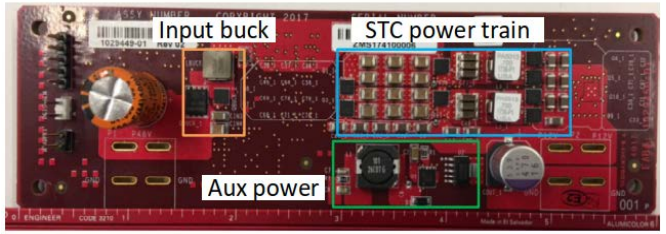


Comparison of 48V/12V Converter

CPES

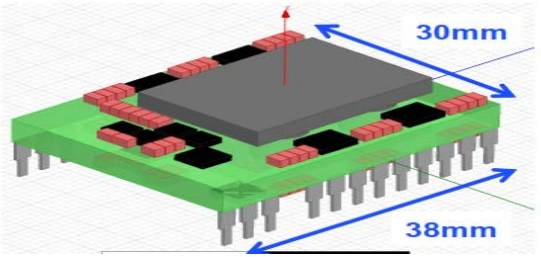
450 W/in²

Google's STC

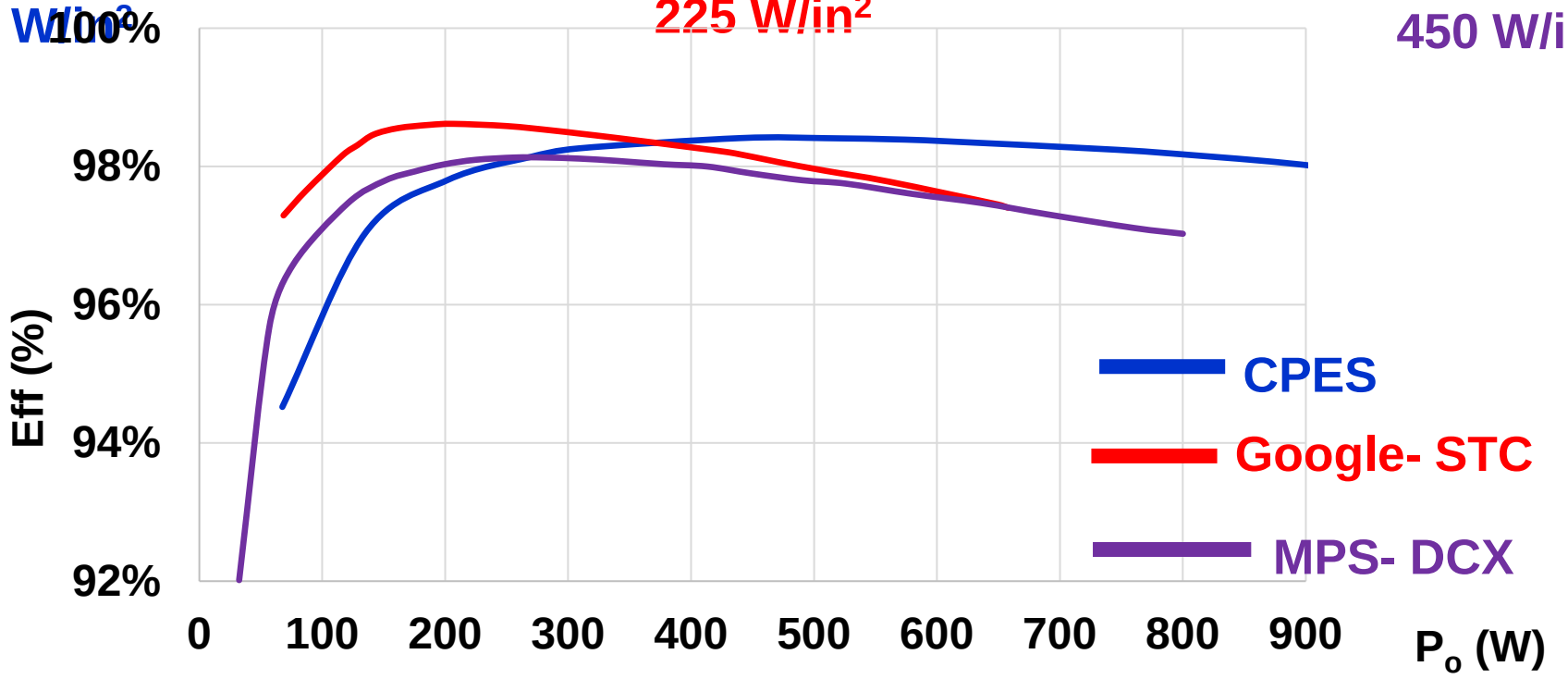


225 W/in²

MPS DCX



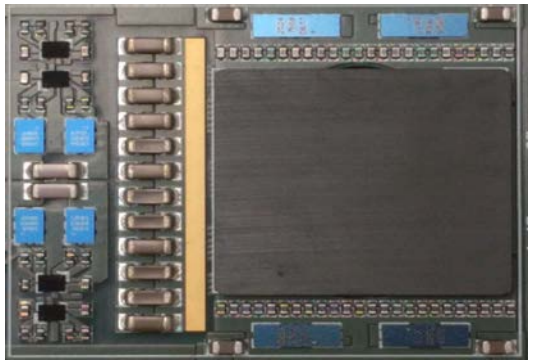
450 W/in²



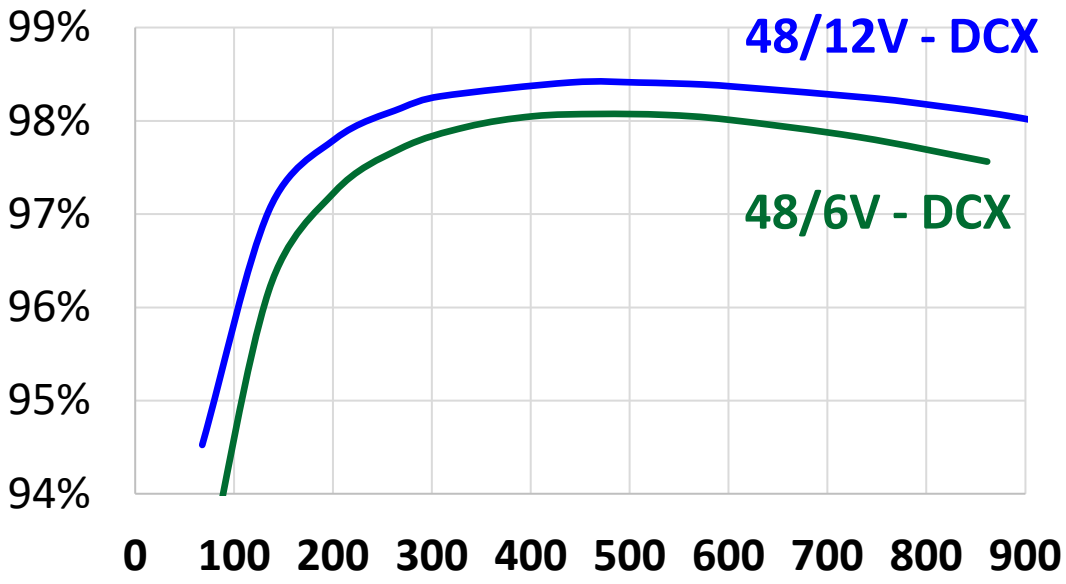
Higher Efficiency and Power Density Than All Other Solutions

Comparison: 48V/12V v.s. 48V/6V

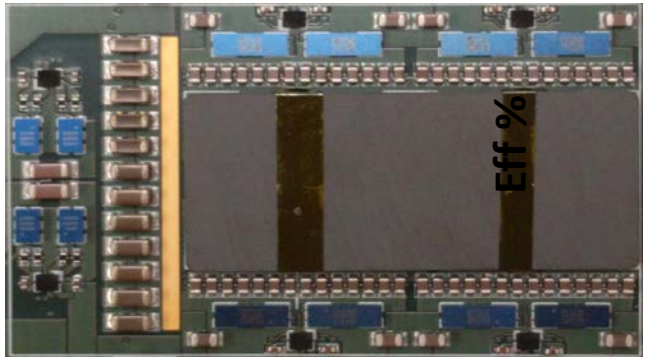
CPES: 48/12V



GaN bases
1MHz
1600 W/in²
98.4%

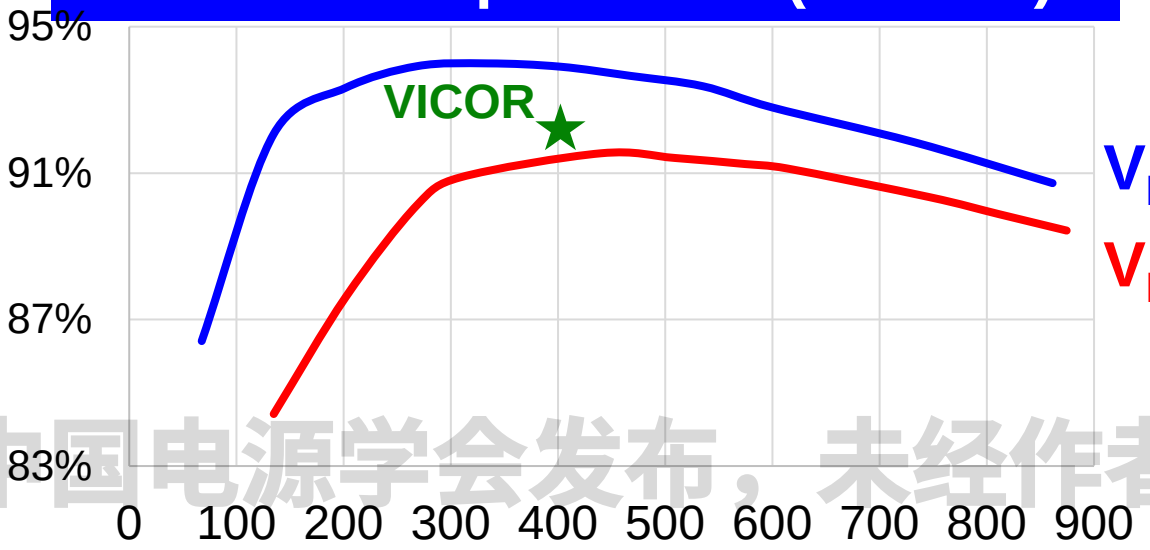


CPES: 48/6V



GaN based
1MHz
1200 W/in²
98%

48V/6V. + 10-phase VR (6V/1.7V)



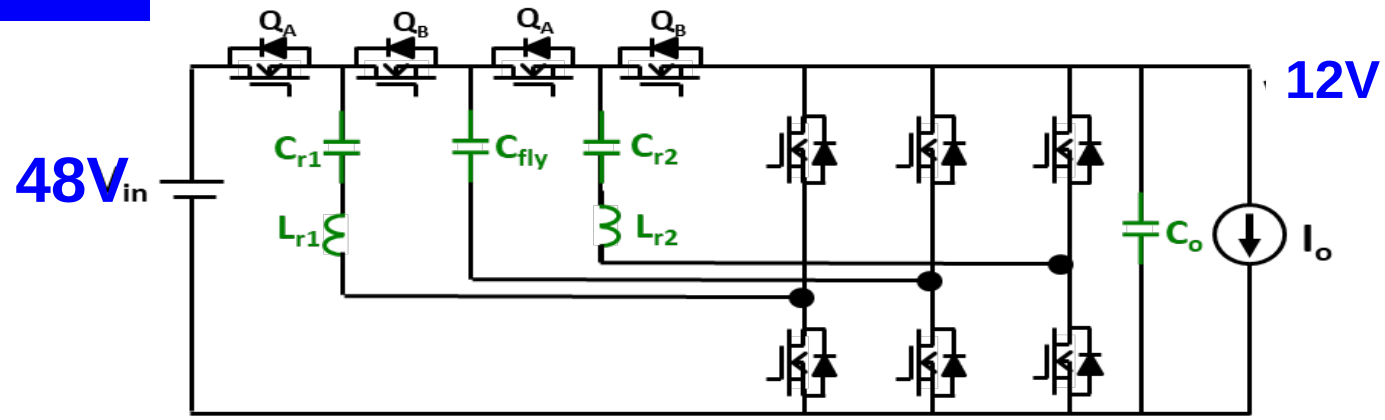
V_{Bus} = 6V

V_{Bus} = 12V

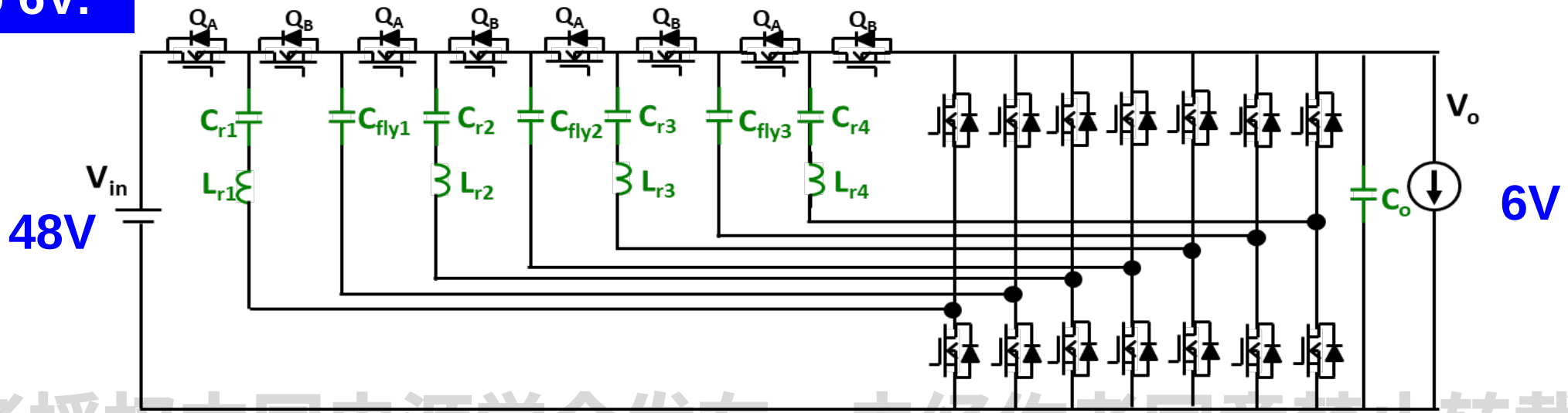
Best efficiency demonstrated

Switch Capacitor Voltage Divider

48V to 12 V



48V to 6V:

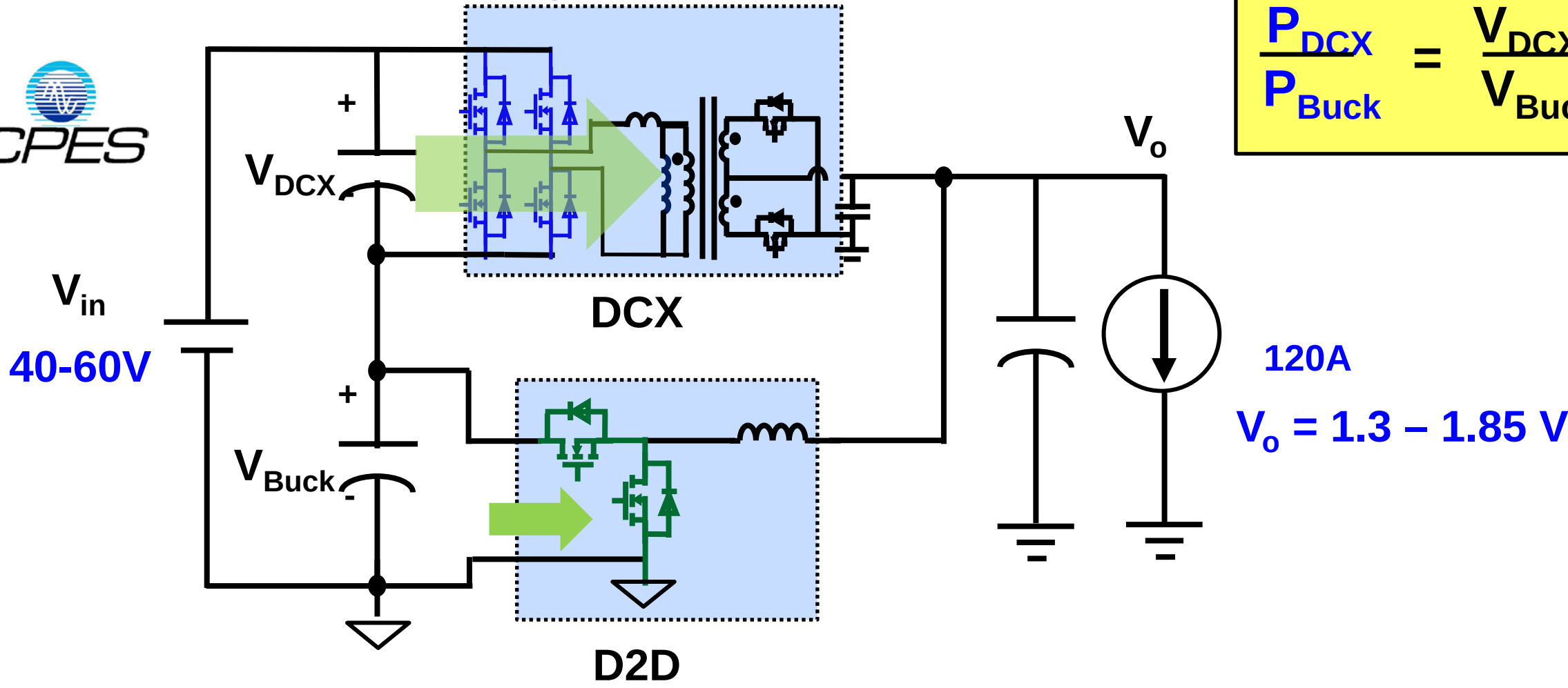


Too complicate, not practical

Alternative # 2: Sigma Converter

LLC DCX with Programable Gain

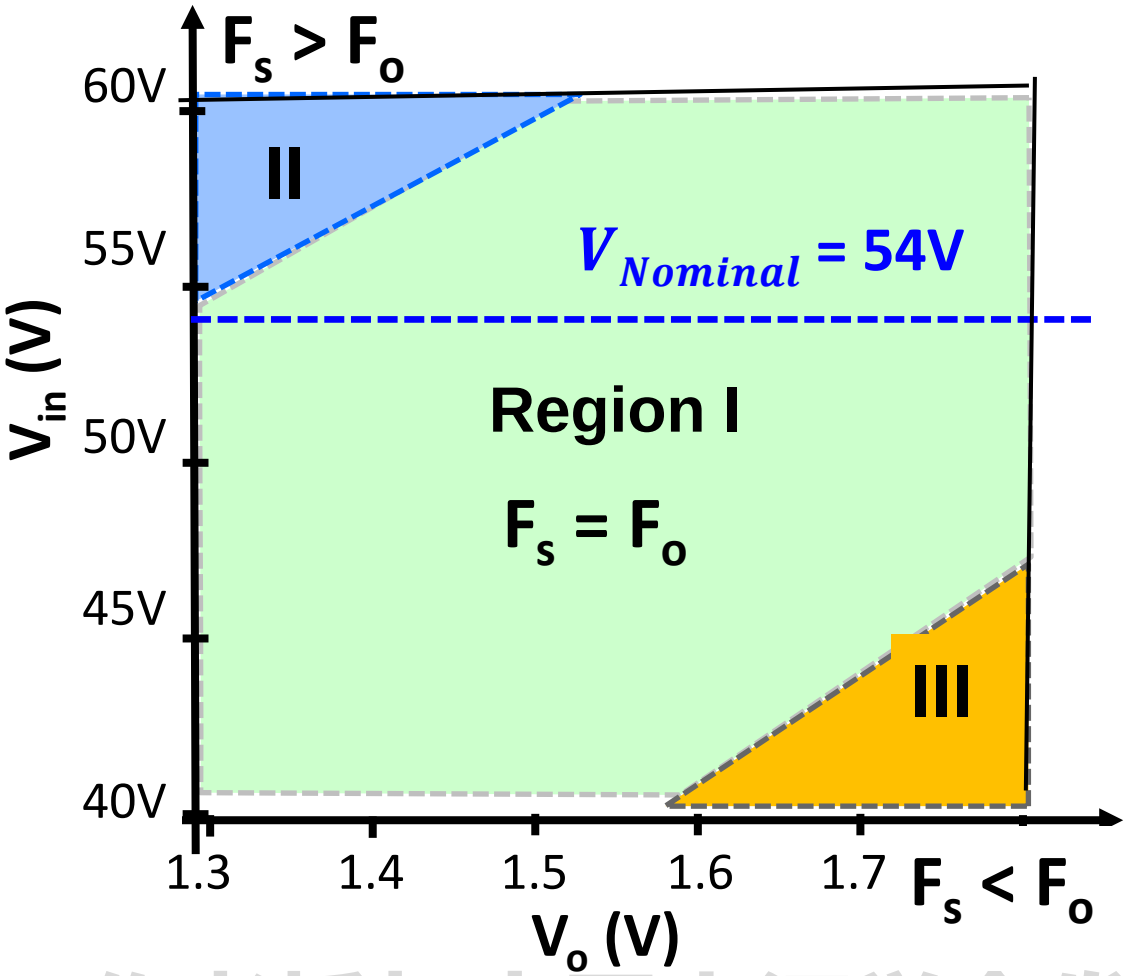
$$\frac{P_{DCX}}{P_{Buck}} = \frac{V_{DCX}}{V_{Buck}}$$



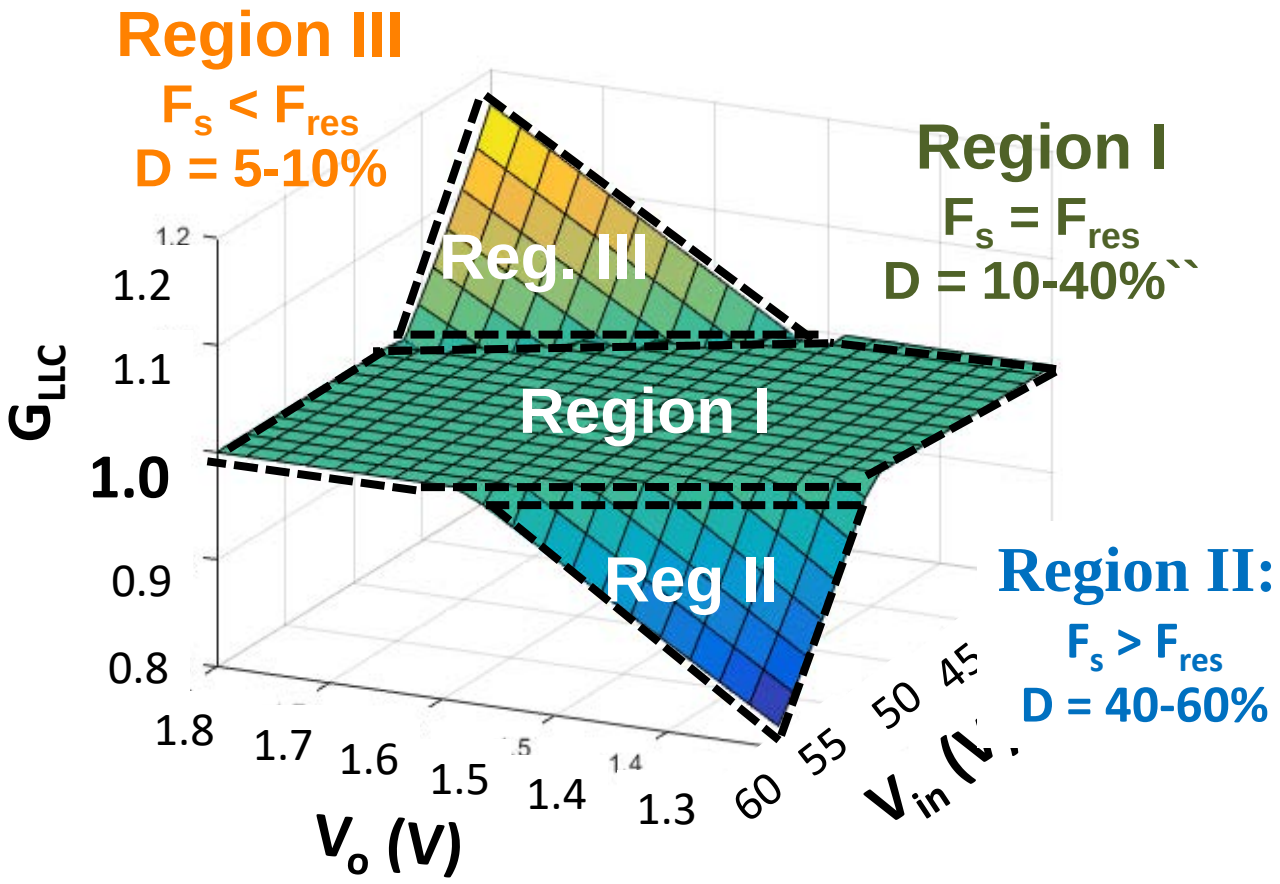
More efficient power conversion comparing to two-stage

Operation Regions for Sigma Converter

Operating Regions



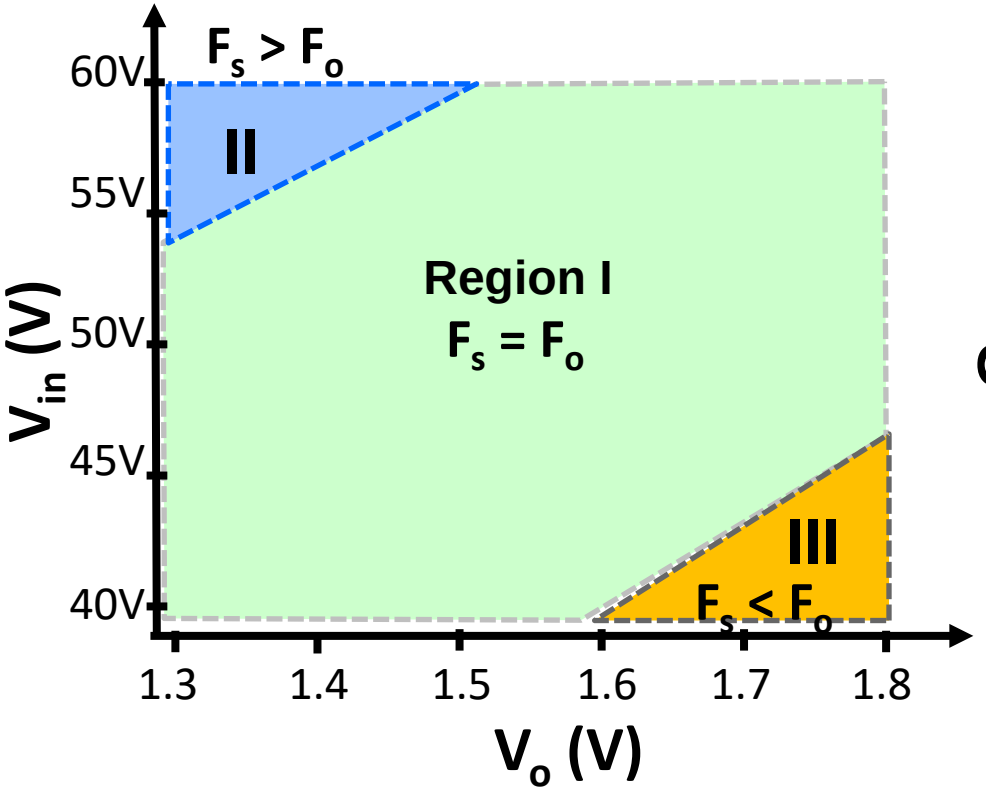
Required LLC Gain



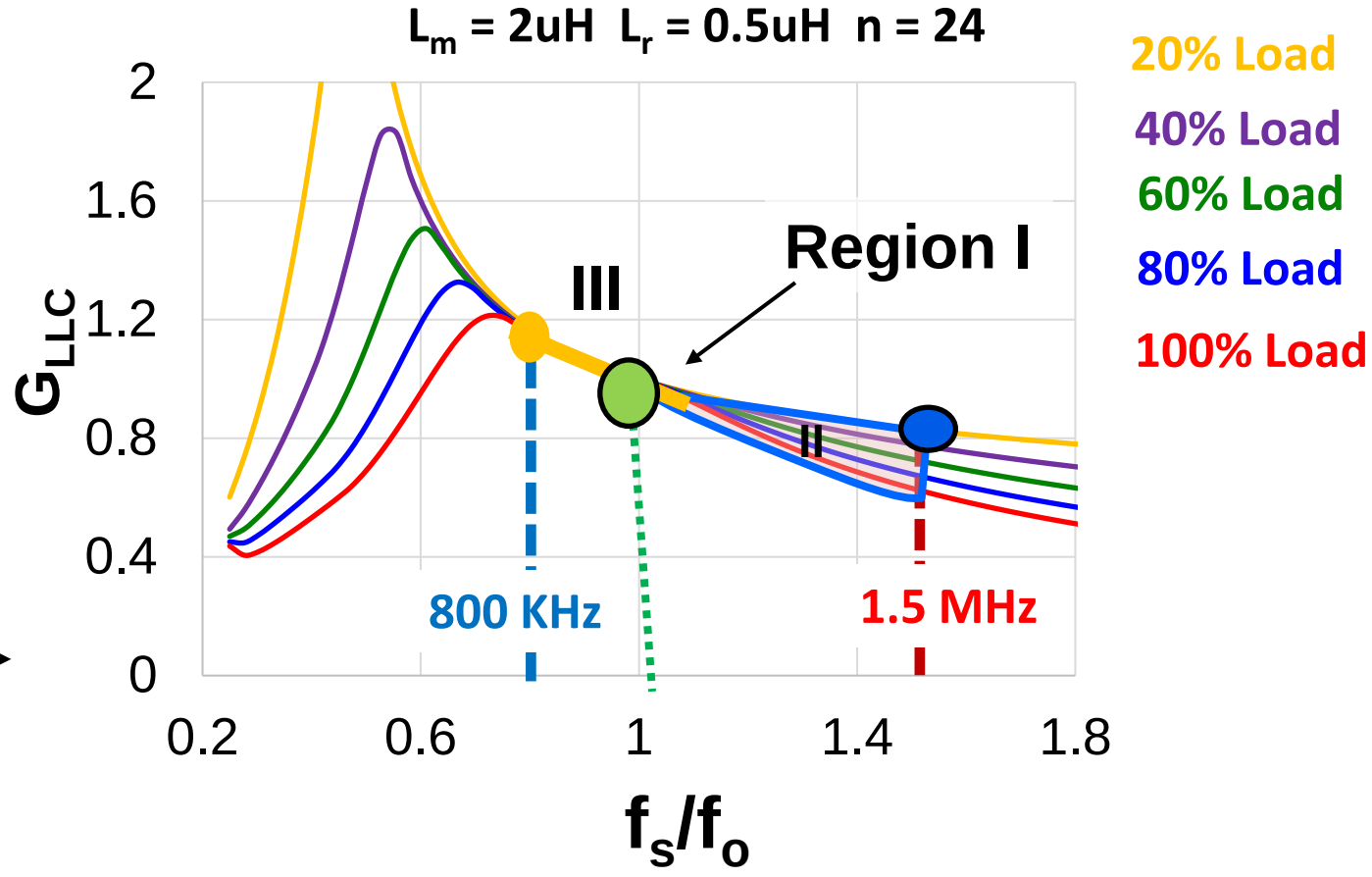
Optimal LLC Operation with $F_s = F_{Res}$ During Nominal Voltage Ranges

LLC Gain Requirements For Wide Range Operation

Operating Regions

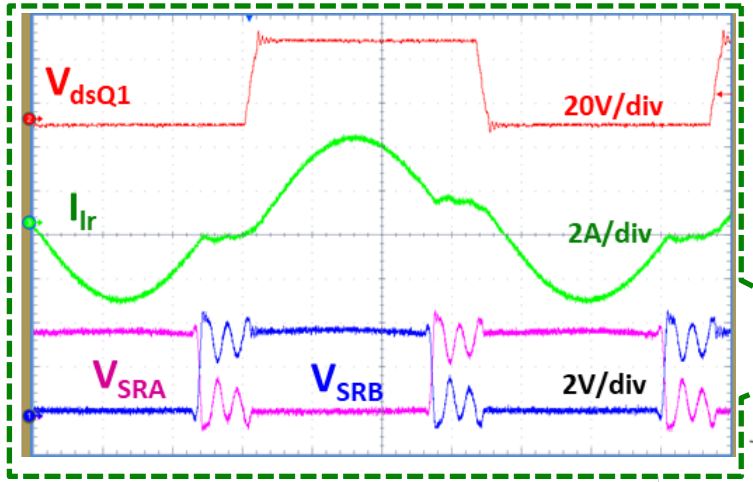


LLC Gain Characteristics

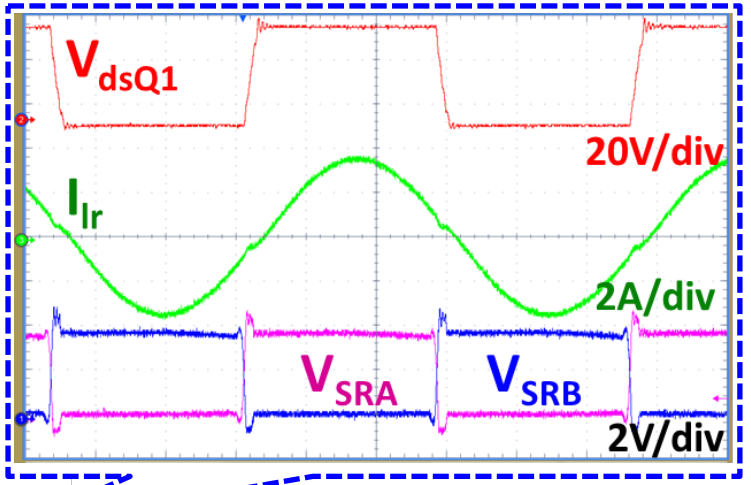


Relatively narrow frequency range for required LLC gain

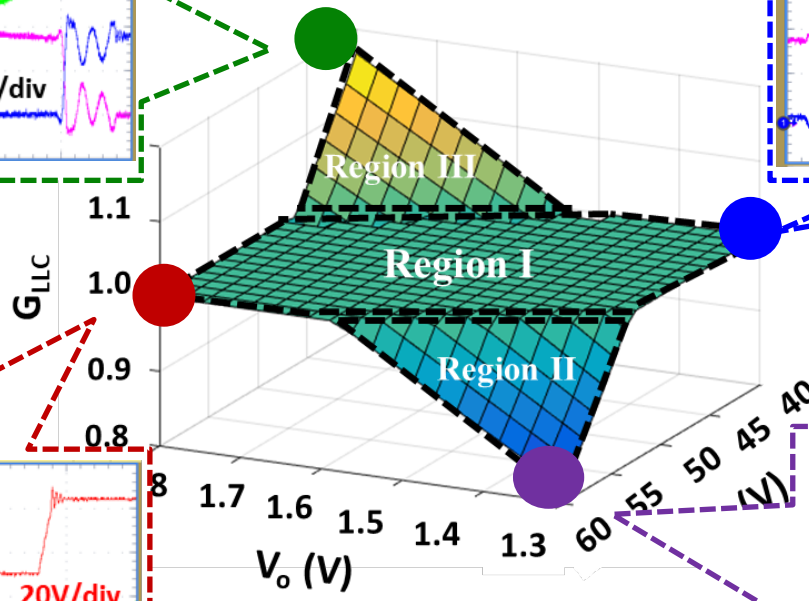
Sigma VRM Experimental Results



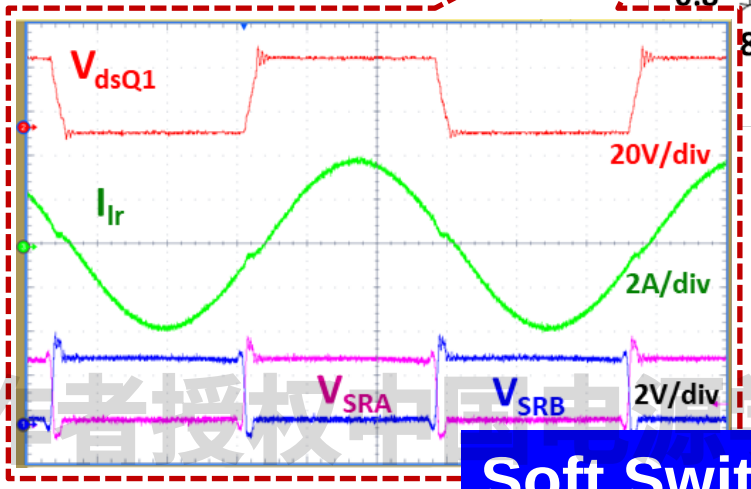
$F_s < F_o$



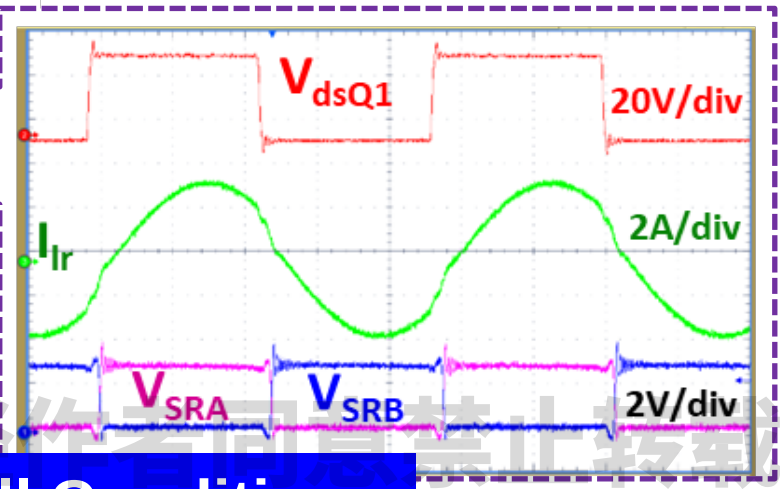
$F_s = F_o$



$F_s = F_o$

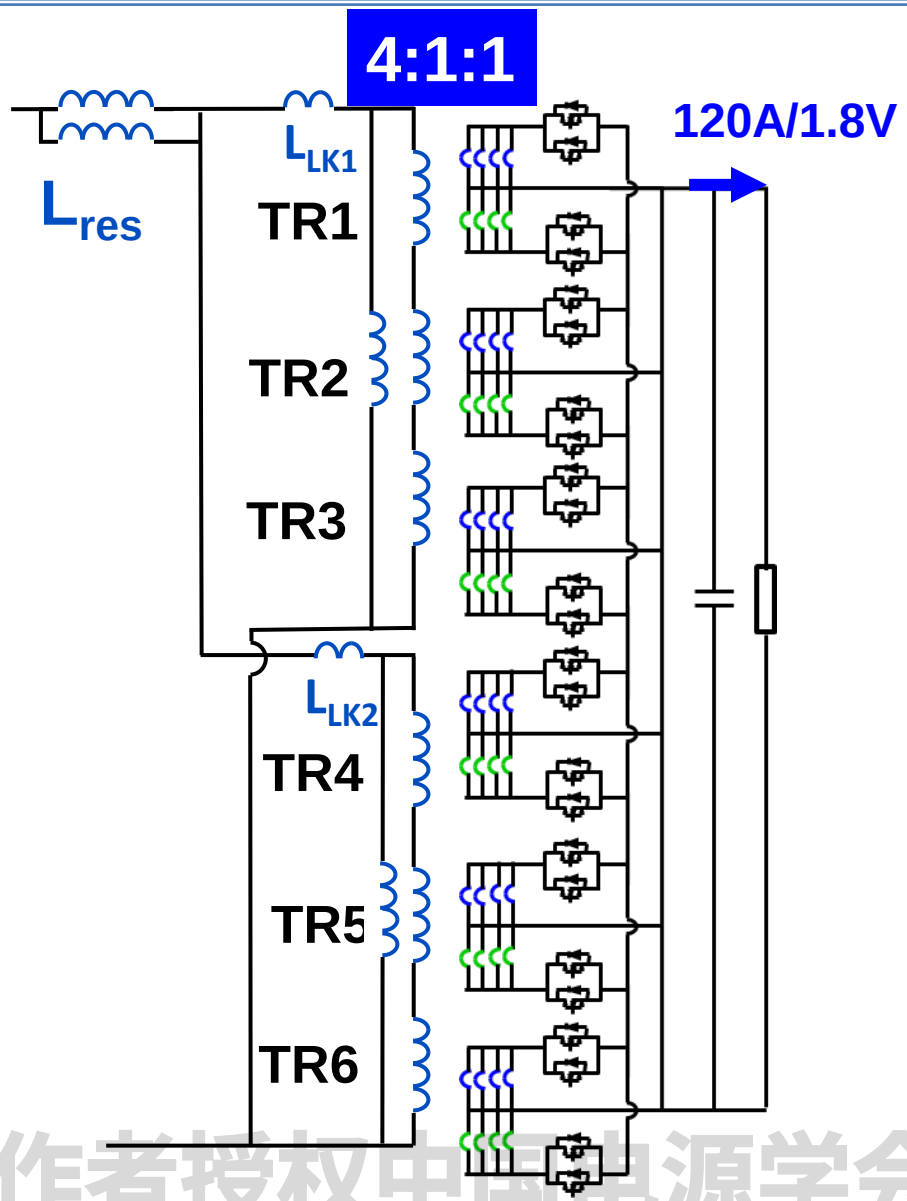


$F_s > F_o$

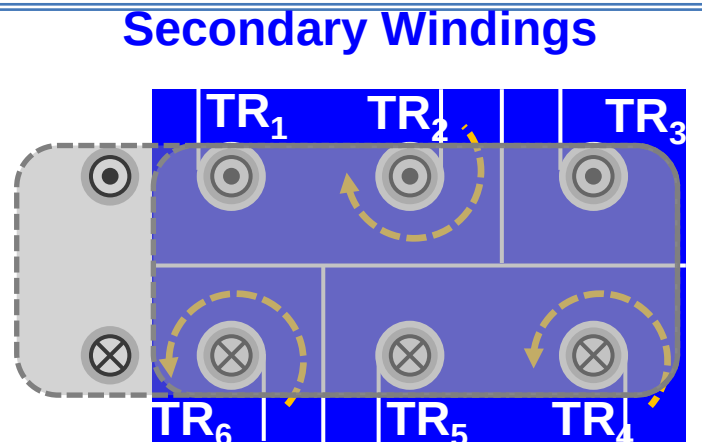


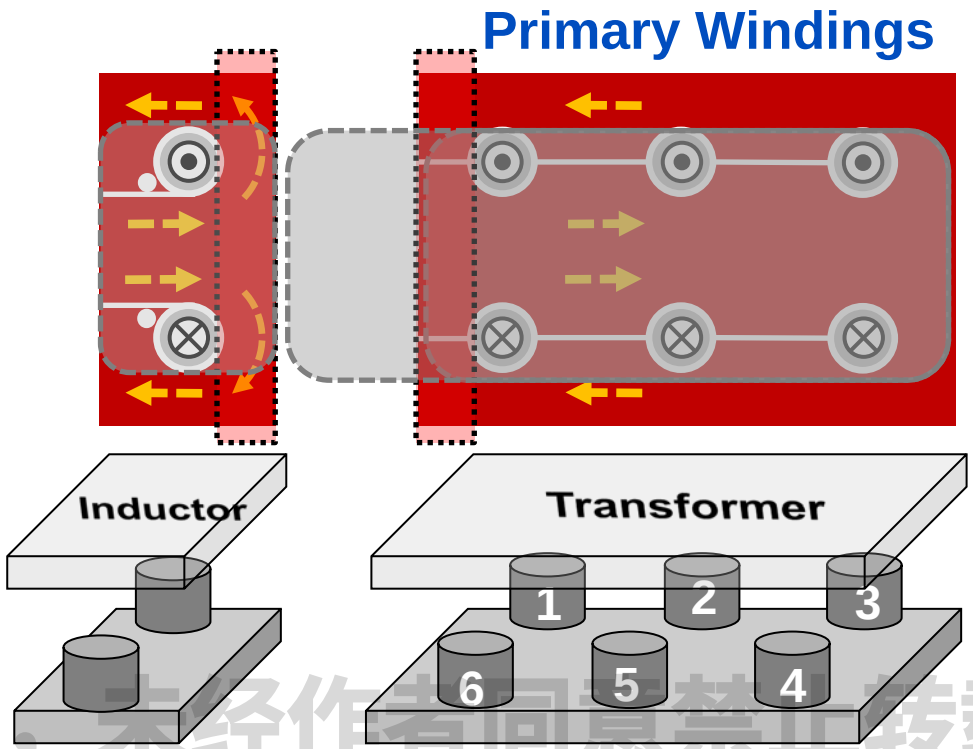
Soft Switching Operation in All Conditions

Integrated Inductors and Transformers



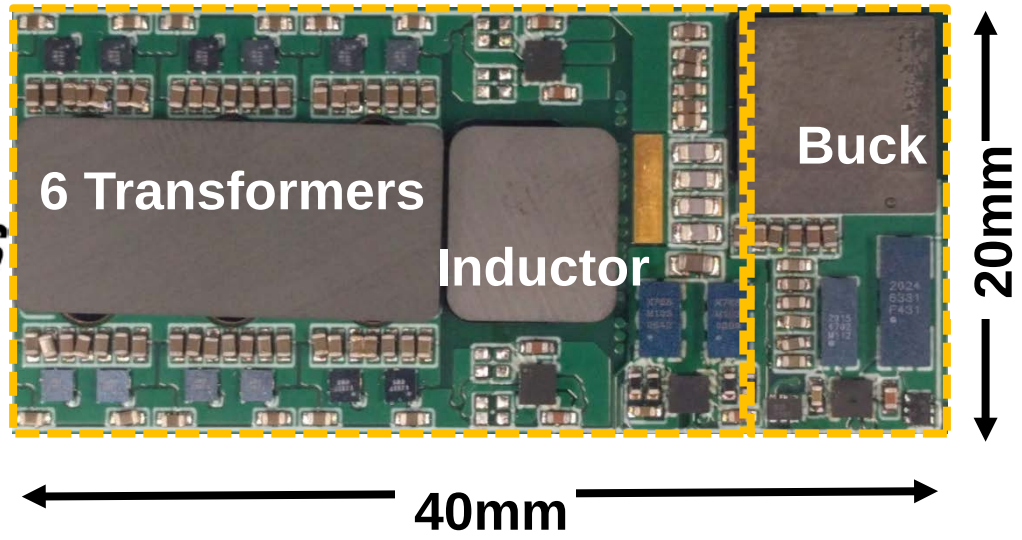
Integrated L & T



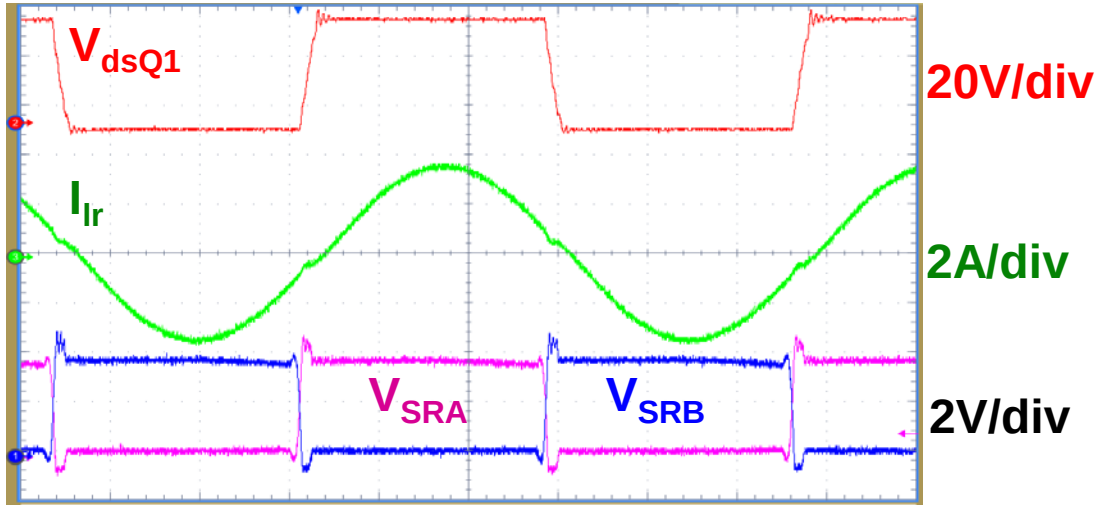


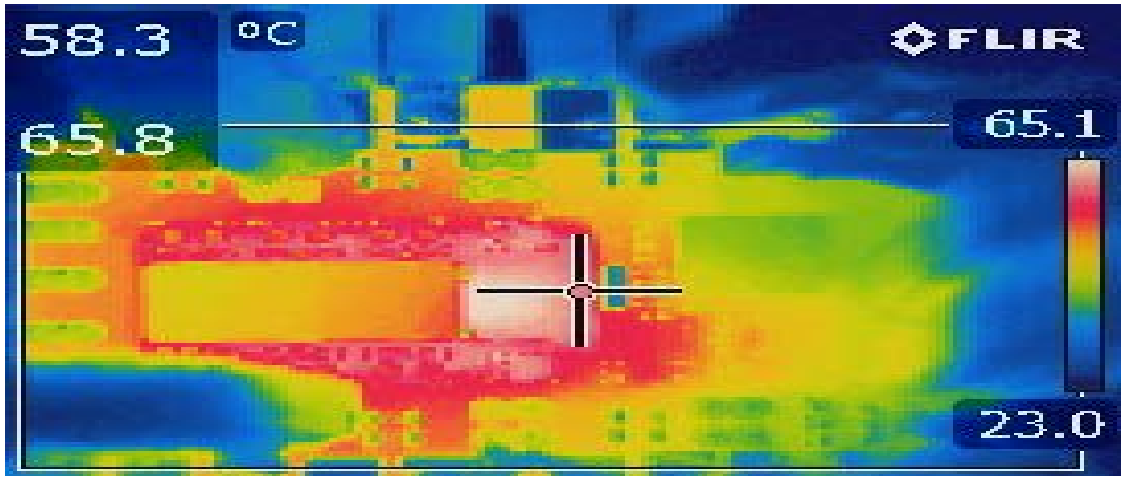
Sigma Converter Hardware Prototype

V_{in} = 40 – 60 V V_o = 1.3 – 1.85 V $I_o \approx 120A$



V_{in} = 54V, V_o = 1.8V, $F_s = F_o$





300 LFM

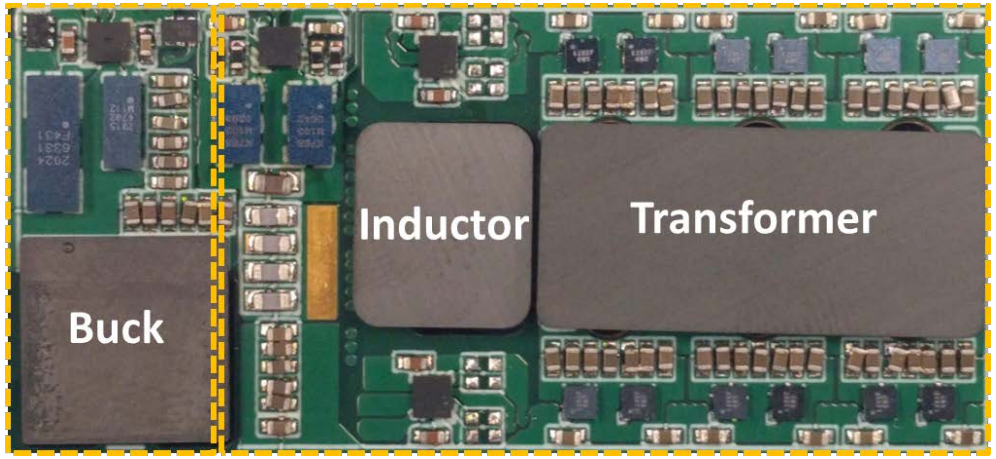
- Power Density > 700W/in^3
- ZVS Operation
- Excellent Thermal Performance

Wide Range 48V VRM Design Example

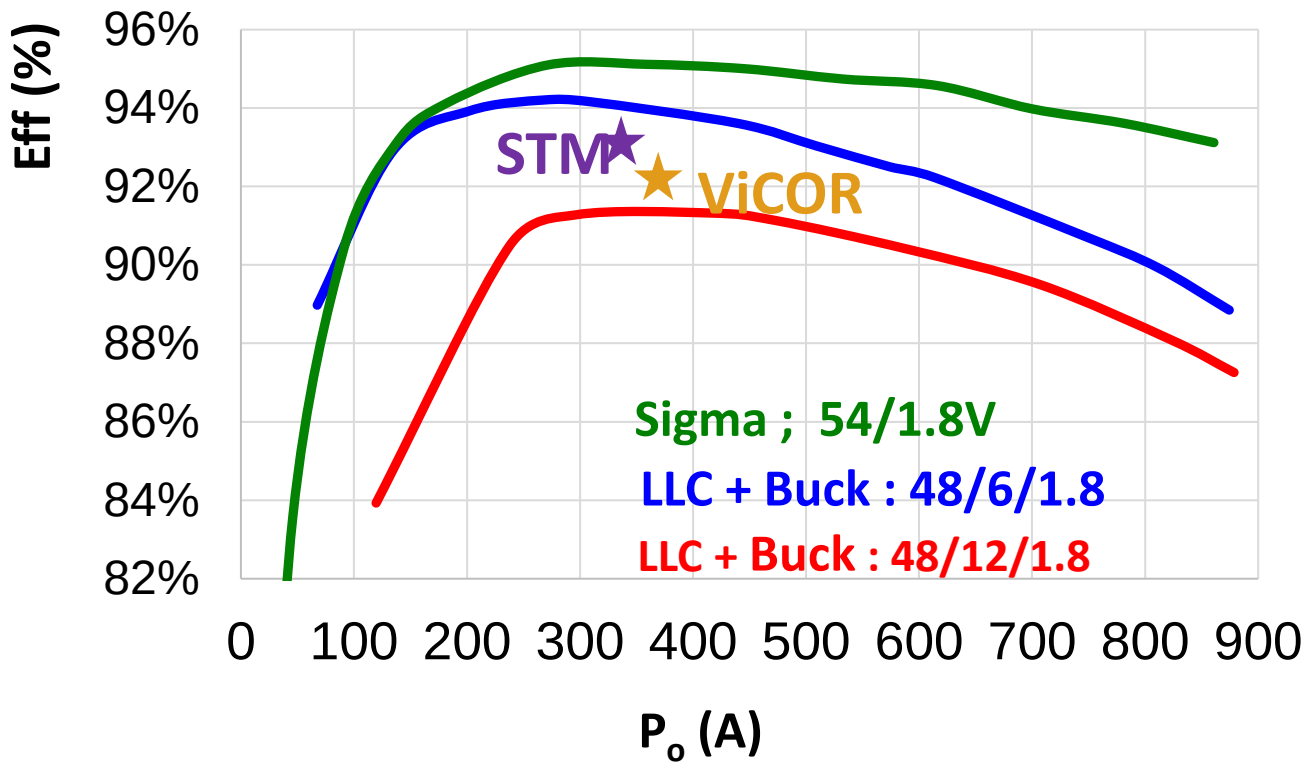
V_{in} = 40 – 60 V

V_o = 1.3 – 1.85 V

I_o ≈ 120A



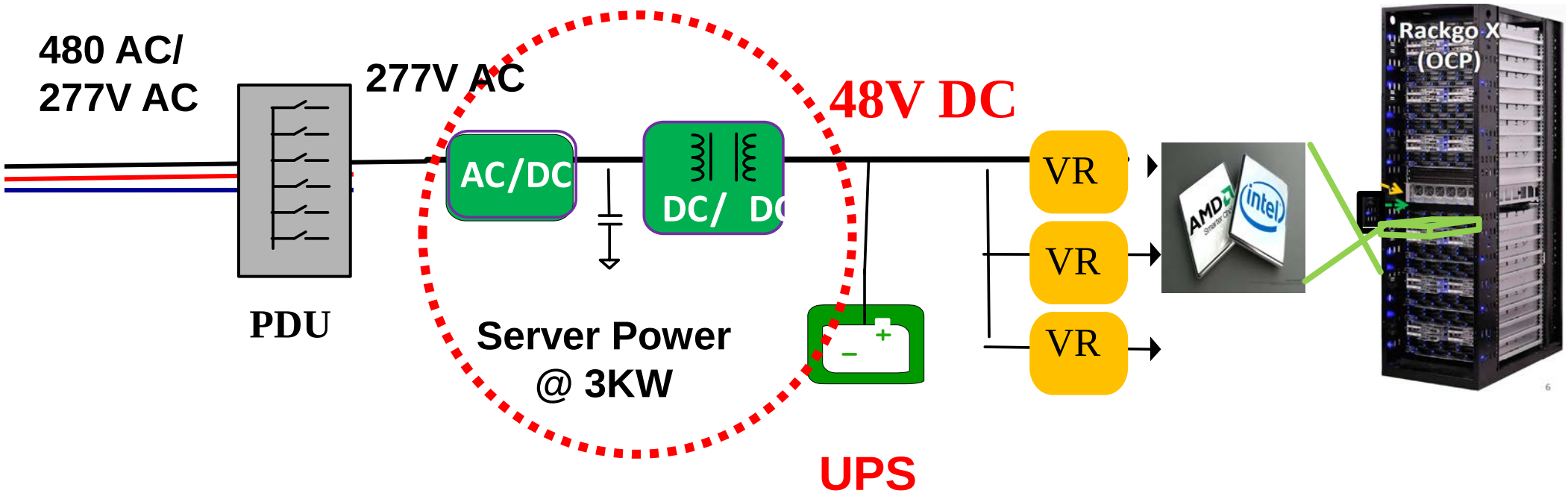
700W/in^3



LLC converter serves as a variable gain DCX

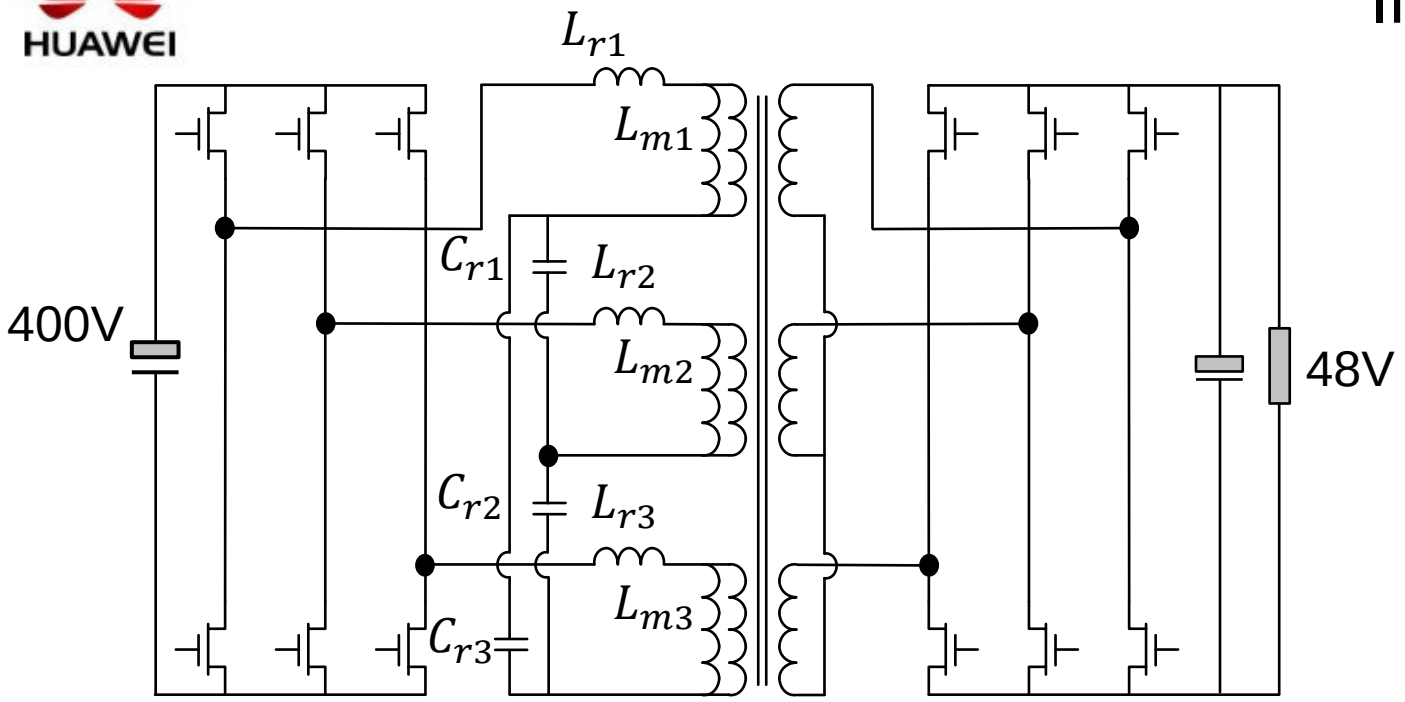
Buck converter for regulating output voltage

Generation 2: Data Center Power Architecture



Efficiency	97%		96 %	91%	=	85 %

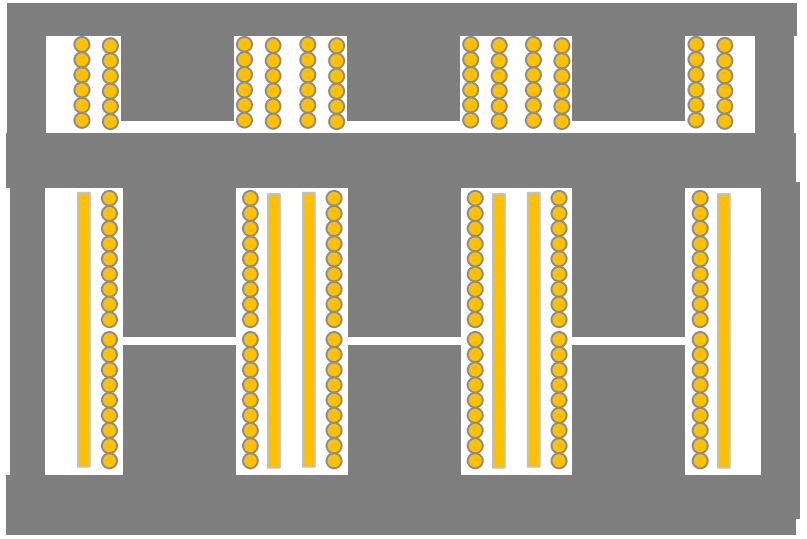
Huawei: 3KW Three-Phase Interleaved LLC



Primary: Y
(Δ-connection for Cr)

Secondary : Y

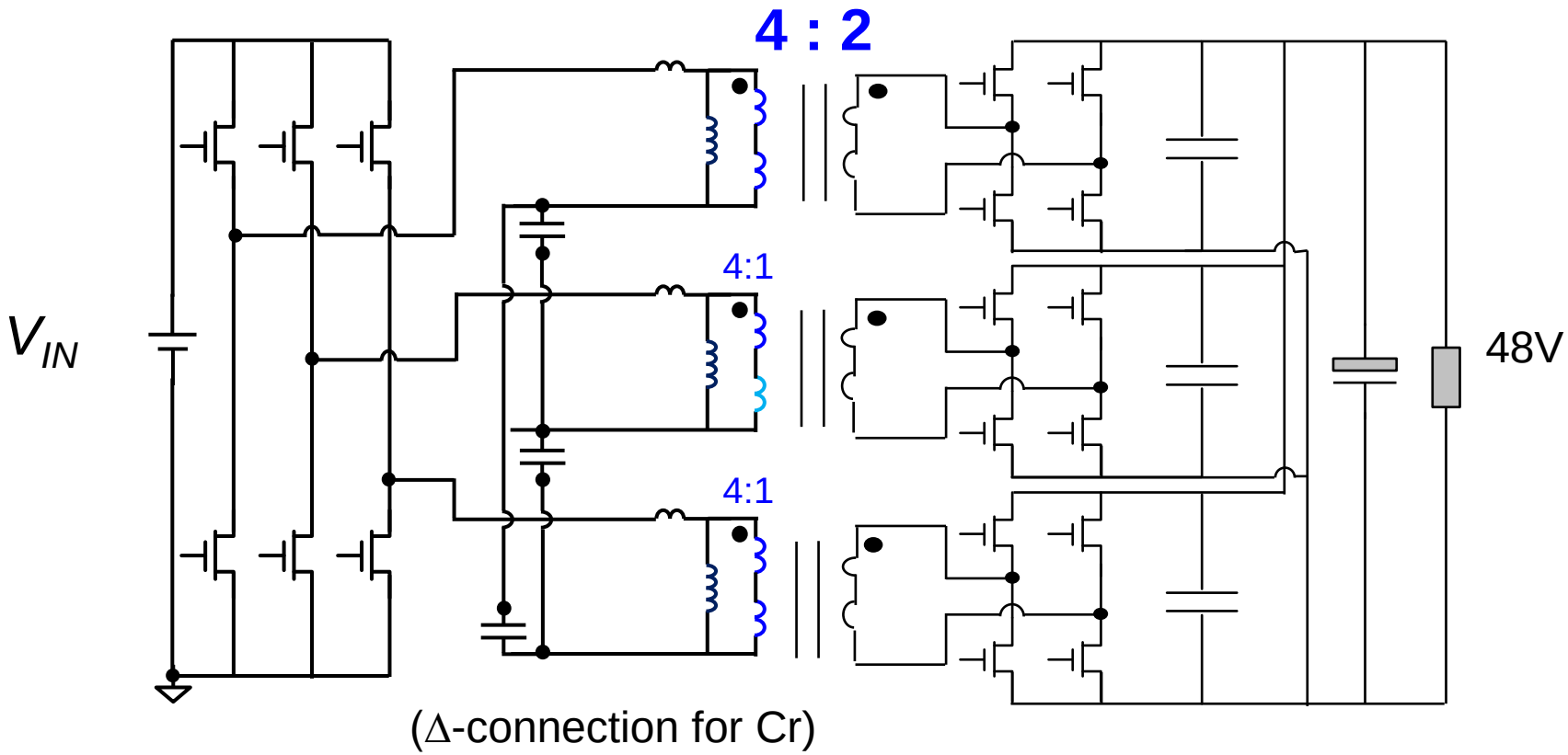
Integrated Magnetics (3L & 3T)



- **Switching frequency 100 kHz**
- **Power Density 40.8 W/in³**
- **Peak efficiency ~ 99%**

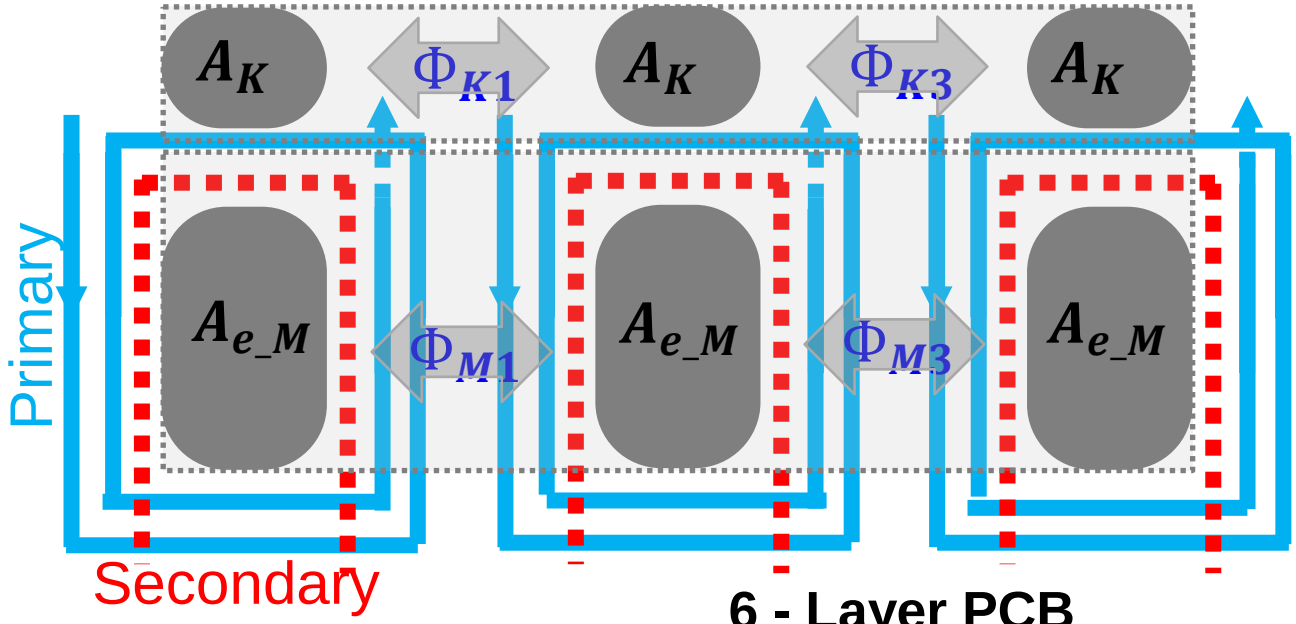
*"Magnetic interleaved device and power conversion circuit." *US patent application, US 2016/0254756 A1** "Super Efficiency Rectifier Module R4850S " Huawei, 2014.

Primary Y Secondary in Parallel

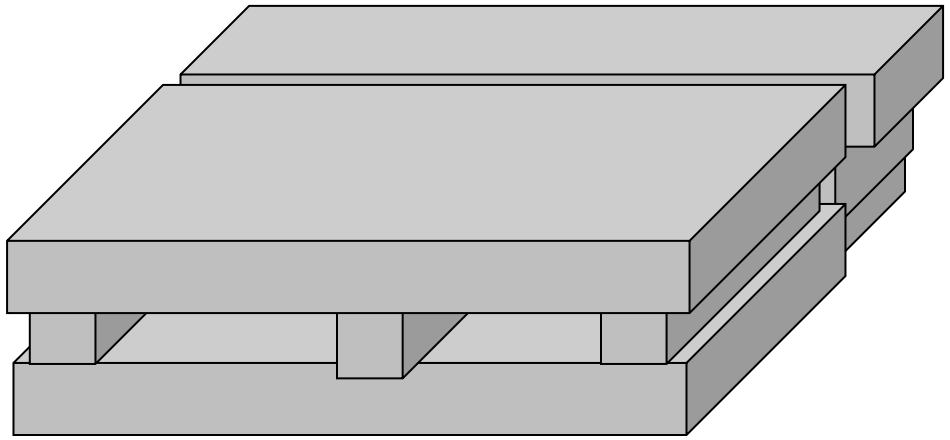


- Switching frequency 1MHz using GaN
- Shielding to reduce the CM noise

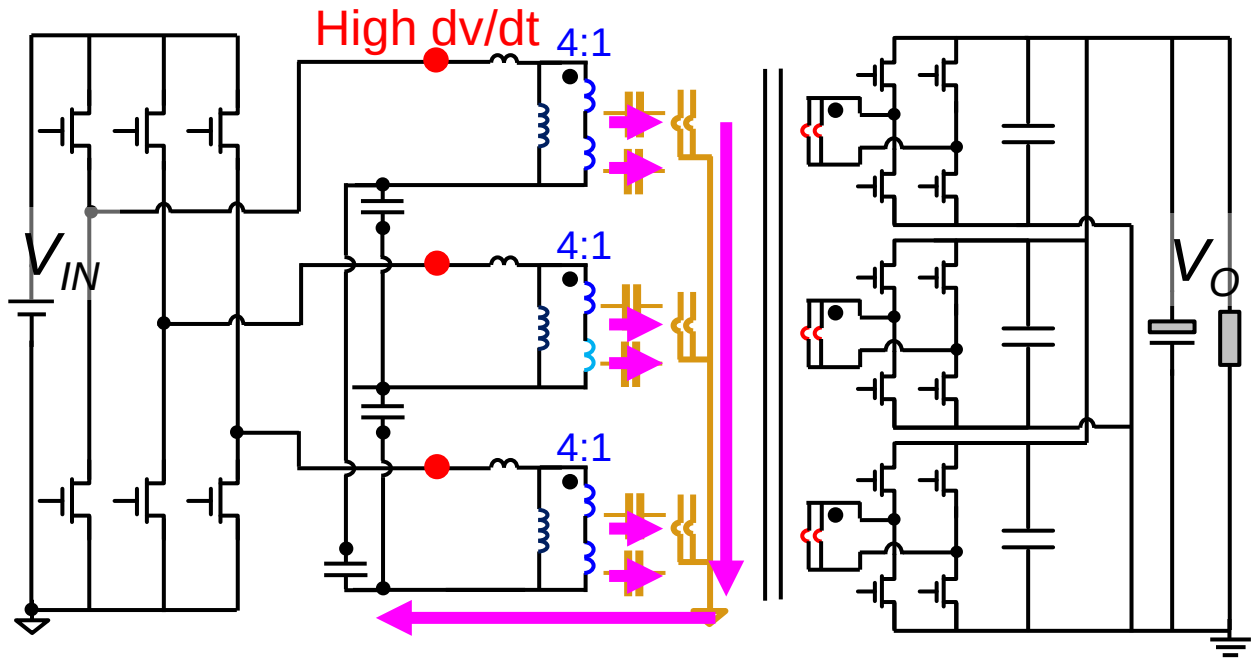
Integrated Magnetics (3L & 3T)

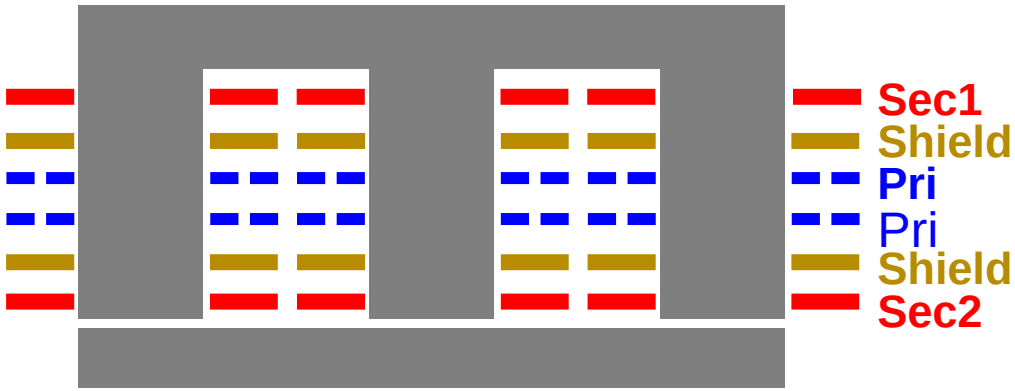


6 - Layer PCB



Shielding for 3-phase LLC

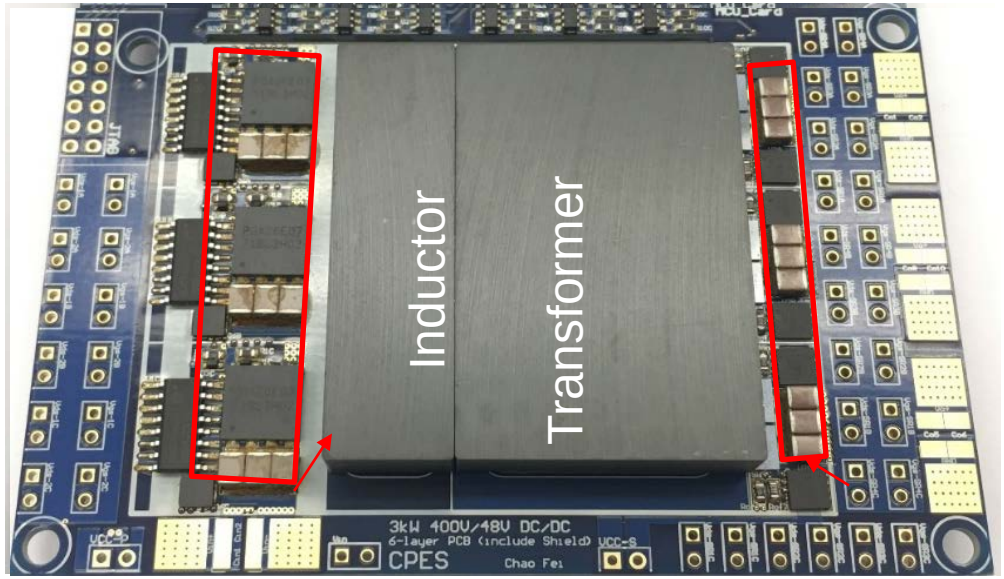




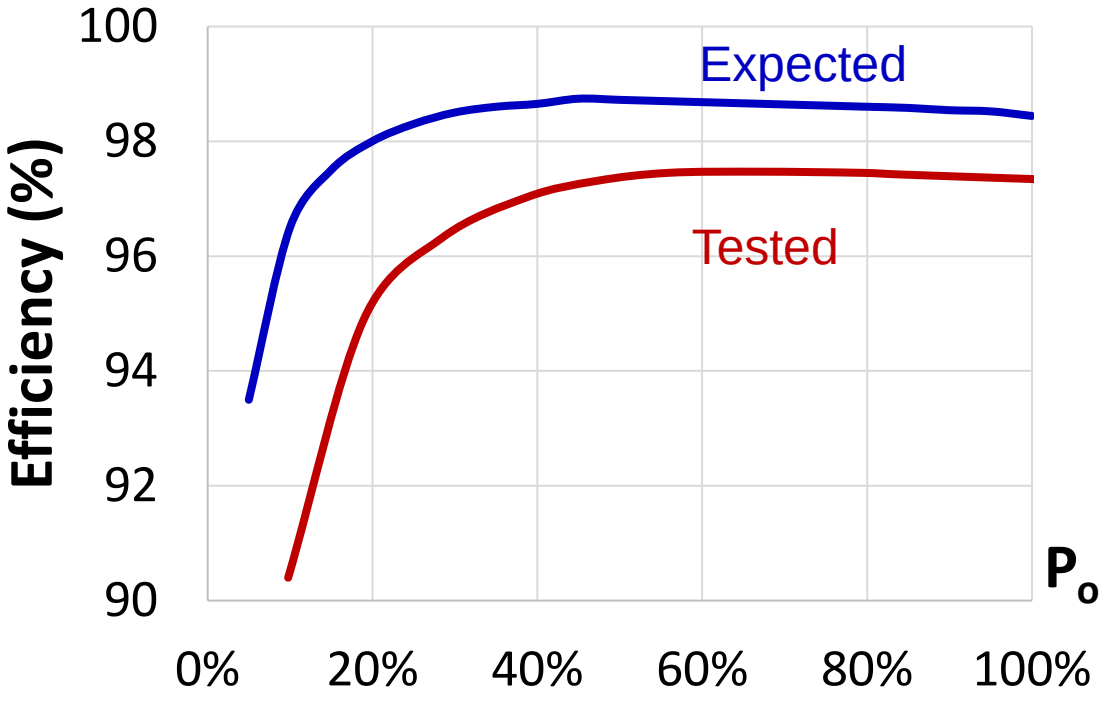
6-layer PCB

CM current flows to shielding and comes back to primary

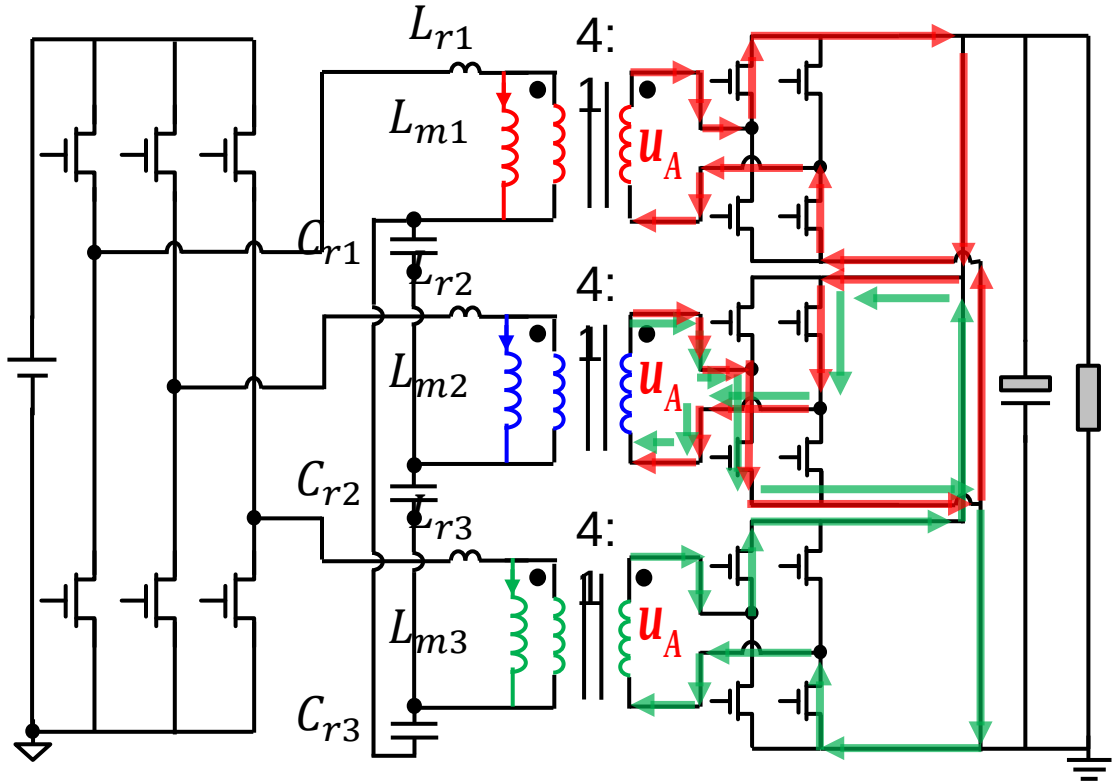
Primary Y Secondary in Parallel

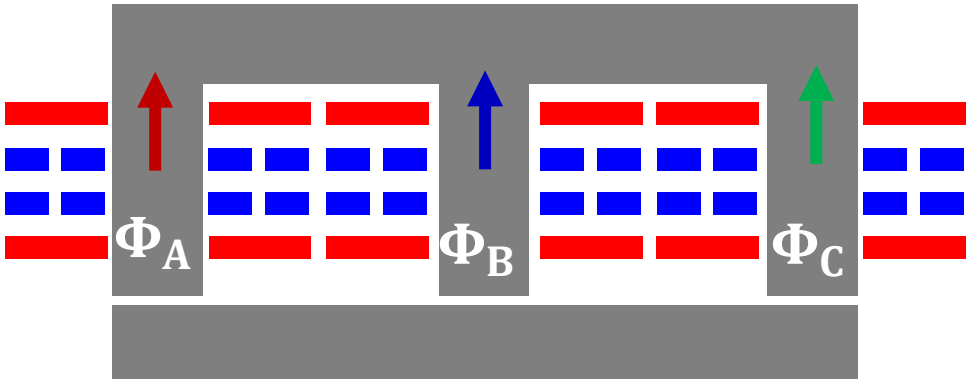


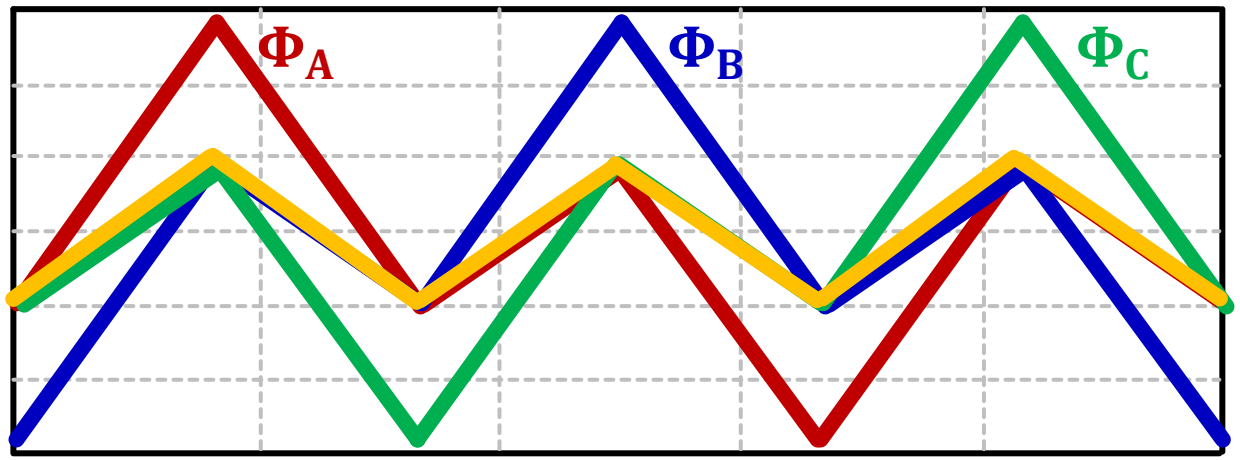
Power Density 600 W/in³



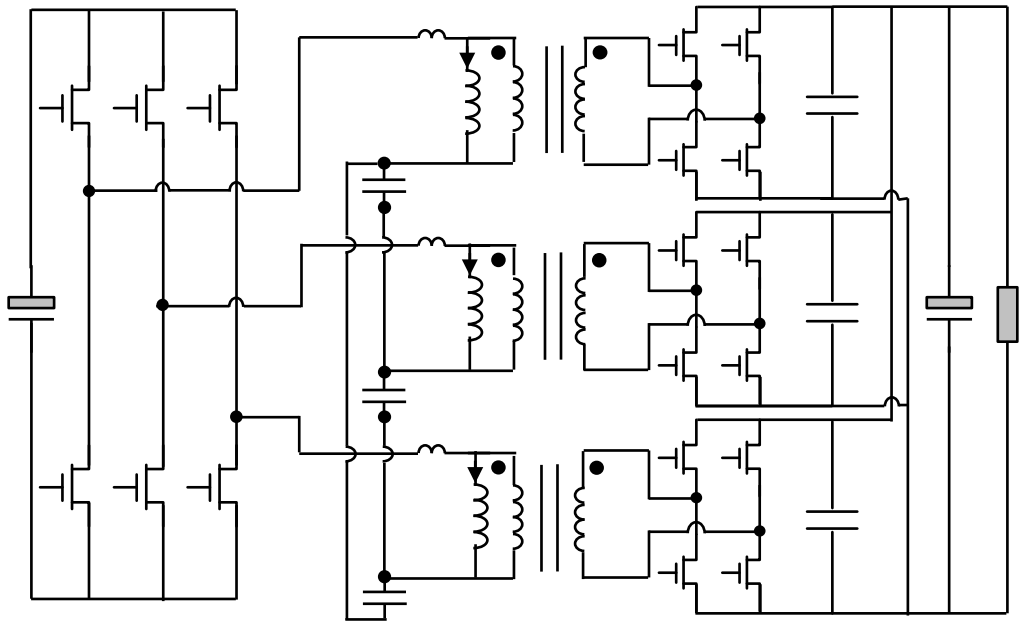
Issue1: Unwanted 3rd Harmonics Current



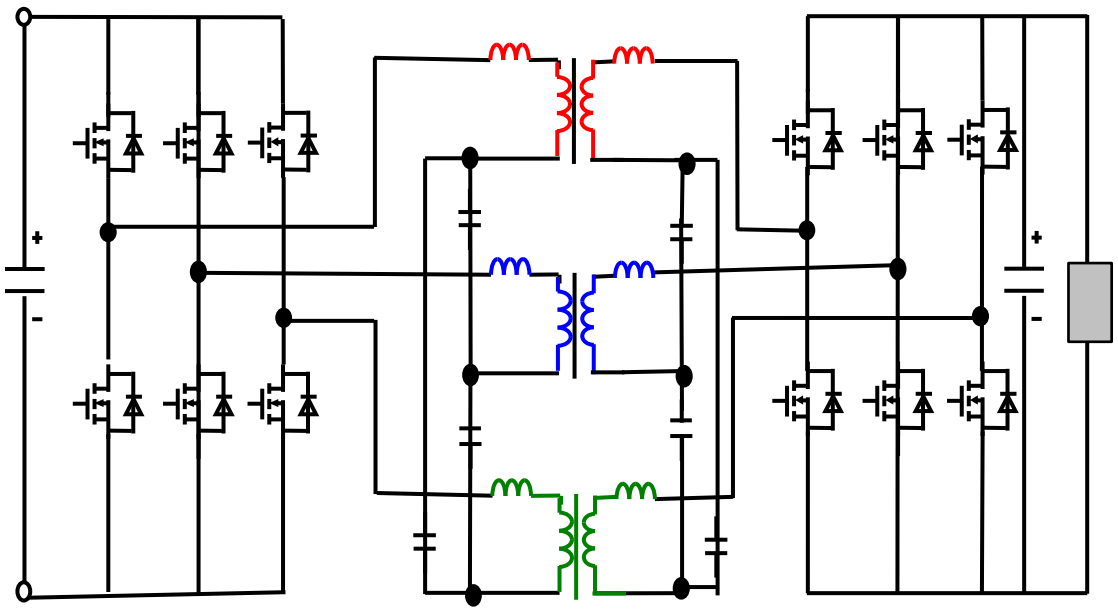




Improved Topologies



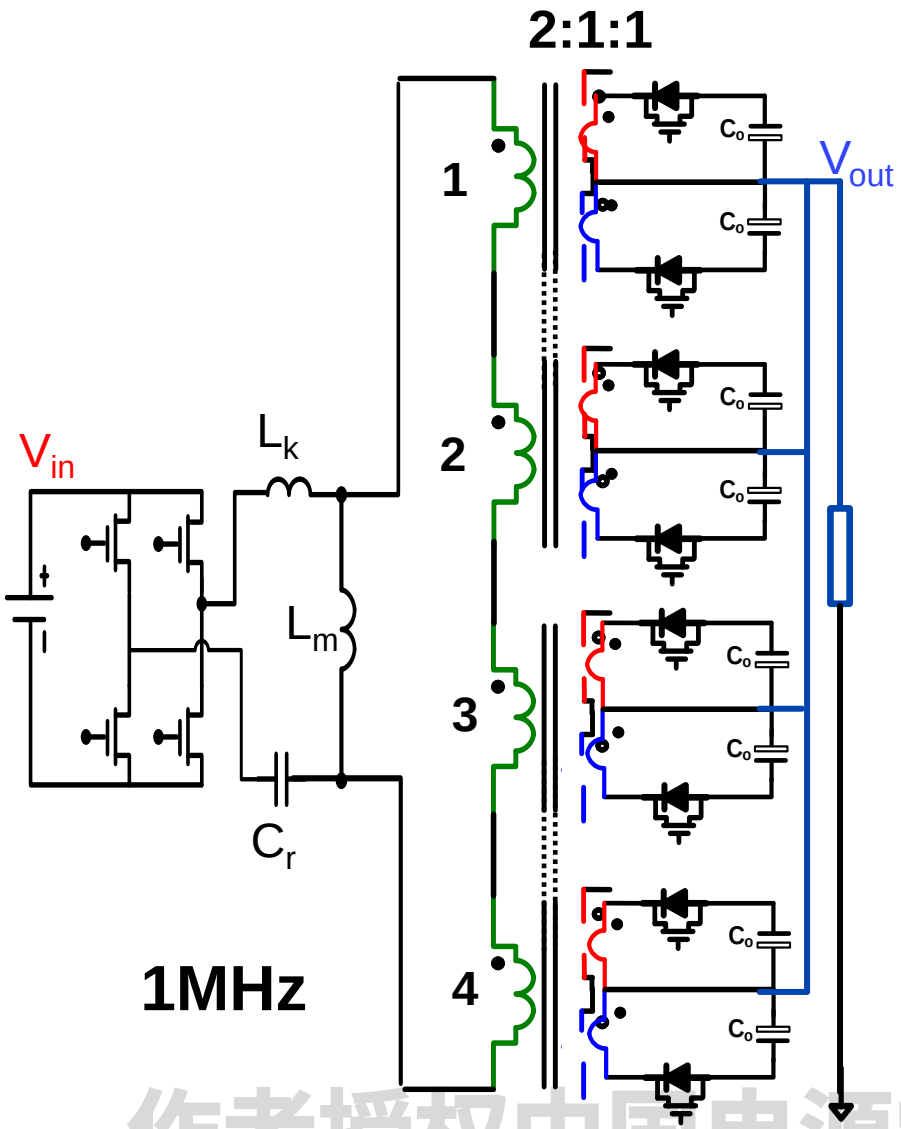
(Δ-connection for Cr)

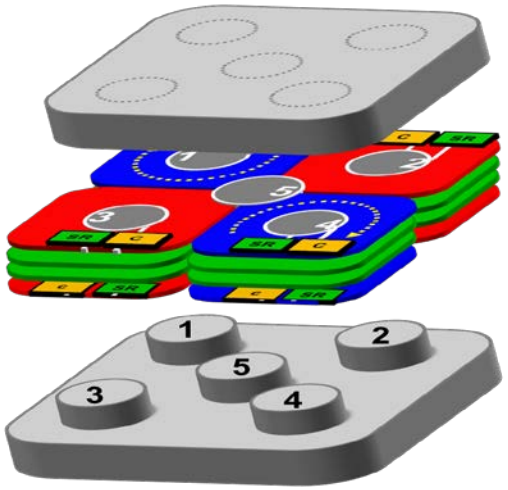


Integration of 3 Transformers & 3 Inductors

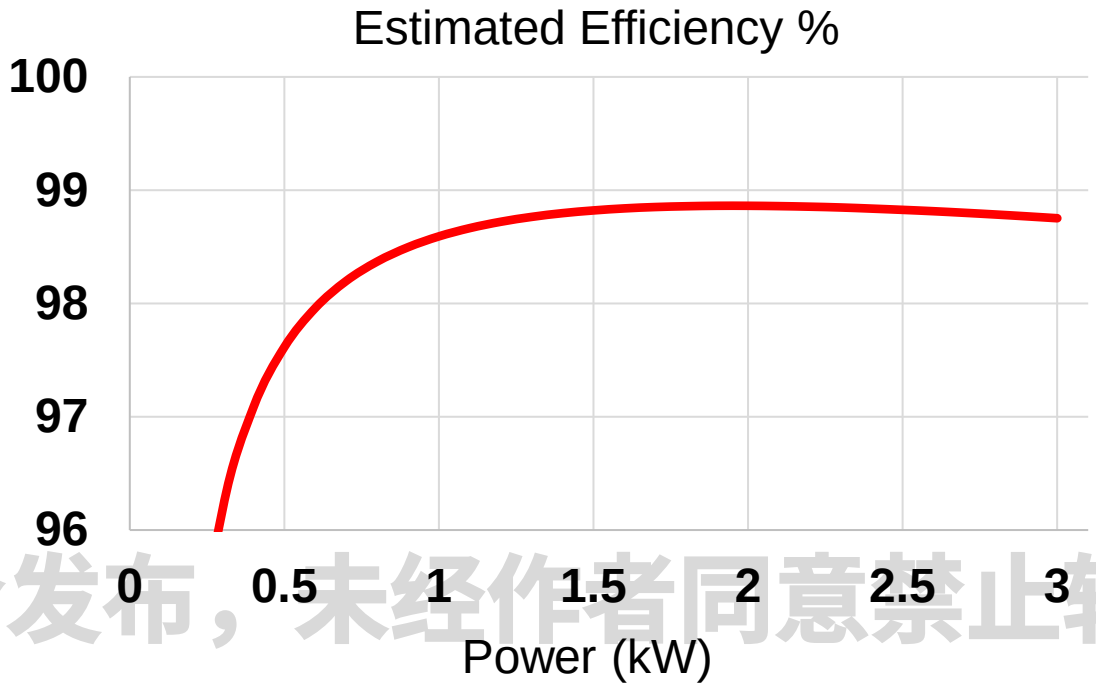
CPES Version 2

Single-Phase LLC Resonant Converter

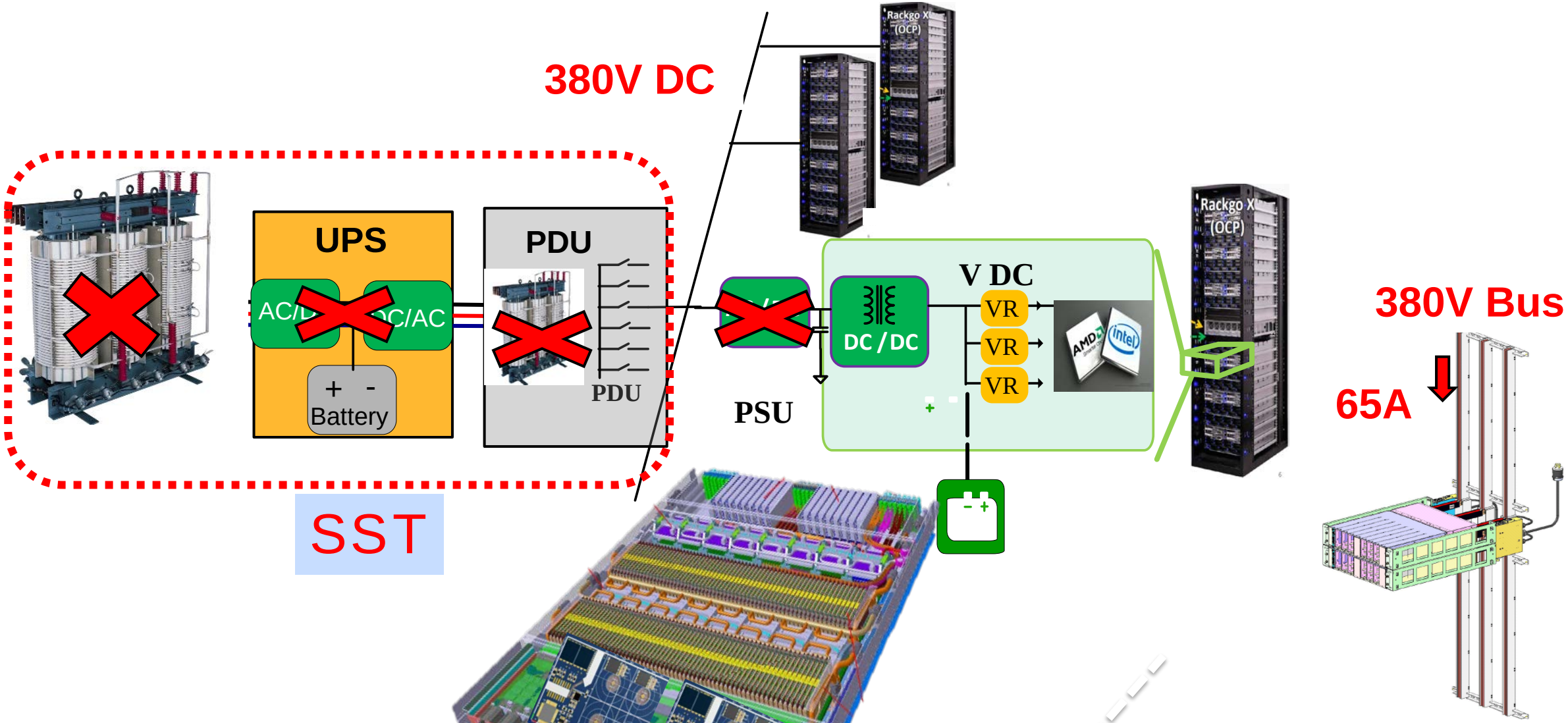




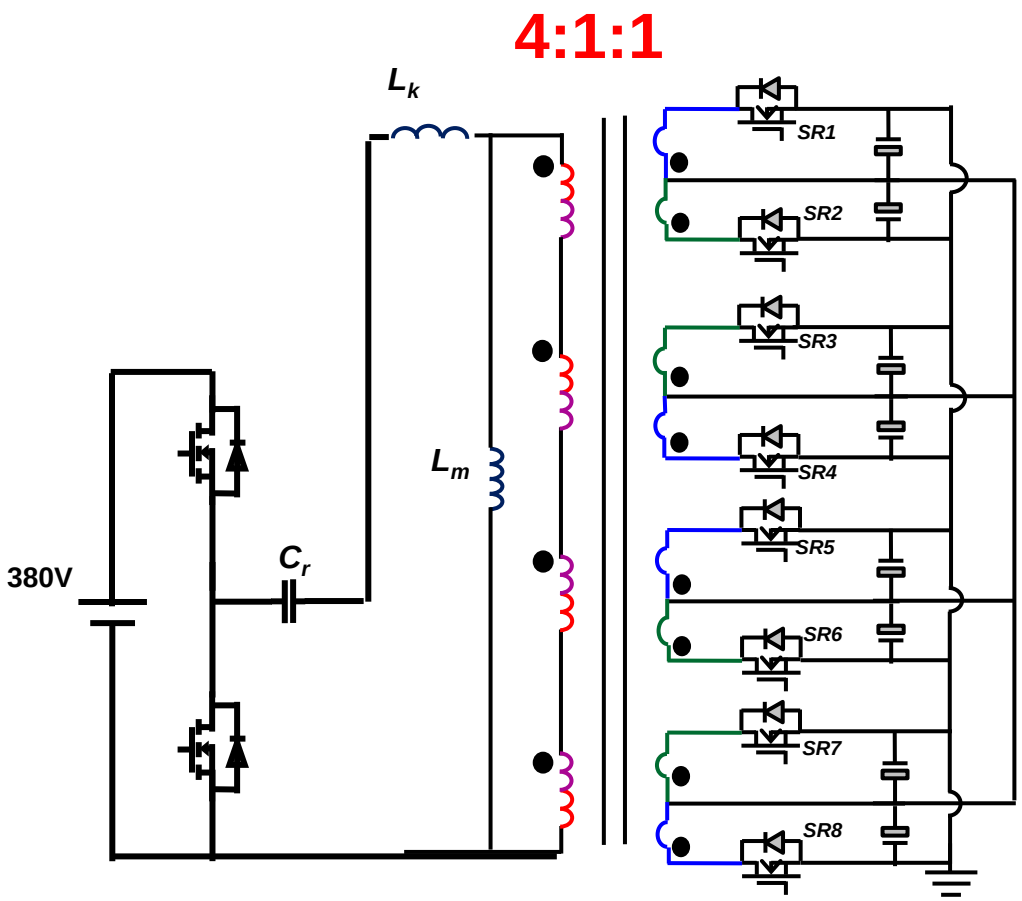
4 - Layer PCB

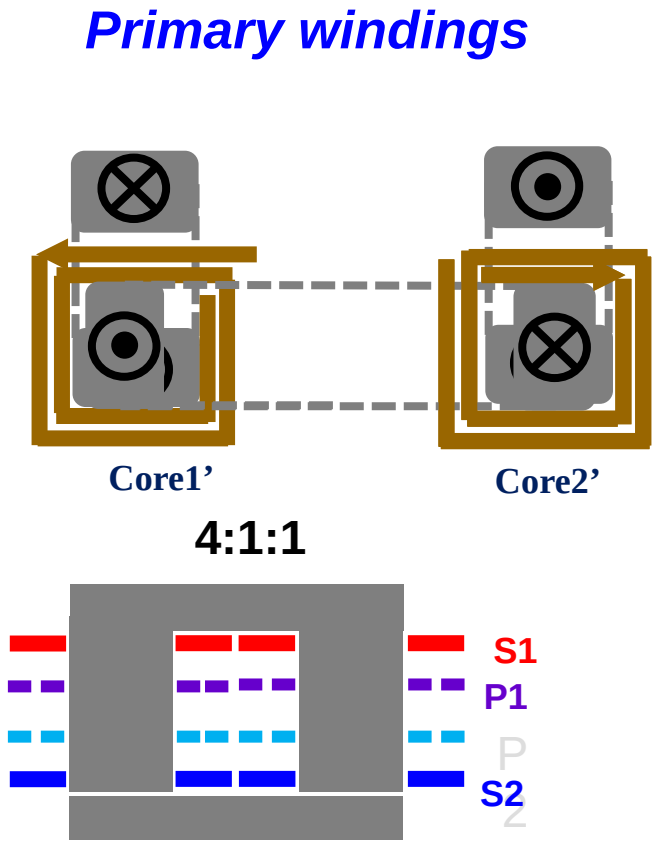


Next Generation Data Center



GaN Based Server Power Supplies

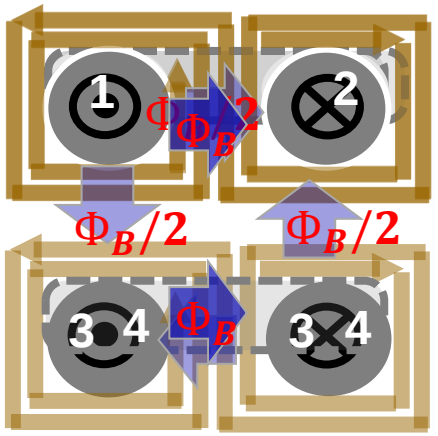




4 layers PCB

Matrix Transformer

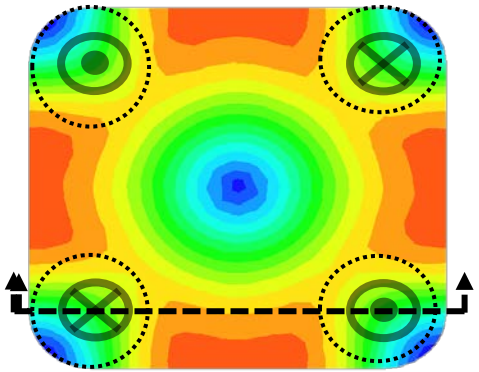
4-layer PCB

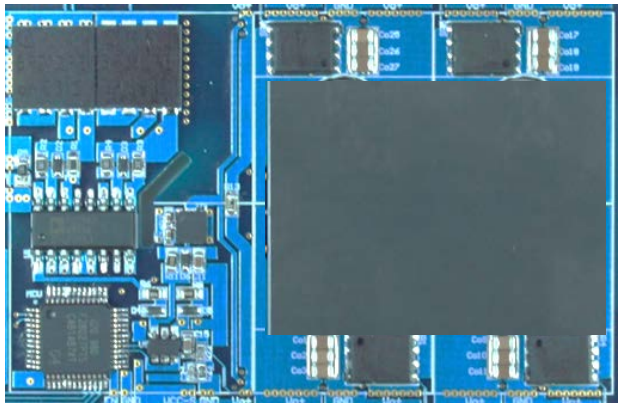


Core1

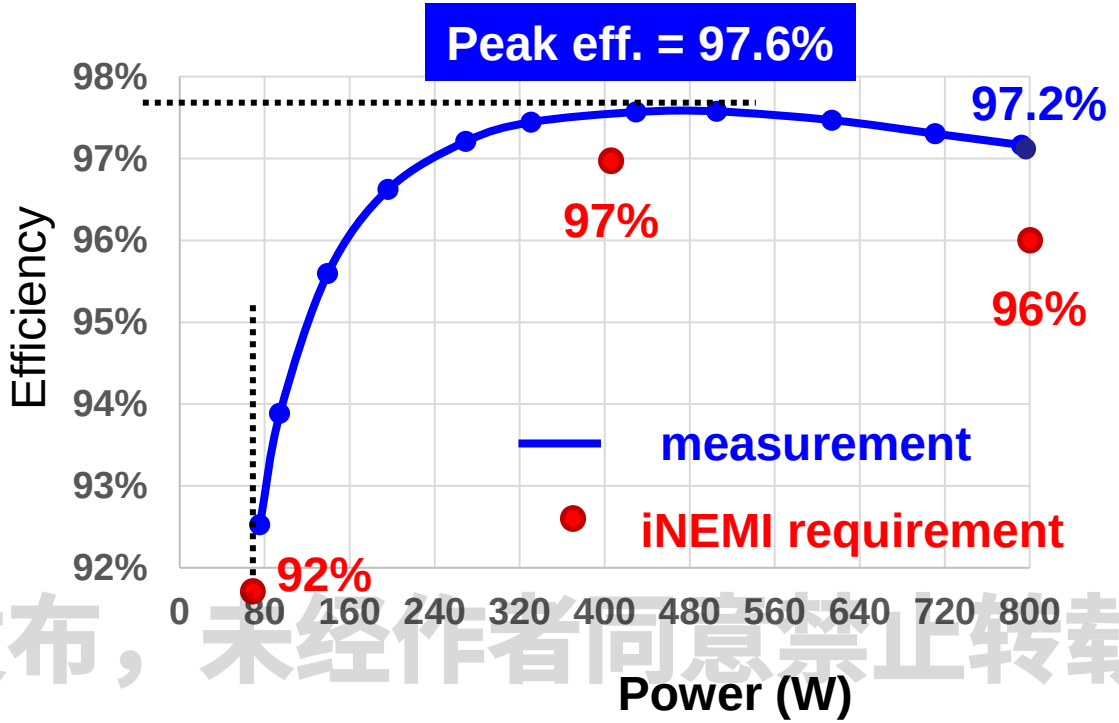
Core2

Flux Distribution

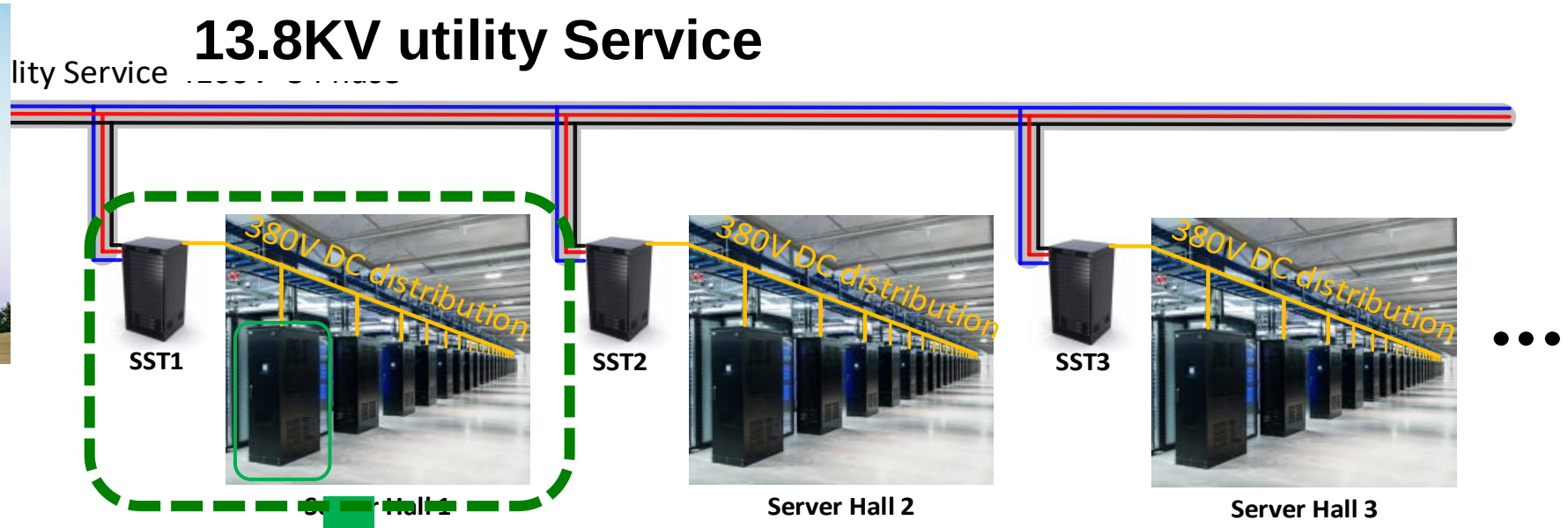


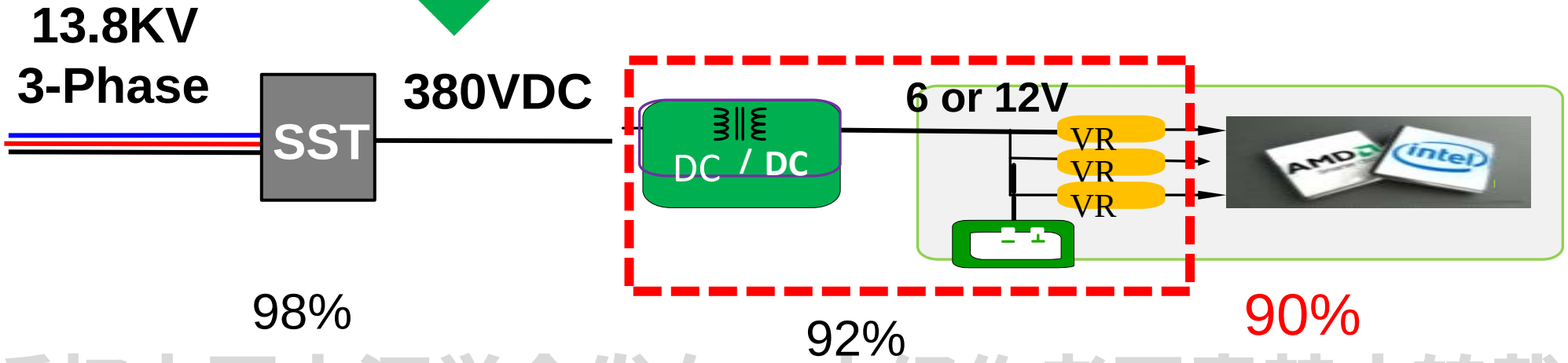


900W/in³



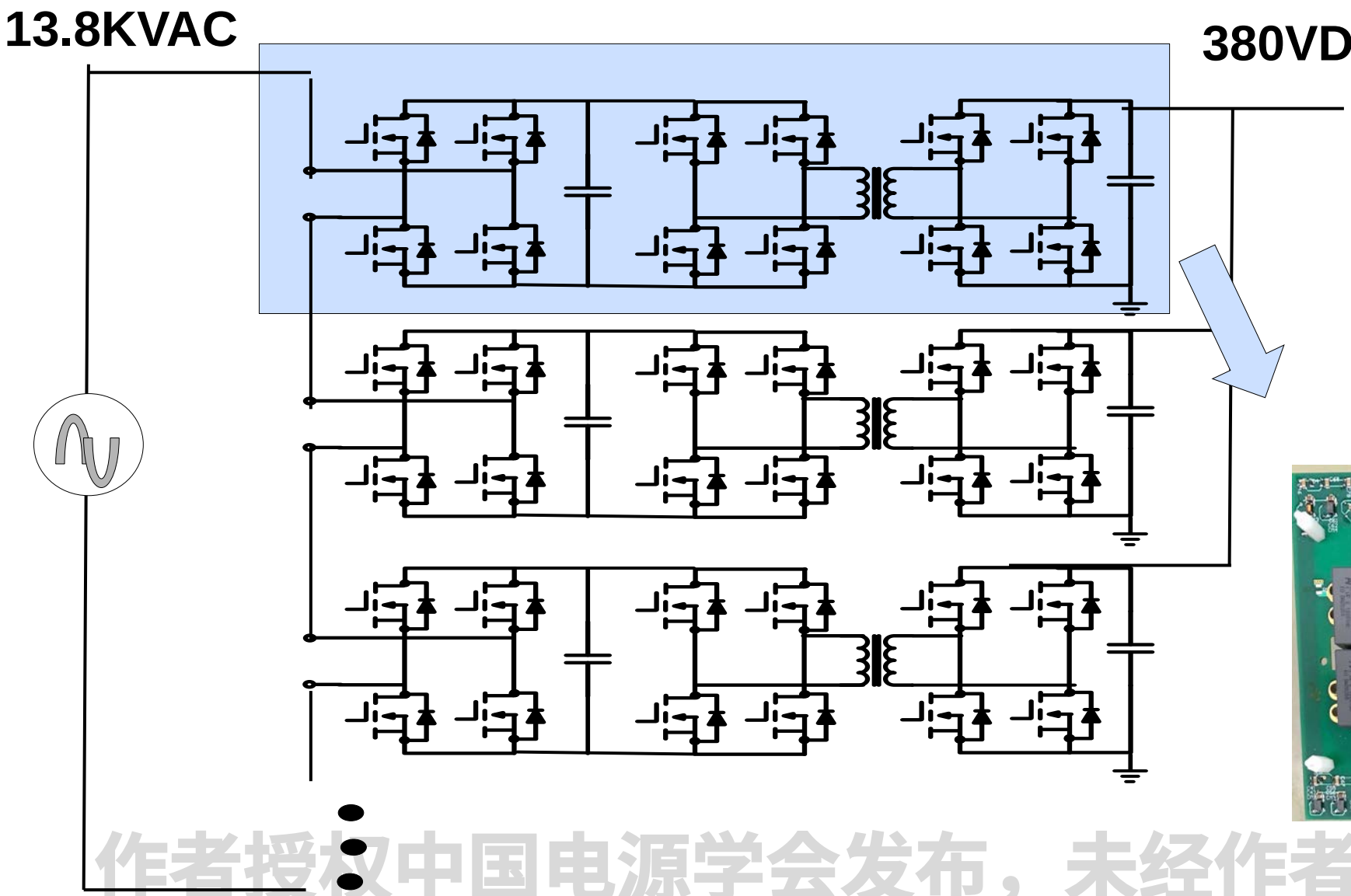
Generation 3 Data Center





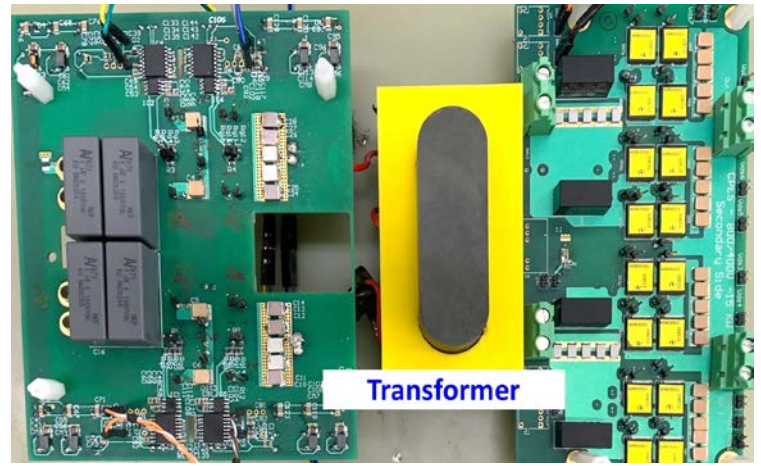
Truly Modular and Scalable Data Center

Solid-State Transformer



SST

200 KHz @ 98.5%



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Thank You