電力與能源技術研發中心
Center for Power and Energy Technologies

ROHDE&SCHWARZ
台灣羅德史瓦茲有限公司

電動車電源研發現況與未來趨勢

Presented by HJ Chiu
Dean, R&D Office, NTUST
04/14/2023

臺灣科大

TAIWAN TECH
National Taiwan University of Science and Technology

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Industry-University collaboration


MOST 科技部
Ministry of Science and Technology

國立臺灣科技大學 邱煌仁 特聘教授
所主持之**先進電源產學技術聯盟**

榮獲
108 年度「產學技術聯盟合作計畫」
（產學小聯盟）

績優聯盟

特頒此狀 以資表揚

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產學及園區業務司

產學及園區業務司
代理司長
涂君怡

中華民國 109 年 11 月 24 日

先進電源產學技術聯盟
Advanced Power Technology Industry-Academia Alliance

Funding over US$1,000,000/year supported by industry

Achievement and Honors

Grand Prize, US$10,000

- 2013 International Future Energy Challenge (IEEE IFEC) – Columbus, Ohio

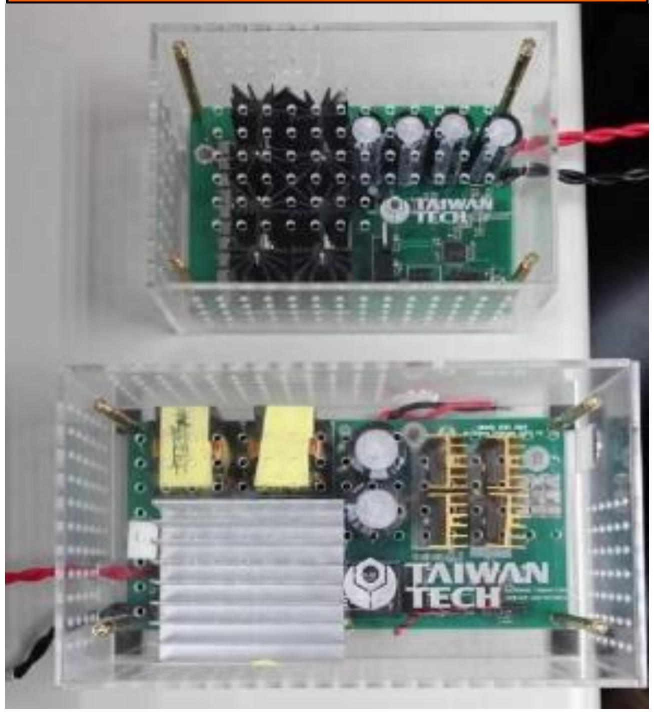
High Efficiency Solar Micro Inverter

Achievement and Honors

Grand Prize, US$10,000

- 2015 International Future Energy Challenge (IEEE IFEC) – Dearborn, Michigan

WPT Charging System



Achievement and Honors

Google granted US$30,000

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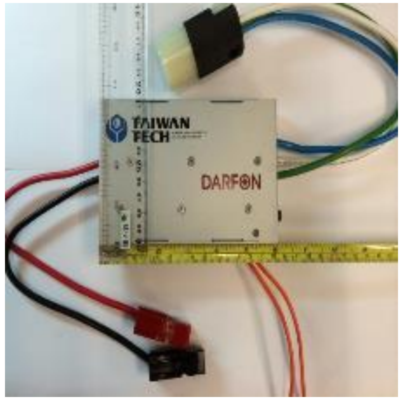
Queensland University of Technology	Geoff Walker



IEEE POWER ELECTRONICS SOCIETY
Powering a Sustainable Future

IEEE
Advancing Technology for Humanity

Achievement and Honors

Empower a Billion Lives (EBL) US$4,000

Pacific Asia Regional Award


EMPOWER A BILLION LIVES

pels IEEE POWER ELECTRONICS SOCIETY

CPSS

DELTA CUP - EBL PACIFIC ASIA

Delta Cup – IEEE Empower a Billion Lives - Pacific Asia Regional Competition

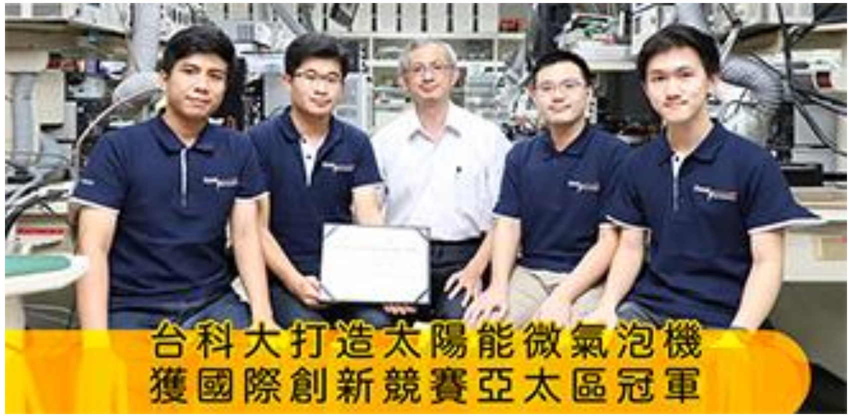
The Certificate is Proudly Presented for:

Best Track Award - 1B

to the Team Apollo from

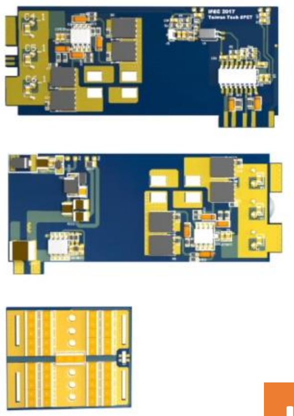
National Taiwan University of Science and Technology and partners

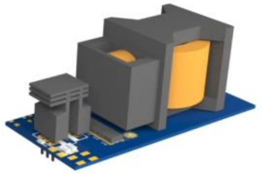
Dehong Xu Steering Committee Chair of EBL Pacific Asia	Tianhao Tang Organizing Committee Chair of EBL Pacific Asia	Philip Krein Judging Committee Chair of EBL Pacific Asia

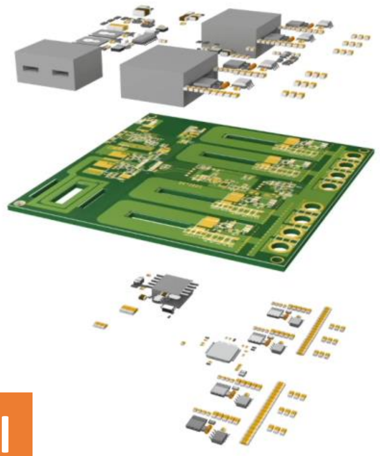


Core technologies

GaN based server power supply



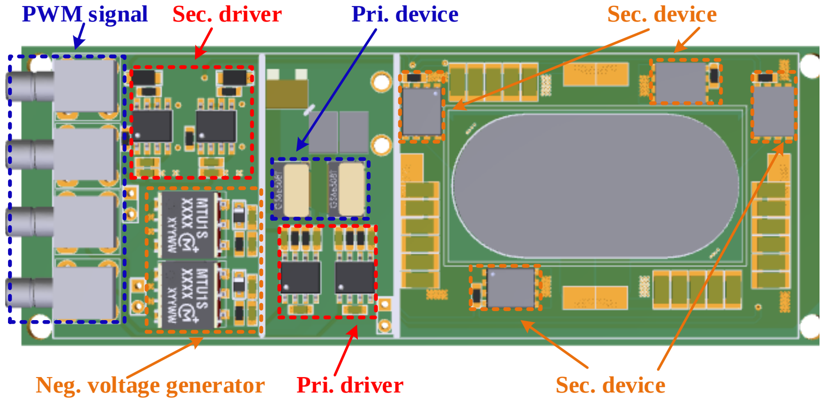




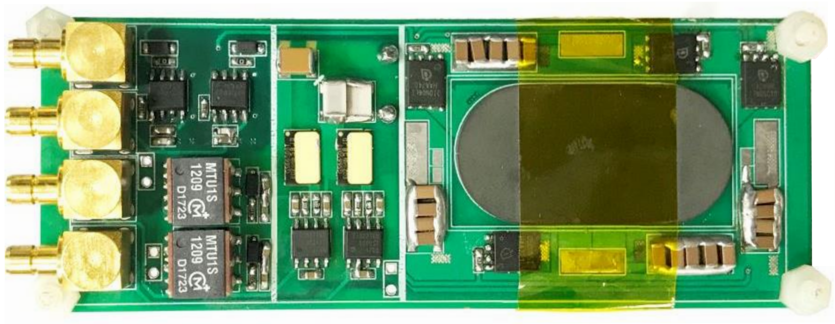
high power density/ low profile/ digital control

Core technologies

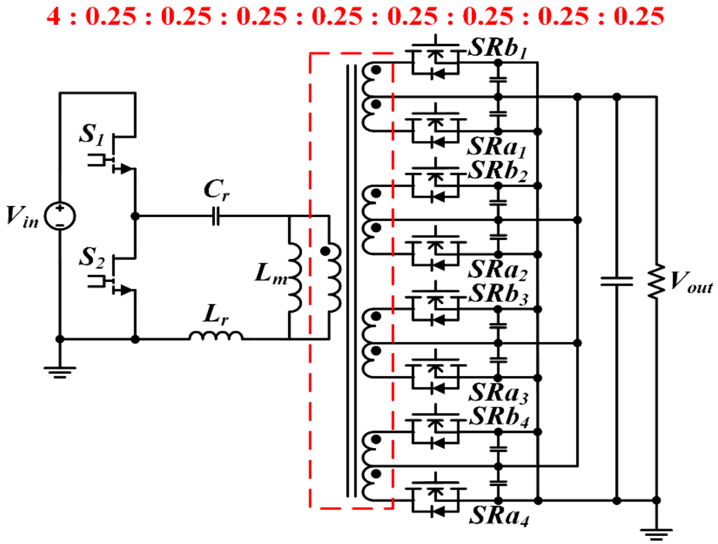
GaN based server power module high power density/ low profile	
Circuit parameters	
Input/ output voltages	380V/12V
Rated power	800W
Switching freq.	1MHz
Primary switches	GS66508T
Secondary switches	BSC0500NSi
Core material	ML91S
Transformer Turns ratio	16:1
Converter size	6.5cm x 3.2cm x 0.7cm

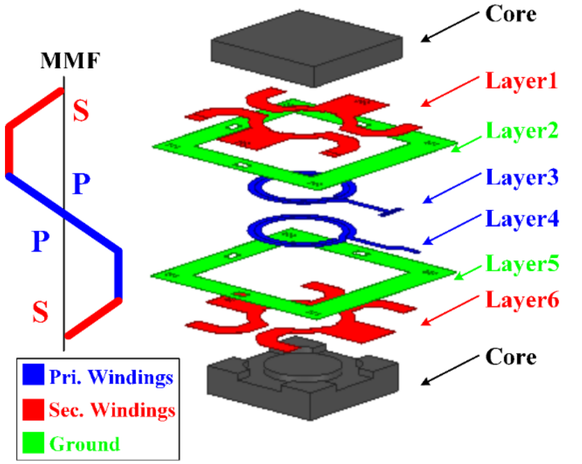


3D電路佈局圖



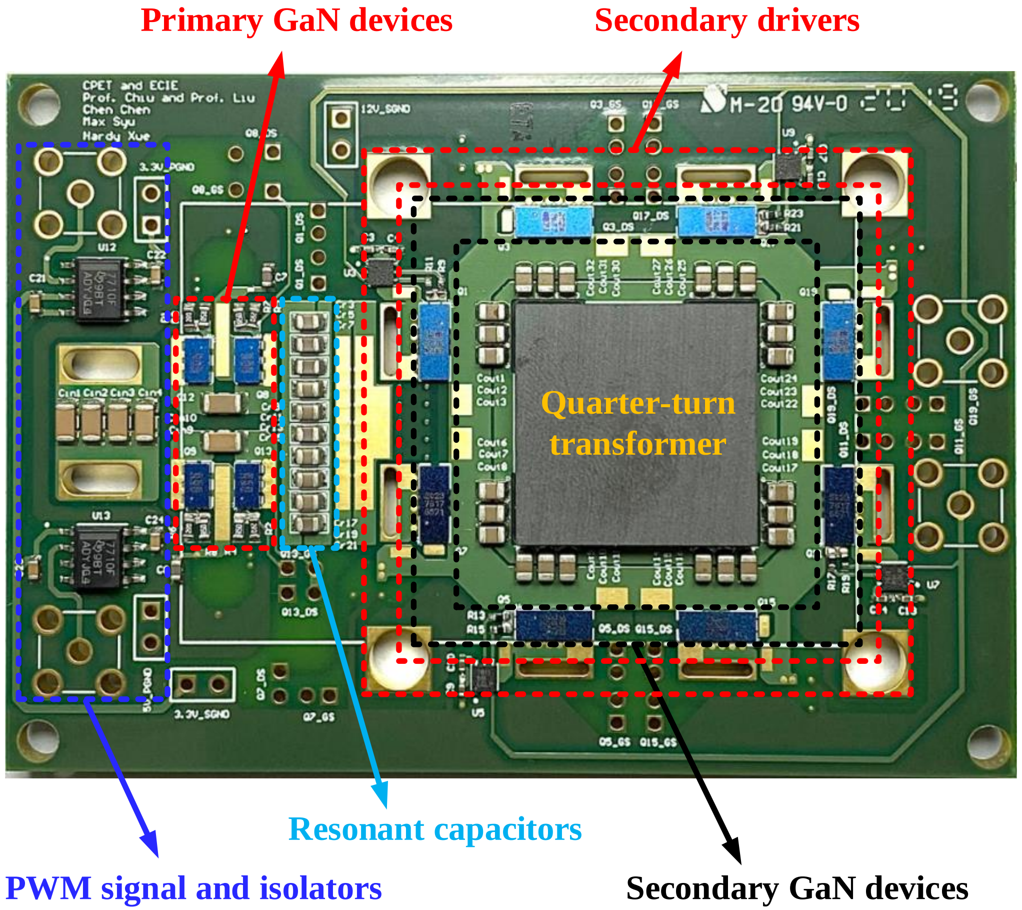
實體電路圖

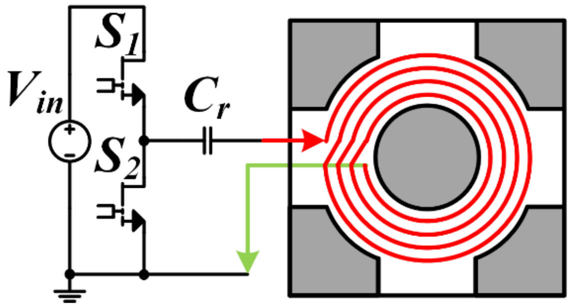


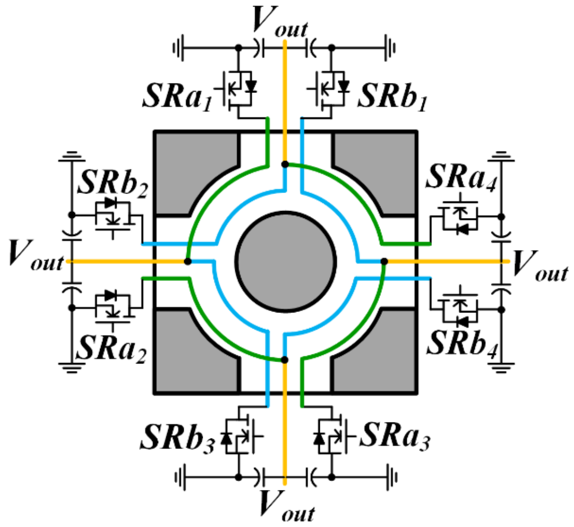


Core technologies

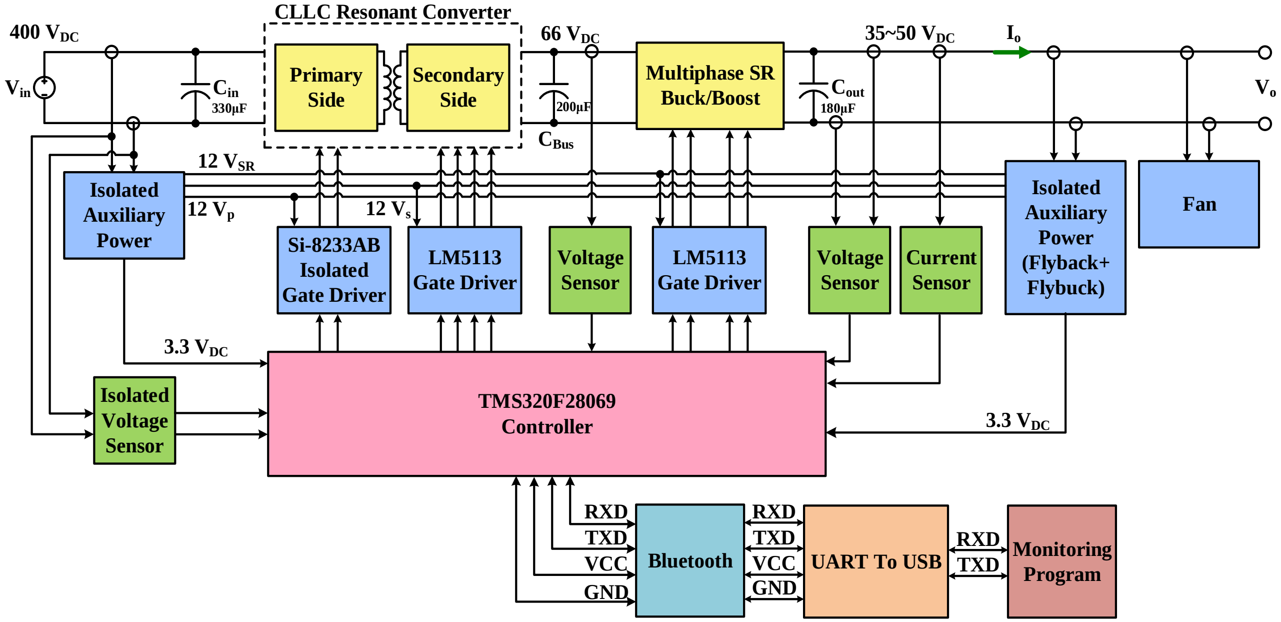
GaN based 48V power module	
Spec.	
Input voltage	48 V
Output voltage	6 V
Output current	190 A
Rate power	1100W
Efficiency	98%
Power density	70 W/cm³

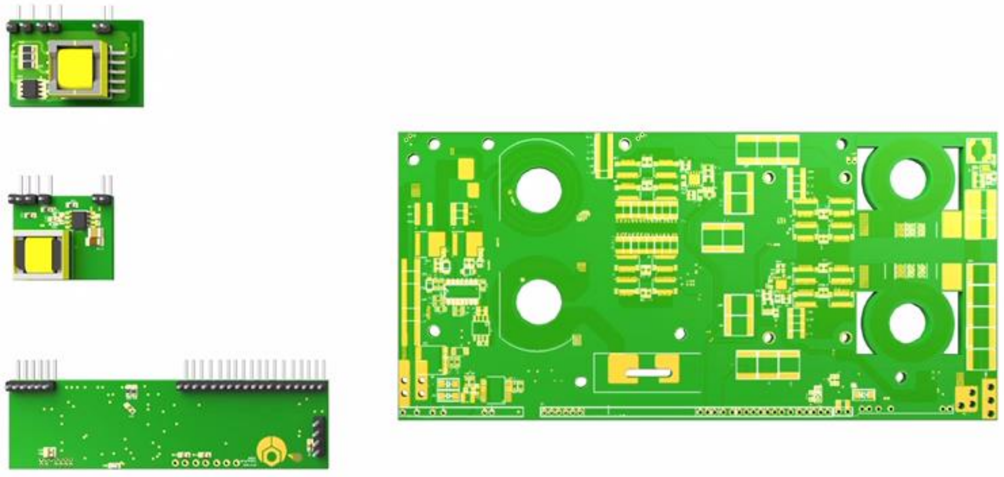




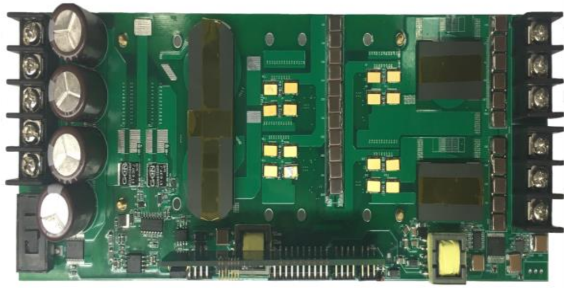


Core technologies





GaN based bidirectional power module

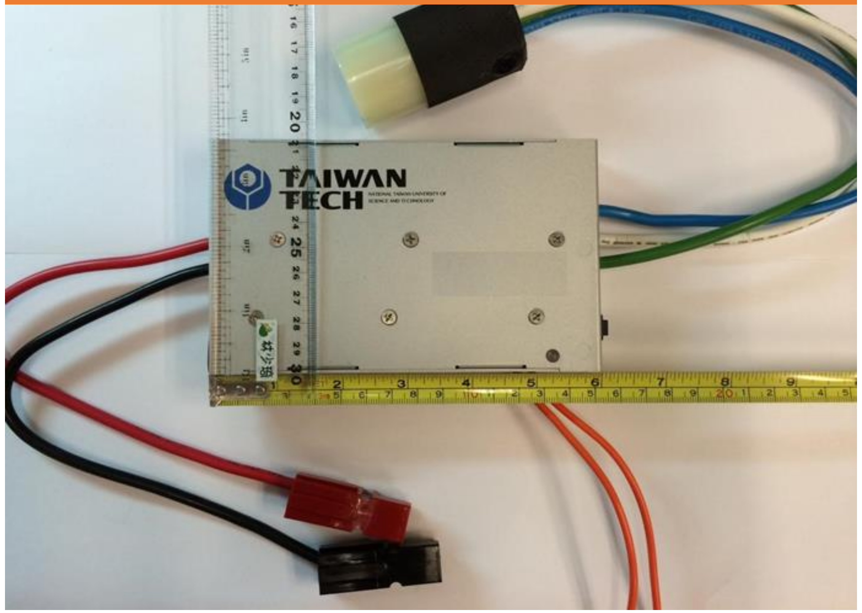


≈

Core technologies

Parameter	Value
Maximum load	2 kW
Input voltage	450 V DC, 10 Ω resistor
Output voltage	240 V AC
Output frequency	60 Hz
Power factor of load	1 (Resistive load)
Ripple decoupler switching frequency	700 kHz
Inverter switching frequency	200~500 kHz

GaN based high power density PV inverter

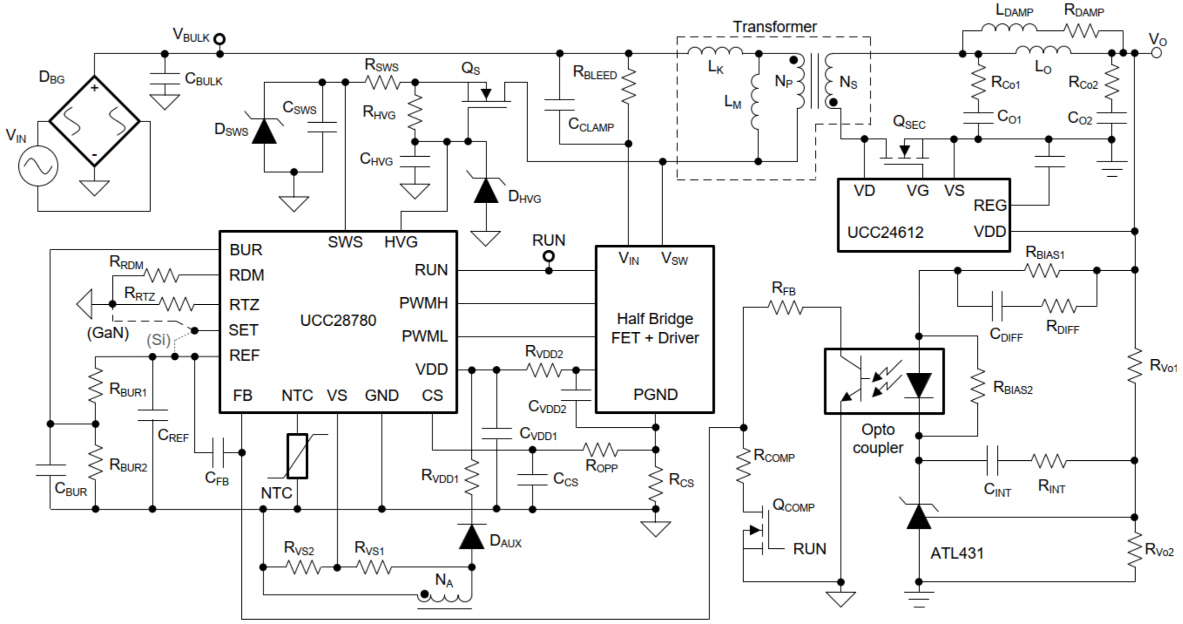


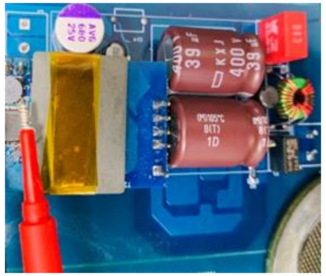
Volume : 22.055 in^3
Dimensions : 5.985 inch x 3.685 inch x 1.000 inch
Power density: 90.682 W/ in^3

Core technologies

High power density GaN based adaptor	
Item	**Value**
V_{in}	110 Vac
V_o	19 Vdc
P_o	45 W
Turns ratio	12:2
F_s	518kHz
Core	ERI25
Efficiency	93%

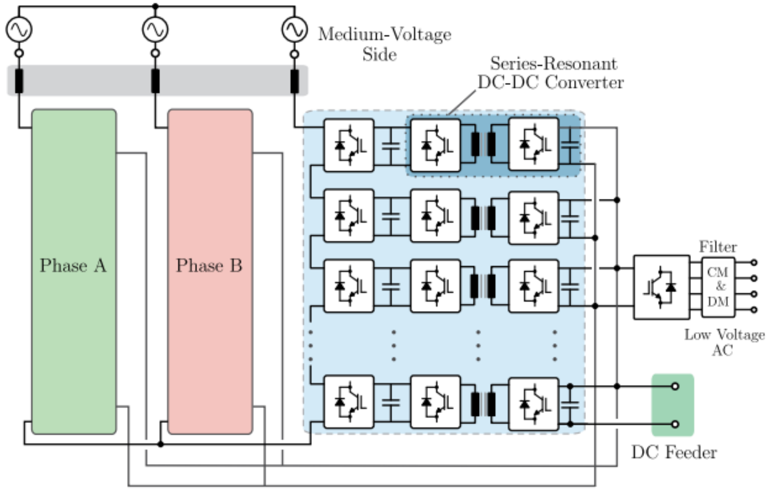
V_{out} (V)	I_{out} (A)	P_{out} (%)	Efficiency (%)
19.065	0.5945	25	91.40
19.064	1.1799	50	92.57
19.063	1.7644	75	93.77
19.063	2.3647	100	94.18



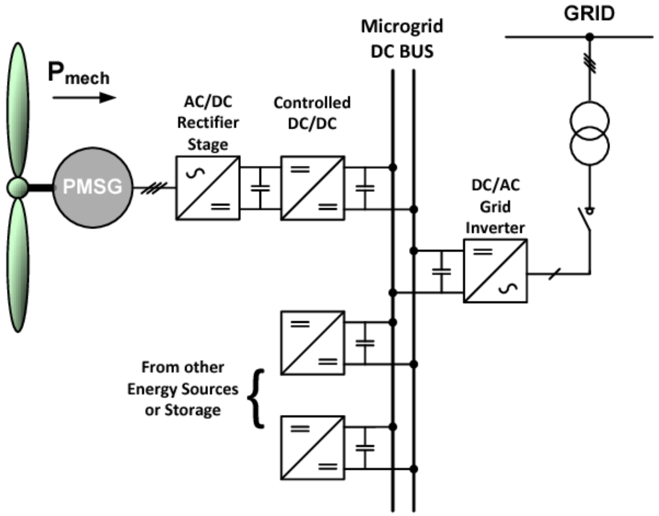


Miniaturization

Core technologies



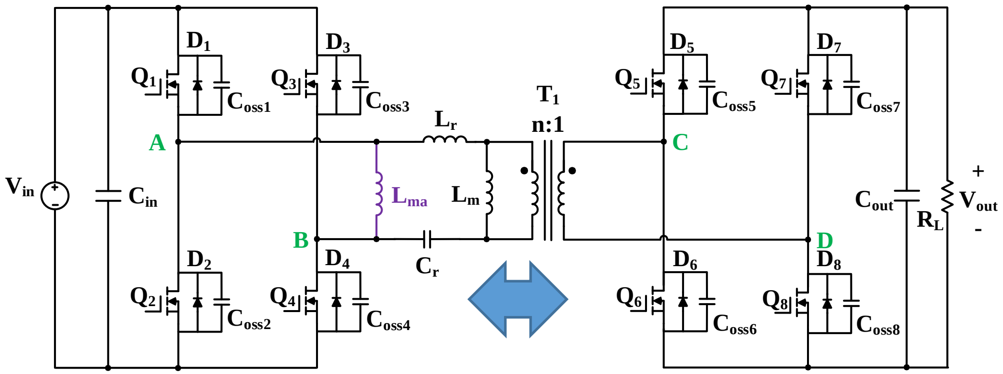
Modular Smart Transformer Architecture Application

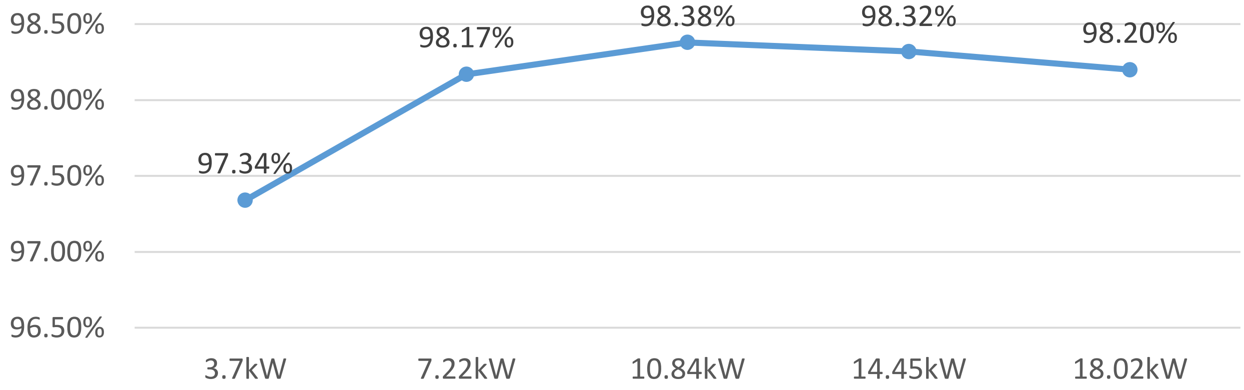


Wind Turbine in a Grid-Connected DC Microgrid

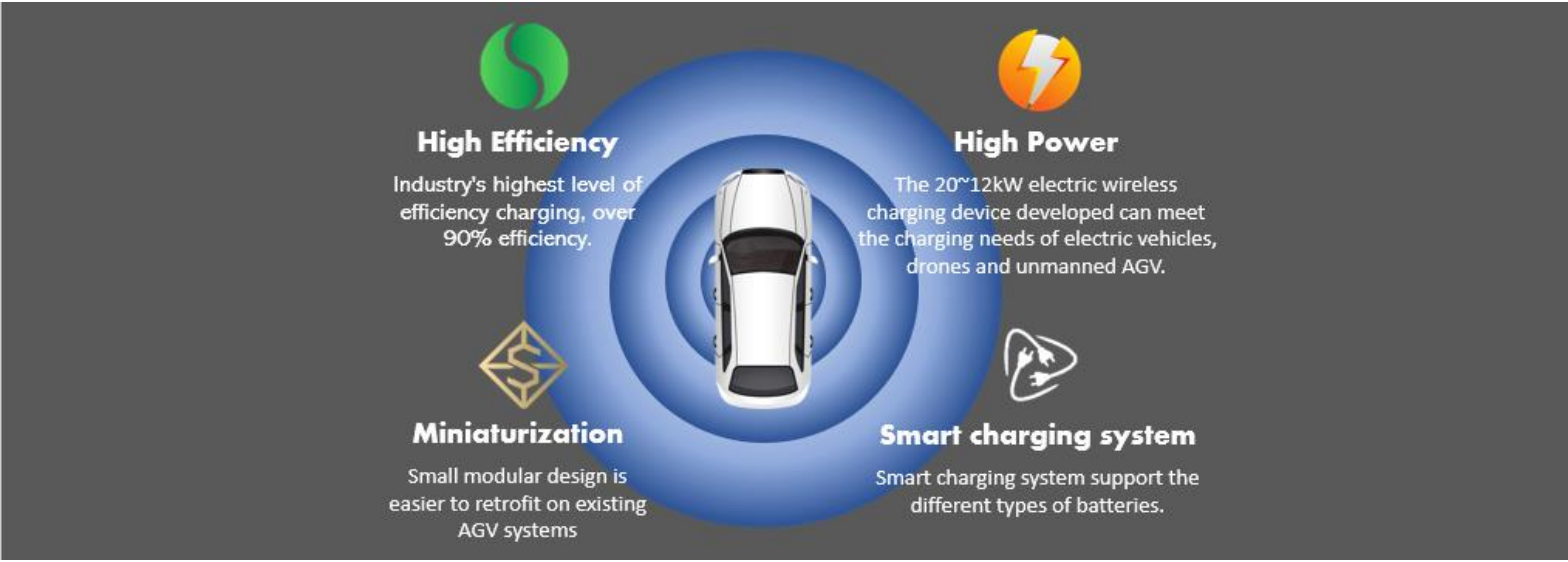
SiC based bidirectional power module

- ☐ Switching frequency > 300kHz
- ☐ High power density
- ☐ Robust and simple control
- ☐ Bi-directional power conversion





Core technologies



Core technologies

High Power - Wide range of output power

The **100W~20kW** wireless charging system has been developed and can be applied to the charging needs of unmanned aircraft, electric bicycles, electric motors, unmanned vehicles, AGV, electric vehicles, etc.

- Battery Range: 5V ~ 48V
- Power Range: 100W~3kW
- Application: Drone, AGV, robot…

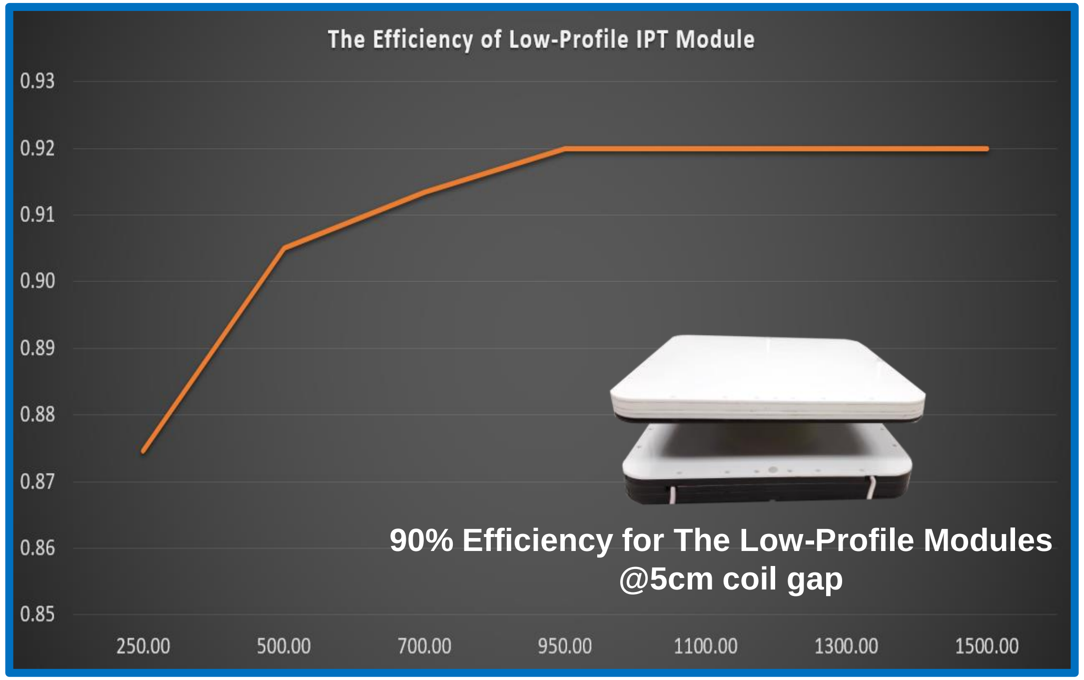
- Battery Range: ~ 96V
- Power Range: 1kW~6kW
- Application: Electric Stacker, electric bicycle, electric motorcycle….

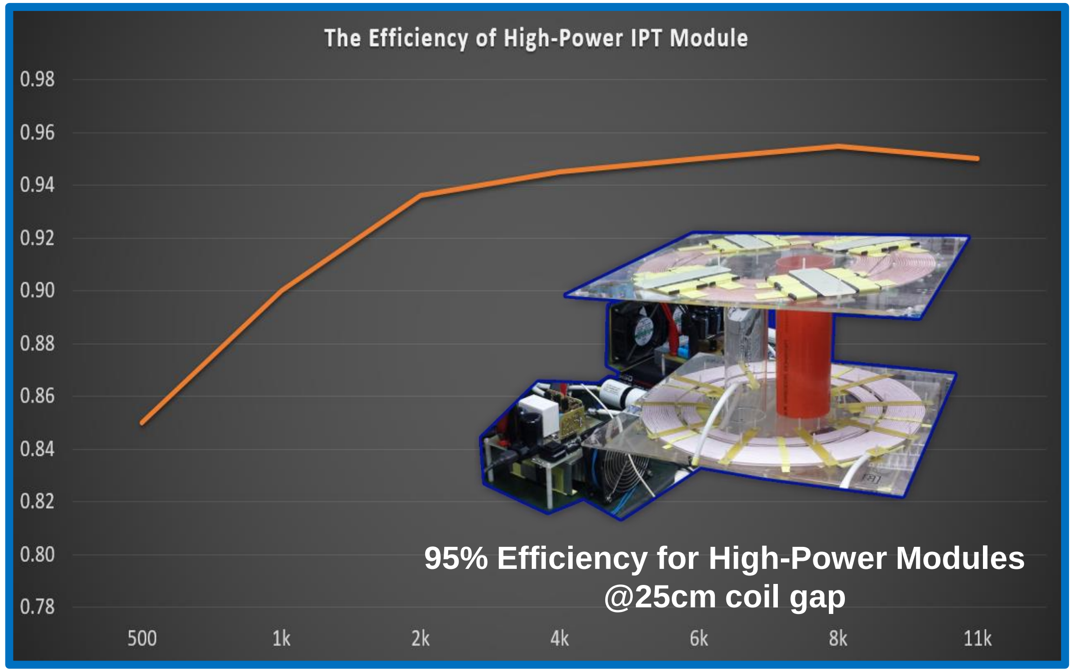
- Battery Range: ~ 400V
- Power Range: 8kW~20kW
- Application: electric vehicle, electric bus…

Electric Stacker

Core technologies

High Efficiency - Industry's highest level of efficient charging





Core technologies

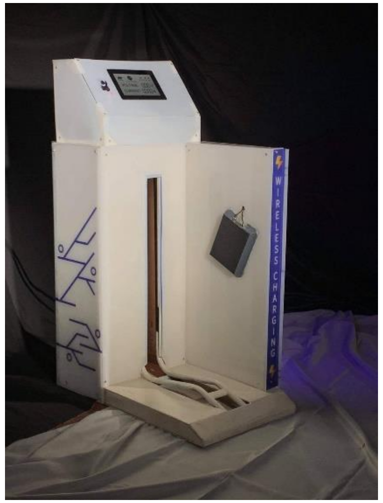
Miniaturization - easy to retrofit on existing charging system

Wireless charger for E-bike

Solar Panel Installed in the station's roof as the renewable energy source for E-Bike charger

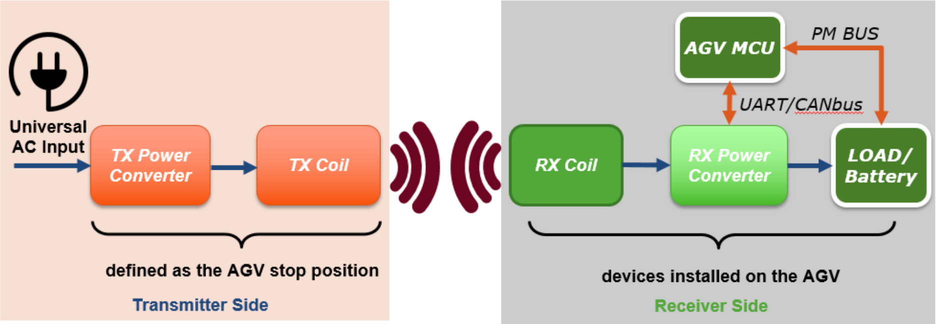
- ➢ Non-contact charging – Ensure safety
- ➢ IP67 design – No leakage risk
- ➢ No need to plug, stop and charge
- ➢ Wireless charger – Extend the route range
- ➢ Solar charging – To solve the outdoor power problem

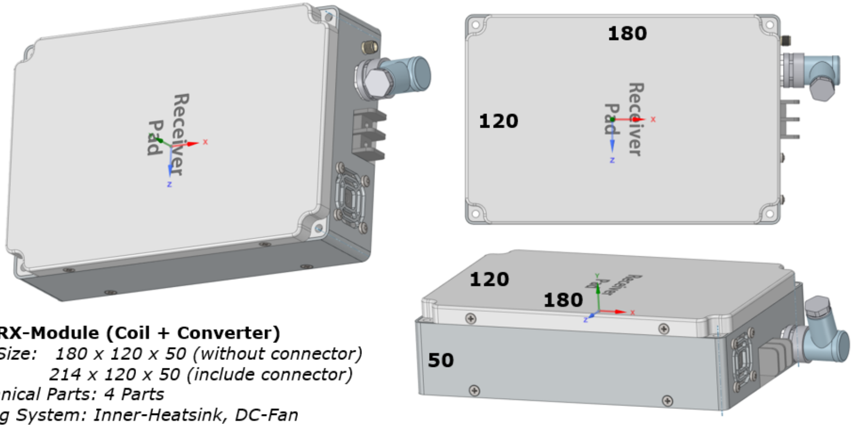
Wireless Charger is Utilized to charge the E-bike battery during the docking-mode



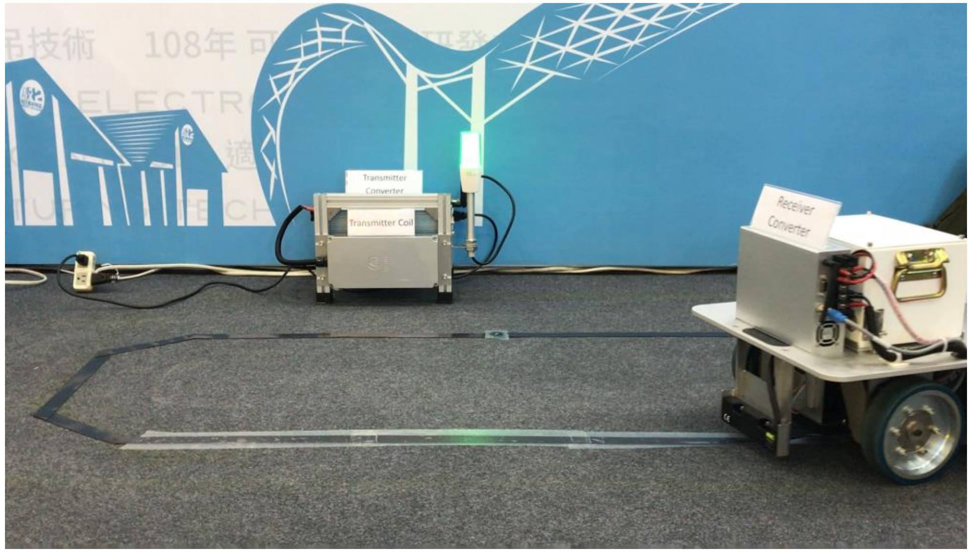
6.78-MHz, 240-W Wireless Power Supply for electric bicycles using GaN Devices

Wireless charger for AGV/ UV light robot





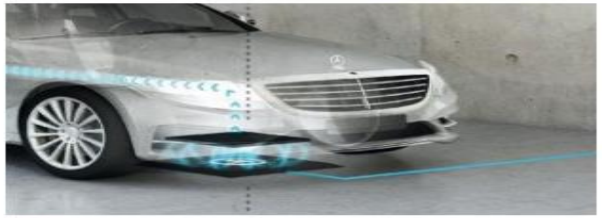
V4.0 RX-Module (Coil + Converter)
Total Size: 180 x 120 x 50 (without connector)
214 x 120 x 50 (include connector)
Mechanical Parts: 4 Parts
Cooling System: Inner-Heatsink, DC-Fan
Power Rating: 1kW

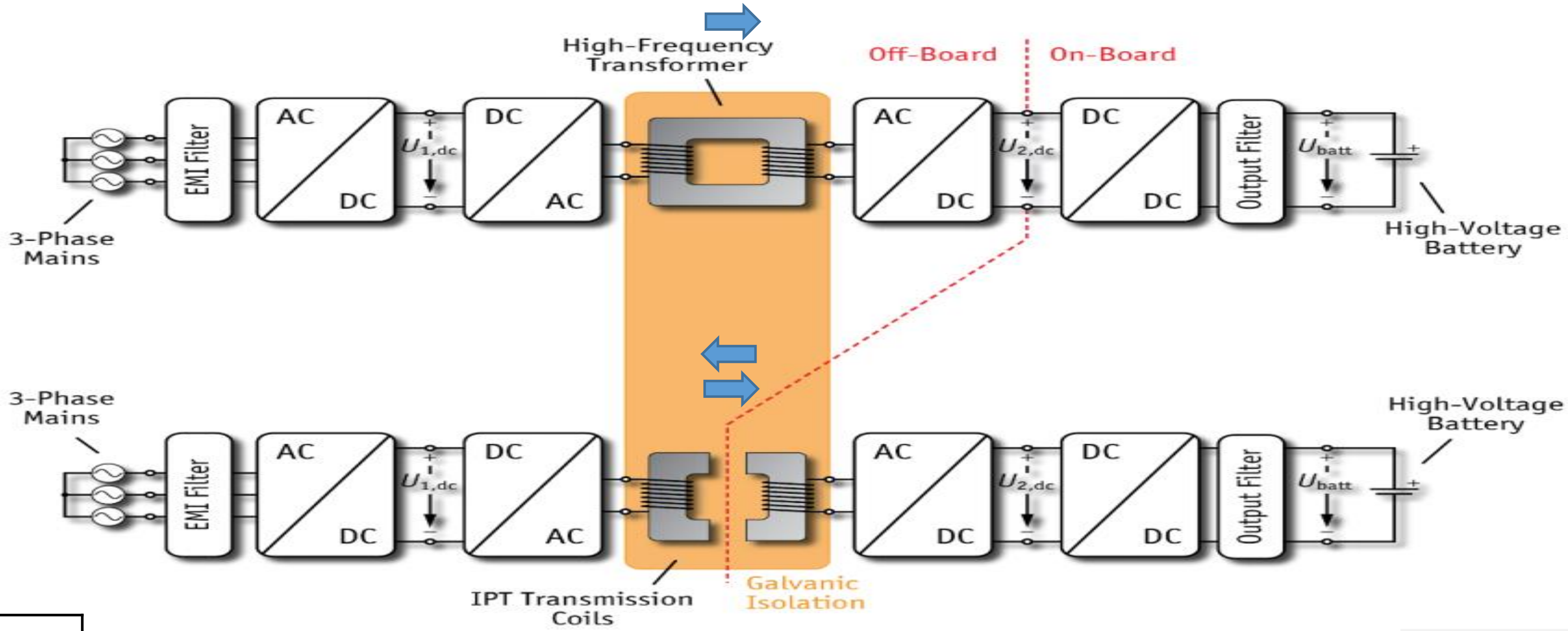


Bidirectional WPT system for V2G application

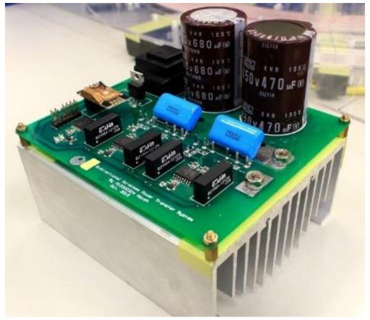
- **Conductive EV Charging**

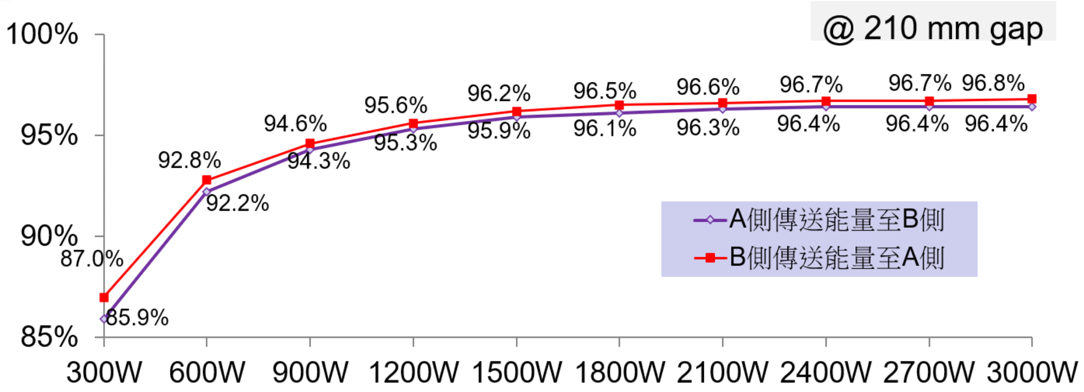
- **Wireless EV Charging**



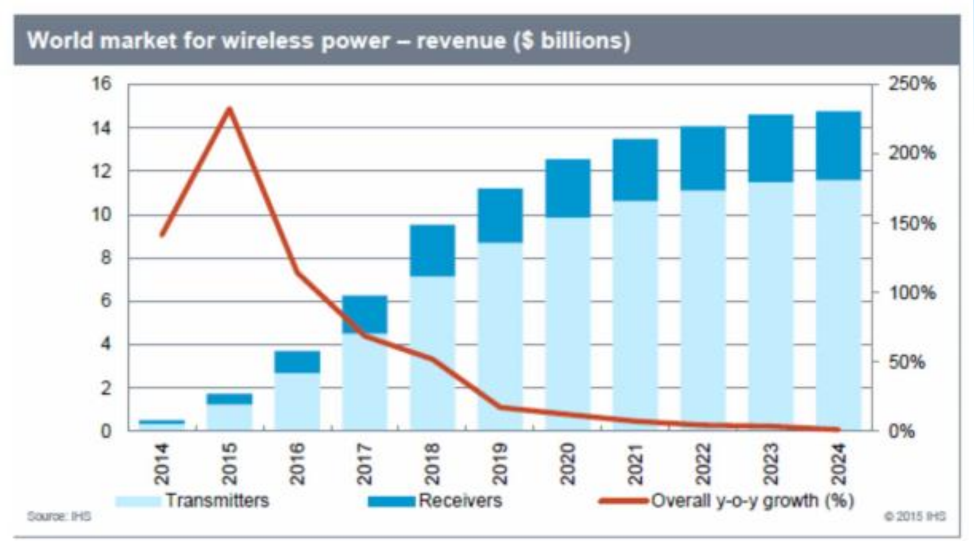


Parameters	Value
Output Power (P_o)	3kW
Input Voltage (V_{in})	400V
Output Voltage (V_{out})	400V
Coupling Coefficient Renge (k)	0.15~0.2
Switching Frequency Range (f_{sw})	81-89kHz





Market

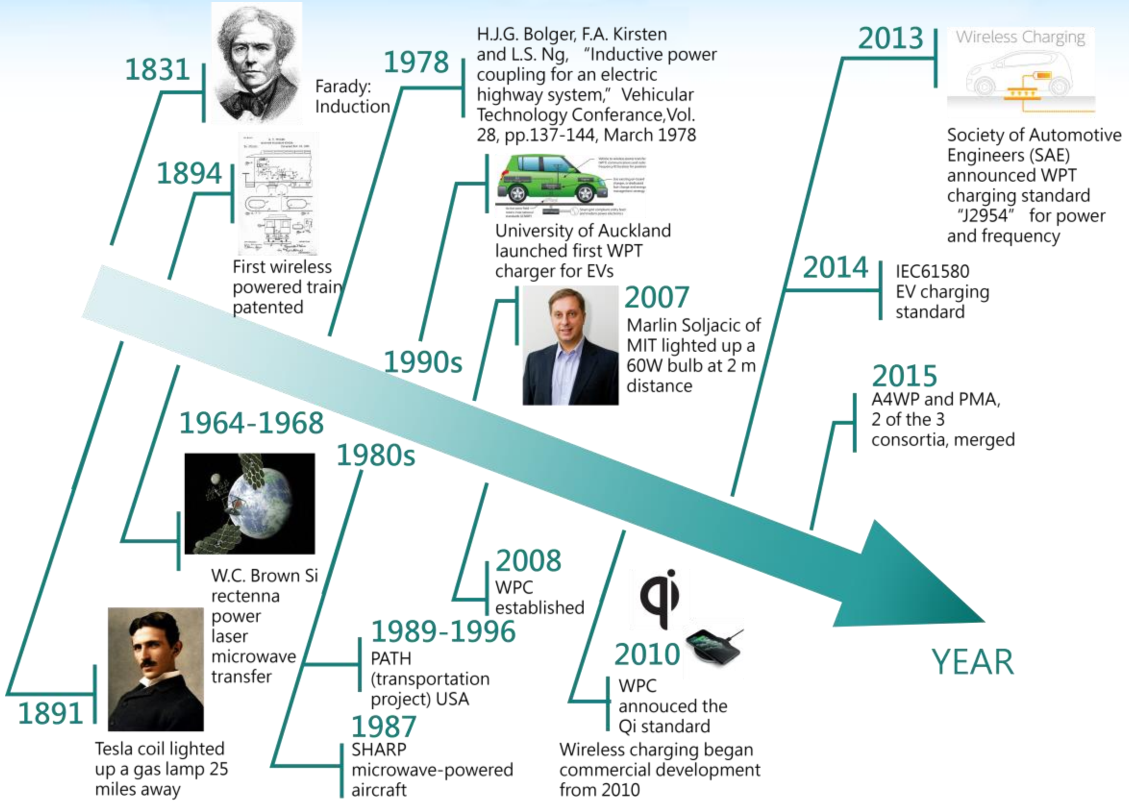


World market for wireless power

While a majority of the receivers are currently mobile phones, the market for other products, such as wearable devices, is rapidly growing with a number around 20 million units in 2015.

Source: "Wireless charging - from industry push to consumer pull, an IHS white paper on the rise of wireless power", freely available at https://technology.ihs.com/550357.

Timeline



RECENT KEY CONTRIBUTORS

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Waseda Univ., Japan
Kyoto Univ., Japan
Sojo Univ., Japan
Nat. Yokohama Univ., Japan
Univ. Zaragoza, Spain
NTUST, Taiwan
NUAA, China
Southeast Univ., China
Harbin IT, China
SCUT, China
HUST, China
Tianjin UT, China
Zhejiang Univ., China

Surveyed by Qianhong Chen, NUAA, China

Highly Efficient Wireless Charger

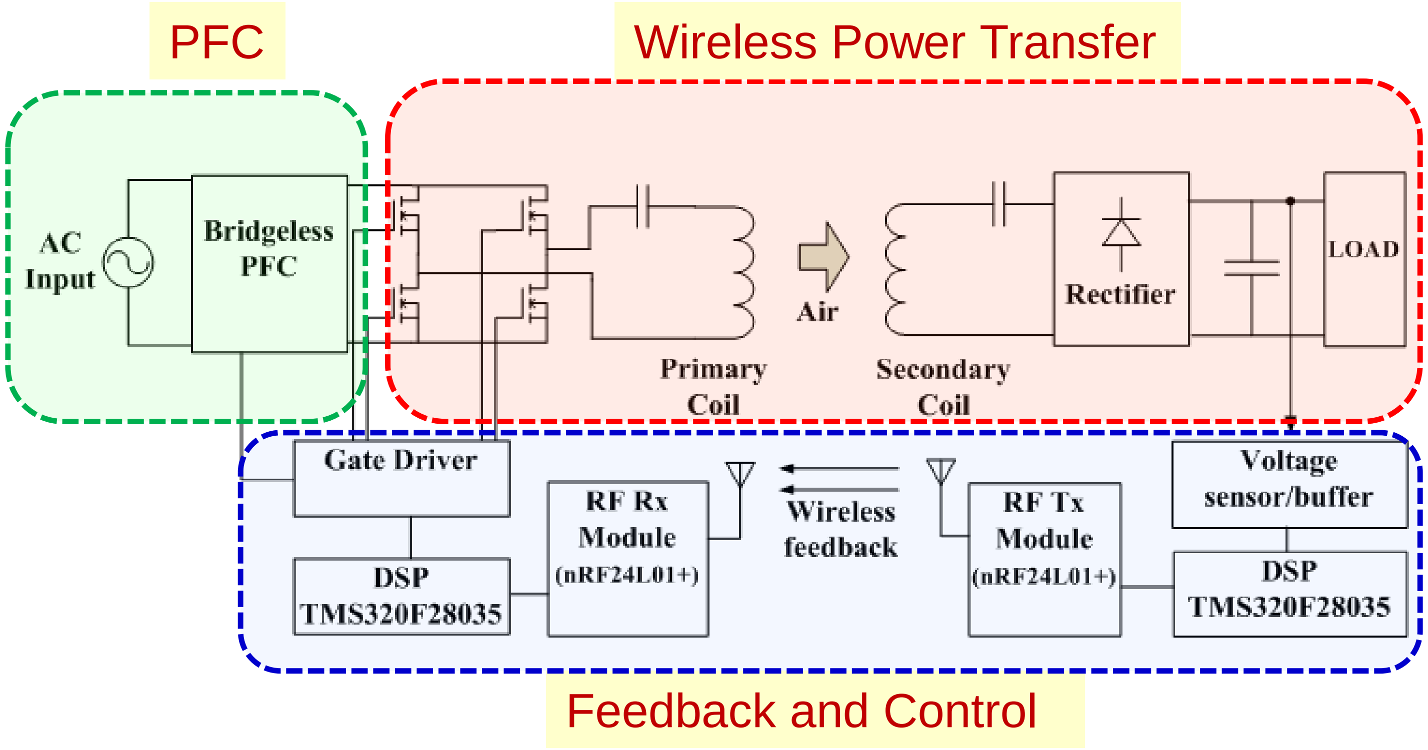
Grand Prize, IEEE IFEC 2015, Michigan

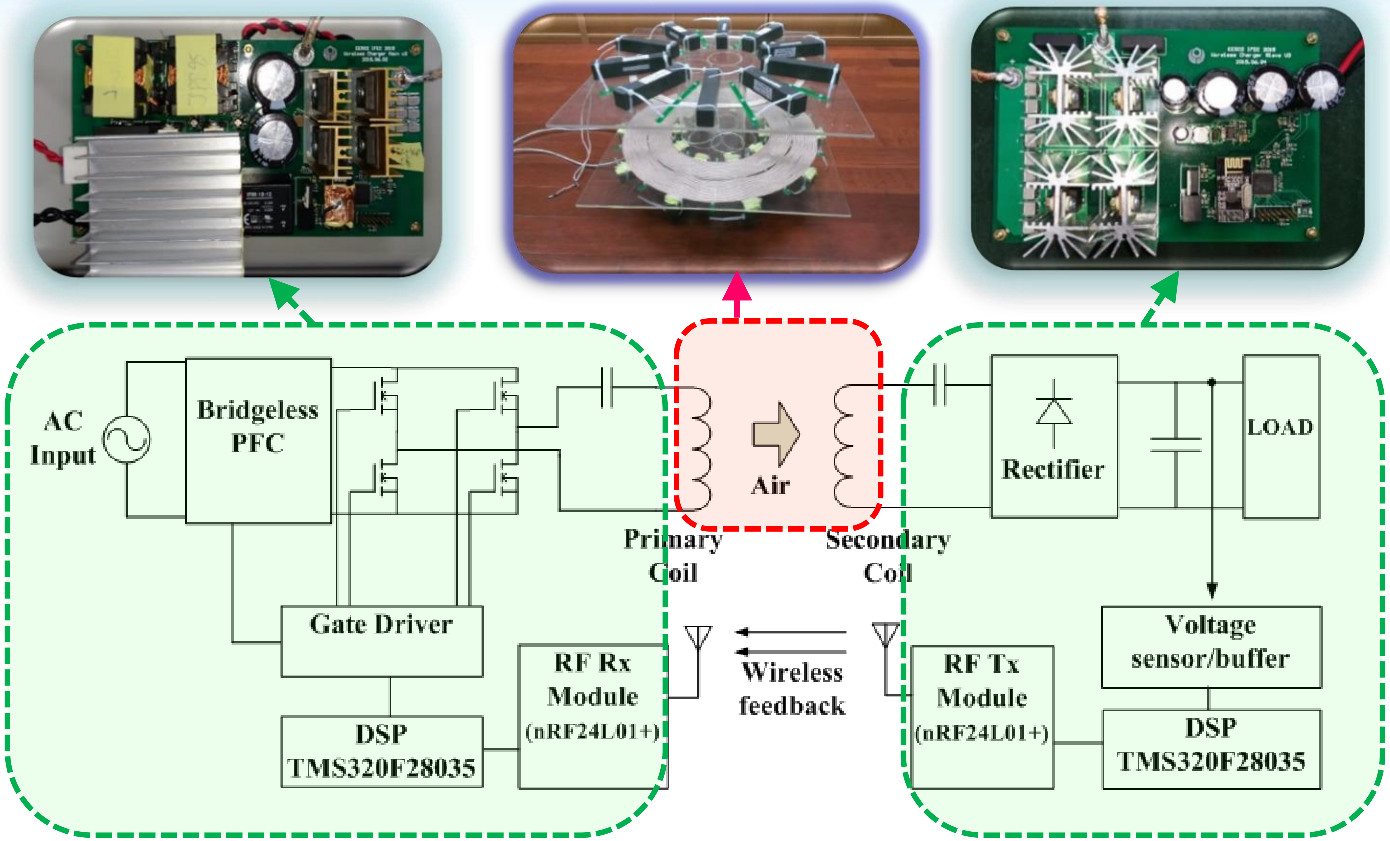
邱煌仁
台科大電子系特聘教授兼研發長

Specifications

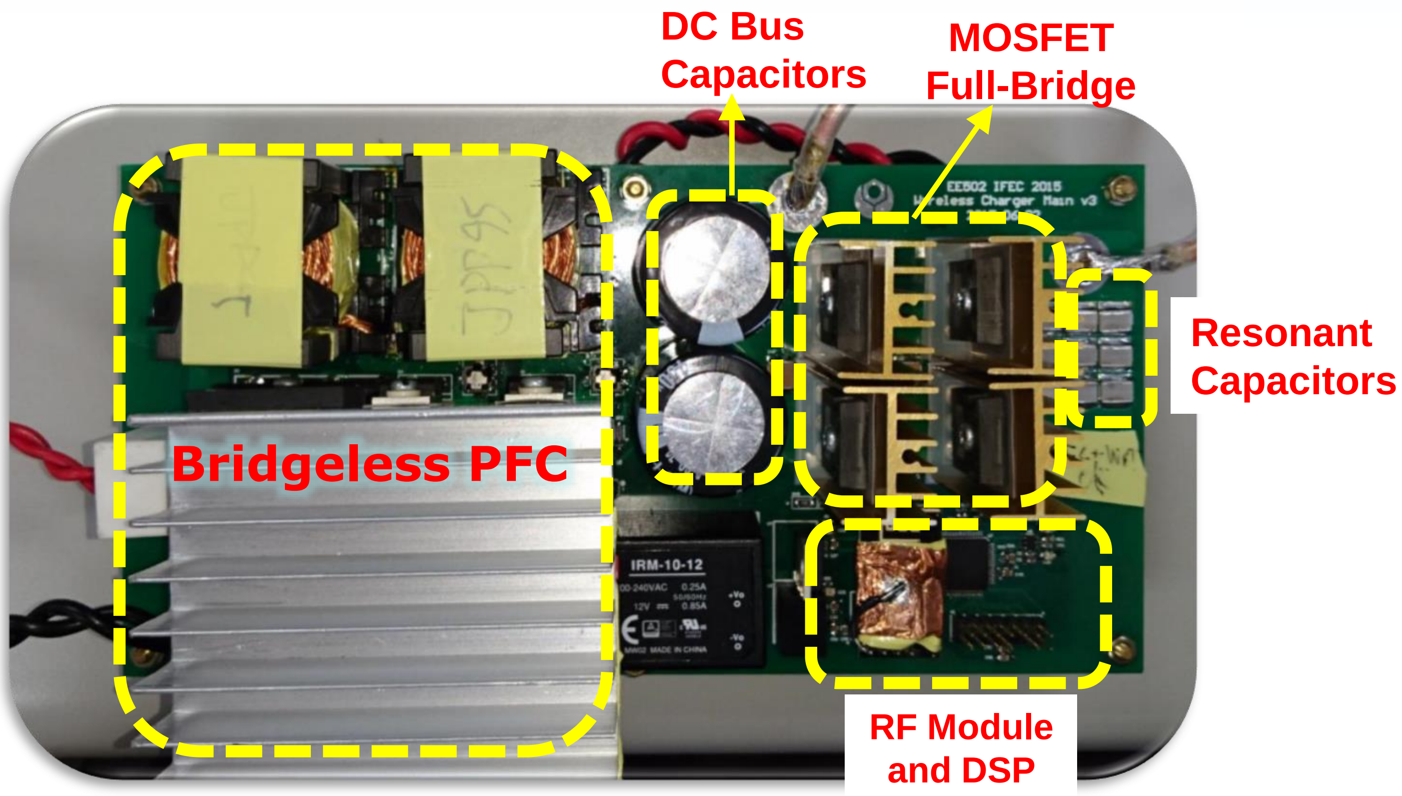
Input voltage	**85~240 V AC 50/60 Hz (Universal input)**
Output voltage	**48 V nominal (30 V~60 V)**
Air gap	**15 cm**
Output power	**500 W @ 15 cm gap, no misalignment 400 W @ 15 cm gap, 10 cm misalignment)**
Size and weight	**Less than 1 liter and 1kg**
THD and PF	**THD < 5% @ 500 W; PF > 0.95**
Protection	**OVP, OCP, UVP, Soft-start**

Design Overview

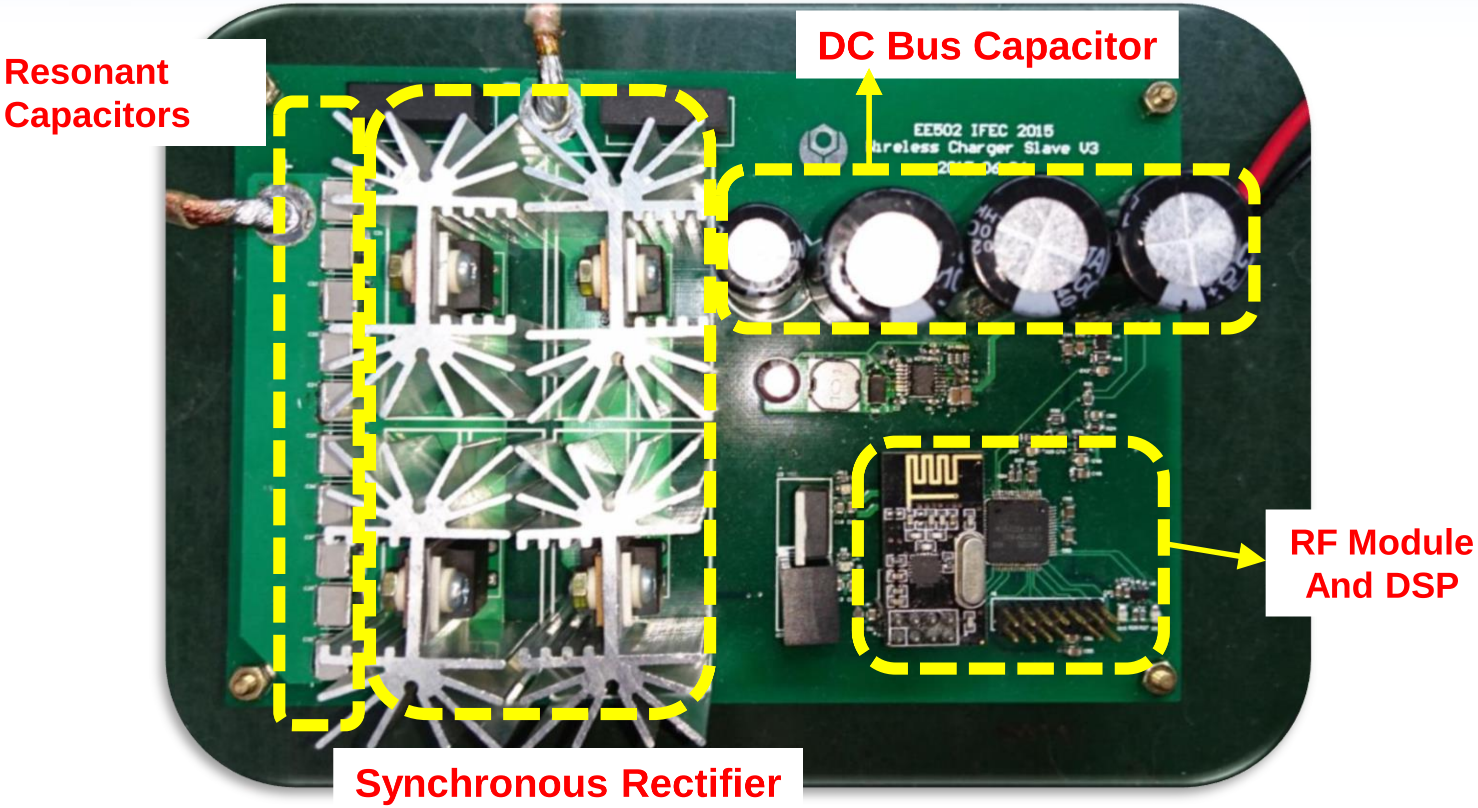



AC Input
Bridgeless PFC
Gate Driver
DSP TMS320F28035
RF Rx Module (nRF24L01+)
Air
Primary Coil
Secondary Coil
Wireless feedback
Rectifier
LOAD
Voltage sensor/buffer
RF Tx Module (nRF24L01+)
DSP TMS320F28035

Primary Side PCB

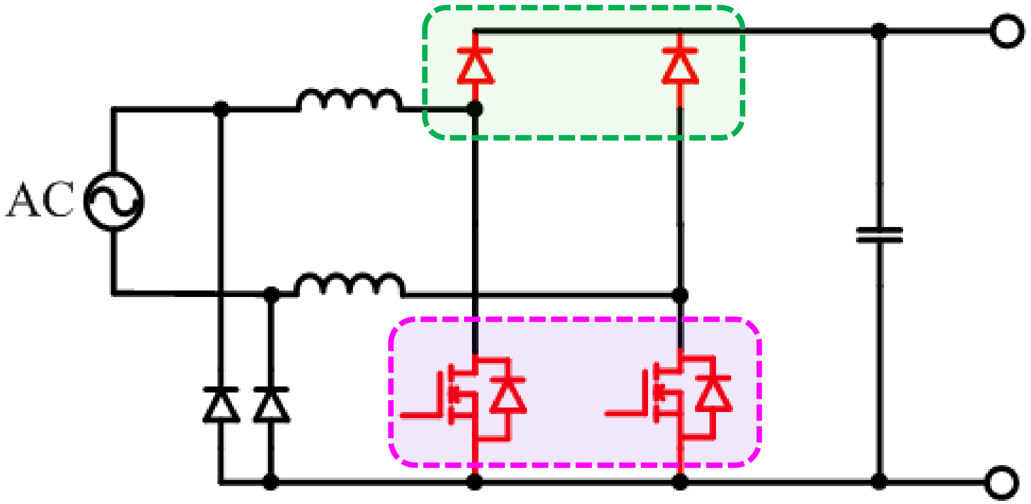


Secondary side PCB



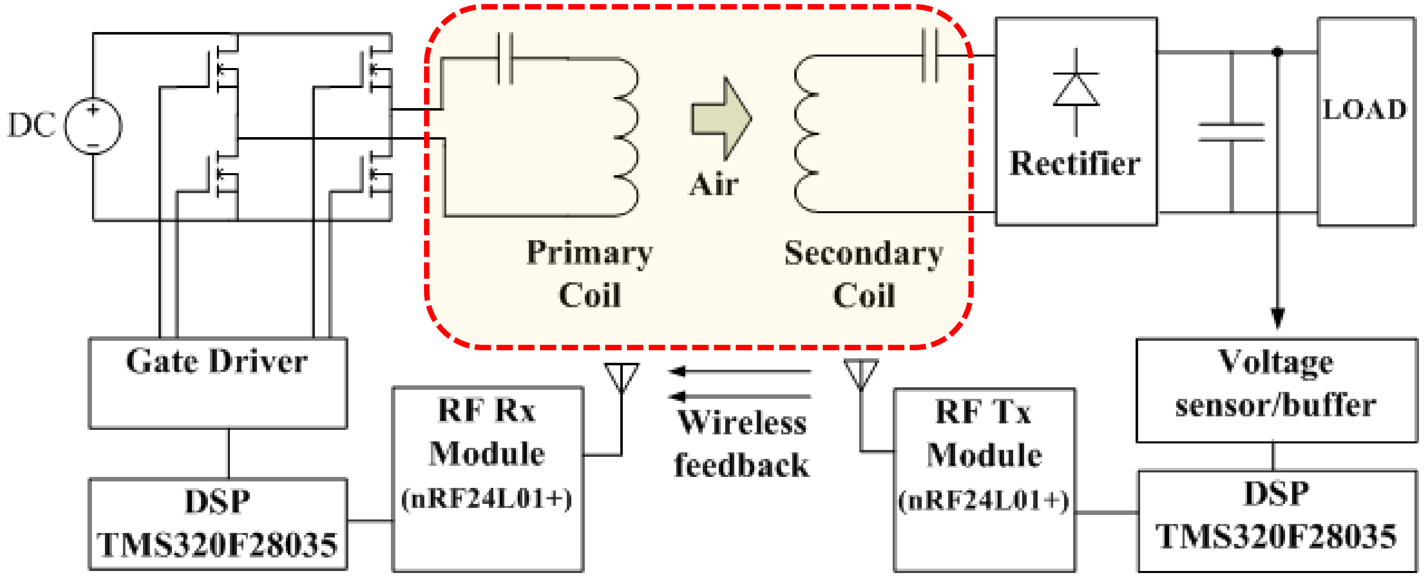
Bridgeless PFC

- Lower loss than conventional boost PFC
- GaNFET and SiC Schottky diode is used to further improve efficiency

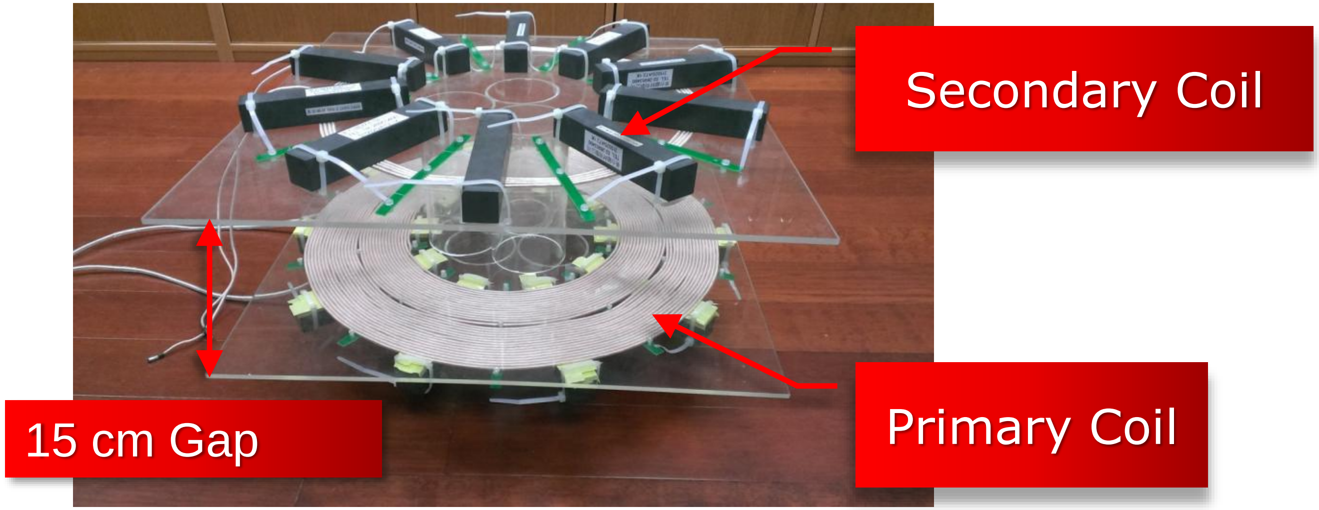


Wireless Power Transfer (WPT)

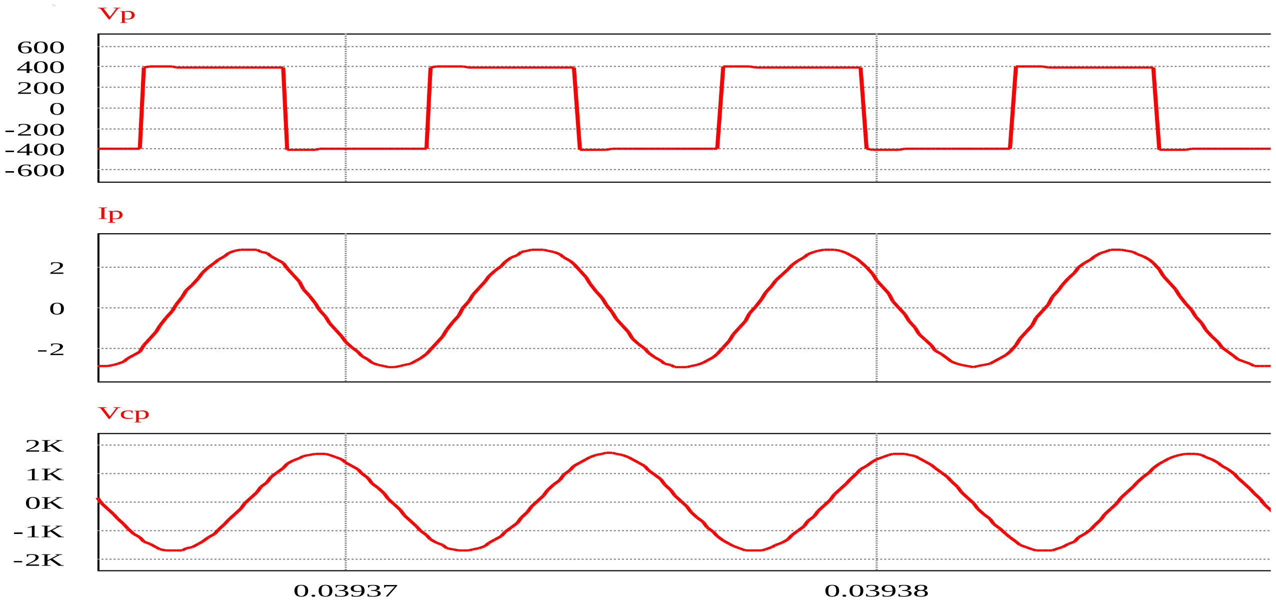
- Series-Series topology



Charging Pad/ Coil Design

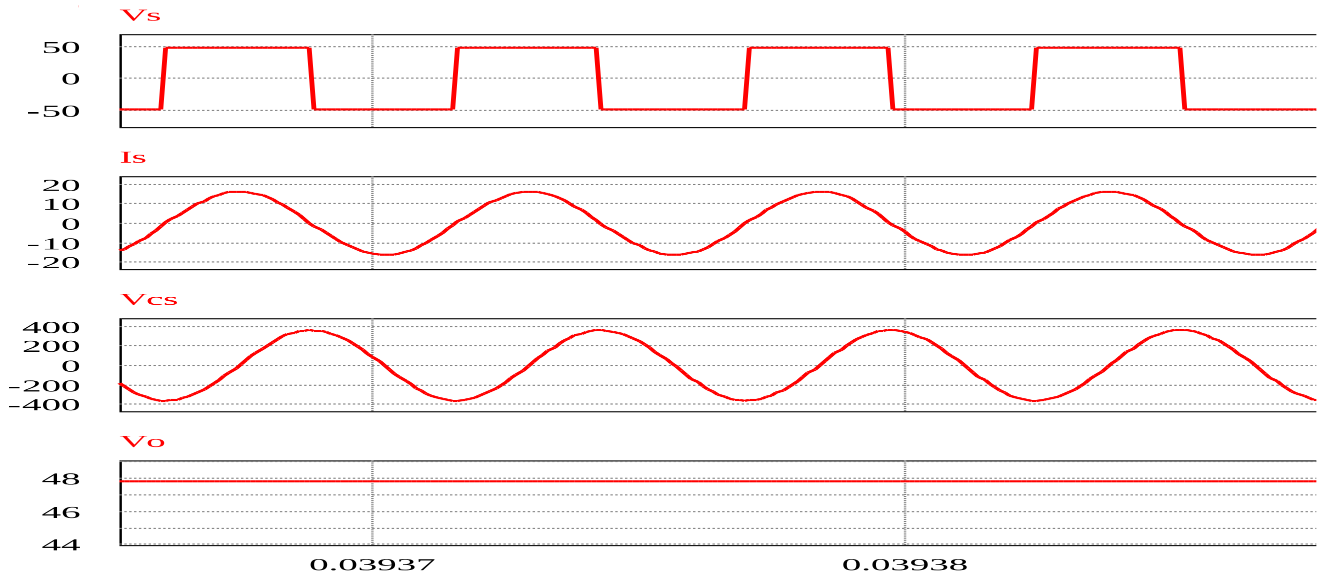


Circuit Simulation



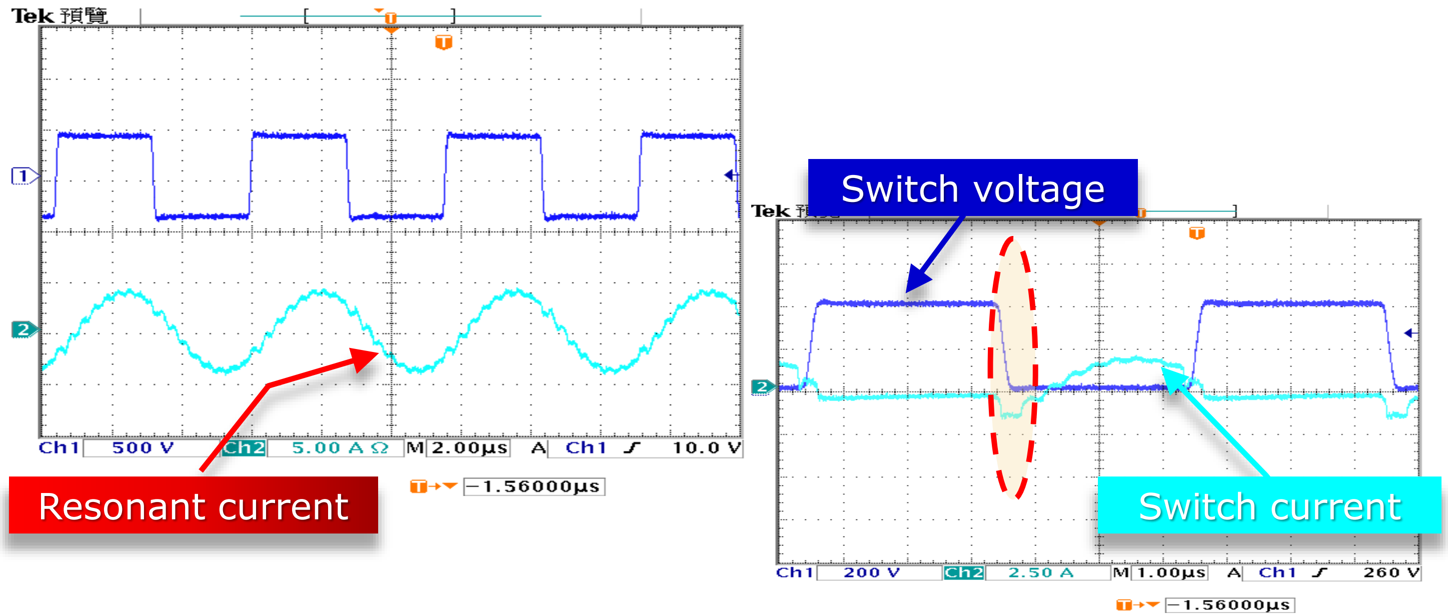
Simulated waveforms at 500 W load: primary voltage, primary current and primary resonant capacitor voltage

Circuit Simulation



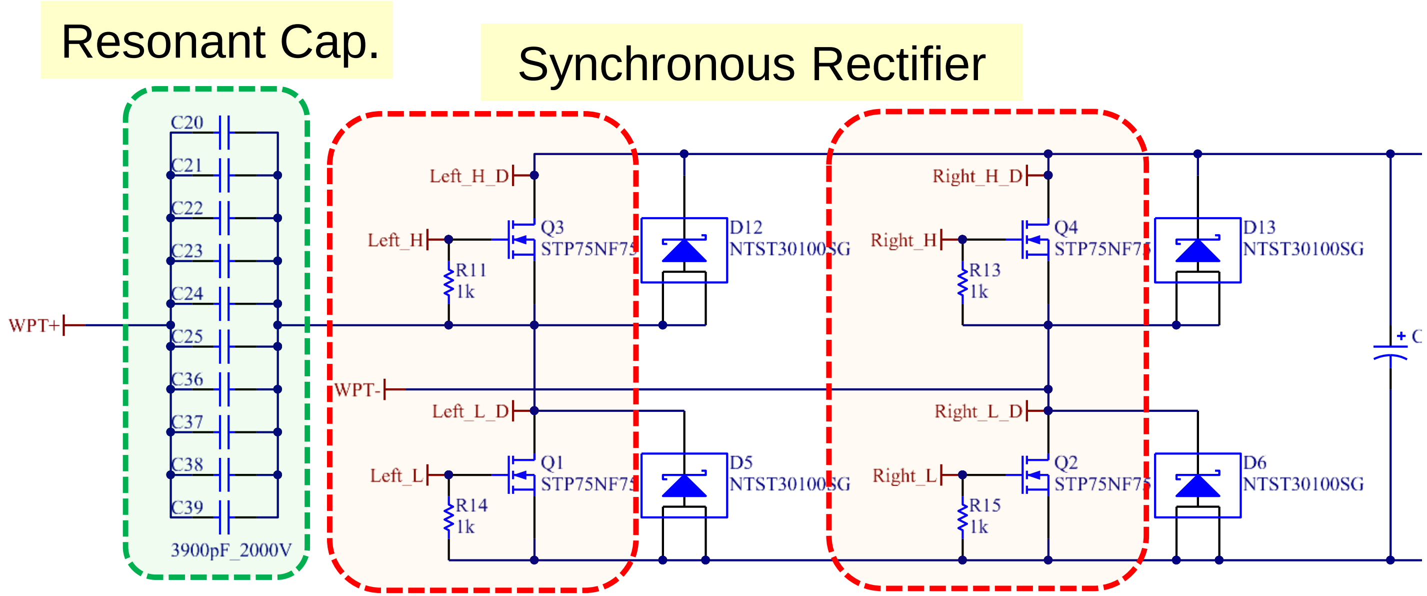
Simulated waveforms at 500 W load: secondary voltage before rectifier, secondary current, secondary resonant capacitor voltage and output voltage

Soft-switching Waveforms



Voltage and current across drain and source of primary side MOSFET.
Soft switching characteristic is verified

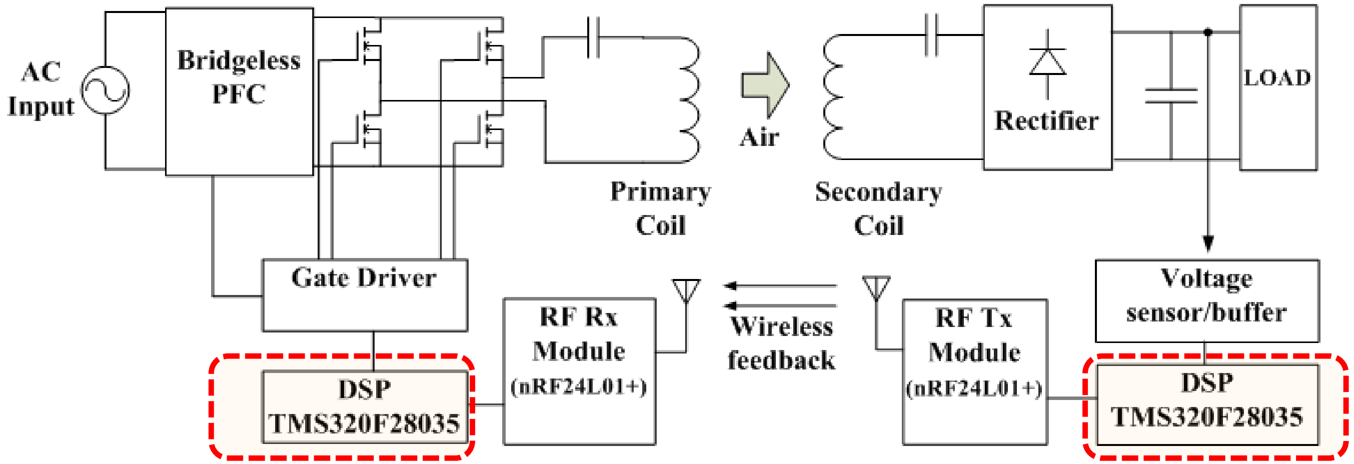
Secondary Side



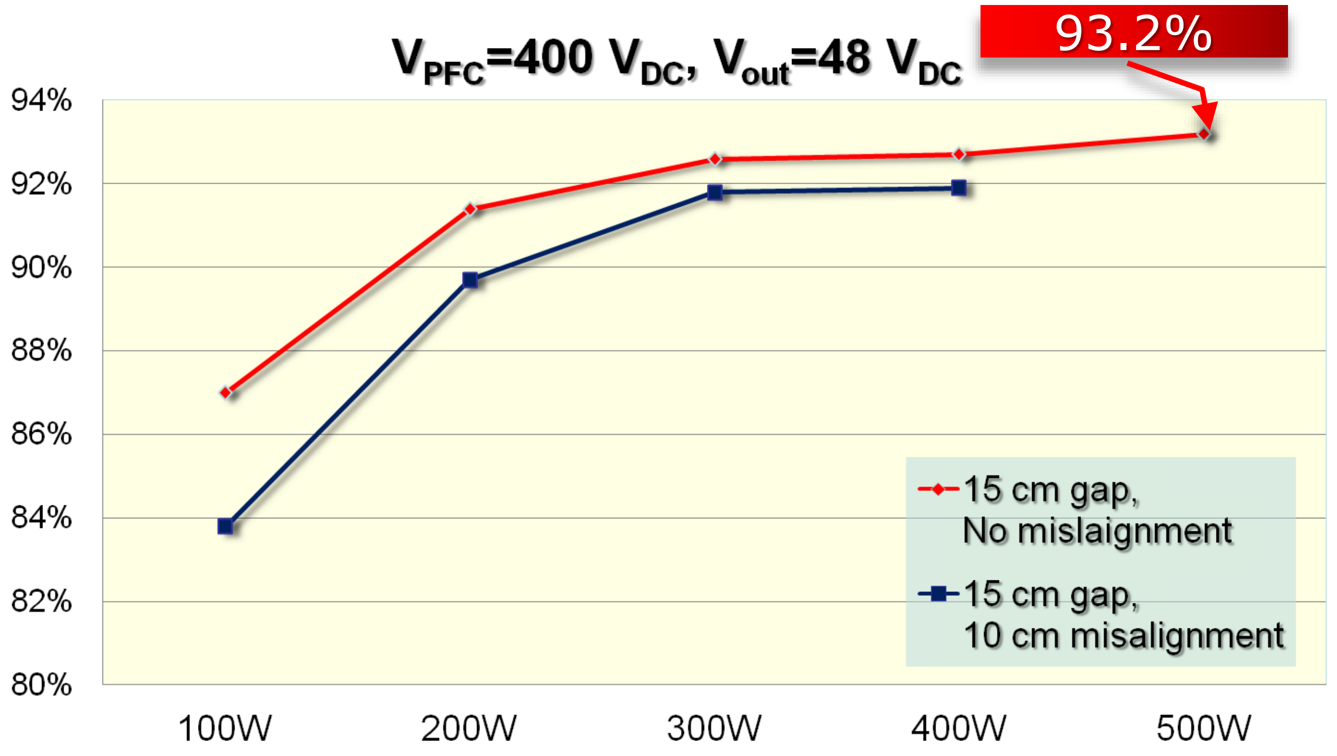
Diode Rectifier (92%)→ Semi-SR (92.7%)→ Full-SR (93.2%)

Feedback and Control

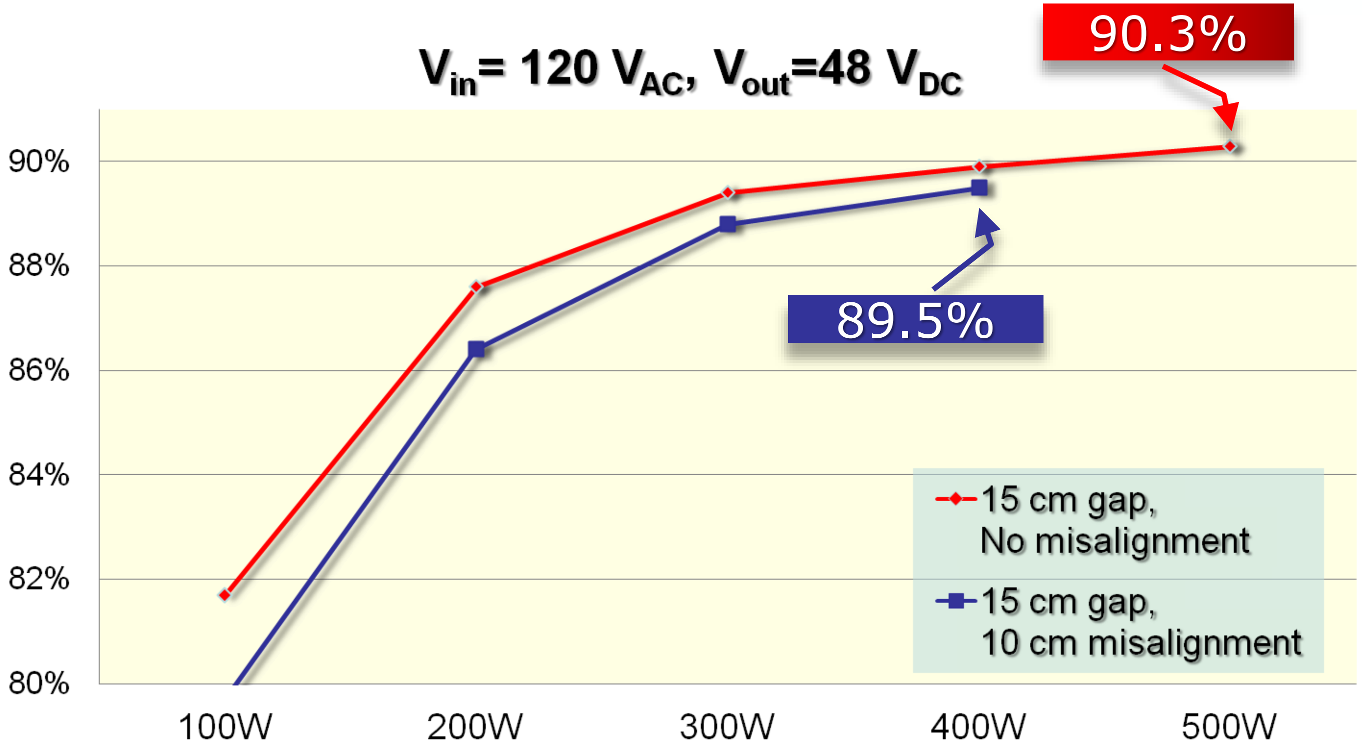
- Digital control with TI DSP TMS320F28035



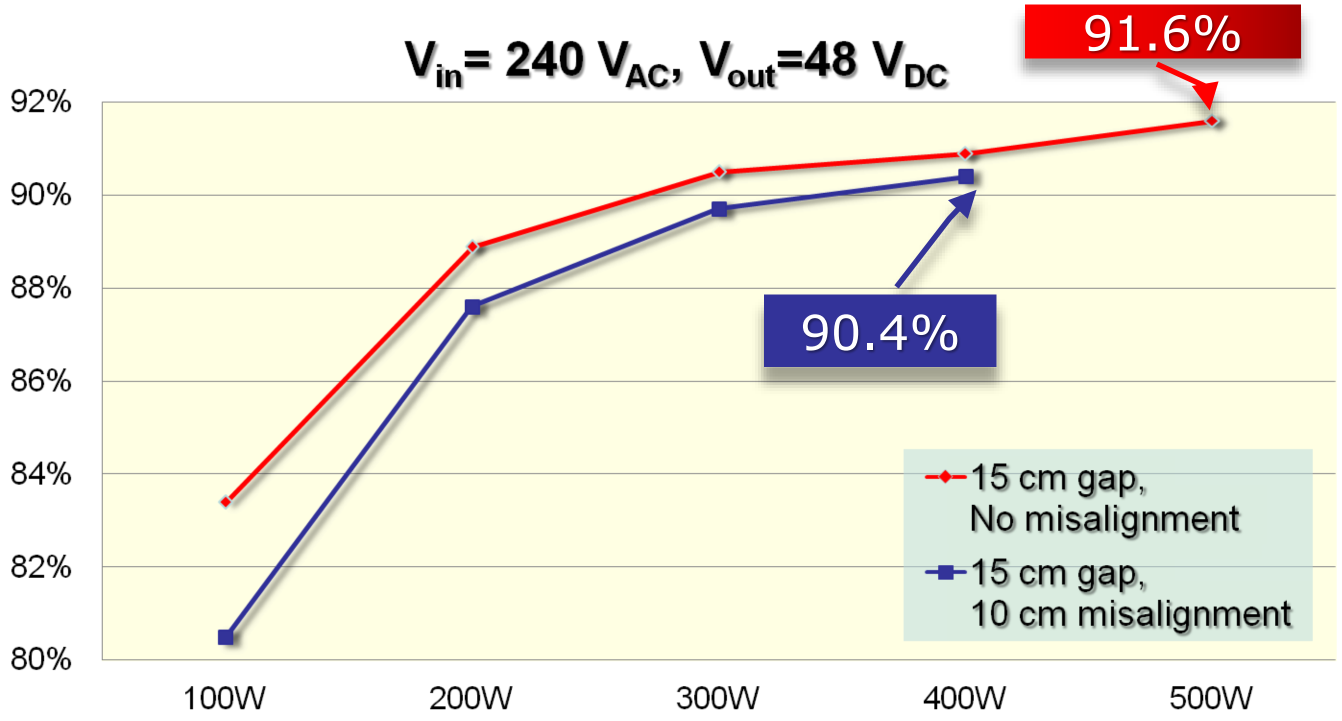
Measured Efficiency of Wireless Power Transfer (DC-DC)



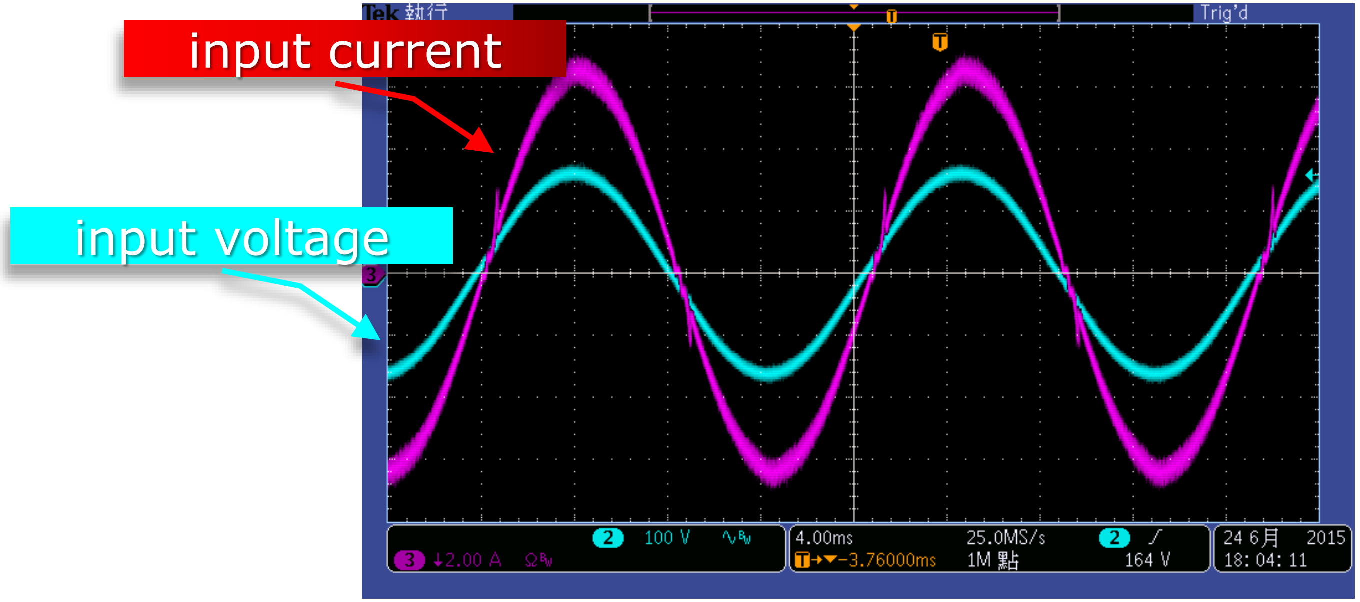
Overall Efficiency (PFC + WPT)



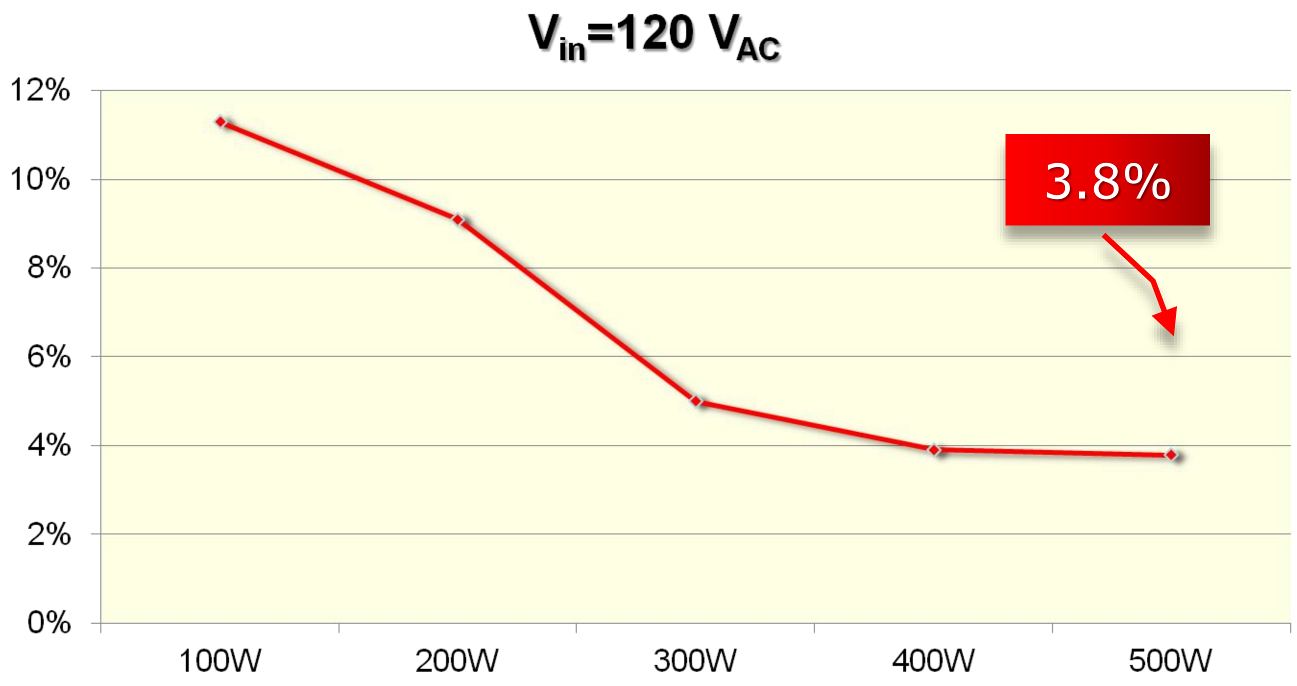
Overall Efficiency (PFC + WPT)



Measured Input Waveforms



Measured THD_i



Summary

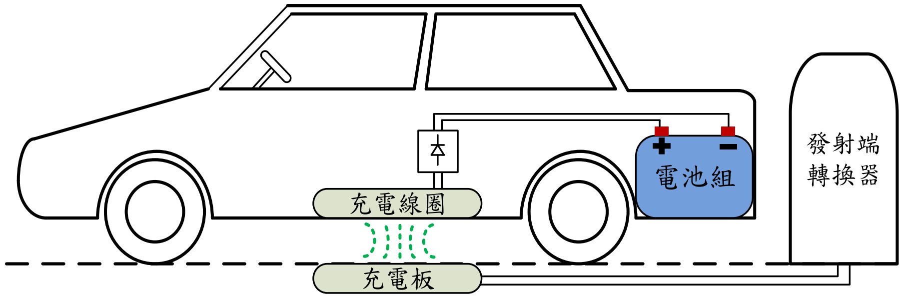
- **Efficiency:**
  - -- 93.2% @ 500W, no sliding (WPT)
  - -- 90.3% @ 500W, 120V AC input, no sliding (overall)
  - -- 89.5% @ 400W, 120V AC input, 10cm sliding (overall)
  - -- 91.6% @ 500W, 240V AC input, no sliding (overall)
  - -- 90.4% @ 400W, 240V AC input, 10cm sliding (overall)
- **THD_i:** 3.8%; **PF >** 0.99 @ 500W, 120V AC input
- **Output Voltage Range:** 30V~60V
- **CC/CV Charging Function**
- **Protections:** Brownout, OVP, OCP, soft-start, inrush current
- **Volume:** 1,228 cm^3; **Weight:** 960g < 1 kg
- **BOM Cost: USD** 98.8

Bidirectional WPT System

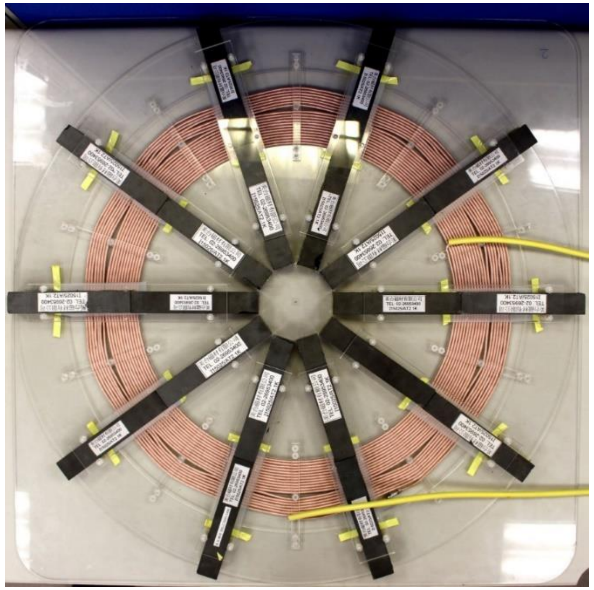
邱煌仁
台科大電子系特聘教授兼研發長

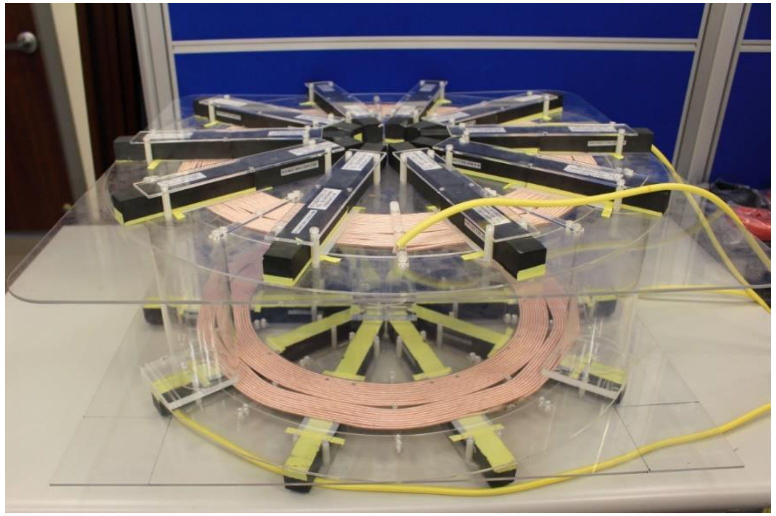
Bidirectional WPT System

- WPT technology has received much attention recently because of its convenience and safety feature and has been used to charge electric vehicle wirelessly.
- Most current WPT systems only allow unidirectional power transfer (grid to vehicle), therefore unsuitable for V2G application.

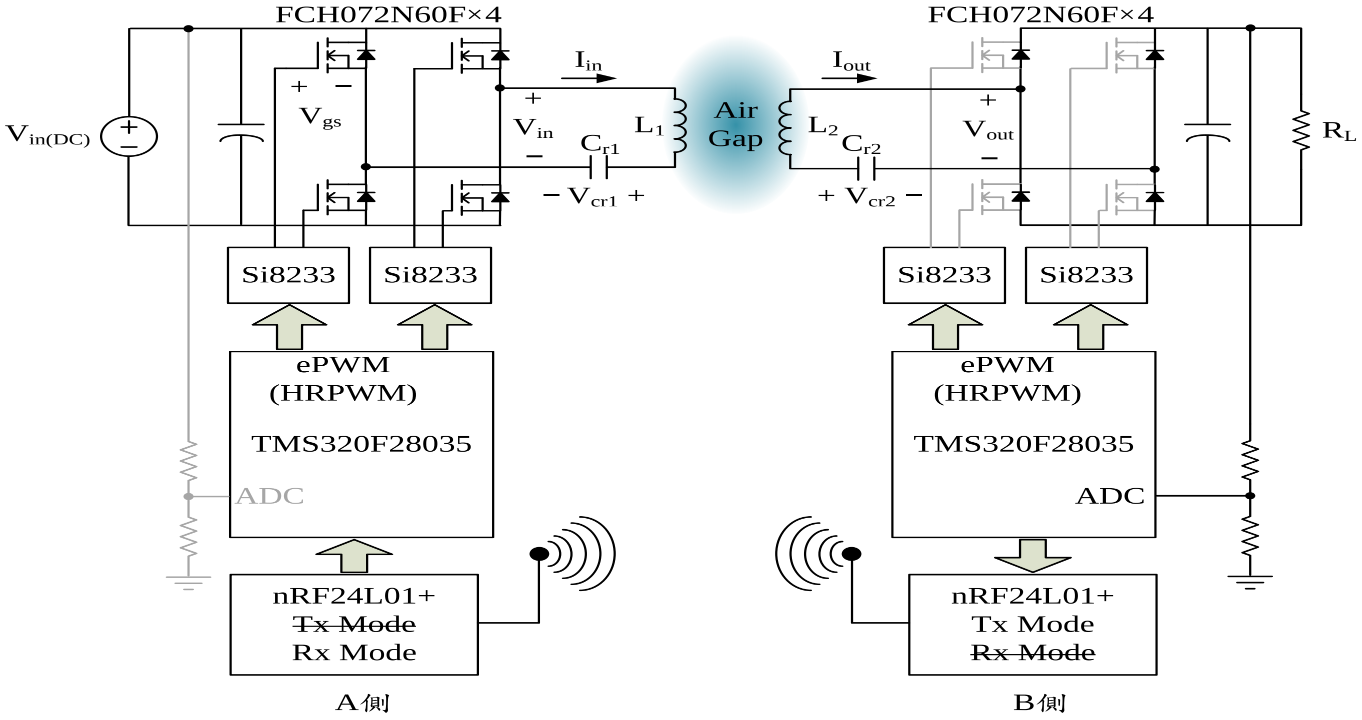


Prototype of Coils



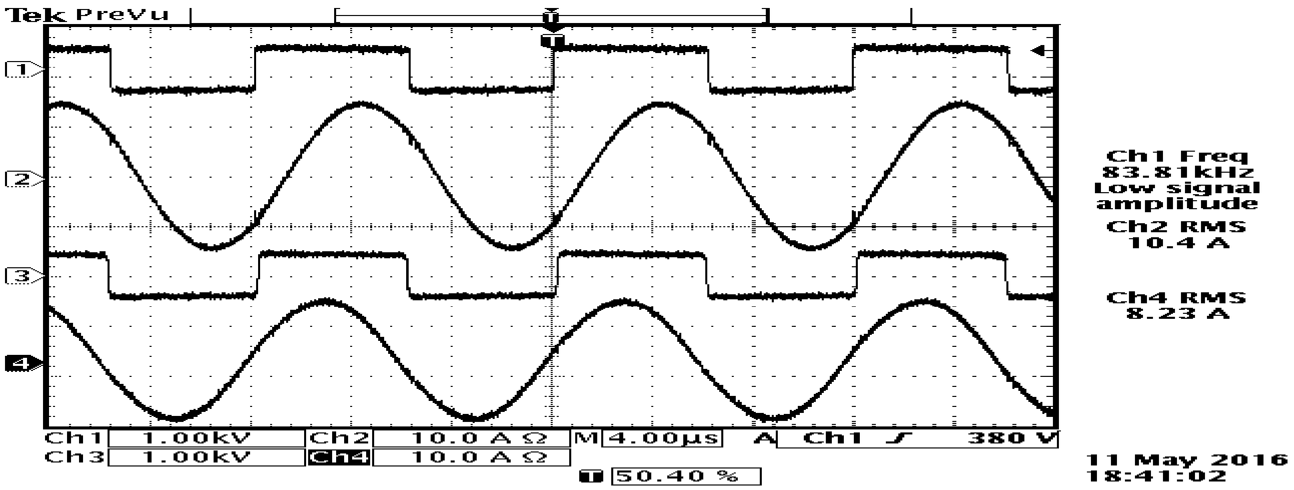


Laboratory Prototype



Measured Coil Currents

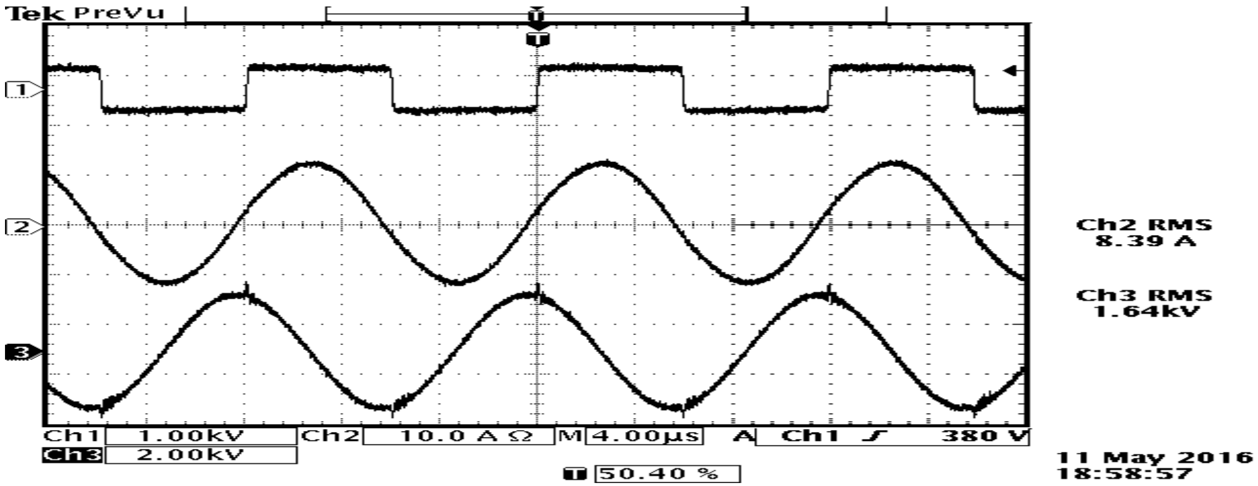
Ch1: v_{pri}、Ch2: i_{pri}、Ch3: v_{sec}、Ch4: i_{sec}



@ 3 kW/ 210 mm gap

Measured Primary Waveforms

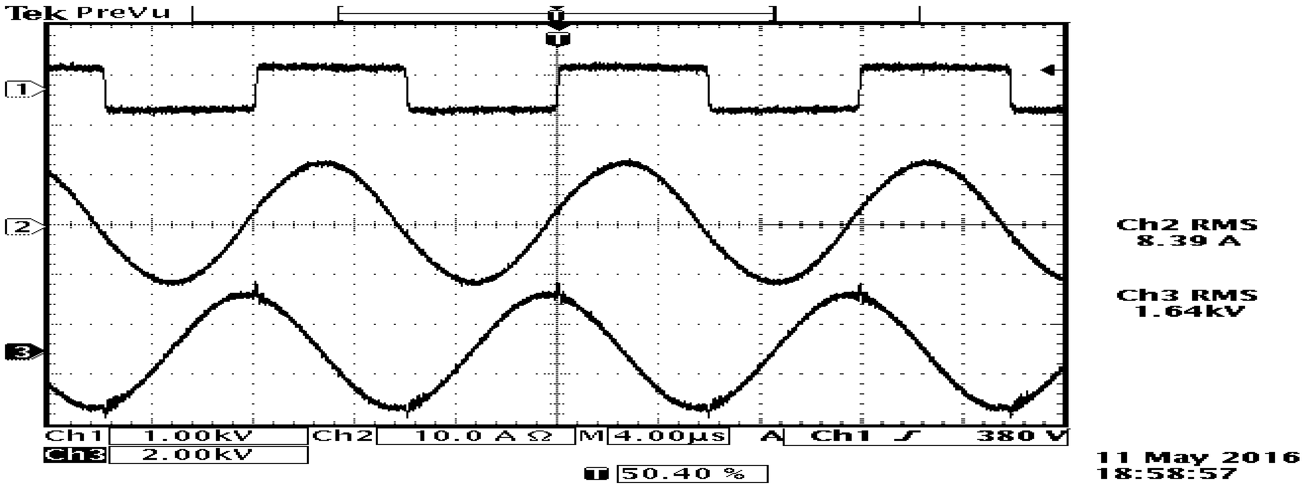
Ch1: v_{pri}、Ch2: i_{pri}、Ch3: v_{cr1}



@ 3 kW/ 210 mm gap

Measured Secondary Waveforms

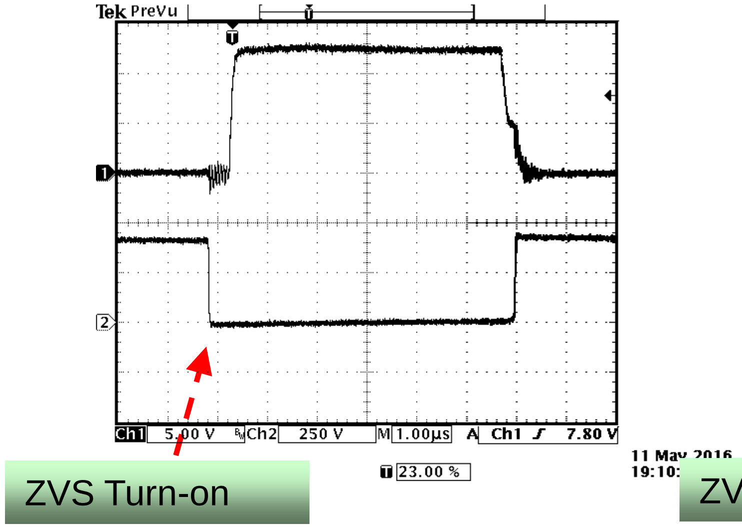
Ch1: v_{sec}、Ch2: i_{sec}、Ch3: v_{cr2}



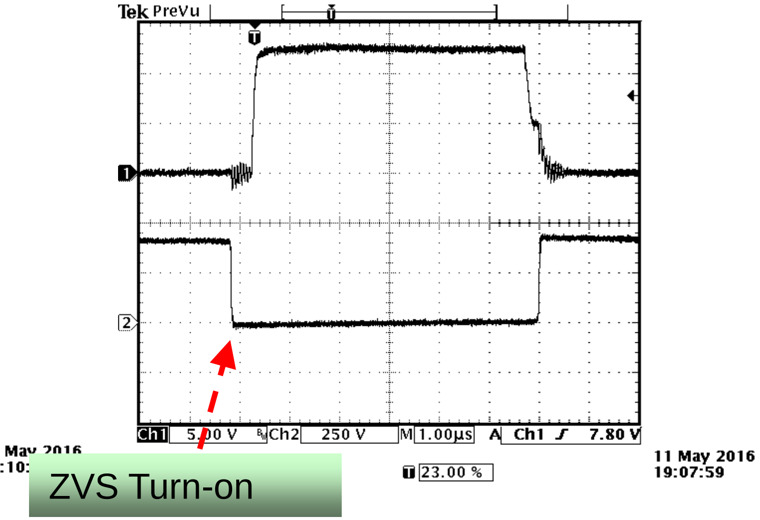
@ 3 kW/ 210 mm gap

Measured Switching Waveforms

Ch1: v_{gs} 、Ch2: v_{ds}

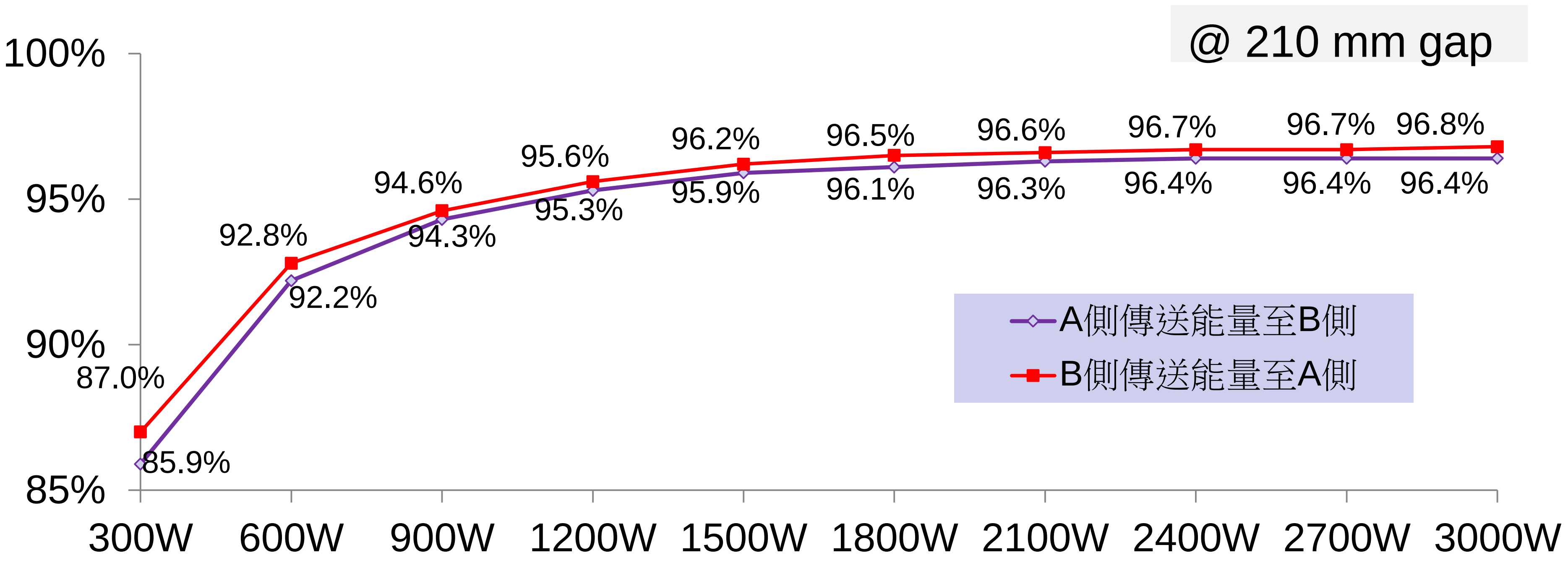


@ 300 W/ 210 mm gap

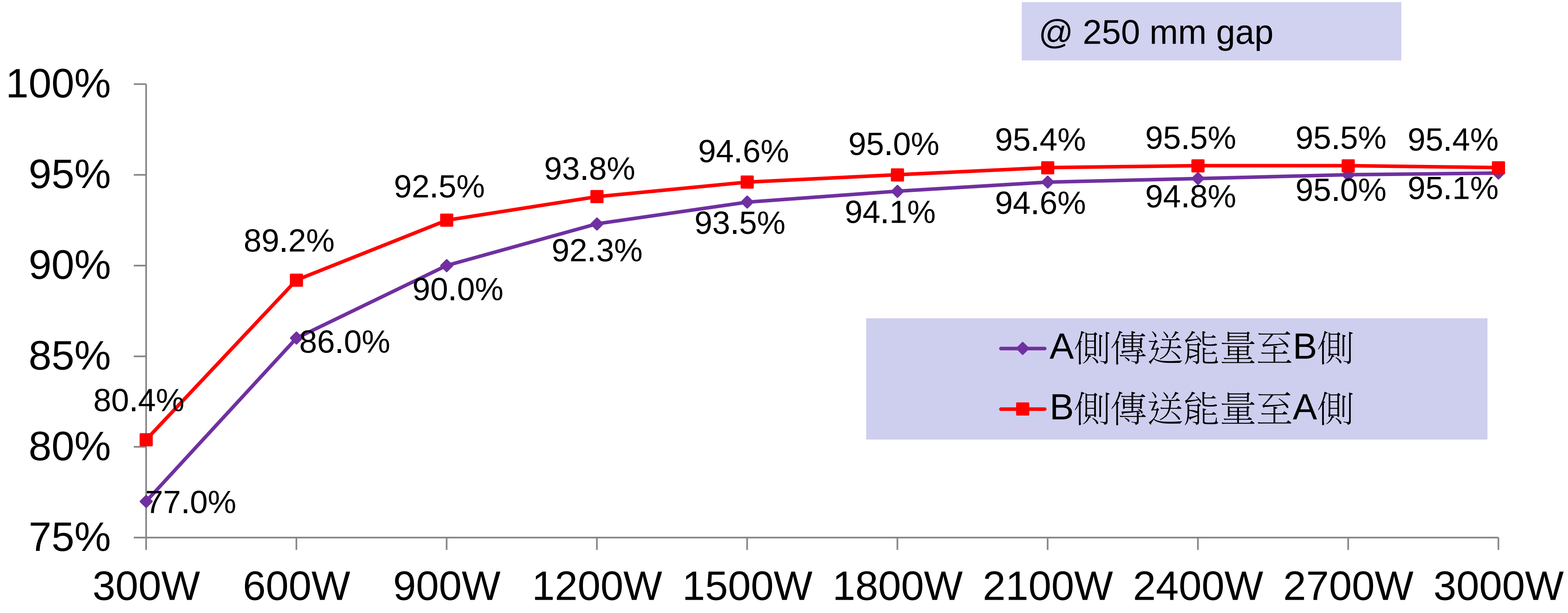


@ 3 kW/ 210 mm gap

Measured Efficiency



Measured Efficiency



Technical Trend for Each EV Classes

800V Class

・Inverter Cost
＝ 800 USD

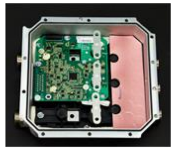
- SiC（1200V Rating Device）
- High Voltage Material Applications
- Custom Design
- Low Noise Technologies
- e-Axle

400V Class

・Inverter Cost
＝ 500 USD

- SiC（650V Rating Device）
- High Temperature Material Applications
- General-purpose Design
- Low Loss Technologies
- In-wheel Motor

200V Class



・Inverter Cost
＝ 200 USD

- Si（under 200V Rating Device）
- High Temperature Material Applications
- General-purpose Design
- Air Cooling System
- Super Low Cost

Masayoshi YAMAMOTO
@Nagoya University

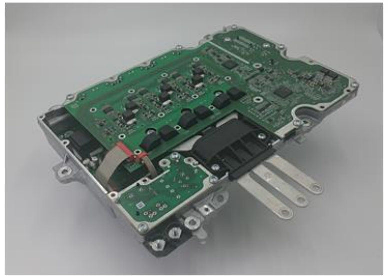
Evolution of EV Inverter

Si IGBT

I-Pace (Jaguar)

ID.4 (VW)

ID.3 (VW)



iX3 (BMW)

Capacitor Air Cooling

EC6 (NIO)

High Performance Inverter

SiC MOS-FET

Model 3 (TESLA)

IONIQ5 (Hyundai)

Super Thin
Double-side Cooling
150°C Capacitor
Oil Cooling
Low dv/dt
Multi-level Inverter

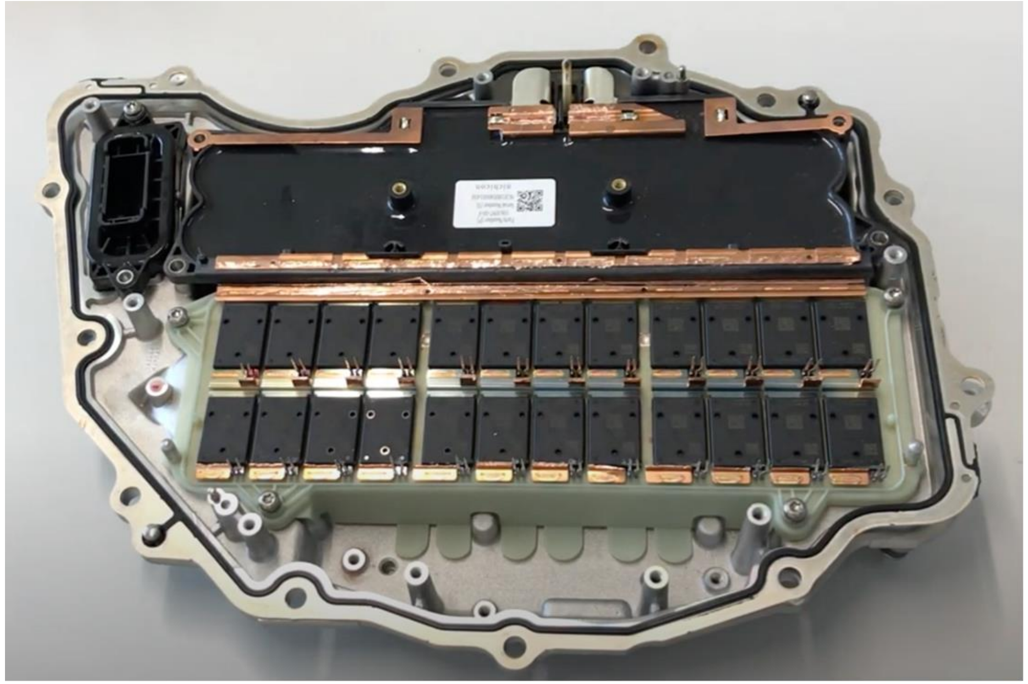
Masayoshi YAMAMOTO
@Nagoya University

SiC Power Device Application on Tesla EVs

Model S：June, 2012～

SiC
（Main Inverter, Onboard Charger）

Model 3：July, 2017～

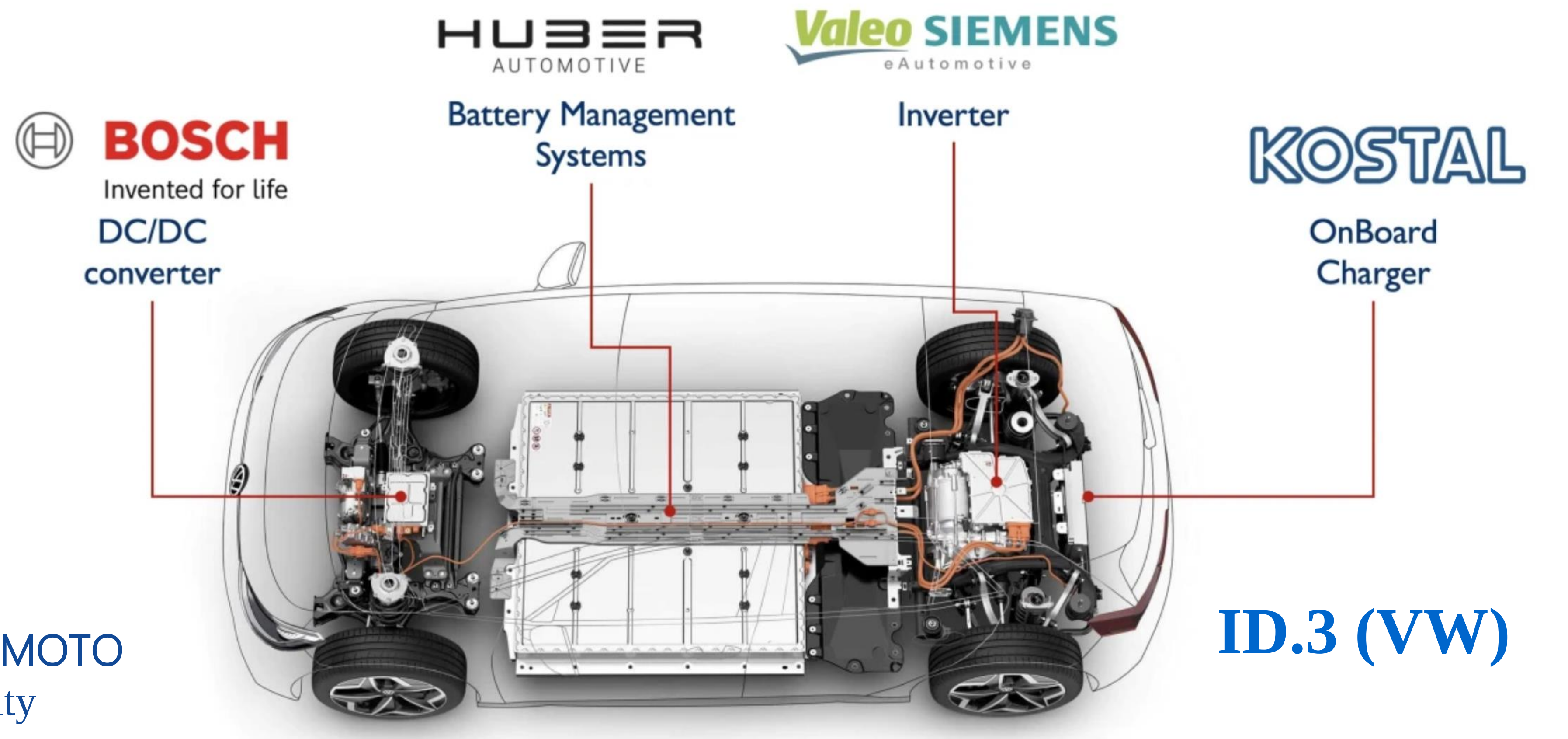


World First Model of SiC Power Device Application

Achieved Miniaturized Performance!

Masayoshi YAMAMOTO
@Nagoya University

Technical Trend of Power Electronics Systems for Automotive Applications

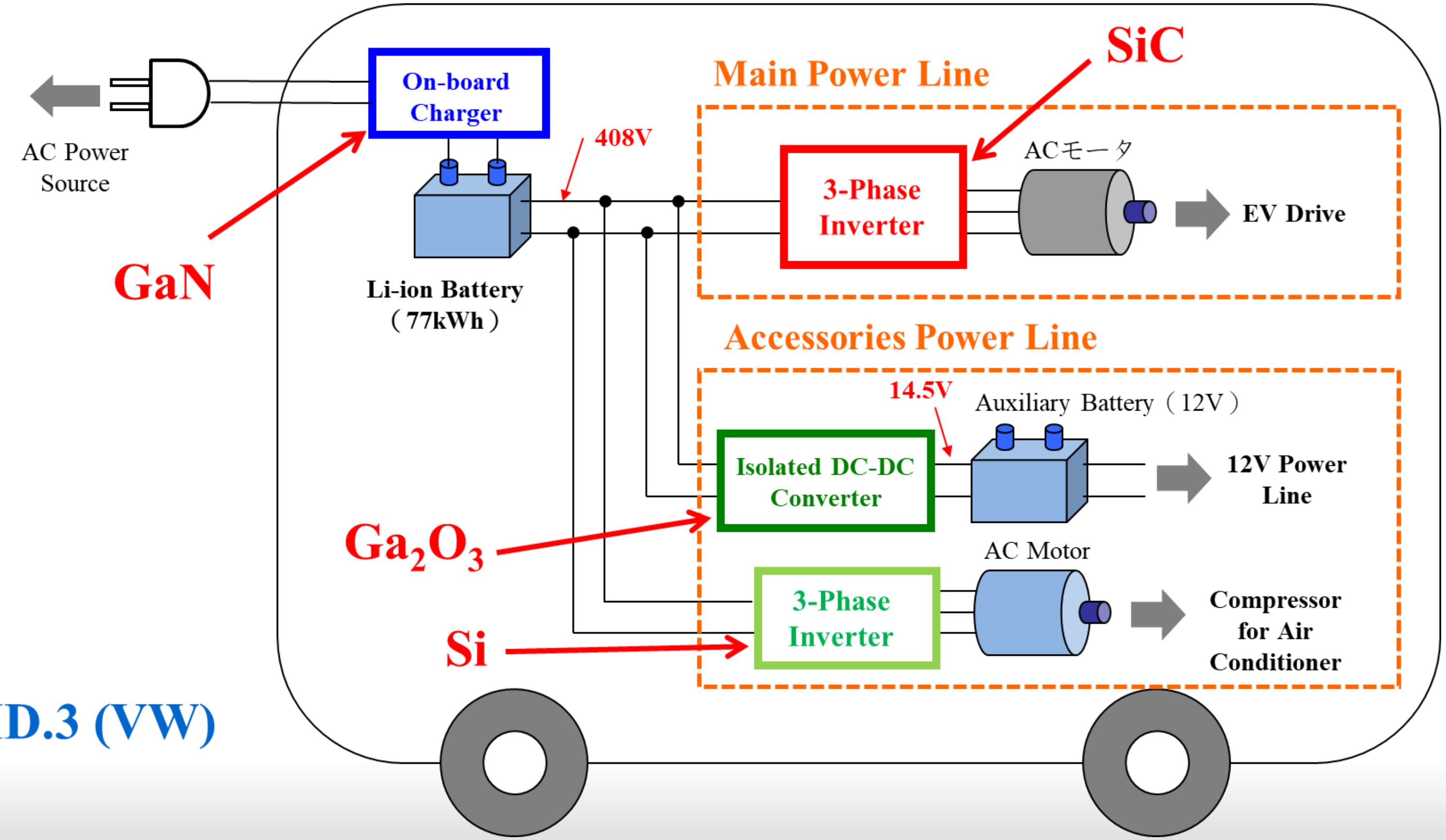


ID.3 (VW)

Masayoshi YAMAMOTO
@Nagoya University

Ref：System Plus Consulting

Technical Trend of Power Electronics Systems for Automotive Applications



ID.3 (VW)

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@Nagoya University

All GaN Vehicle from Nagoya University

All Gan Vehicle
（Main Inverter、DC-DC Converter、OBC、Head Light）

Masayoshi YAMAMOTO
@Nagoya University

Multi-Phase Bi-directional Converter for MHEV

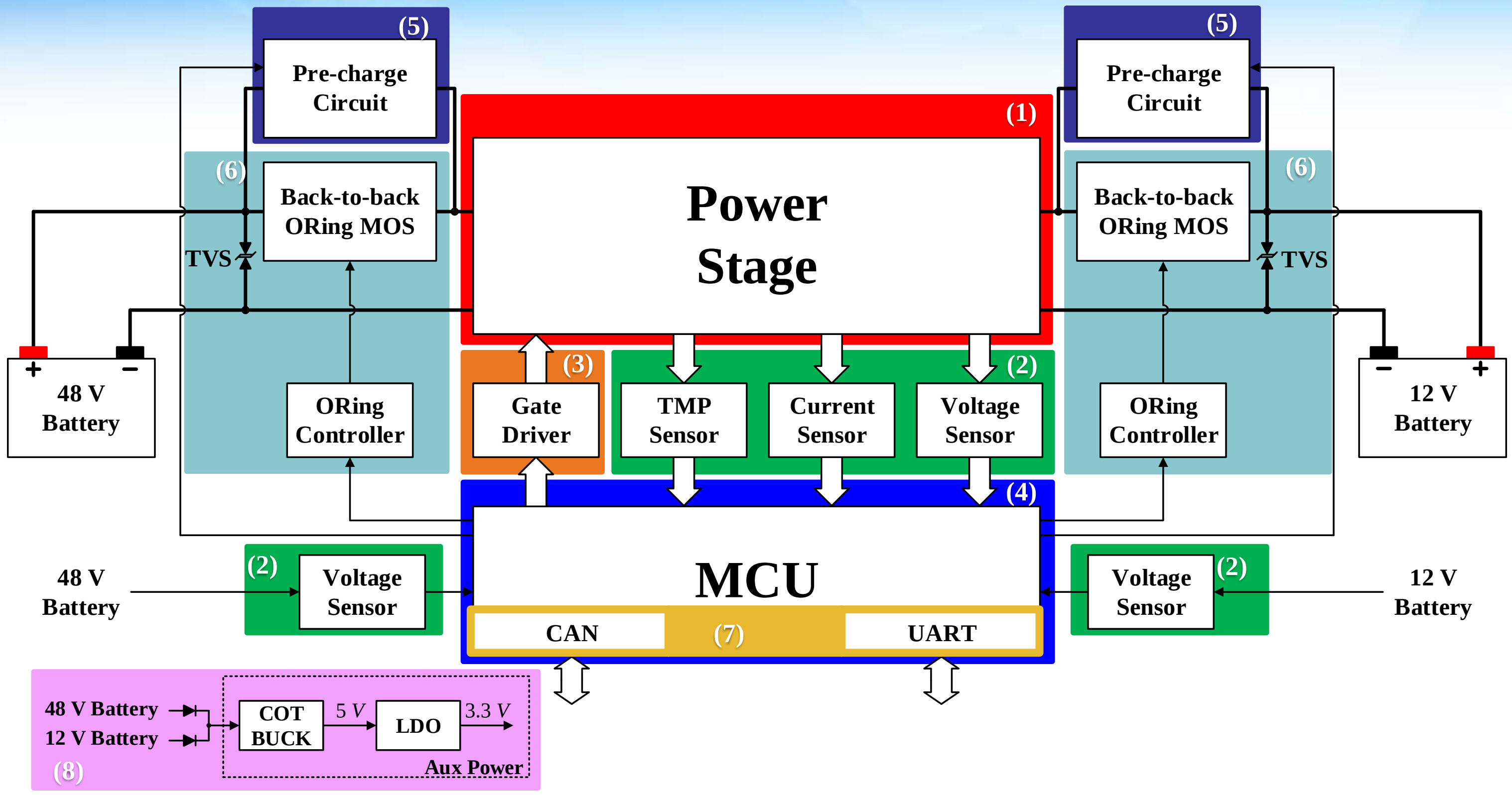
邱煌仁
台科大電子系特聘教授兼研發長

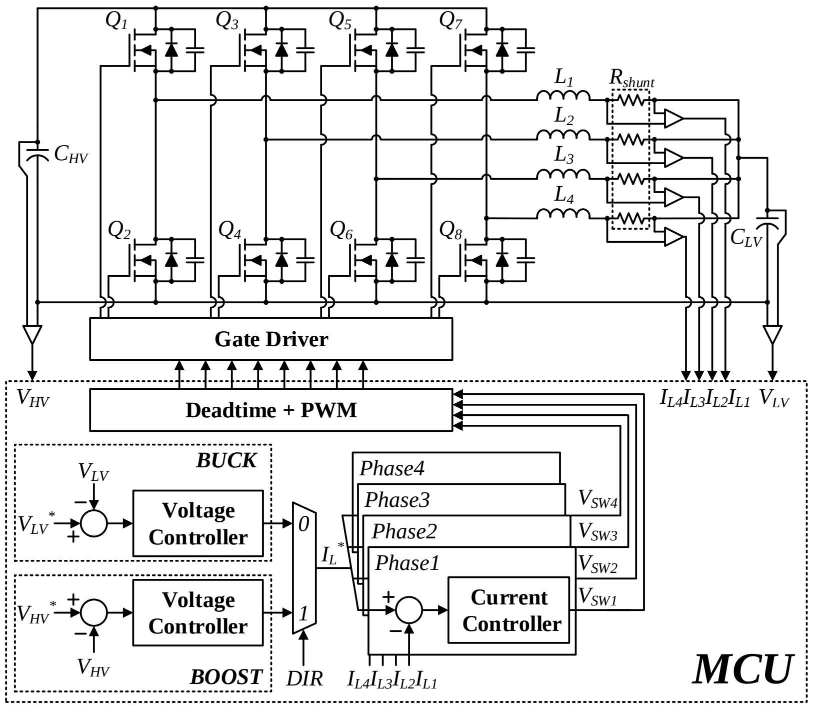
Circuit Spec.

Items	Spec.
operating modes	Buck/Boost/Pre-charge
HV range	36 V ~ 52 V (nominal 48 V)
LV range	8 V ~ 16 V (nominal 14 V)
LV maximum current	180 A
HV maximum current	50 A
rated power	2.5 kW
switching freq.	250 kHz
efficiency	> 96%
protection	OVP/UVP/RPP/OCP/OTP
interface	CAN/UART

15.5 cm*14.5 cm*1.51 cm (L*W*H)

System Configuration

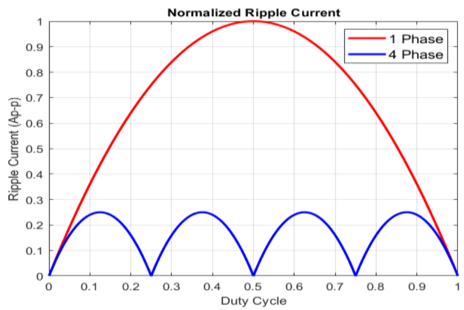


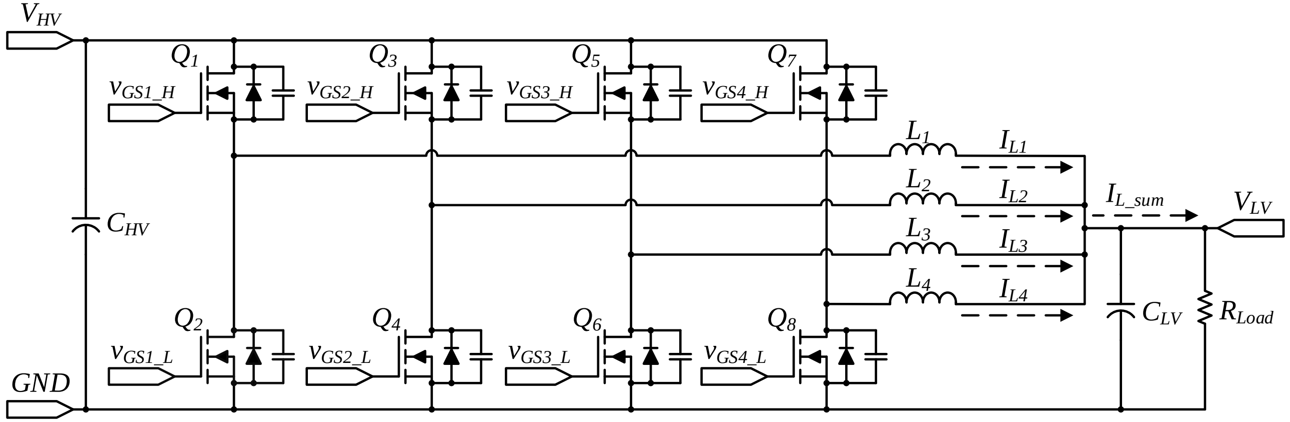


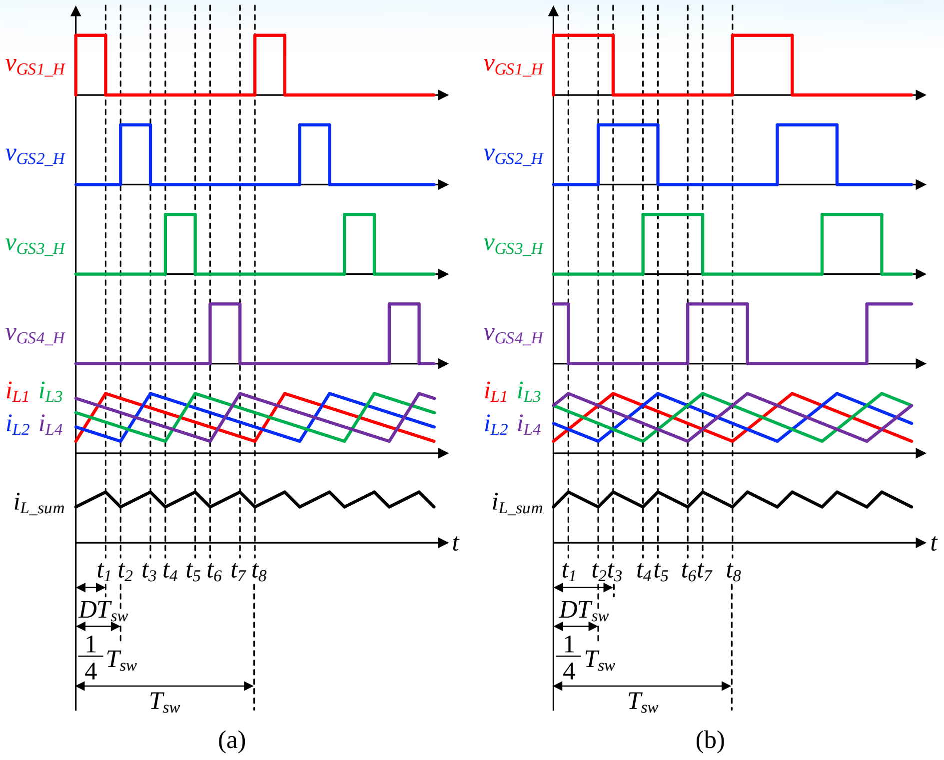
(1) Power stage	(3) Gate drive	(5) Pre-charge	(7) Interface
(2) Sensor	(4) MCU	(6) Protection	(8) Aux. power

Four-phase Interleaved DC-DC Converter

- Simple circuit and high reliability
- Bidirectional power conversion
- High current capacity
- Current ripple cancellation

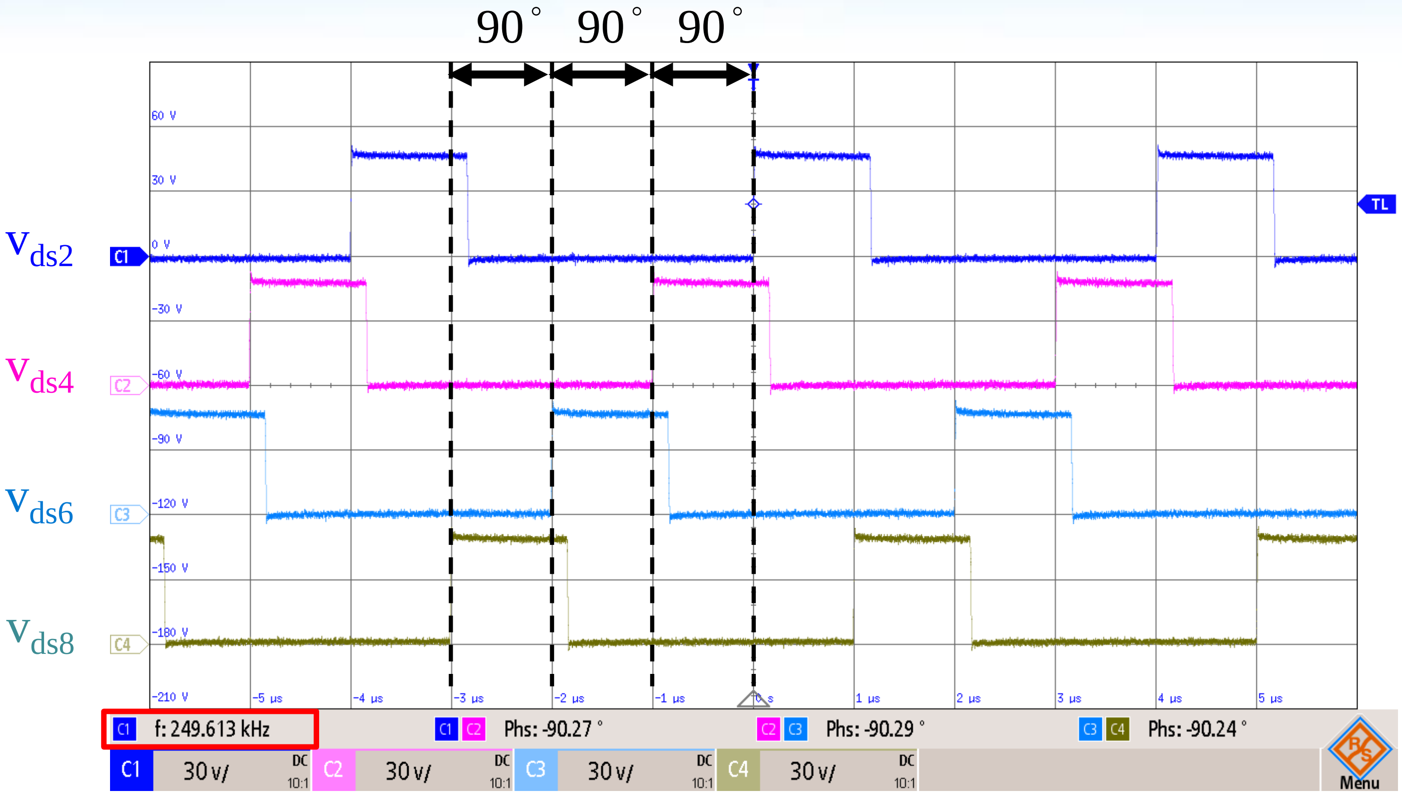






(a) 0% $\leq D <$ 25% (b) 25% $\leq D <$ 50%

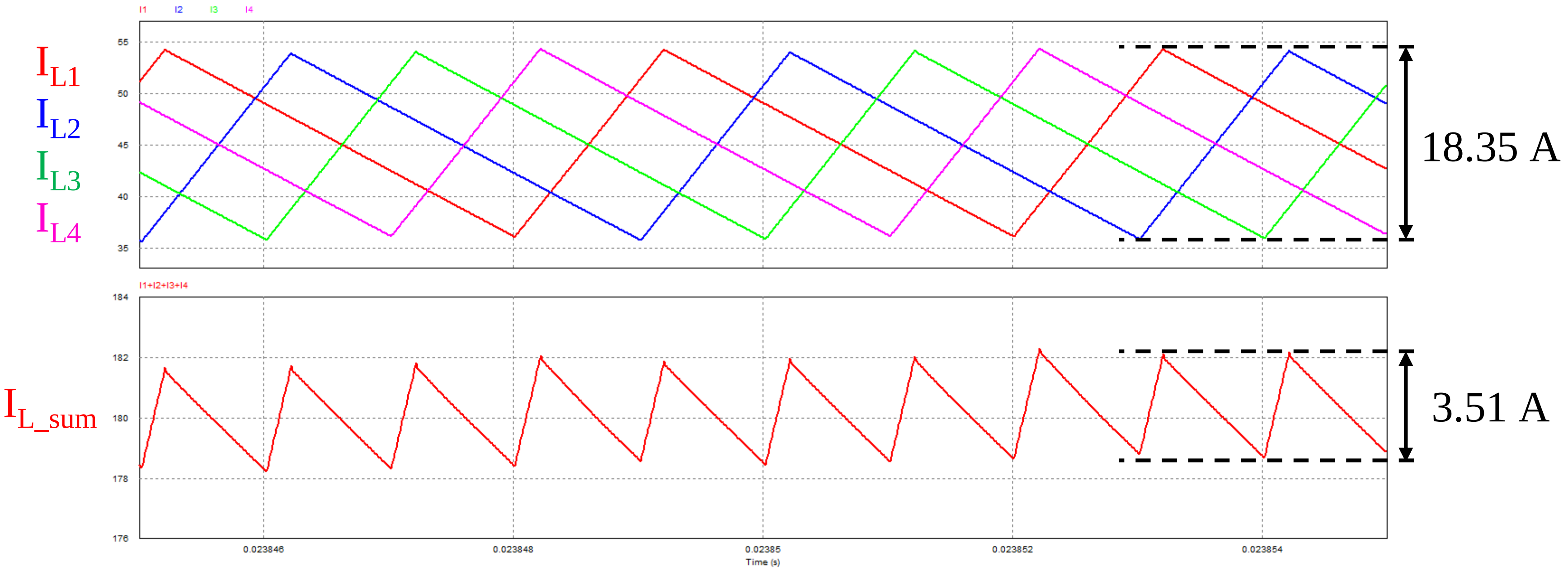
Four-phase Interleaving



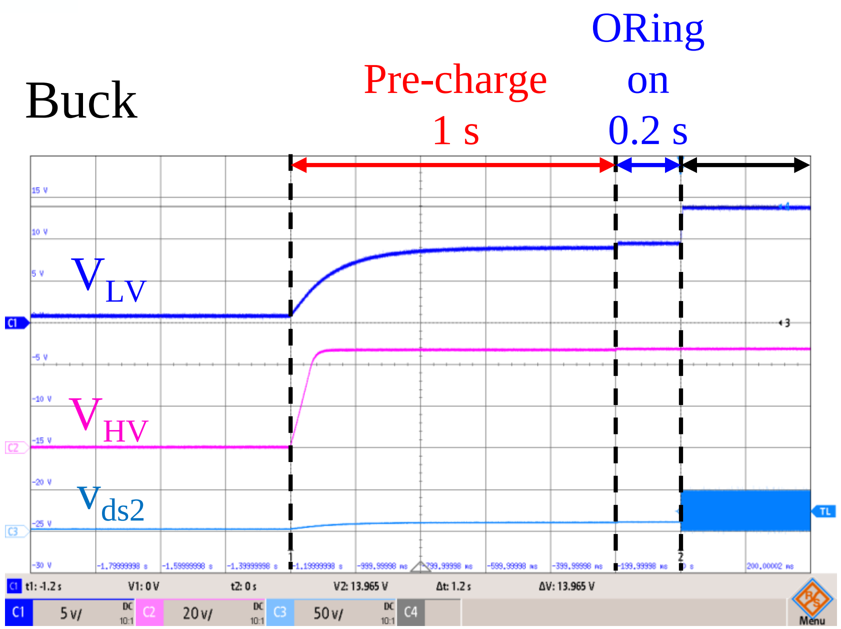
(Ch1：v_{ds2}(30 V/div)；Ch2：v_{ds4}(30 V/div)；Ch3：v_{ds6}(30 V/div)；Ch4：v_{ds8}(30 V/div)；Time：1 μs/div)

Ripple Cancellation

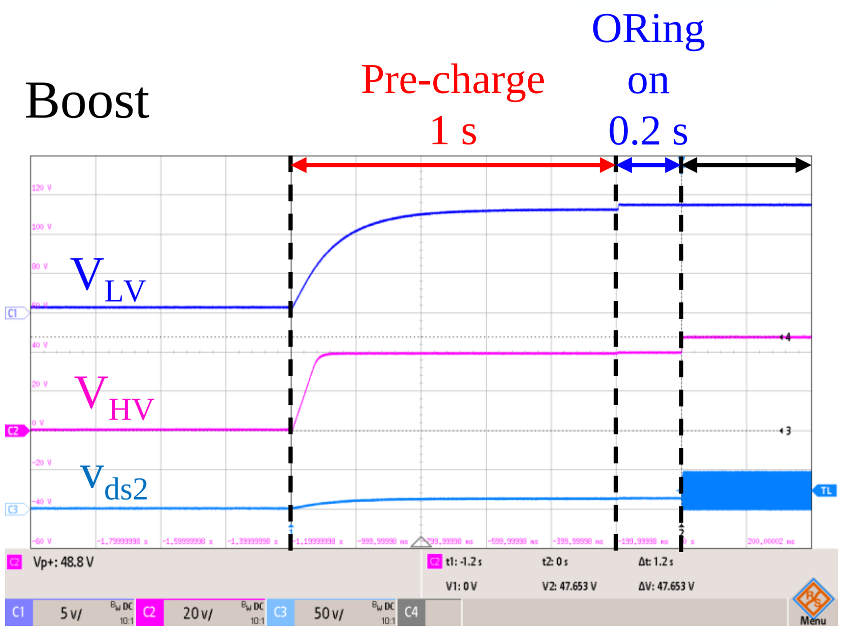
Buck mode: V_{in} = 48 V, V_{out} = 14 V, 100% Load



Start-up Waveforms



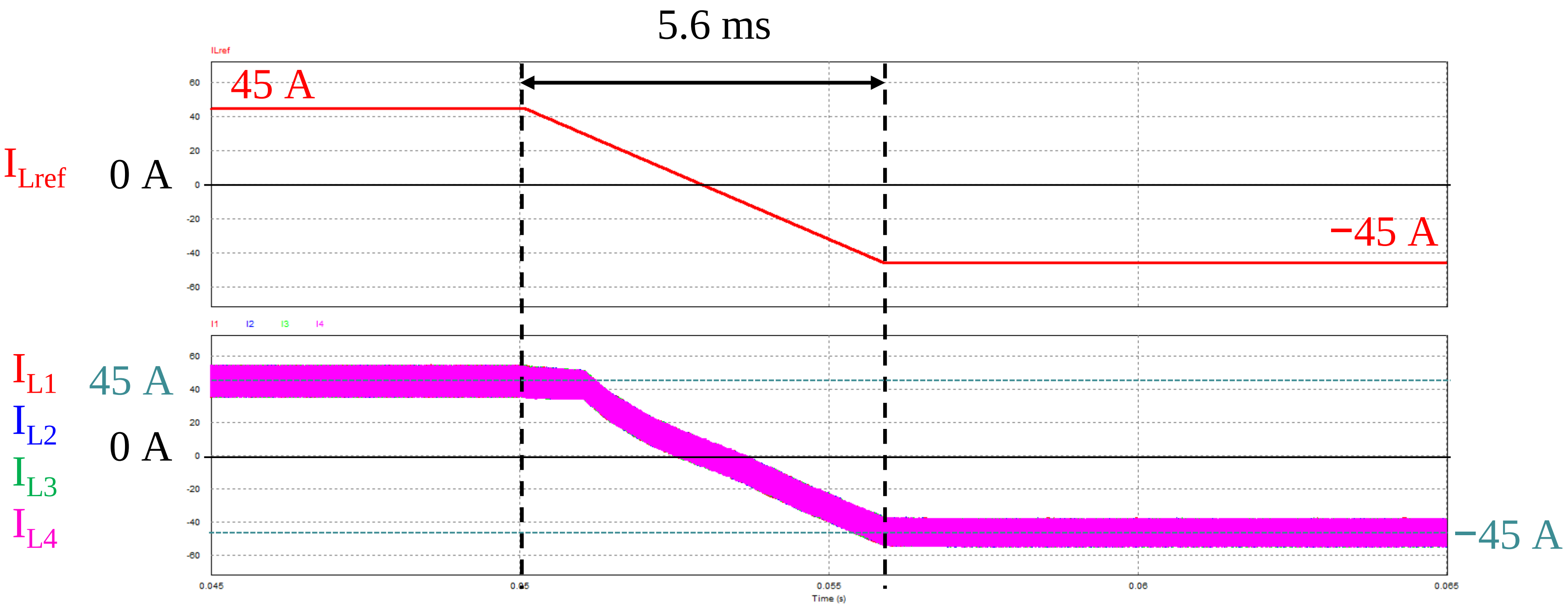
(Ch1：V_{LV}(5 V/div)；Ch2：V_{HV}(20 V/div)；Ch3：v_{ds2}(50 V/div)；Time：200 ms/div)



(Ch1：V_{LV}(5 V/div)；Ch2：V_{HV}(20 V/div)；Ch3：v_{ds2}(50 V/div)；Time：200 ms/div)

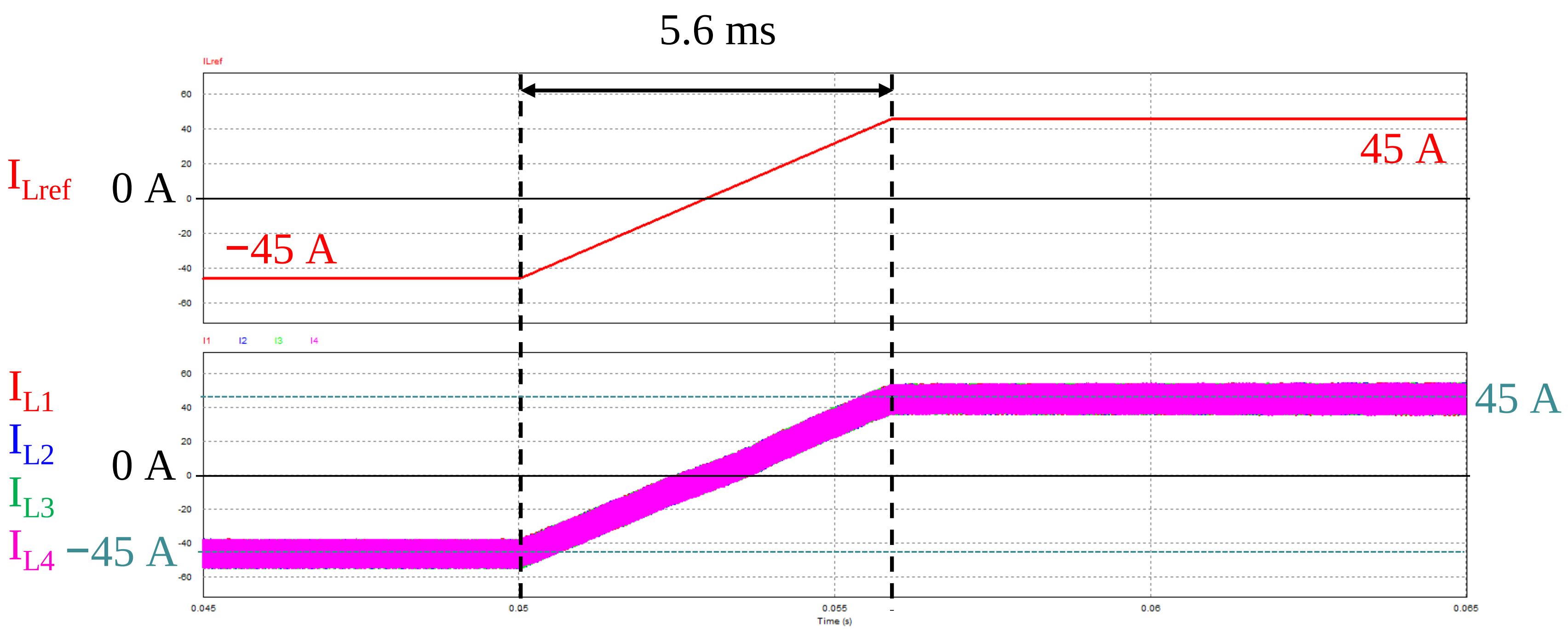
Buck to Boost

HV 48 V, LV 14 V, 100% Load



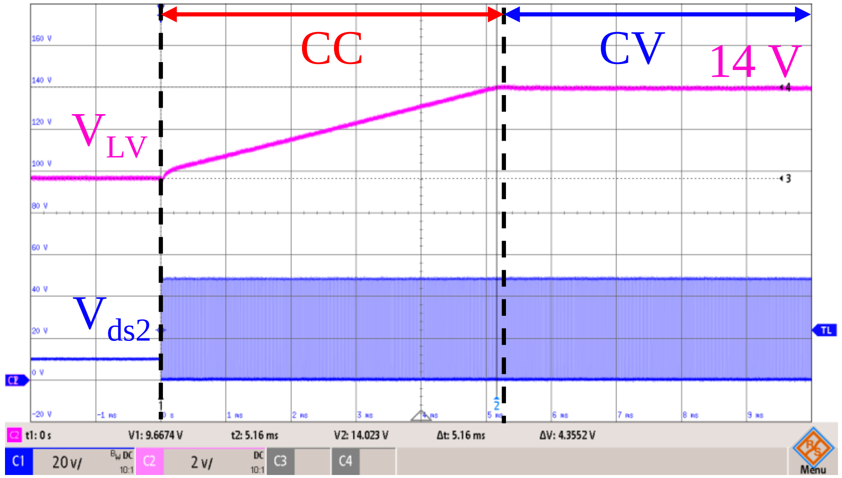
Boost to Buck

HV 48 V, LV 14 V, 100% Load



CC/ CV Waveforms

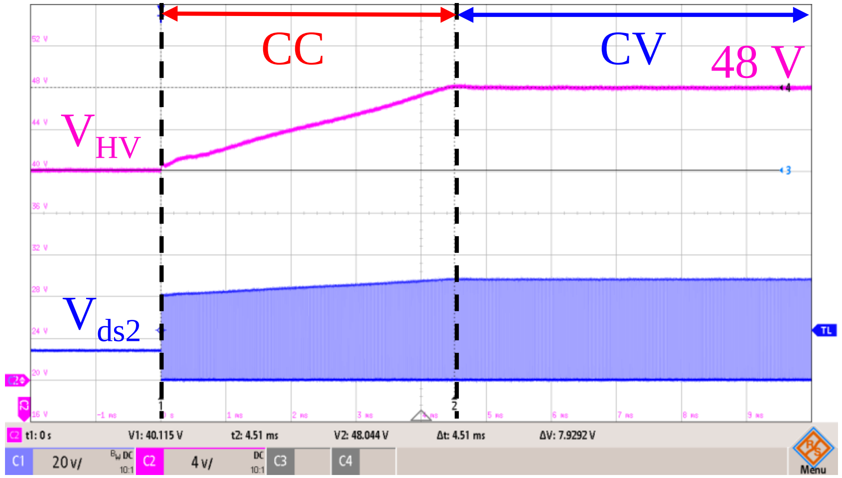
Buck



Ch1：v_{ds2}(20 V/div)；Ch2：V_{LV}(2 V/div)；

Time：1 ms/div

Boost

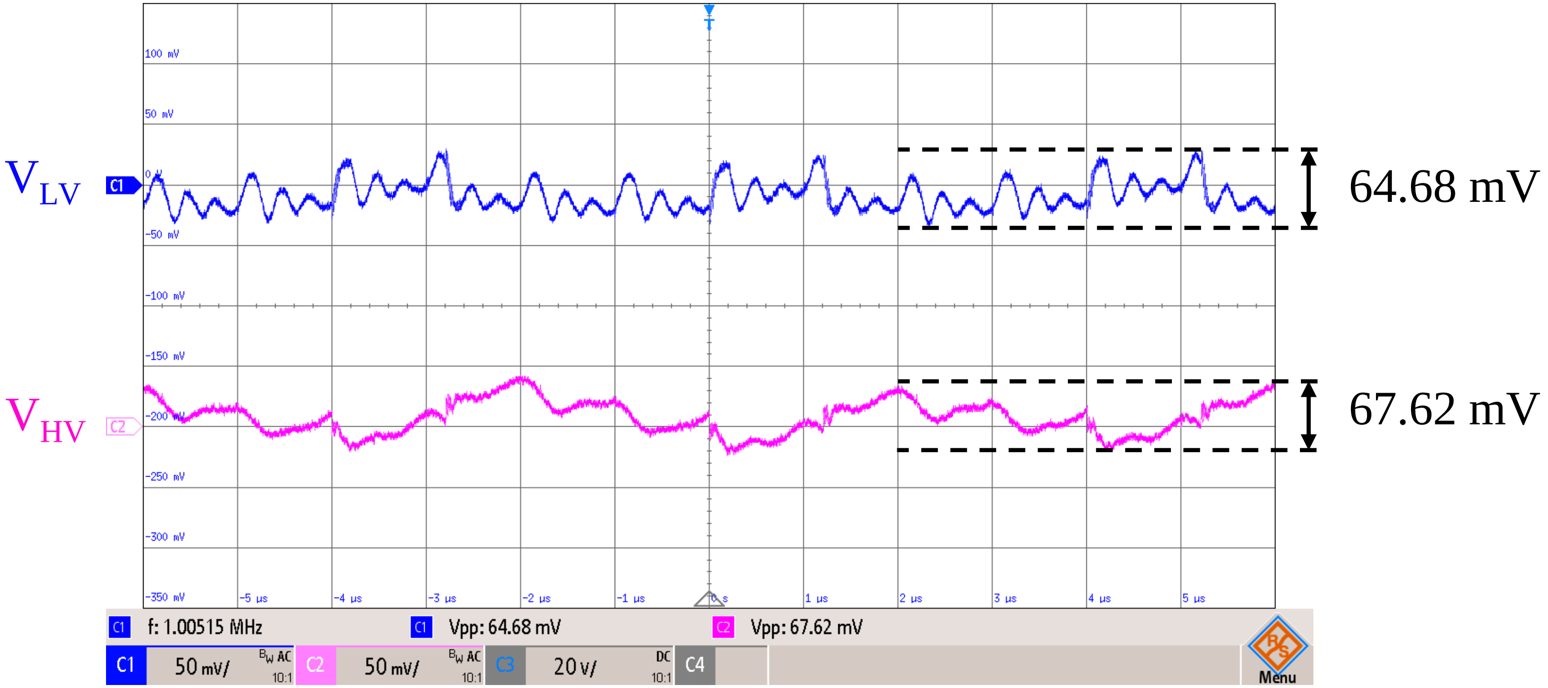


Ch1：v_{ds2}(20 V/div)；Ch2：V_{HV}(4 V/div)；

Time：1 ms/div

Voltage Ripple

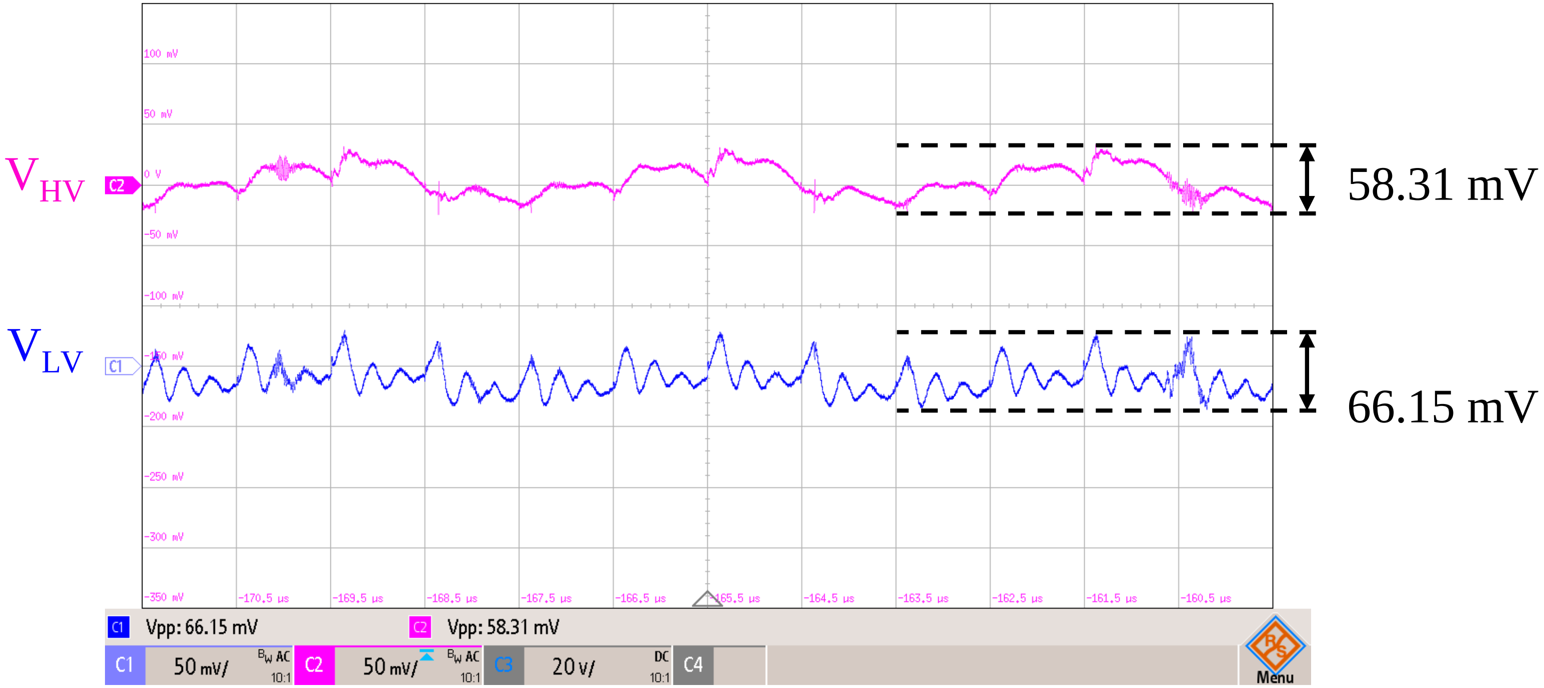
Buck: V_{in} = 48 V, V_{out} = 14 V, 100% Load



Ch1：V_{LV}(50 mV/div)；Ch2：V_{HV}(50 mV/div)；Time：1 μs/div

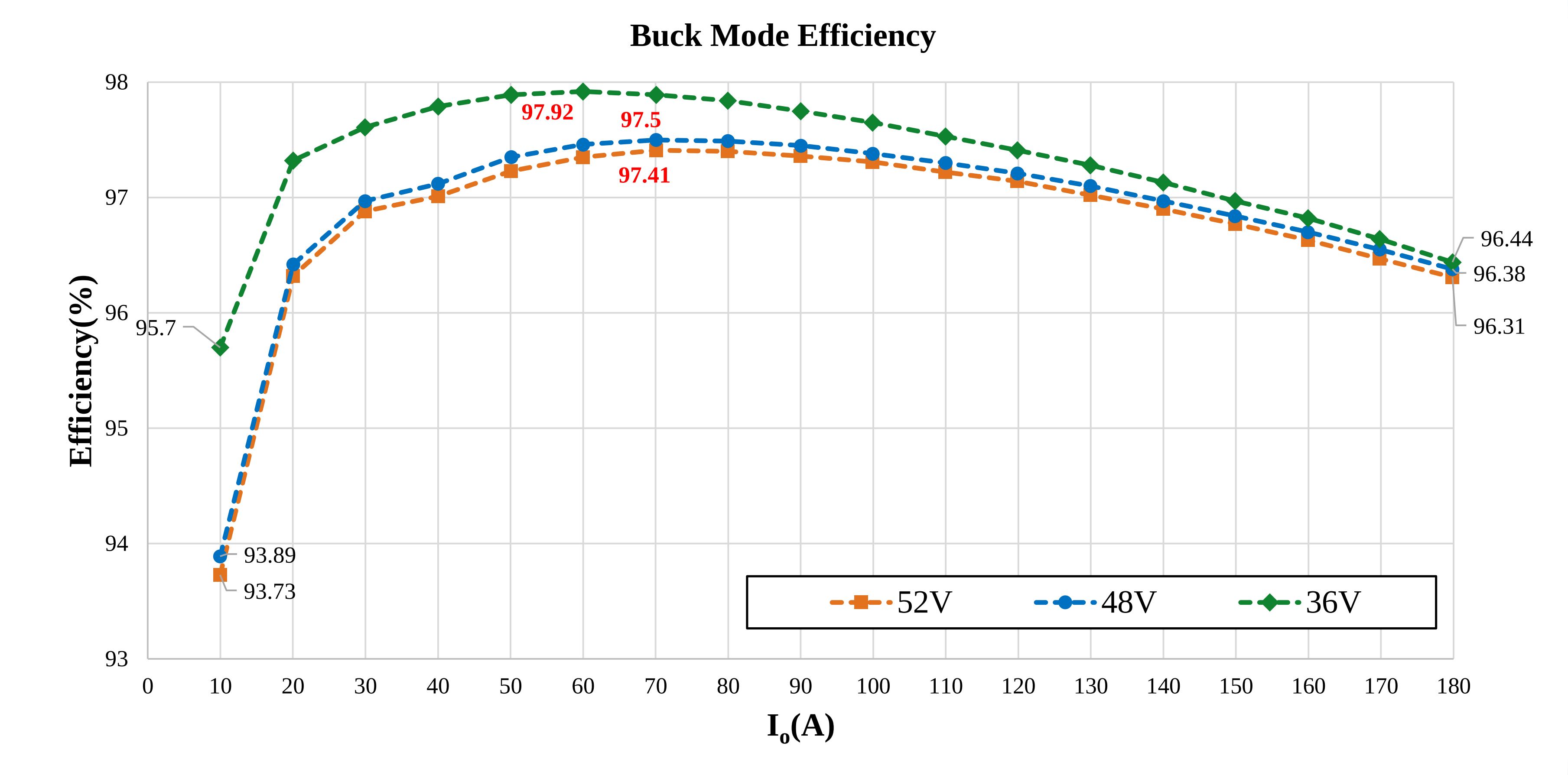
Voltage Ripple

Boost: V_{in} = 14 V, V_{out} = 48 V, 100% Load



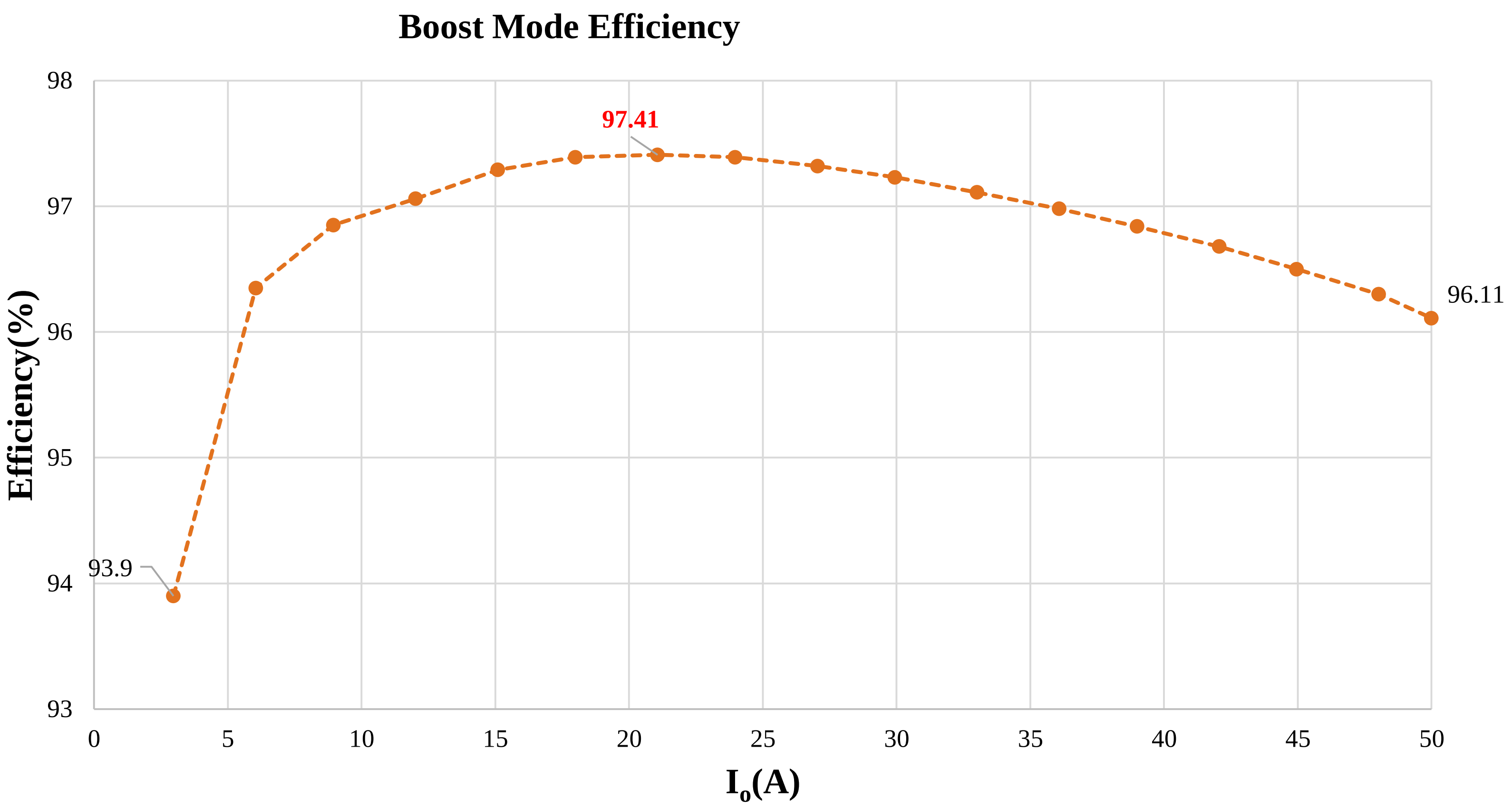
Ch1：V_{LV}(50 mV/div)；Ch2：V_{HV}(50 mV/div)；Time：1 μs/div

Efficiency



Buck Mode Efficiency
Efficiency(%)
I_o(A)
98
97
96
95
94
93
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
97.92
97.5
97.41
95.7
93.89
93.73
96.44
96.38
96.31
52V
48V
36V

Efficiency

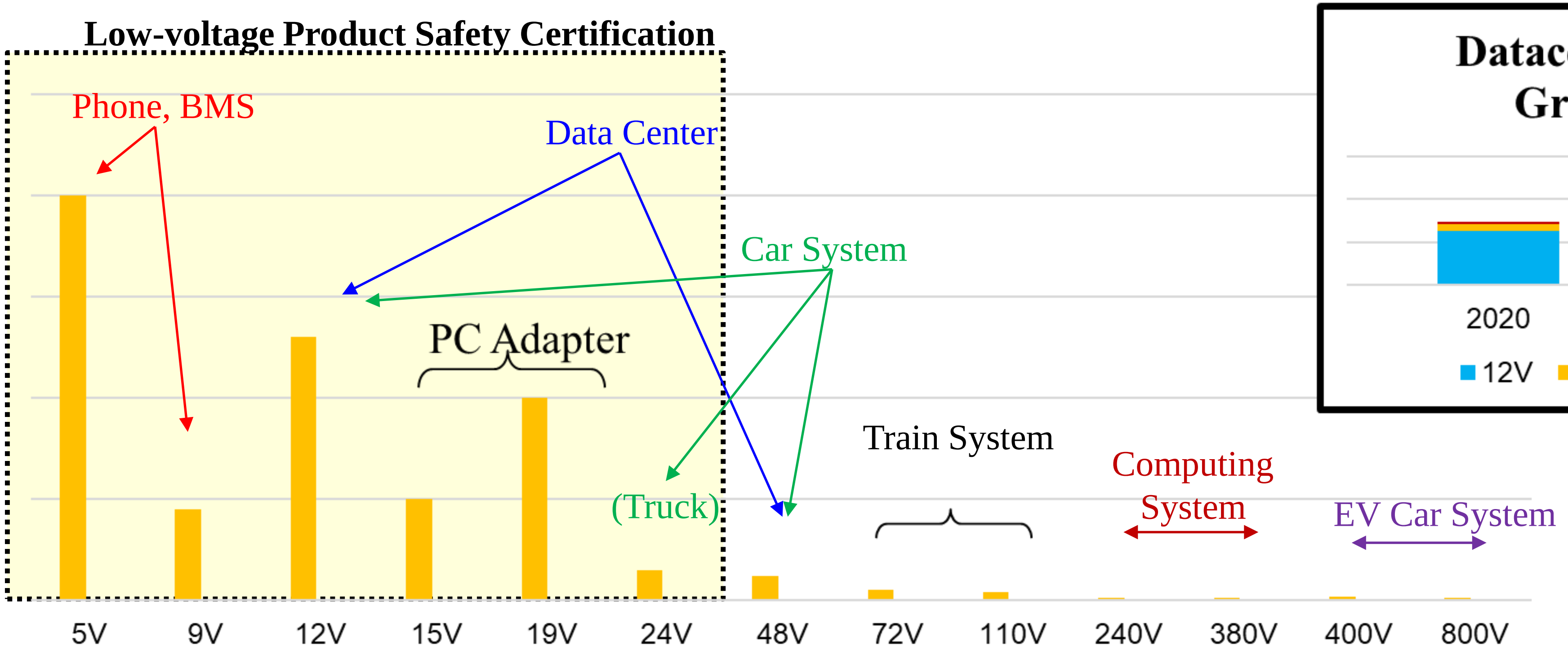

Boost Mode Efficiency
98
97
96
95
94
93
Efficiency(%)
97.41
96.11
93.9
0
5
10
15
20
25
30
35
40
45
50
I_o(A)

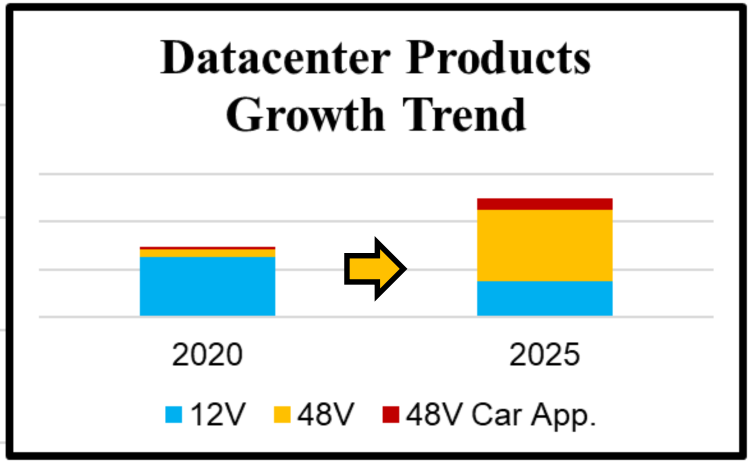
Outline

- ✓ **48V-to-12V Power Solutions for Data Center Applications**
  - ❑ Why use 48V as the DC bus voltage to meet the industrial trend
  - ❑ Benchmark solutions
- ✓ **Non-isolated Resonant Switched Capacitor Converters**
  - ❑ Potential resonant switched capacitor converters
  - ❑ Pipelined RSCC
  - ❑ Prototype converter
- ✓ **High Power Density Three-level Buck for Voltage Regulation**
  - ❑ Output voltage regulation design
  - ❑ Effect between V_O regulating and V_{CF} balancing
  - ❑ Efficiency

48 V-to-12 V Power Solutions for Data Center Applications

DC Bus Voltage Trends and Market Applications



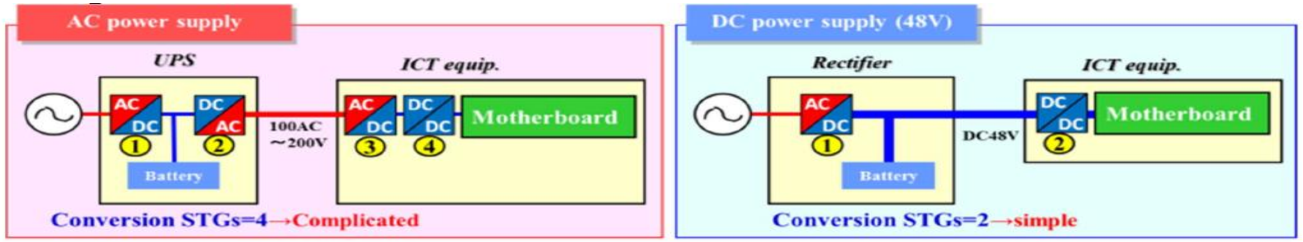


*Reference data from Vicor

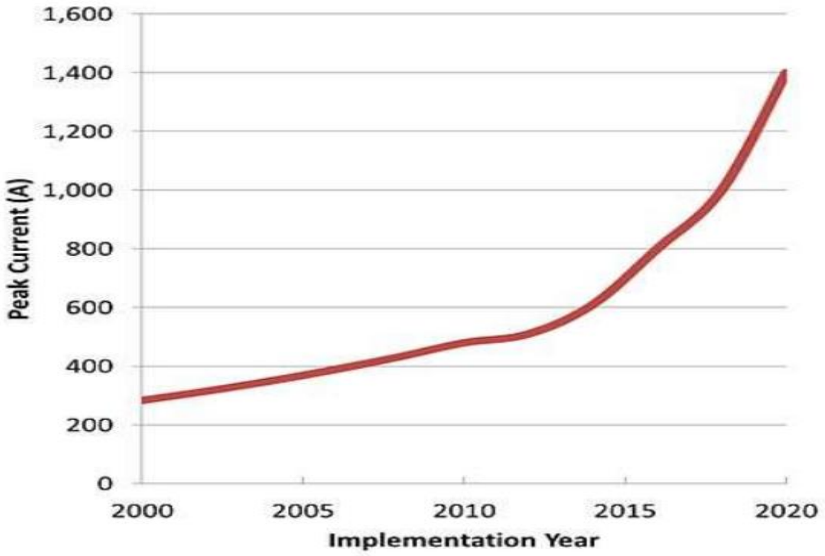
New Specification for Data Center

- Advances in the peak current requirements of CPUs, GPUs, ASICs, FPGAs require increasingly larger currents to achieve their power efficiency.
- Higher current requirements will result in higher conduction losses and lower power efficiency.
- Typically, beyond 15kW per rack, 12V systems become too inefficient to manage.

Power Distribution Network:



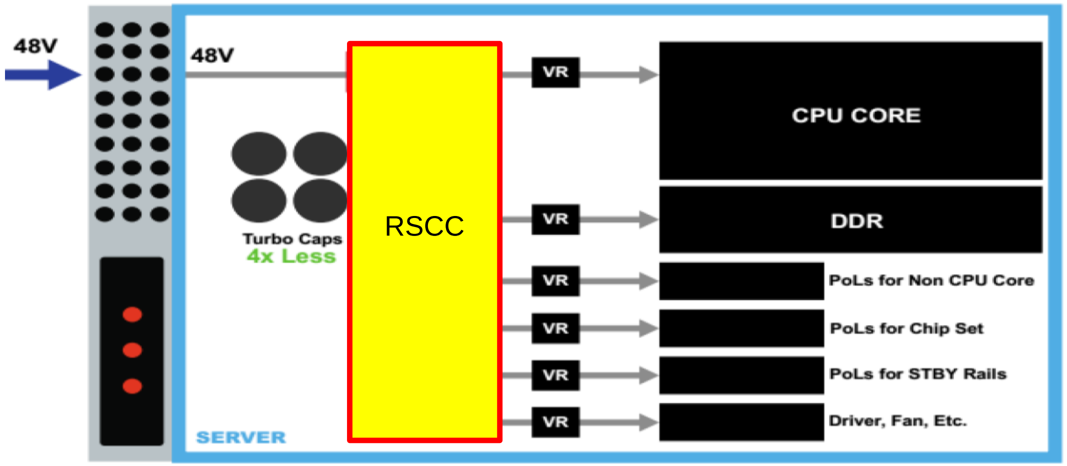
12V System ⇨ 48V System



*Reference figure from Vicor and The HVDC Power Supply System Implementation in NTT Group and Next Generation Power Supply System

Why Use 48V as The Bus Voltage

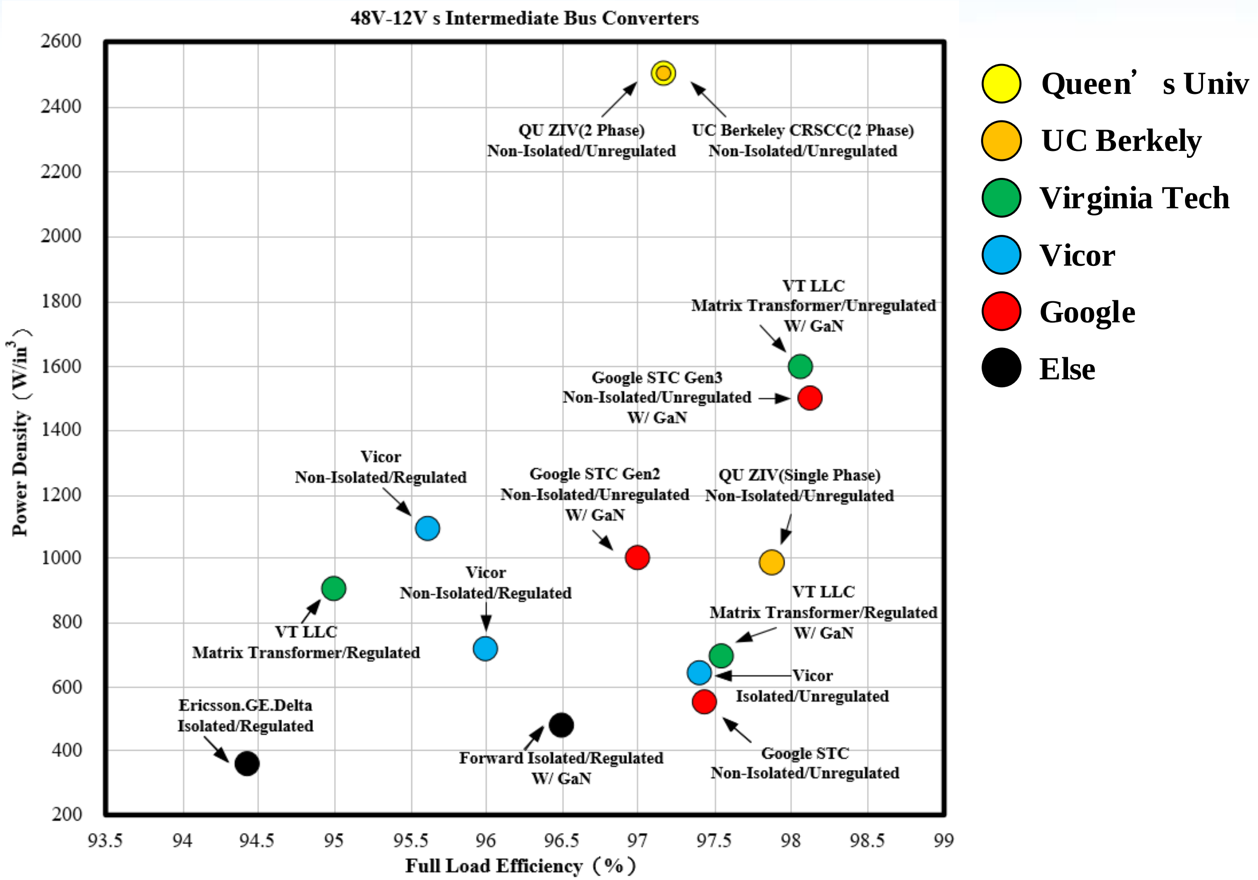
- Based on the UL-60950-1 standard, 60V_{DC} is considered the SELV limit. Utilizing distribution voltages above 60V_{DC} would require additional insulation, spacing, and testing (such as hi-pot or fault testing). Therefore, 48V has the same safety level as 12V without extra safety concerns for 48V application.
- 48V is 4X voltage of 12V, which reduces power loss by 16 times.
- Cabling, cost, energy storage volume.
- CPU, DDR just needs a non-isolated high step-down ratio.
- Fans, HDDs, DDR5, POLs, etc. require VR to obtain precise voltage regulation.



*Reference figure from Wiwynn

Benchmark solutions

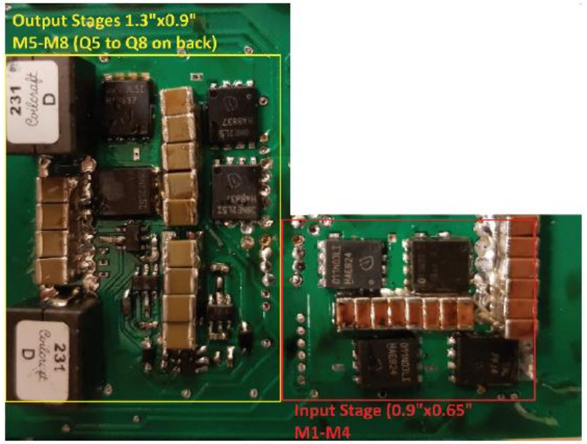
Comparison of Intermediate Bus Converters

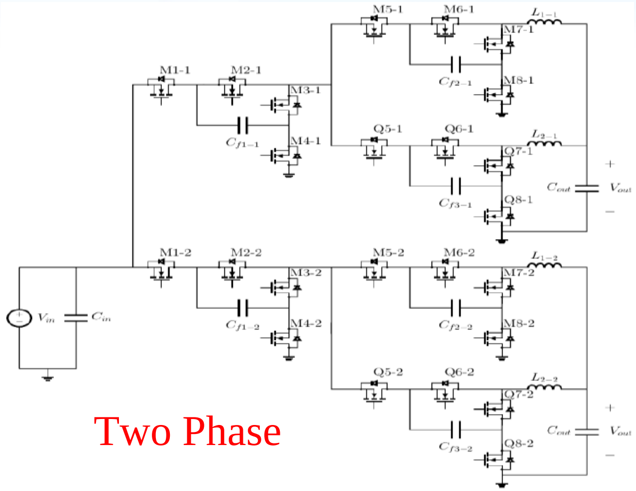


- Vicor’s solution has the advantage of highly integrated package.
- Even GaN transistor applied, conventional topologies still remain low power density due to bulky output inductor（high current output）.
- LLC with matrix transformer solves the issue of output filter but the efficiency remains around 95%.
- By applying GaN transistor, LLC with MT has better efficiency but lower power density.
- Google STC with Si MOSFET has excellent performance between density and efficiency.

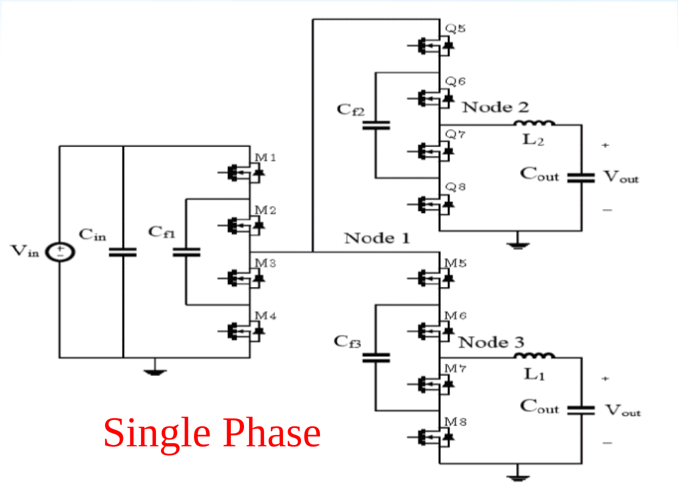
D. Reusch, S. Biswas and Y. Zhang, "System optimization of a high power density non-isolated intermediate bus converter for 48 V server applications," 2018 IEEE Applied Power Electronics Conference and Exposition (APEC), San Antonio, TX, USA, 2018, pp. 2191-2197

Zero-Inductor Voltage Converter





Two Phase



Single Phase

ZIV (Zero-Inductor Voltage Converter)

- Consisted by Inductor and Switched Capacitor
- Fixed-Ratio Output
- Hard Switching
- High Power Density

Two Phase

Vin＝48V, Vout＝12V
Iout＝70A, Fsw＝60kHz

Full Load Efficiency ≒97.2%

Peak Efficiency ＝99.1%

Power Density＝2500W/in^3

Single Phase

Vin＝48V, Vout＝12V
Iout＝40A, Fsw＝60kHz

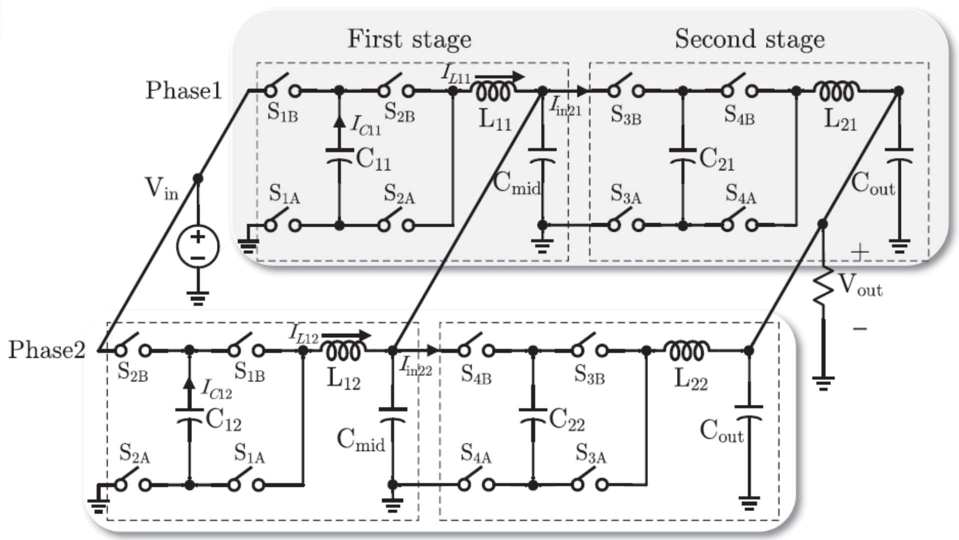
Full Load Efficiency ≒97.8%

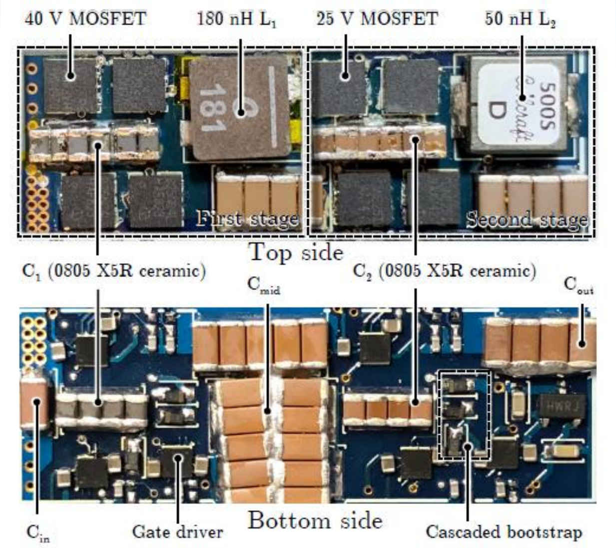
Peak Efficiency ＝99.2%

Power Density＝990W/in^3

S. Webb and Y. Liu, "A Zero Inductor-Voltage 48V to 12V/70A Converter for Data Centers with 99.1% Peak Efficiency and 2.5kW/in3 Power Density," 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, 2020, pp. 1858-1865,

Cascaded Resonant SCC





1.38*0.46*0.22 inch

CRSCC (Cascaded Resonant SCC)

- Consisted by Inductor and Switched Capacitor
- Fixed-Ratio Output
- ZVS or ZCS
- High Power Density

Interleaved Two Phase

Vin＝48V, Vout＝12V, Iout＝60A, Fsw＝100kHz

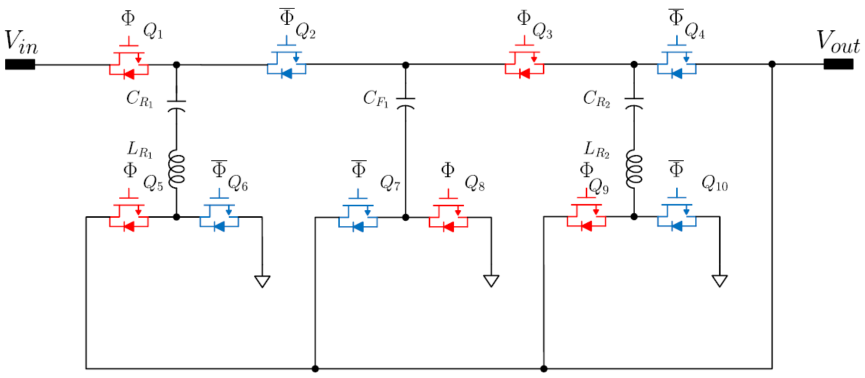
Full Load Efficiency ≒97.23%

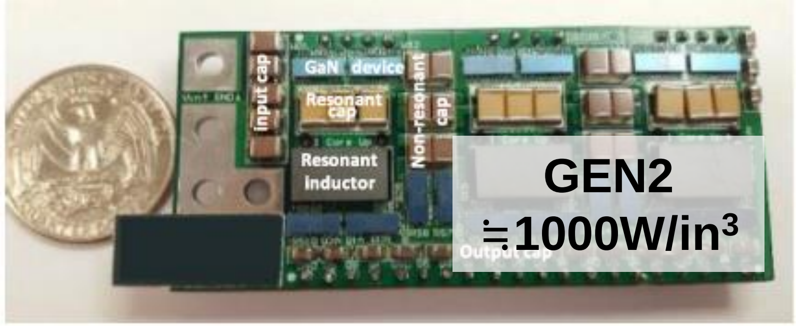
Peak Efficiency ＝99.2%

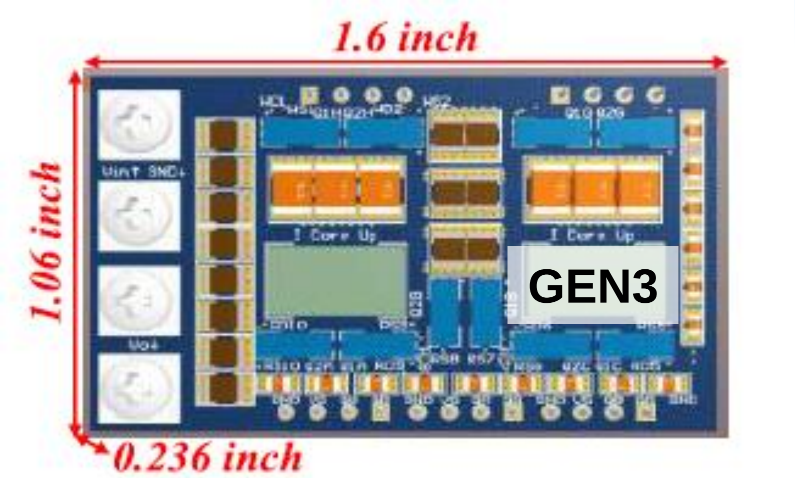
Power Density＝2500W/in^3

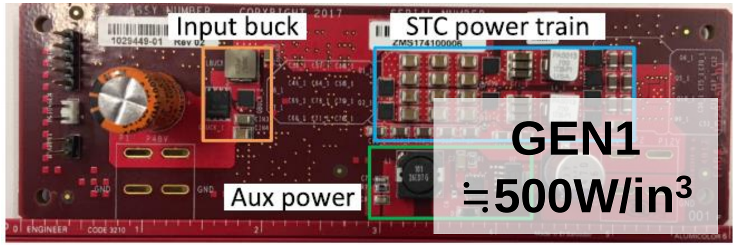
Z. Ye, Y. Lei and R. C. N. Pilawa-Podgurski, "A 48-to-12 V Cascaded Resonant Switched-Capacitor Converter for Data Centers with 99% Peak Efficiency and 2500 W/in3 Power Density," 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, USA, 2019, pp. 13-18

Switched Tank Converter









STC (Switched Tank Converter)

- Consisted by Inductor and Switched Capacitor
- Fixed-Ratio Output
- ZVS or ZCS
- High Power Density

Vin＝48V, Vout＝12V
Iout＝50A, Fsw＝350kHz

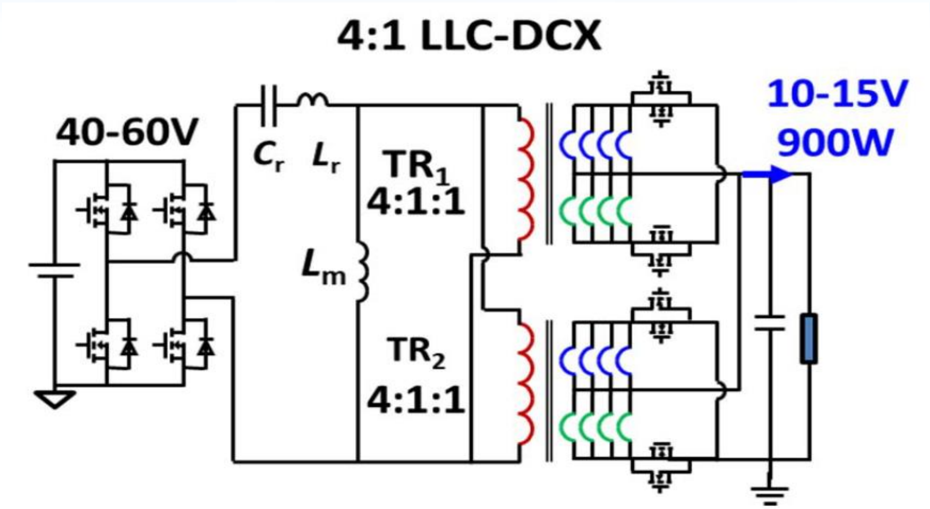
Full Load Efficiency ≒98.2%

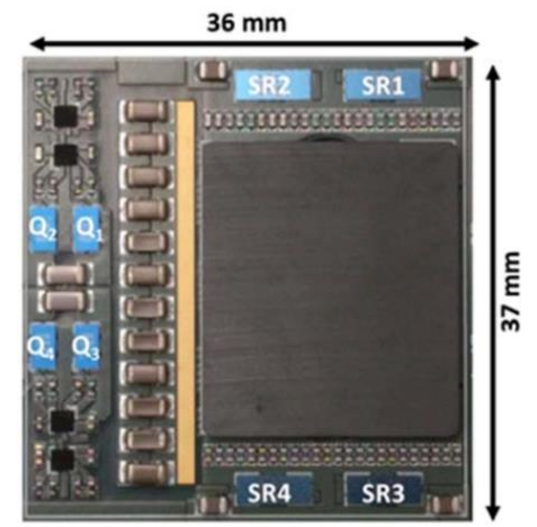
Peak Efficiency ＝98.79%

Power Density＝1500W/in^3

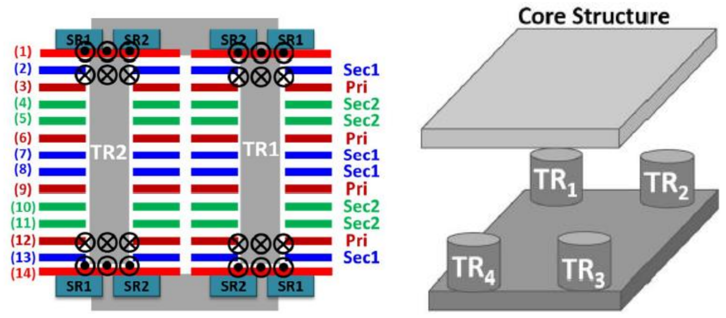
X. Lyu, Y. Li, N. Ren, S. Jiang and D. Cao, "A Comparative Study of Switched-Tank Converter and Cascaded Voltage Divider for 48-V Data Center Application," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 8, no. 2, pp. 1547-1559, June 2020

LLC with Matrix Transformer





Matrix Transformer Core Structure
And PCB Winding Arrangement



LLC with Matrix Transformer

- Fixed-Ratio Output(DCX)
- ZVS, Hard Switching When Light Load
- Integrated Planar Transformer(Inductor +Transformer)
- Complexity of PCB winding and Customized Core

Vin＝48V, Vout＝12V, Iout＝75A, Fsw＝1MHz

Full Load Efficiency ≒98.1%

Peak Efficiency ＝98.4%

Power Density＝1600W/in^3

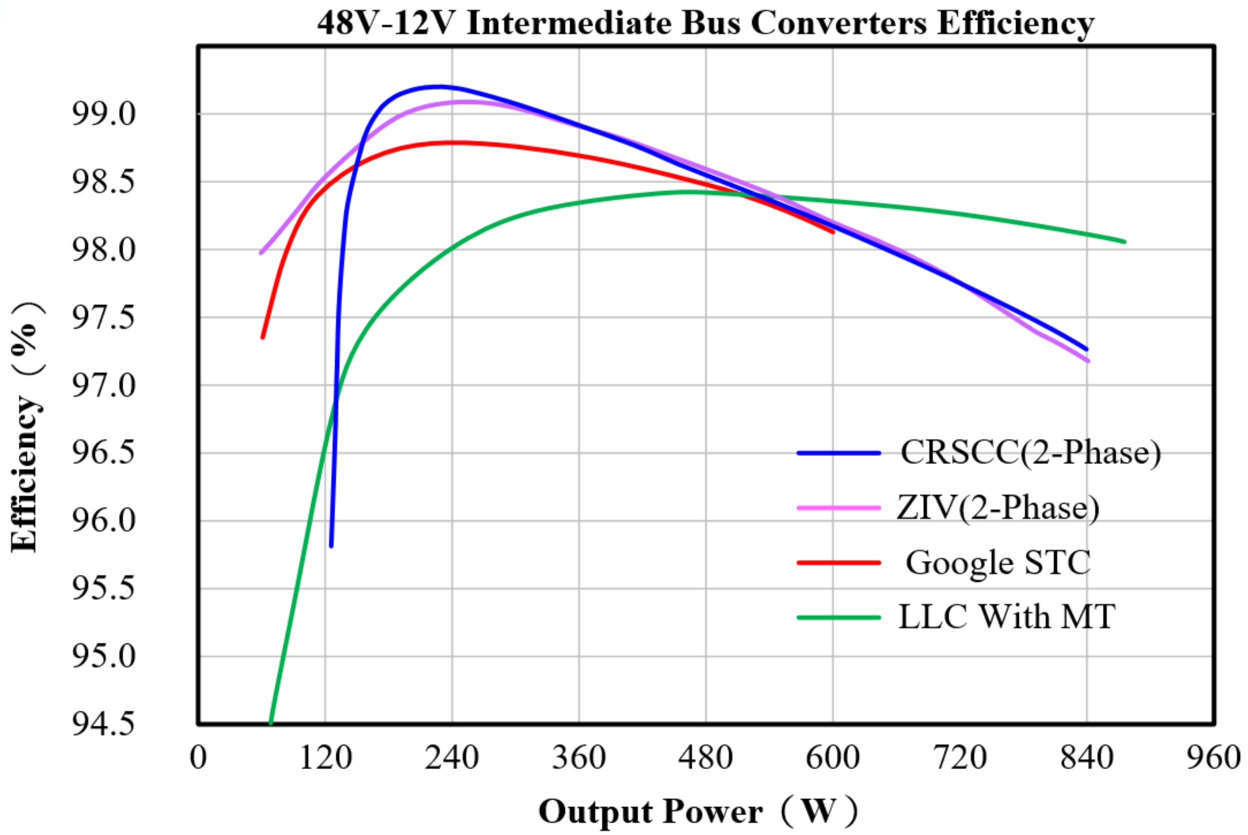
M. H. Ahmed, A. Nabih, F. C. Lee and Q. Li, "High-efficiency, High-density Isolated/Regulated 48V Bus Converter with a Novel Planar Magnetic Structure," 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, USA, 2019, pp. 468-475

Comparison of State of the Arts (48V to 12V)

	STC	ZIV	ZIV (Two Phase)	CRSCC (Two Phase)	LLC with MT
Switches	10	12	12+12	8+8	8
Capacitors	2(Resonant)+1(Clamping)	3(Clamping)	3+3(Clamping)	4(Resonant)+1(Clamping)	1(Resonant)
Inductors	2	2	4	4	0(Integrated)
Power Density	1500W/in^3	990W/in^3	2500W/in^3	2500W/in^3	1600W/in^3
Transistor Material	GaN(350kHz)	Si(60kHz)	Si(60kHz)	Si(100kHz)	GaN(700kHz~1.6MHz)
Components	Commercial Products	Commercial Products	Commercial Products	Commercial Products	Customized

- Though ZIV and CRSCC have highest density performance, but quantities of MOSFET is way too much (Cost Consideration).
- Due to consideration of switching losses, ZIV and CRSCC choose to operate at low frequency.
- LLC with MT have least Components and fine density performance but need customized magnetic component (PCB + Core).

Efficiency Comparison



- All SCC has better light load and peak load efficiency.
- LLC with matrix transformer has better high output current extensibility.
- Due to light load hard switching, LLC with matrix transformer have poor light load performance.
- LLC with matrix transformer have much more complexity of PCB winding arrange and customized core design.

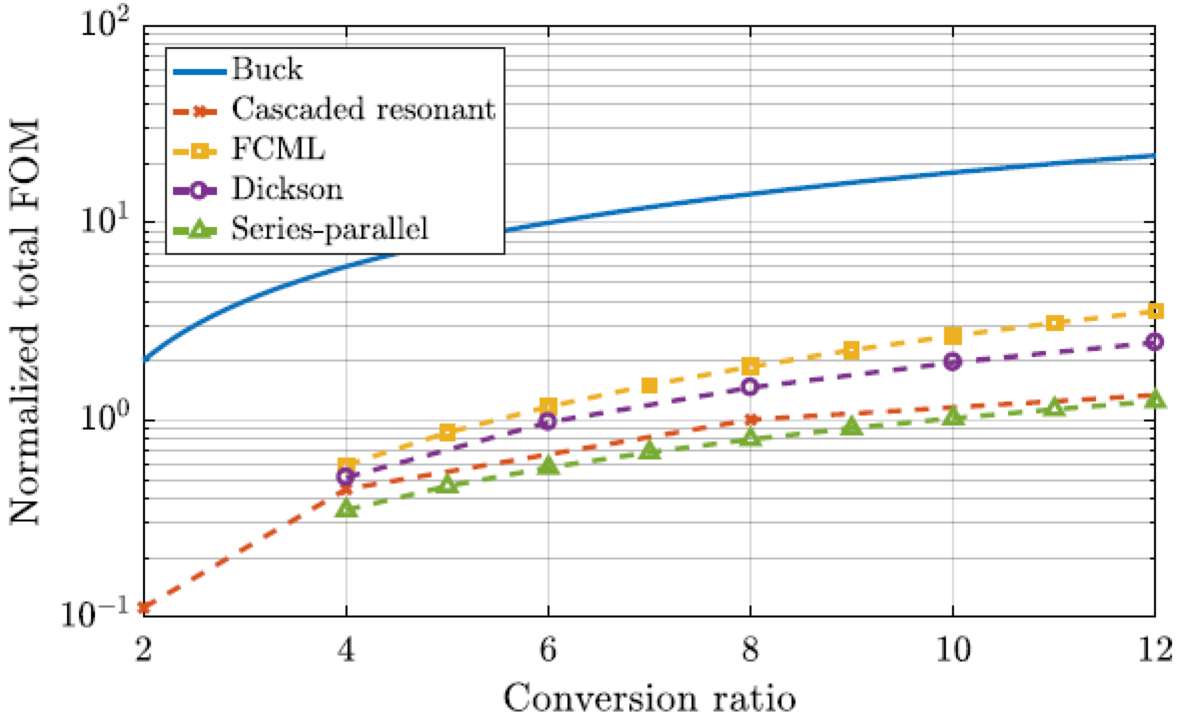
Potential of Resonant Switched-Capacitor Converter

- Compared with matrix transformer, RSCC has lower PCB layout complexity.
- Compared with Vicor, RSCC has more flexible circuit design.
- Topologies have great scalability for output voltage.
- Minimum the RMS current on components.
  - By operating symmetrical 50% duty and resonant frequency
- A great quantity of driver signals and circuit needed.
  - Can be integrated by IC design
- Resonant components can be easily obtained from vender, customization will be unnecessary.

Potential of Resonant Switched Capacitor Converters

Selection of Suitable RSCC for IBC

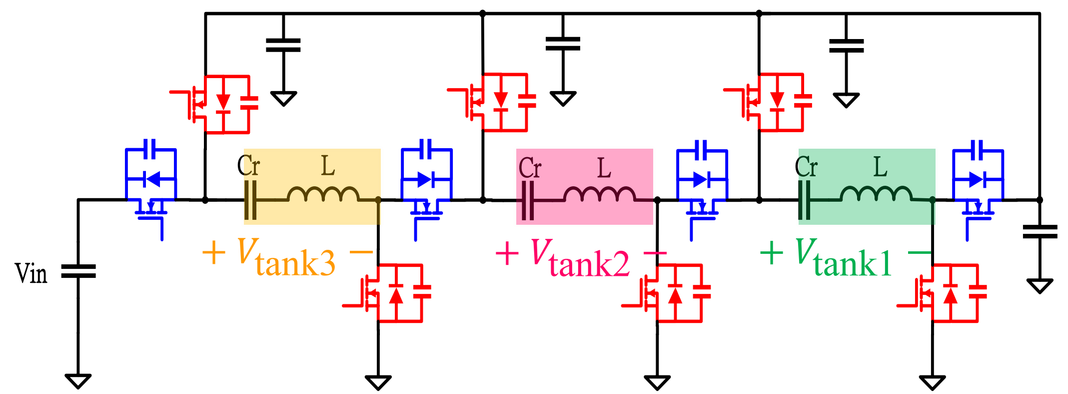
Normalized FOM for various RSCC

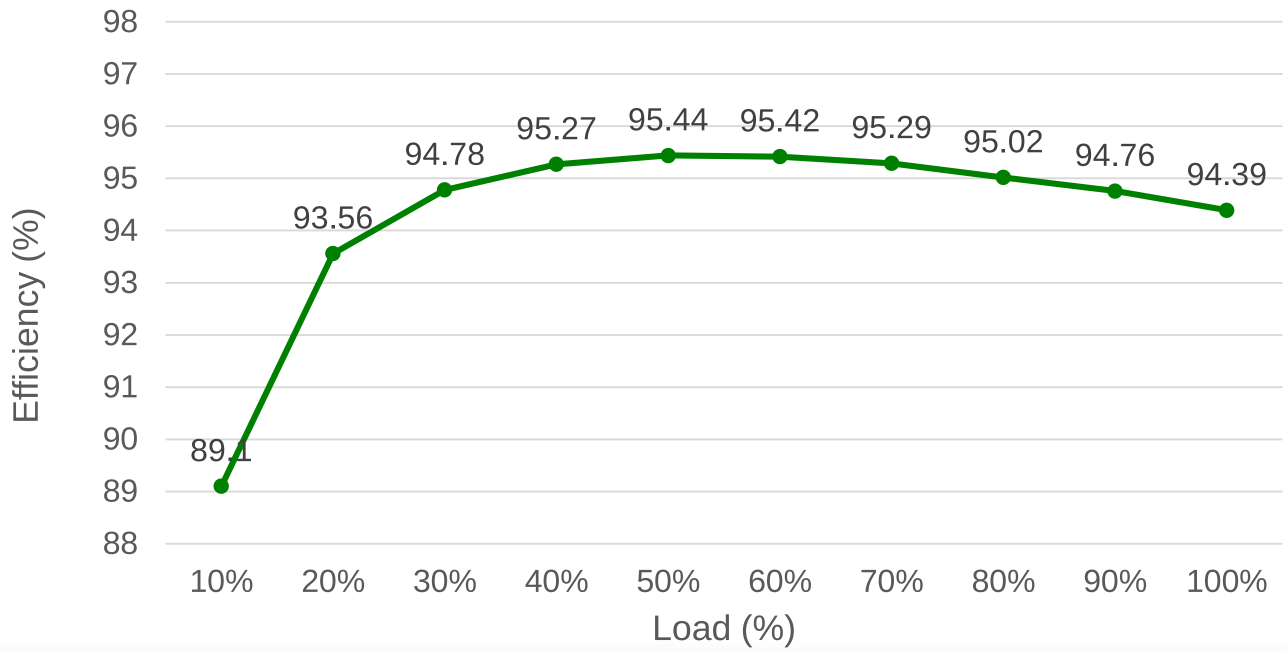


- A overall performance figure of merit (FOM) is a method obtained by multiplying：
  - Normalized switch stress (reflecting power loss)
  - Normalized passive component volume (reflecting power density).
  - Lower is better.
- It is based on the general trade-off that a converter with smaller switch stress can operate at a higher switching frequency for the same conduction and switching loss, which results in reduction in passive component volume.

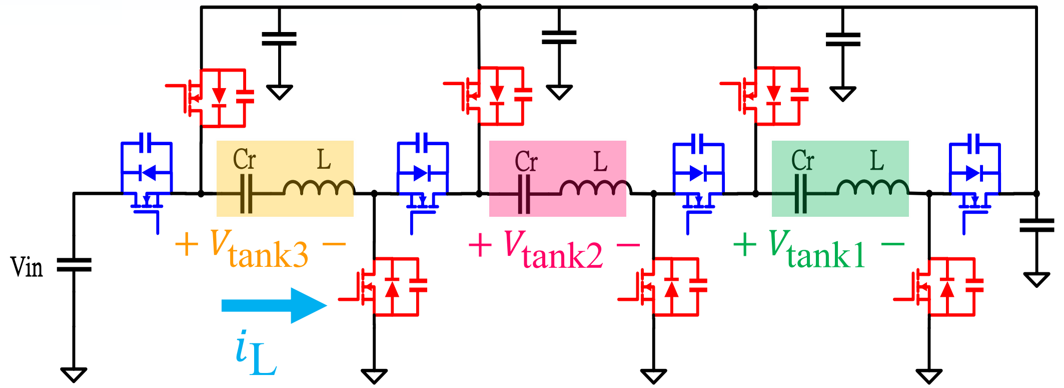
Z. Ye, Y. Lei and R. C. N. Pilawa-Podgurski, "A resonant switched capacitor based 4-to-1 bus converter achieving 2180 W/in3 power density and 98.9% peak efficiency," 2018 IEEE Applied Power Electronics Conference and Exposition (APEC), San Antonio, TX, USA, 2018, pp. 121-126.
Y. Lei, "High-performance power converters leveraging capacitor-based energy transfer," Ph.D. dissertation, University of Illinois at Urbana- Champaign, 2017.

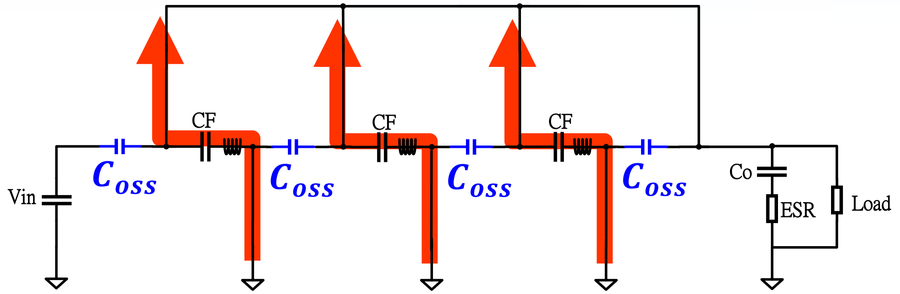
A 48V to 12V/50A Series-Parallel Resonant Switched-Capacitor Converter (SP-RSCC) has been designed and realized that peak and full load efficiency 95.44% and 94.39% respectively.





Test condition: 48V - 12V (50A) ; $f_{sw} = 280kHz$

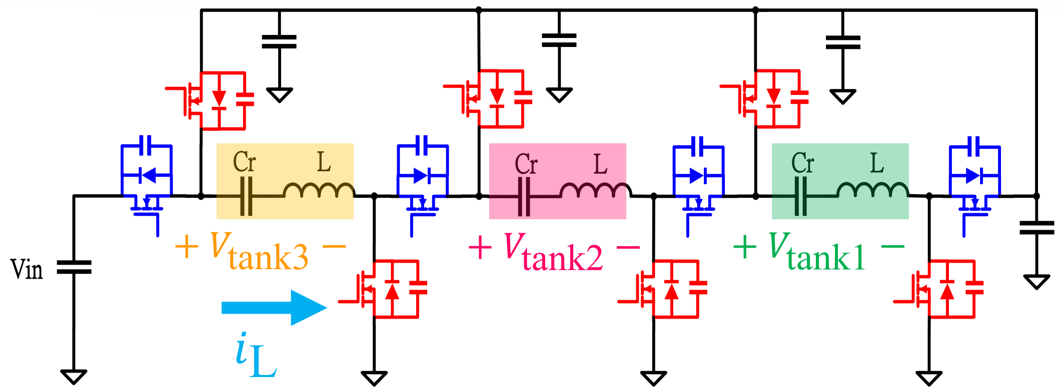


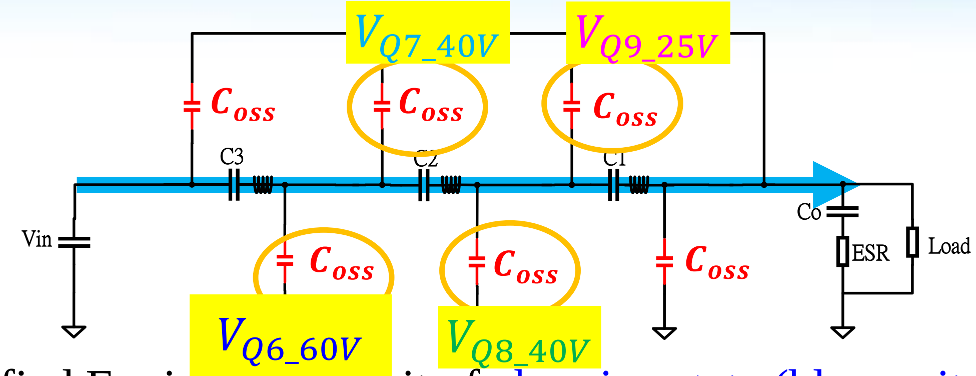


Simplified Equivalent circuit of discharging state (red on)

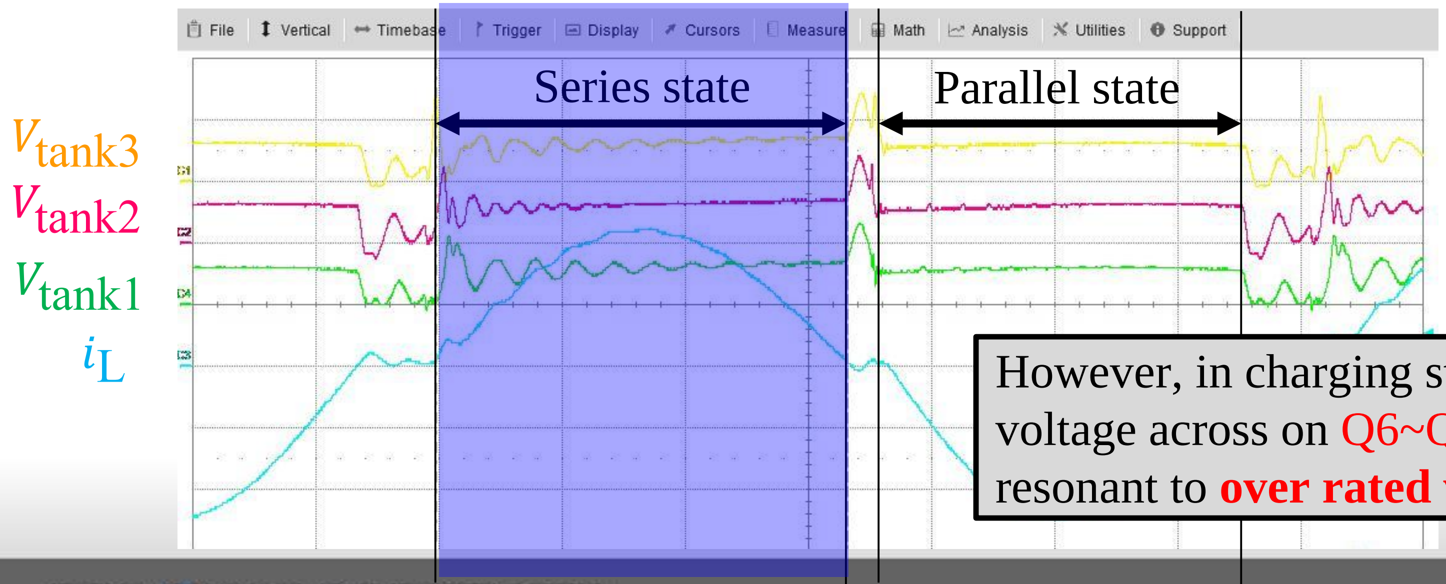
Resonant tanks are greatly clamped by output capacitor.

Test condition: 48V - 12V (50A) ； $f_{sw} = 280kHz$

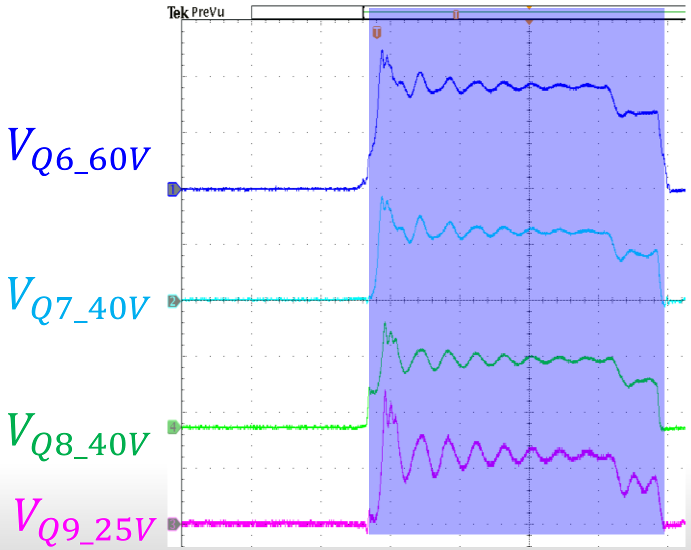




Simplified Equivalent circuit of charging state (blue switch on)



However, in charging state, voltage across on Q6~Q9 will resonant to **over rated voltage**.

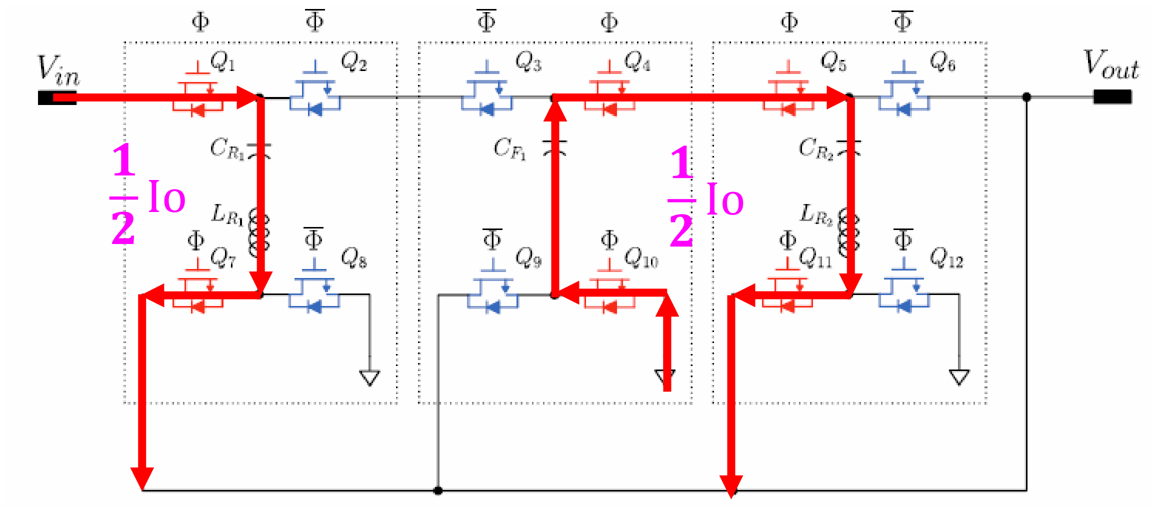


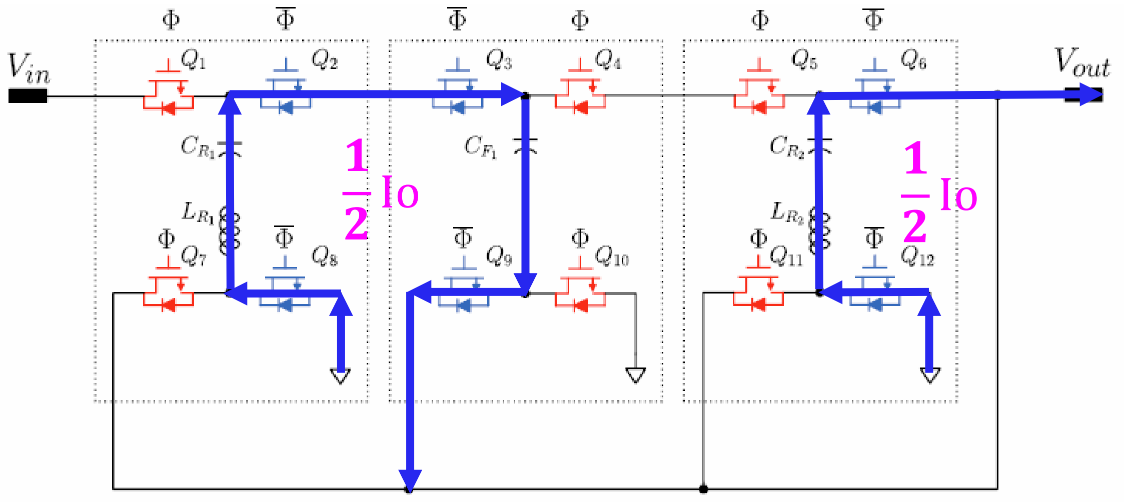
Potential of Resonant Switched Capacitor Converters

- Advantage of STC solution

Google's STC (Dickson)

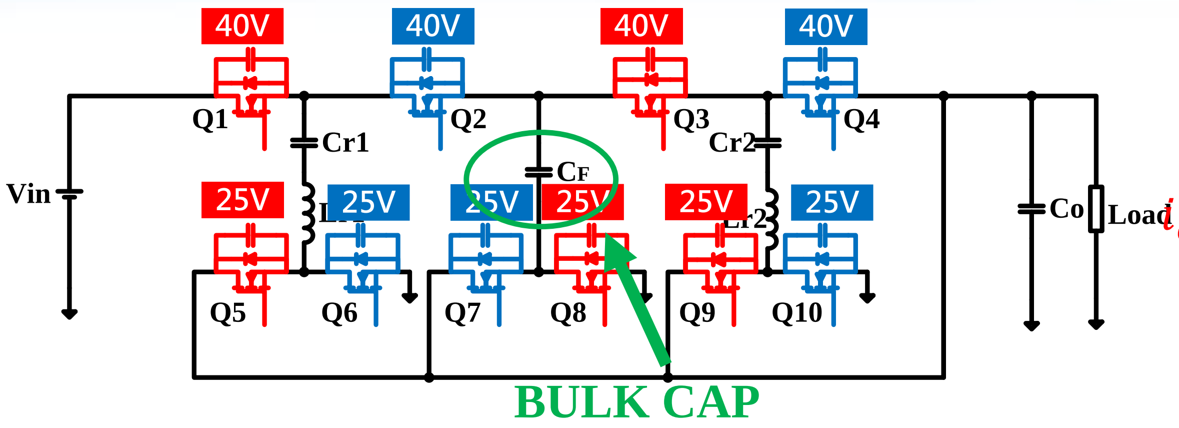
Google STC's Basic Operation Principle

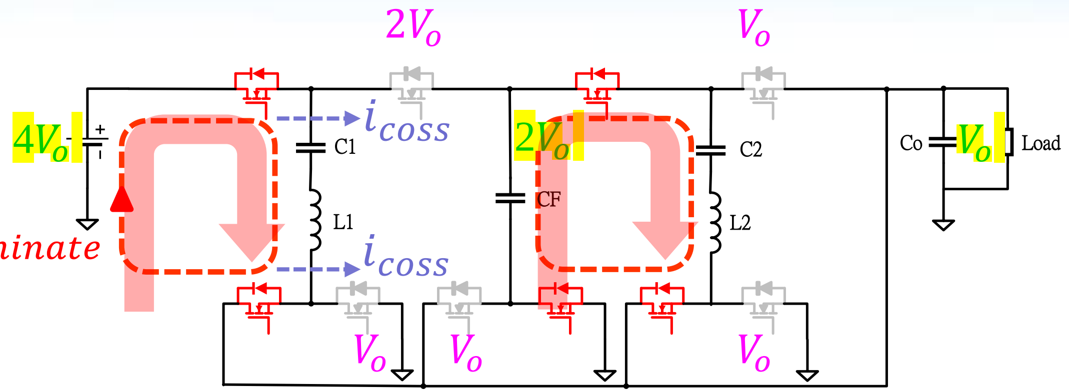




$V_{CR1\_avg} = 3V_{out}$ $V_{CF2\_avg} = 2V_{out}$ $V_{CR2\_avg} = 1V_{out}$

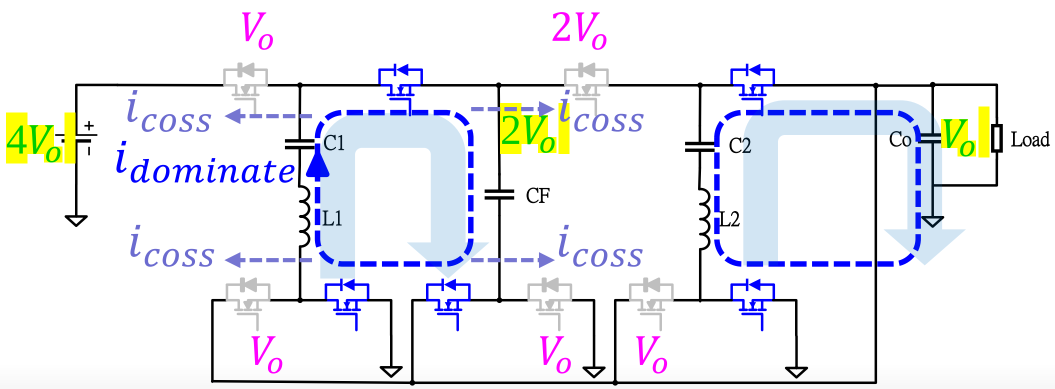
- Stores energy for the resonant capacitor and provides energy to the output by the power supply through the resonant inductor
- The resonant capacitor releases energy, and the resonant capacitor provides energy to the output load through the resonant inductor.





Charging state (red switch on)

- C_F provide a stable voltage to clamp switches voltage stress.
- Due to considering the non-ZCS condition , voltage stress of switches Q1 to Q4 are chose 40V and the others are 25V.



Discharging state (blue switch on)

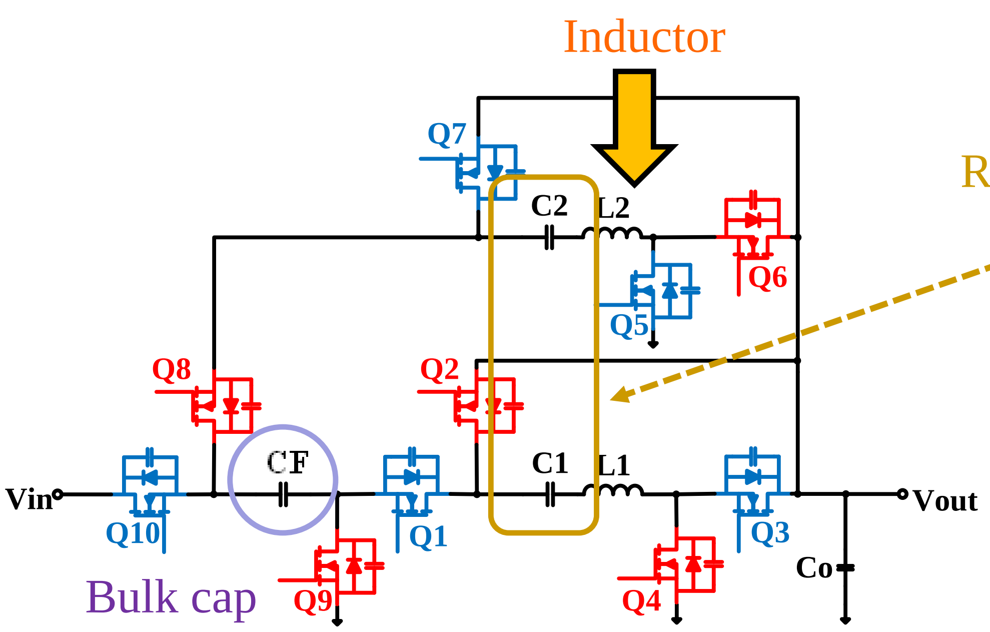
Although the bulk capacitor occupies a larger area, it can provide all switches that are always automatically clamped.

Potential of Resonant Switched Capacitor Converters

- This work (cooperation with Richtek)

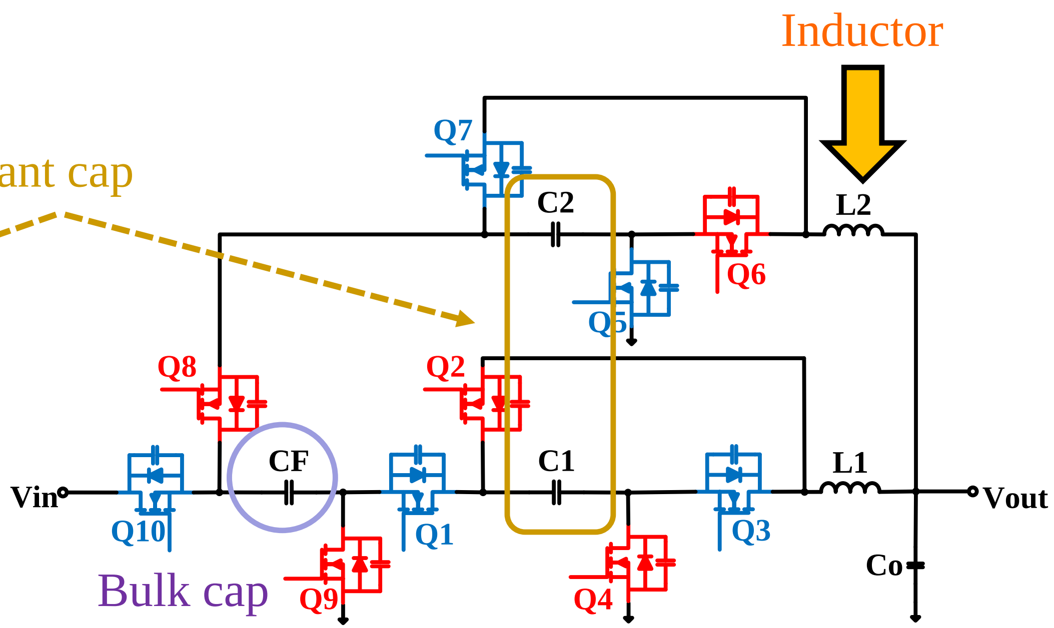
Introduction of RSCC-1 and RSCC-2

- RSCC-1: The inductors are series with resonant capacitors.
- RSCC-2: The inductors are placed on the output side.
- Both of resonant tank and switches are fully clamped by bulk cap (CF), similar to STC.



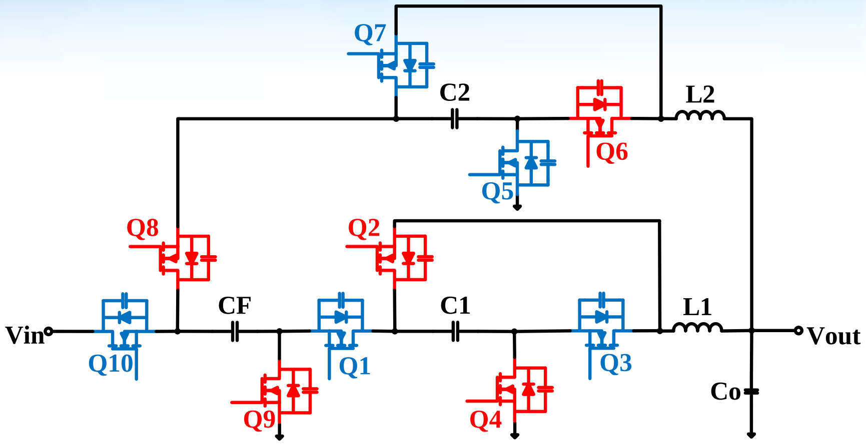
Circuit schematic diagram of **RSCC-1**

Resonant cap



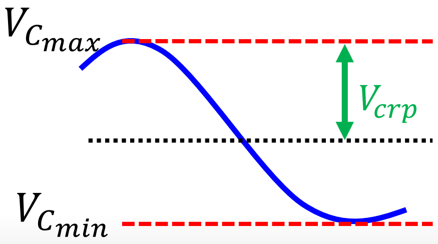
Circuit schematic diagram of **RSCC-2**

Voltage Stress of Switch of RSCC-2

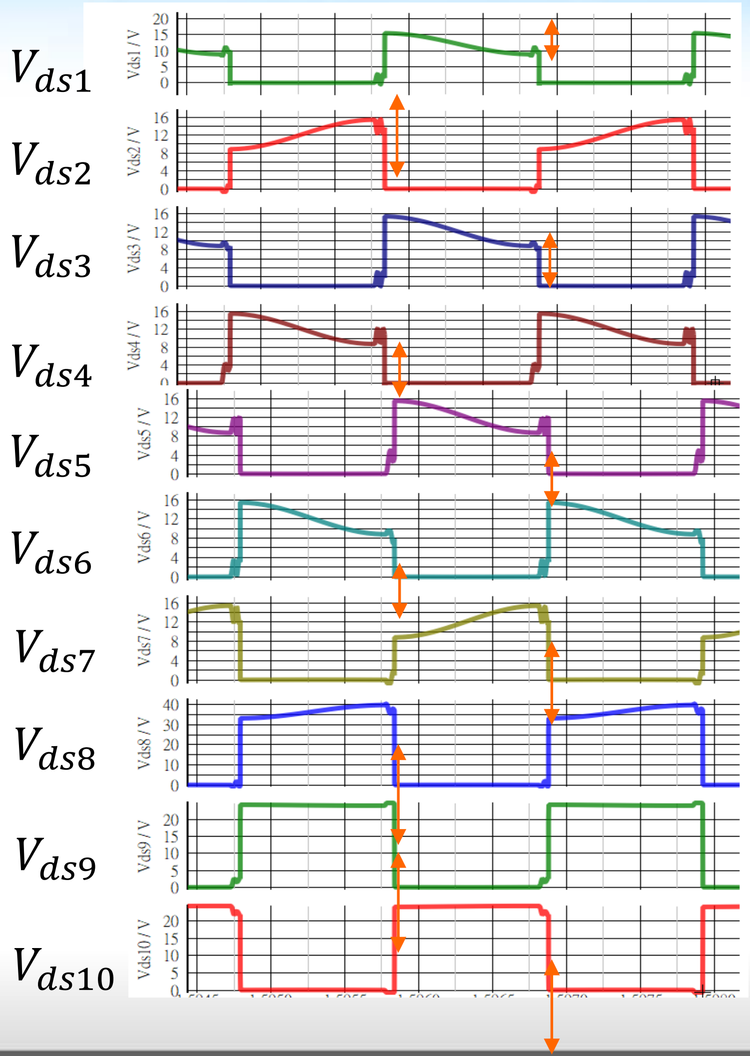


Circuit schematic diagram of RSCC-2

- Since the voltage ripple of capacitor of RSCC-2 is not shielded by the inductor, the voltage stress of switch will be affected by the inductor and capacitor voltage.



Although voltage stress will be affected by the inductor and capacitor voltage, it can be designed.



$V_{ds1(off)} = V_o - V_{crp}$

$V_{ds2(off)} = V_o + V_{crp}$

$V_{ds3(off)} = V_o - V_{crp}$

$V_{ds4(off)} = V_o - V_{crp}$

$V_{ds5(off)} = V_o - V_{crp}$

$V_{ds6(off)} = V_o - V_{crp}$

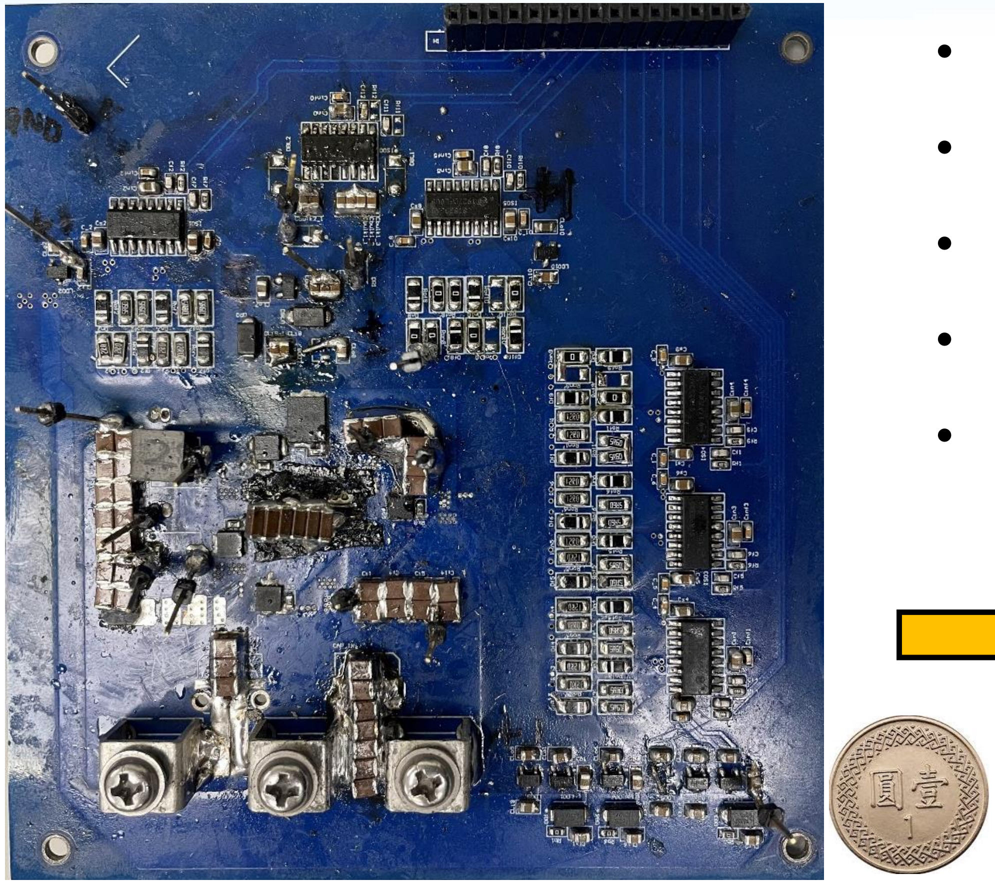
$V_{ds7(off)} = V_o + V_{crp}$

$V_{ds8(off)} = V_o + V_{crp}$

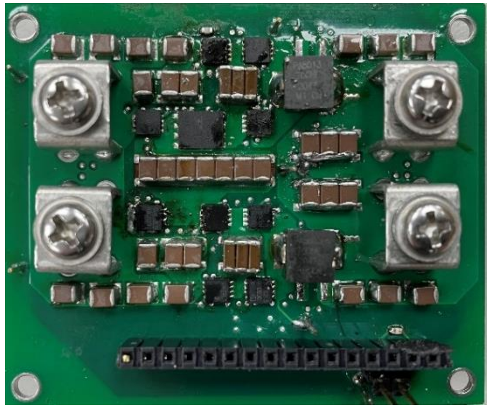
$V_{ds9(off)} = 2V_o$

$V_{ds10(off)} = 2V_o$

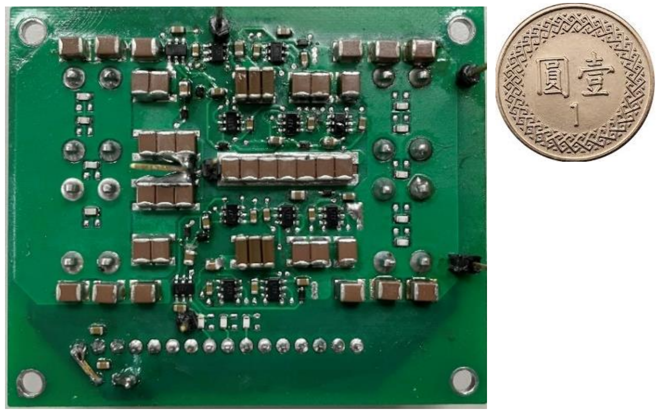
- Power stage and driver stage are combined into 5.2cm × 3.2cm.
- With a six-layer board, sufficient current stress is available.
- Low parasitic inductance and reduced trace resistance.
- Conduction losses due to trace resistance reduced.
- The optimized version is shown below.



TOP VIEW (1^{st} version), 10 layers



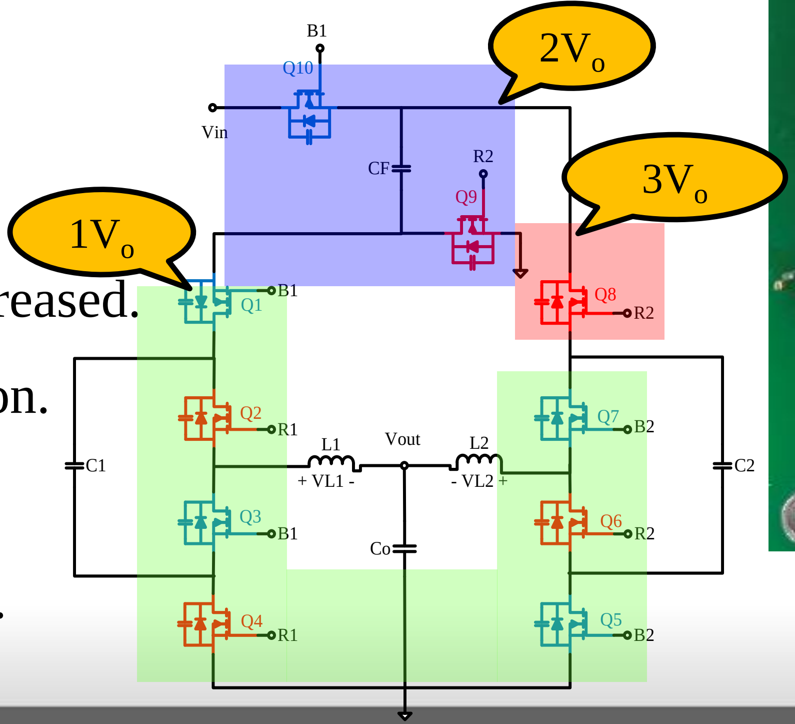
TOP VIEW

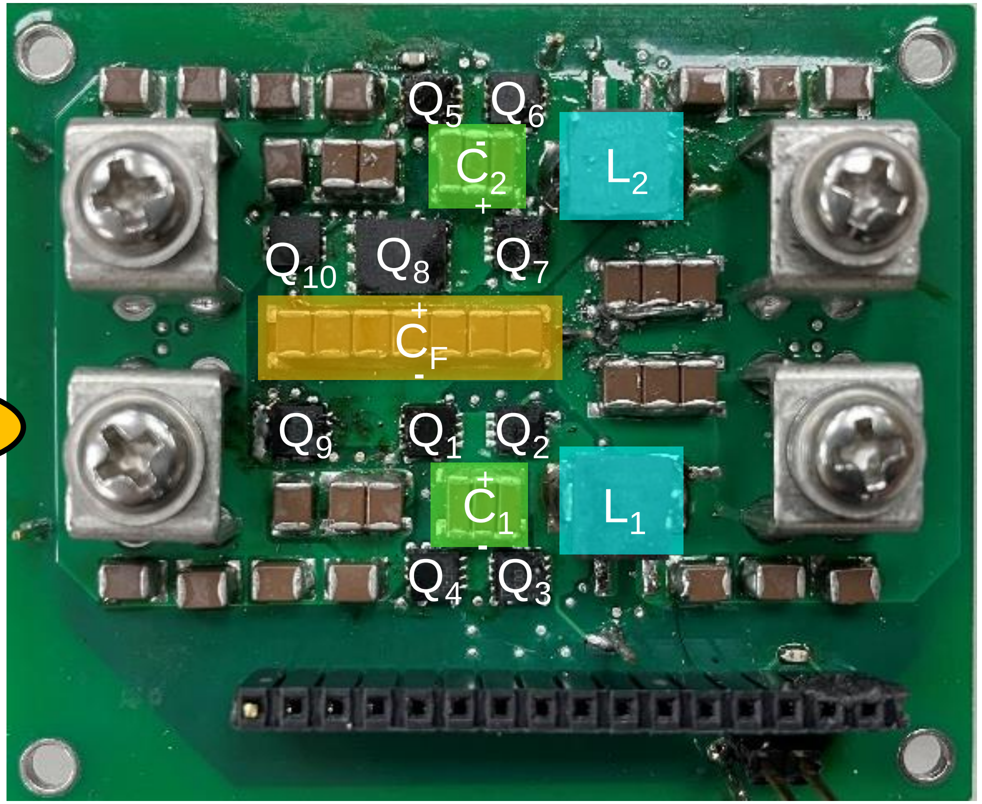


BOTTOM VIEW

- The test results confirmed that the optimized version greatly reduced the voltage spikes of the switches.
- The switching voltage stress shown in the figure can be used.
- The resonant tanks are symmetrical and nearly equal in length.
  - Charging C_F : Q_{10} , Q_1 , Q_3
  - Discharging C_F : Q_9 , Q_8 , Q_6
  - Discharging C_1 : Q_4 , Q_2
  - Discharging C_2 : Q_5 , Q_7
- Switching frequency can be increased.
- Improve effective duty utilization.
- Conduction loss improved

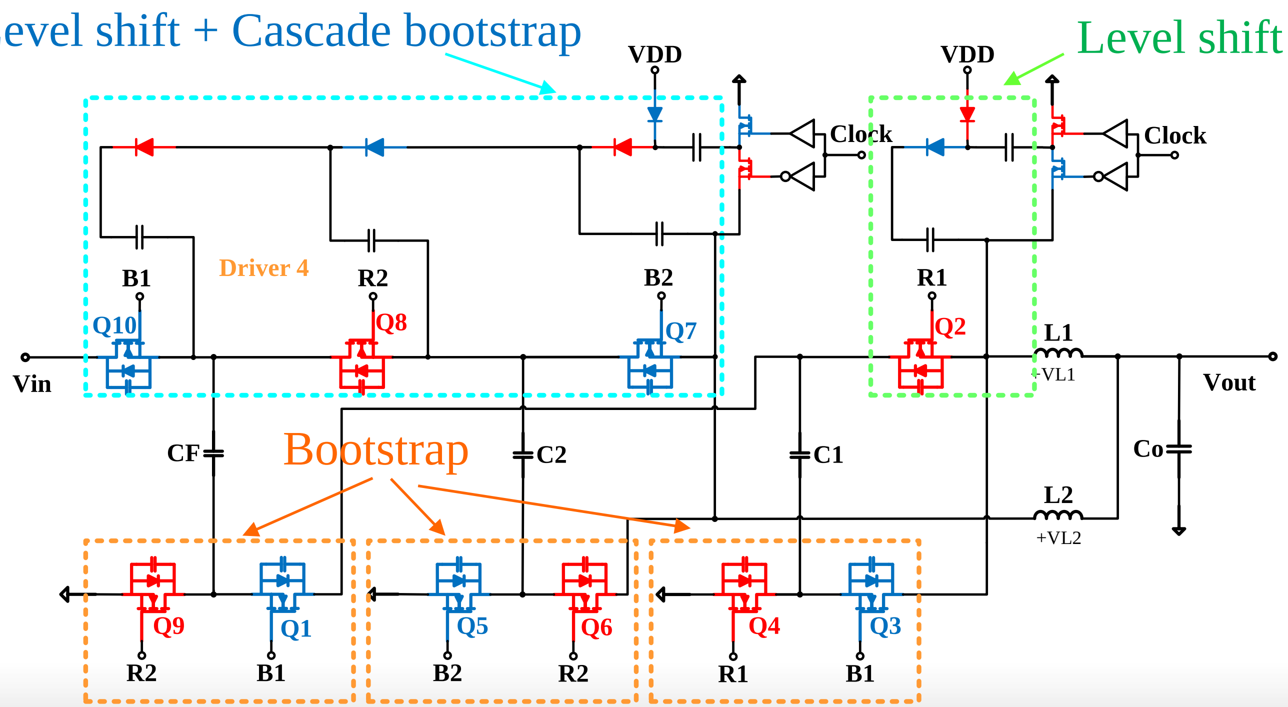
  due to decrease of RMS current.

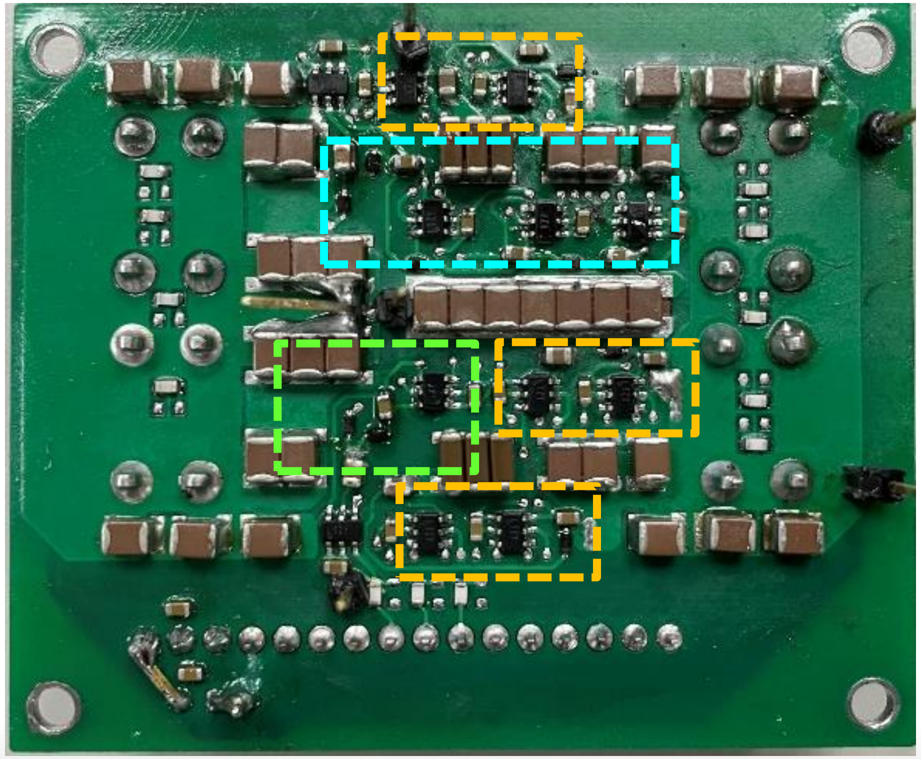




TOP VIEW (Power stage)

- The gate drive voltage is provided by an external 15V power supply and the LDO is removed.
- Use Schottky diode to reduce voltage drop during cascaded transmission.



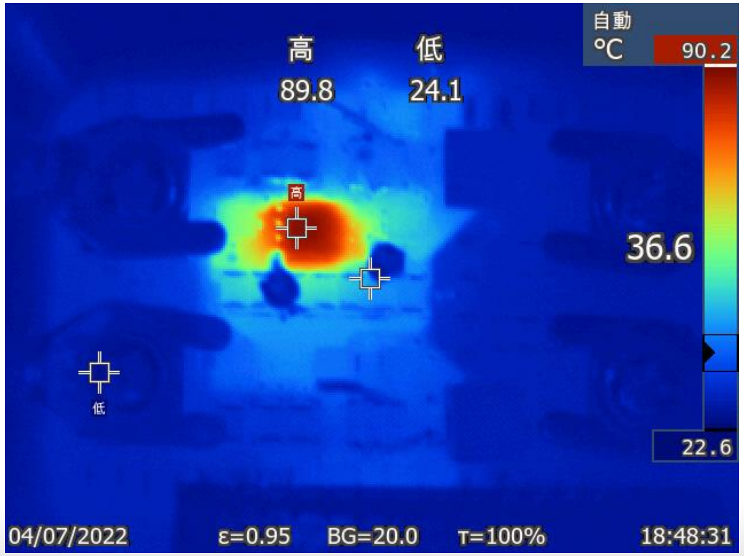


BOTTOM VIEW (Driver stage)

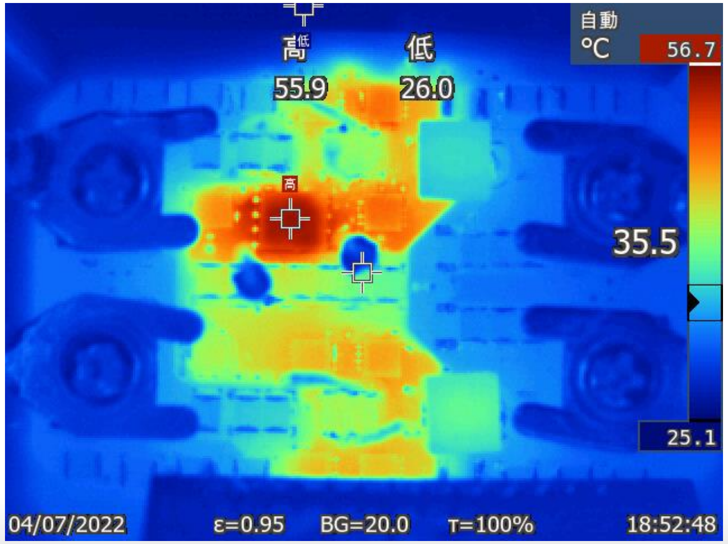
- Test condition : V_{in} = 48 V; V_{out} = 12 V; f_{sw} = 311k Hz
- t_r and t_f of the $3V_o$ switch are large than other switches, which causes the temperature of Q8 to be very high.

Switches	$3V_o$	$2V_o$	V_o
Turn-on delay time (ns)	11	7.1	5.3
Rise time (ns)	15	3.6	2.6
Turn-off delay time (ns)	54	21	27
Fall time (ns)	31	4.9	5.3

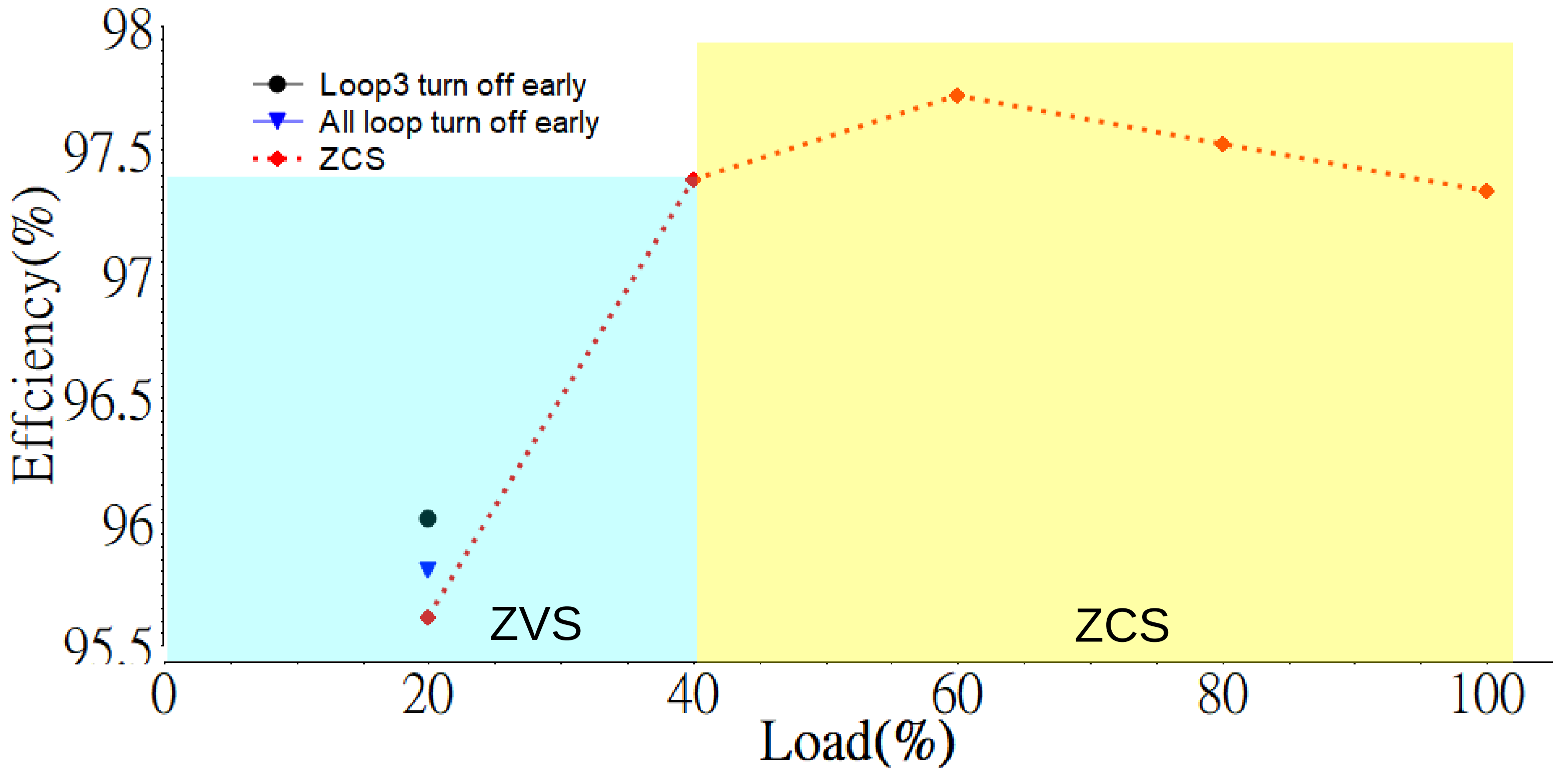
Light Load: 10 A



Full Load: 50 A



- Under light load, turning off early to let loop3 reach ZVS can reduce Q8 switching loss so that improve efficiency, Under heavy load, using ZCS can reduce conduction loss, The best point needs to be found by fine-tune.



Efficiency Comparison

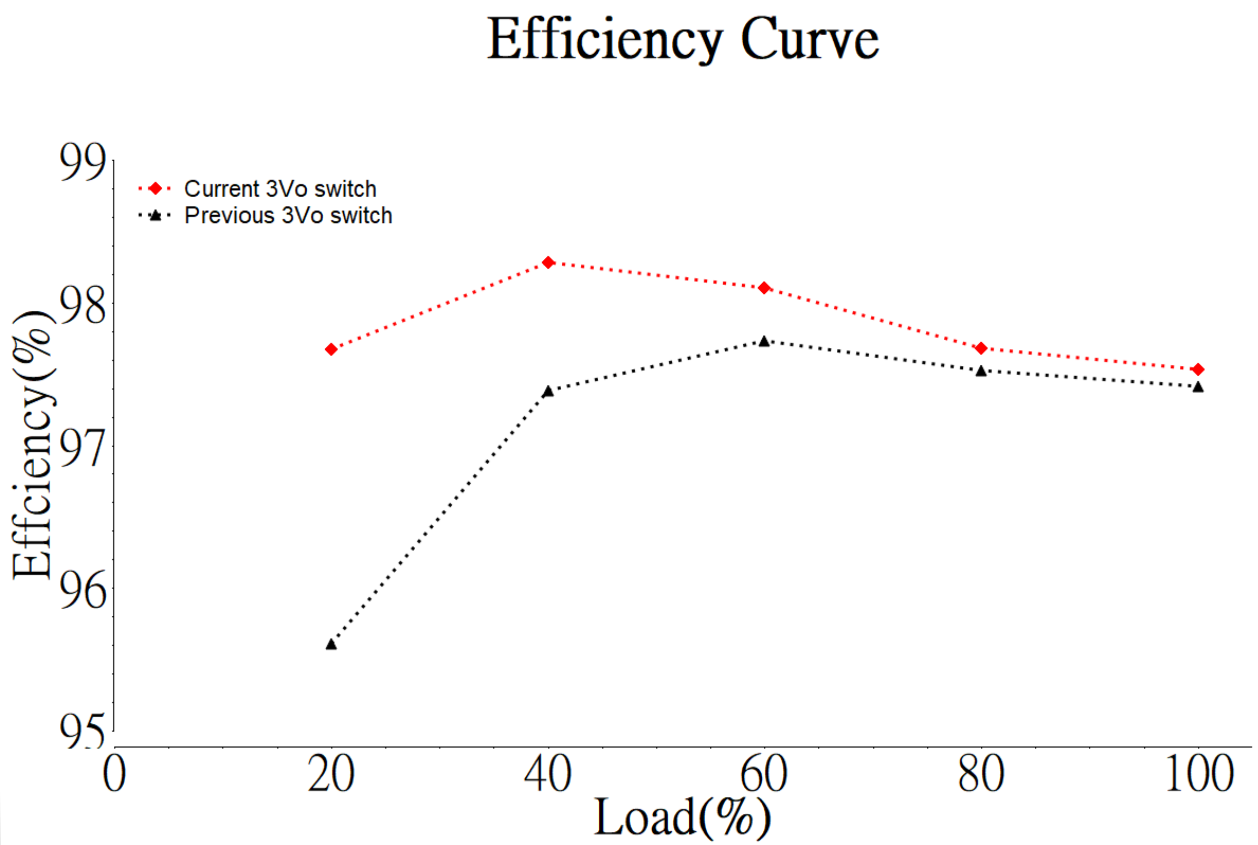
- Test condition : V_{in} = 48 V; V_{out} = 12 V; f_{sw} = 311k Hz
- After replacing the $3V_o$ switch with a lower C_{oss} and Q_g switch, the light-load efficiency has been significantly improved, and the peak efficiency reached 98.3%

Efficiency (Current $3V_o$ switch)

V_{in}(V)	I_{in}(A)	V_O(V)	I_O(A)	Load(%)	Efficiency(%)
48.04	2.54	11.94	10	20	97.67
48.05	5.03	11.89	20	40	98.29
48.03	7.52	11.82	30	60	98.10
48.02	10.04	11.77	40	80	97.68
48.03	12.52	11.73	50	100	97.53

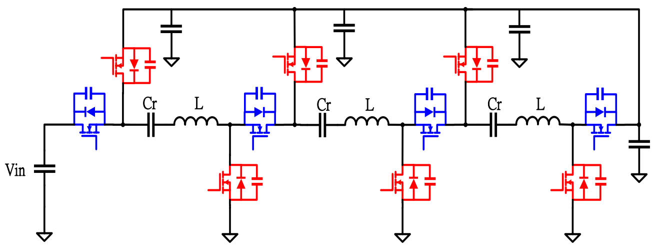
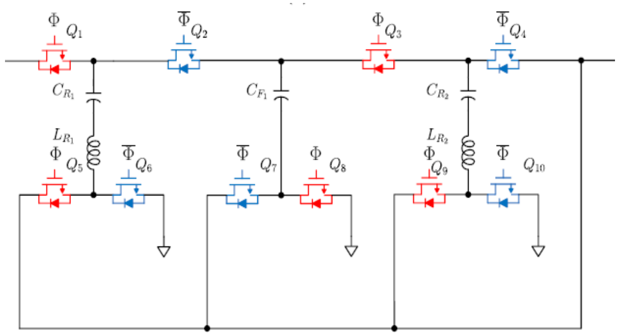
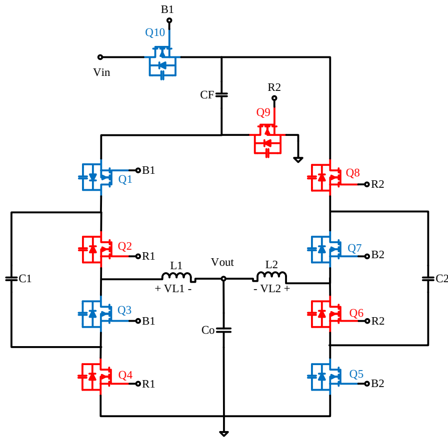
Efficiency (Previous $3V_o$ switch)

V_{in}(V)	I_{in}(A)	V_O(V)	I_O(A)	Load(%)	Efficiency(%)
48.01	2.61	11.98	10	20	95.61
48.01	5.10	11.92	20	40	97.38
48.03	7.58	11.86	30	60	97.73
48.00	10.06	11.79	40	80	97.52
48.00	12.58	11.77	50	100	97.41

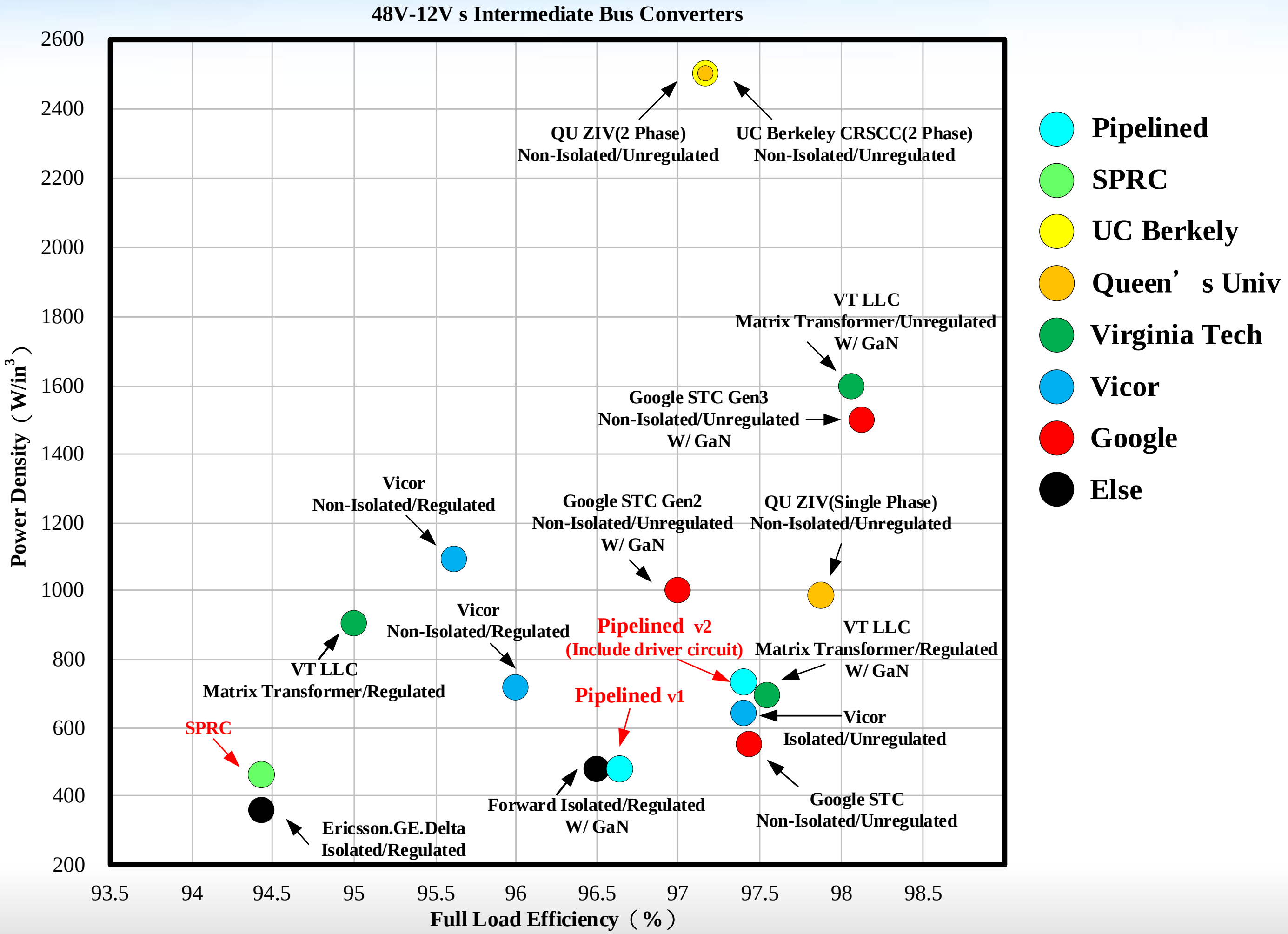


Comparison of Resonant Switched Capacitor Converter (RSCC)

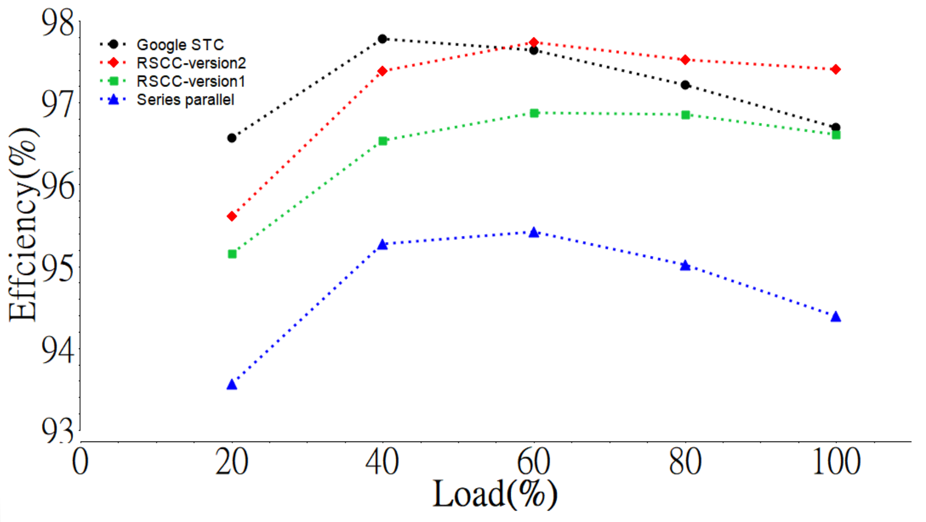
- Compare with matrix transformer, RSCC has lower PCB layout complexity
- Topologies have great scalability for output voltage.
- Minimizes RMS current on components by operating with a symmetric 50% duty cycle and resonant frequency.
- Drive signals and their circuits can be integrated through IC design.

	Series-Parallel	STC	Pipelined RSCC
schematic			
Switch	3 ($3V_O$), 2 ($2V_O$) , 5 ($1V_O$)	4 ($2V_O$) , 6 ($1V_O$)	1 ($3V_O$), 2 ($2V_O$), 7 ($1V_O$)
Inductor	3 (Series)	2 (Series)	2 (Series or locate at output)
Resonant cap	3 ($1V_O$)	2 ($3V_O$) & ($1V_O$)	2 ($1V_O$)
Non resonant cap	-	1 ($2V_O$) clamped	1 ($2V_O$) clamped

Comparison of Existing Intermediate Bus Converters and RSCCs



- We have prototyped Series-Parallel, STC, and Pipelined RSCC, and the efficiency and power density can be further optimized.
- 48V to 12V/50A with peak and full load efficiencies of 98.3% and 97.6%, respectively.
- The pipelined RSCC power density includes the driver circuit area and the results are marked on the graph.

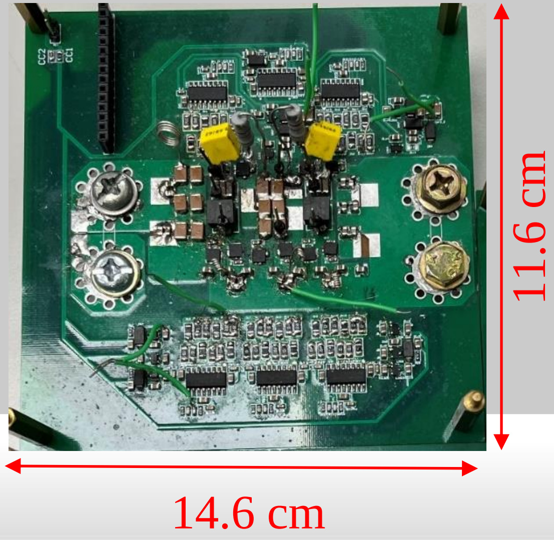
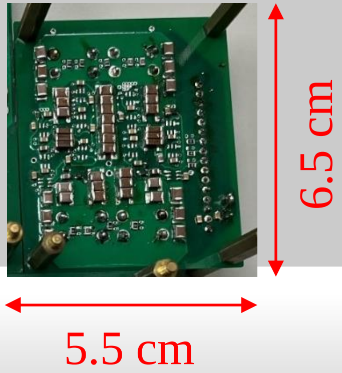
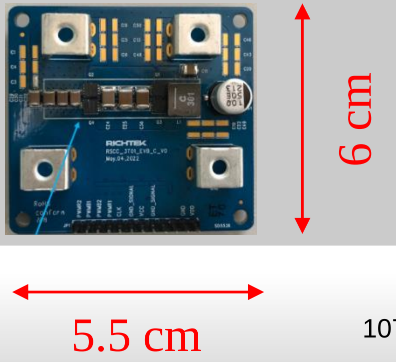


Voltage Regulation, High Power Efficiency, and Power Density

- Three-level buck is chosen to deal with the high efficiency and power density of RSCC to achieve the function of output voltage regulation.
- The efficiency of both is expected to reach 98% respectively.

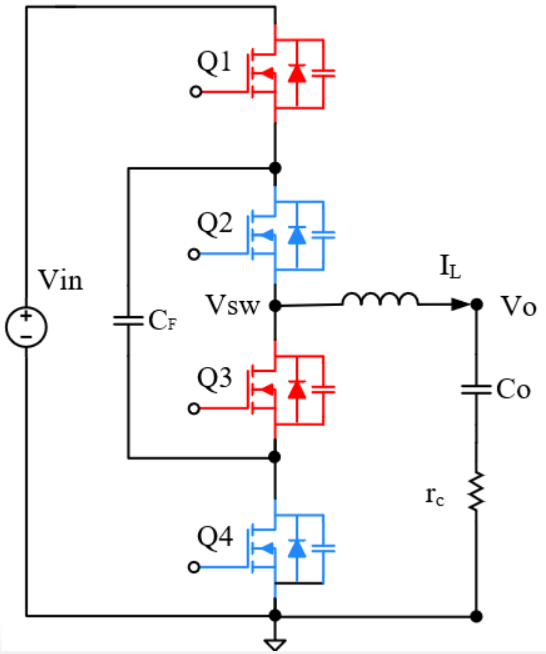
Revolution of Implemented Prototype

- Prototypes of RSCC and Three-Level buck can be further optimized.

Series-Parallel	STC	Pipelined RSCC	Three-Level Buck
			

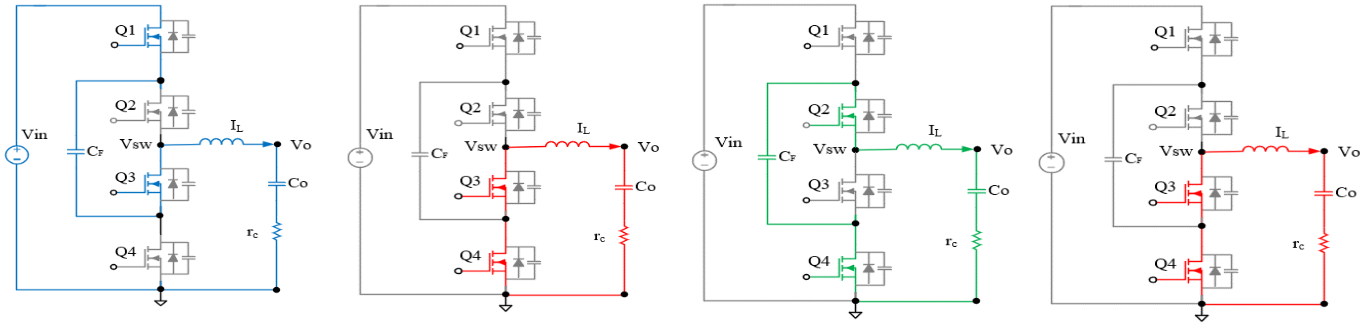
Three-Level Buck Topology

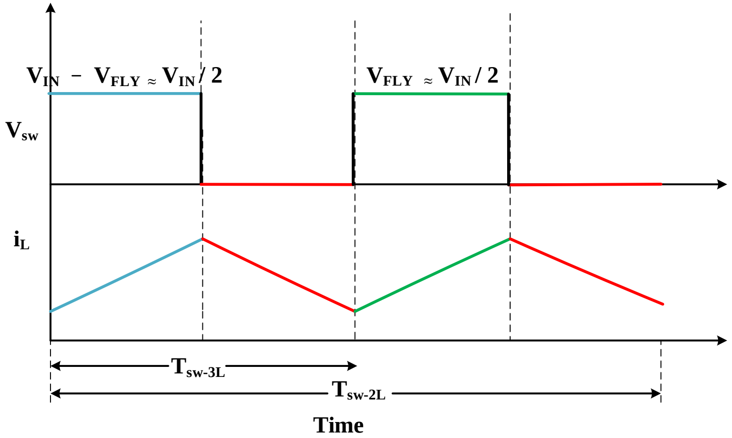
- The topology has two extra MOSFETs and one extra capacitor compared to the traditional two-level buck. The flying capacitor stores $1/2V_{in}$ can reduce the switch voltage rating, and acts as a second source while being discharged.
- Transfer function $V_o/V_{in} = D$, just like 2L buck. The complementary signals drive switches Q1 and Q4, and another pair of complementary signals are phase-shifted by 180 degrees to drive Q2 and Q3.



Operation (D<0.5)

- Phase 1, Q1 and Q3 are turned on. Vin charges the flying capacitor, inductor, and output capacitor as well as supplies the load.
- Phase 2, Q3 and Q4 are turned on. The inductor and output capacitor supplies the load.
- Phase 3, Q2 and Q4 are turned on. The energy stored in the flying capacitor charges the inductor and output capacitor as well as supplies the load.
- Phase 4 has the same configuration as Phase 2.

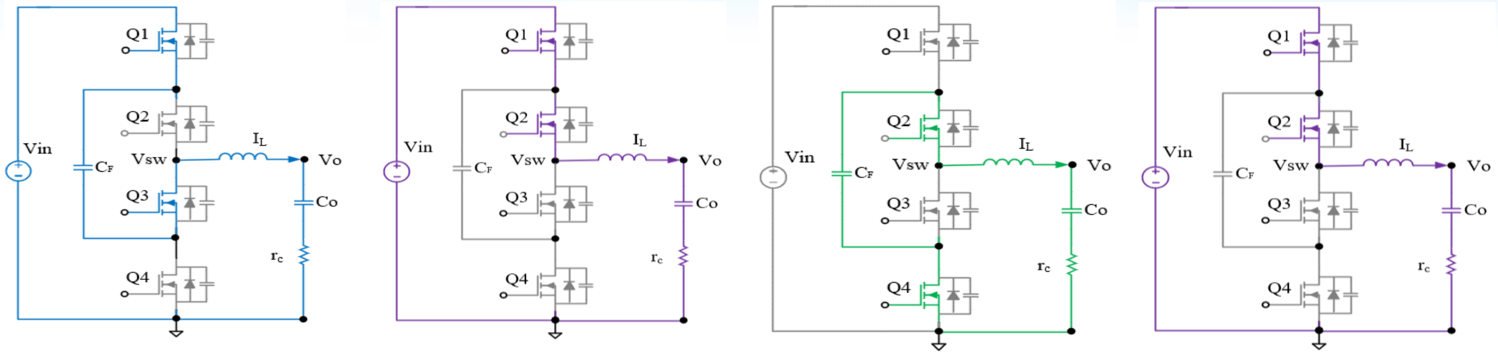


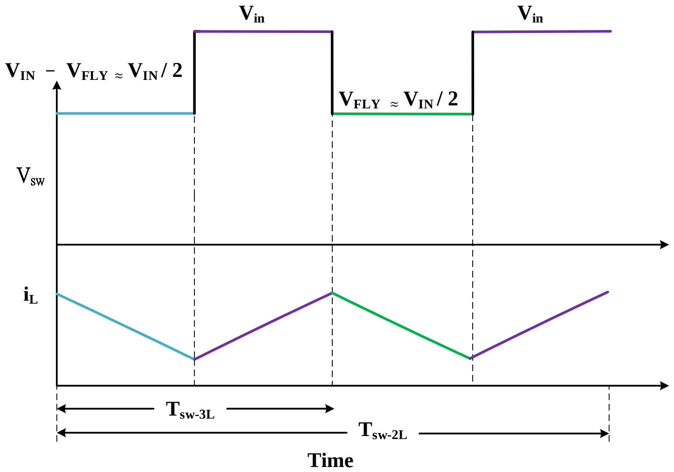


$$DT_s\left(\frac{1}{2}V_{in}-V_o\right)+T_s(0.5-D)(-V_o)+DT_s\left(\frac{1}{2}V_{in}-V_o\right)+T_s(0.5-D)(-V_o)=0 \longrightarrow V_o=DV_{in}$$

Operation (D>0.5)

- Phase 1, Q1 and Q3 are turned on. $V_o>0.5V_{in}$ the inductor discharge.
- Phase 2, Q1 and Q2 are turned on. Vin charges the inductor, and output capacitor as well as supplies the load.
- Phase 3, Q2 and Q4 are turned on. $V_o>0.5V_{in}$ the inductor discharge.
- Phase 4 has the same configuration as Phase 2.





$$T_s(1-D)\left(\frac{1}{2}V_{in}-V_o\right)+T_s(D-0.5)(V_{in}-V_o)+T_s(1-D)\left(\frac{1}{2}V_{in}-V_o\right)+T_s(D-0.5)(V_{in}-V_o)=0 \longrightarrow V_o=DV_{in}$$

Inductor Ripple Current

- C_F as a second source while being discharged, making the effective output ripple frequency two times the MOSFET switching frequency.
- By keeping C_F balanced at $V_{IN}/2$, the three-level converter reduces the volt-seconds across the inductor by half.
- The combination results in a one-quarter reduction in inductor ripple given the same inductor and f_{SW}.
- Smaller inductance and output capacitance can be chosen to reduce total solution size for design requirements.

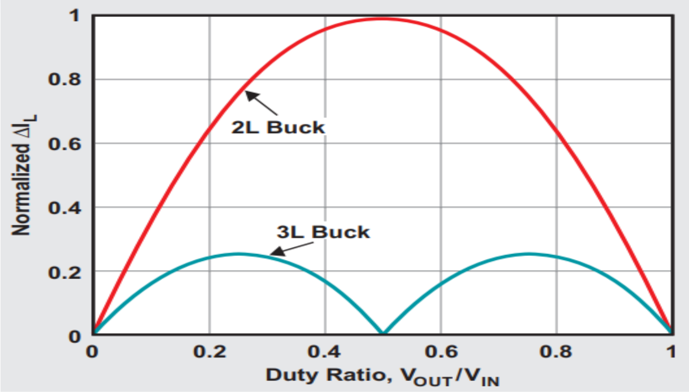


Figure Reference：
Texas Instruments, Maximize power density with three-level buck-switching chargers (2021)

2L Buck：$\Delta I_{L\_2L} = \frac{DT_S V_{in}(1-D)}{L}$ $\quad \Delta I_{L\_2L(max)} = \frac{T_S V_{in}}{4L}, when\ D = 0.5$ $\quad C_{o\_2L} = \frac{\Delta I_L}{8 \cdot \Delta V_o \cdot f_s}$

3L Buck：$\Delta I_{L\_3L} = \frac{DT_S V_{in}(0.5-D)}{L}$ $\quad \Delta I_{L\_3L(max)} = \frac{T_S V_{in}}{16L}, when\ D = 0.25$ $\quad C_{o\_3L} = \frac{\Delta I_L}{16 \cdot \Delta V_o \cdot f_s}$

3L Buck：$\Delta I_{L\_3L} = \frac{T_S V_{in}(1-D)(D-0.5)}{L}$ $\quad \Delta I_{L\_3L(max)} = \frac{T_S V_{in}}{16L}, when\ D = 0.75$ $\quad C_{o\_3L} = \frac{\Delta I_L}{16 \cdot \Delta V_o \cdot f_s}$

Component Design

- The maximum inductor current ripple occurs at duty=0.25 or 0.75, selecting duty=0.25 to design component.
- Design condition：D=0.25; $V_{in(max)}$=54V; $V_{CF(max)}$=27V ;V_o=13.5V; I_o=25A; ΔI_L=5A; ΔV_o=0.135V

Item	Value
Input Voltage (V)	**24~54**
Output Voltage (V)	**3~24**
I_L Ripple (A)	**$0.2*I_{o(max)}$**
V_{CF} Ripple(V)	**$0.1*V_{CF(max)}$**
V_o Ripple (V)	**$0.01*V_o$**
Switching Frequency (Hz)	**240k**
Max Output Current (A)	**25**
Output Power (W)	**600**

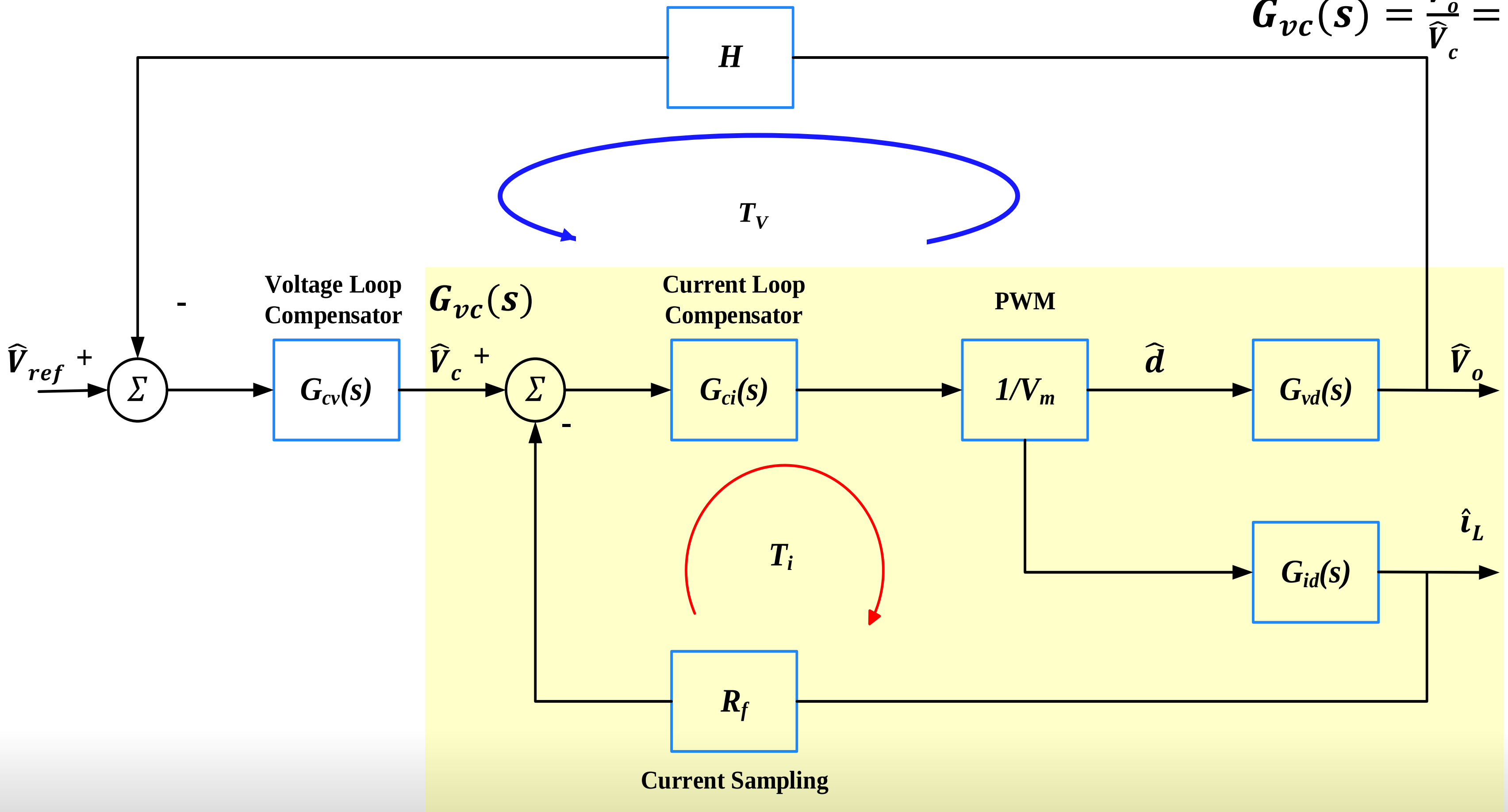
$$L = \frac{V_{in} \cdot (0.5 - D) \cdot D}{\Delta I_L \cdot f_s} = 2.8\mu H$$

$$C_F = \frac{D \cdot I_o}{\Delta V_{CF} \cdot f_s} = 4.82\ \mu F$$

Small Signal Model of Average Current Mode Control (ACM)

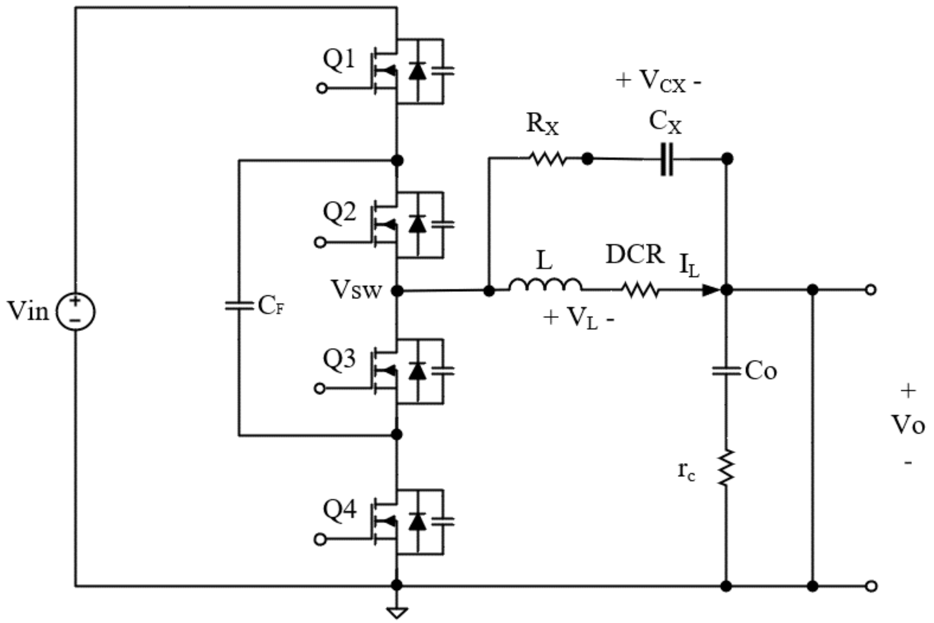
- Outer voltage loop gain ：$T_v = HG_{cv}G_{vc}$
- Inner current loop gain ：$T_i = R_f G_{ci} \frac{1}{V_m} G_{id}$

$$G_{vc}(s) = \frac{\hat{V}_o}{\hat{V}_c} = G_{ci}(s)\frac{1}{V_m}G_{vd}(s)\frac{1}{1+T_i}$$



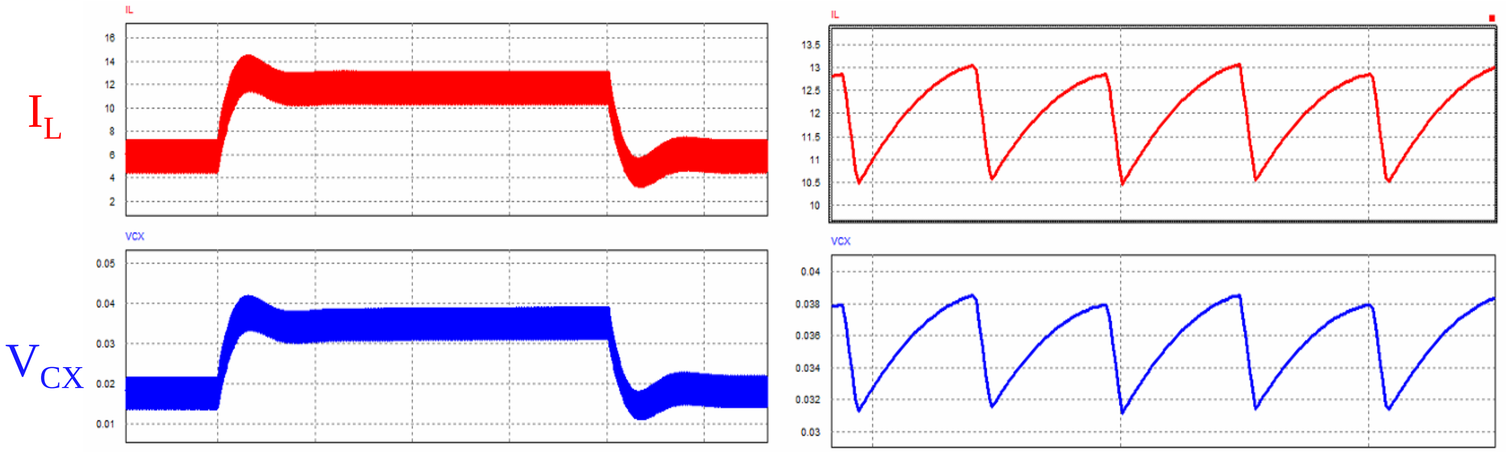
Design and Simulation

- Determined parameters of L and C_X, then R_X can be calculated.
- From the simulation, it can be seen that V_{CX} equals I_L * DCR.



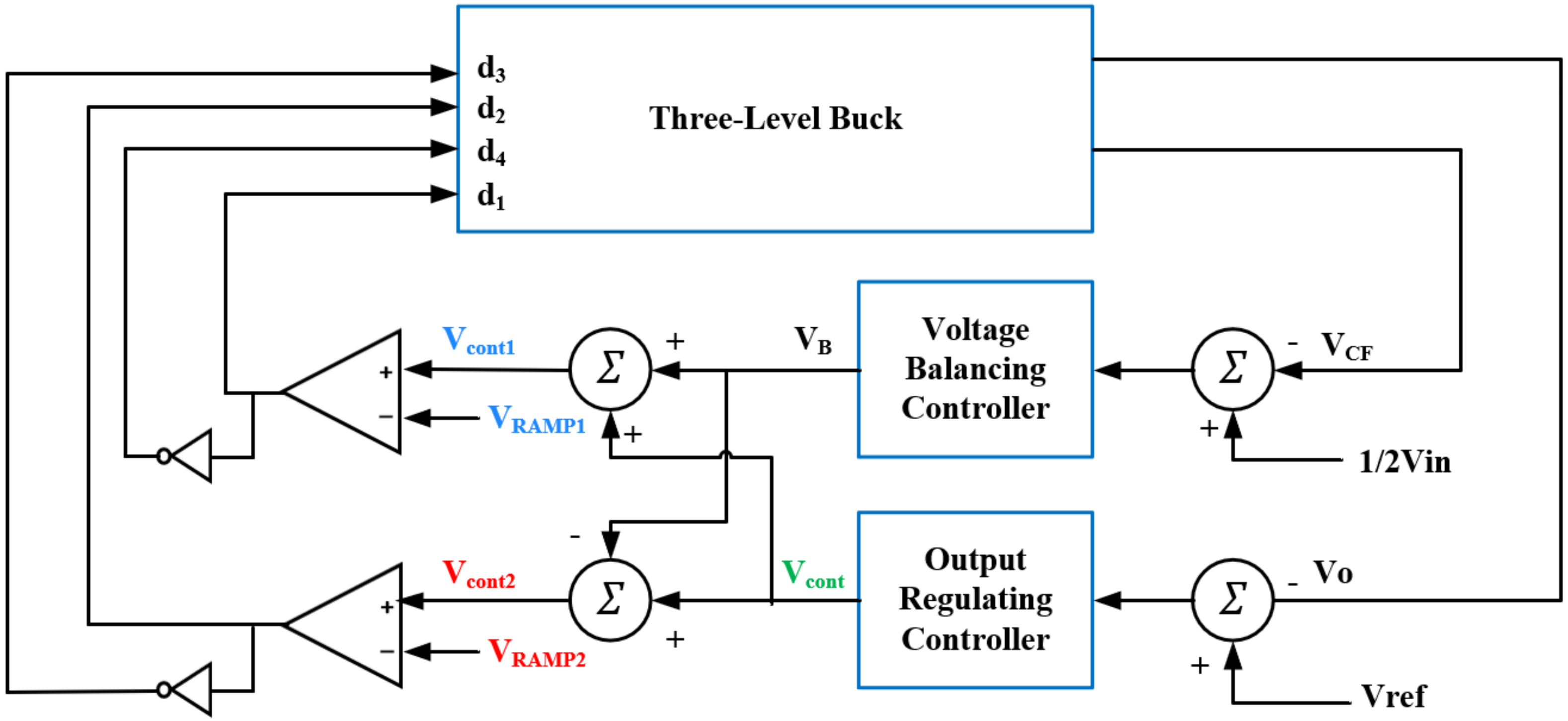
$$L = 2.2\mu H\,;DCR = 2.8m\Omega\,;C_X = 1\mu F$$

$$R_X = \frac{L}{DCR}/C_X = 786\Omega$$

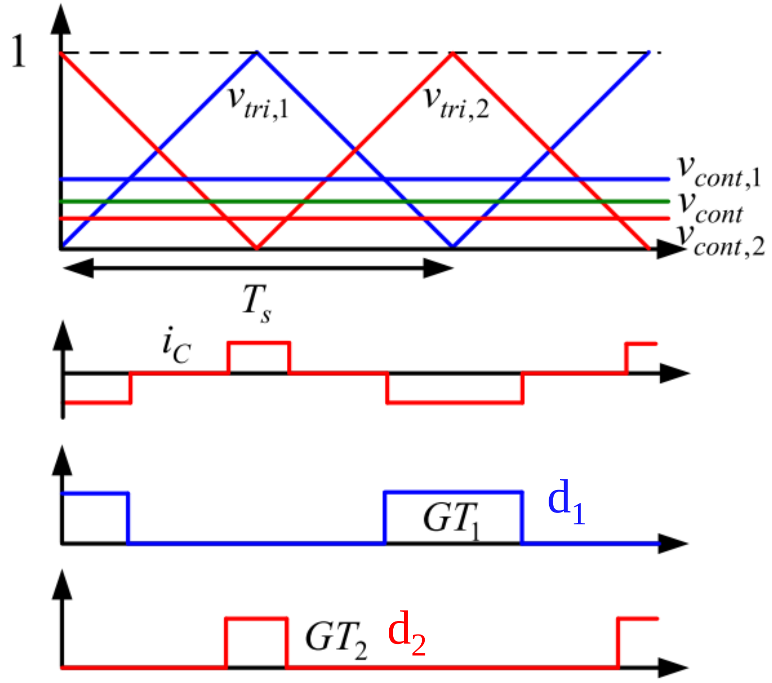


Three-Level Buck Control Scheme with Flying Capacitor V_{CF} Balancing

- Combine two control loops to handle the three-level buck, the output voltage regulating control loop and the flying capacitor voltage balancing control loop.
- V_{cont} as an adjusted duty reference, plus balancing control single V_B generates V_{cont1} and minus V_B generates V_{cont2}.



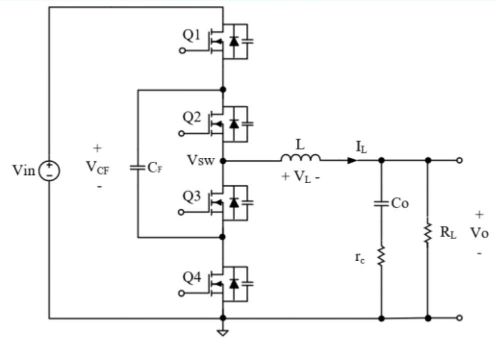
Example Condition: V_{CF}<1/2V_{in}



Reference：
Active Capacitor Voltage Balancing Control for Three-Level Flying Capacitor Boost Converter Based on Average-Behavior Circuit Model;
Hung-Chi Chen, Che-Yu Lu, Wei-Hsiang Lien, and Tien-Hung Chen(2019)

Load Transient for Voltage Balance Testing

- The load transient from 0A to 4A within 10 μs, testing the voltage balance function.
- When V_{CF} overshoot or undershoot occurs, it will return to 1/2Vin in about 200ms



Test condition：

$V_{in} = 12V$; $V_o = 9V$; $D = 75\%$; $f_{sw} = 240$ kHz;

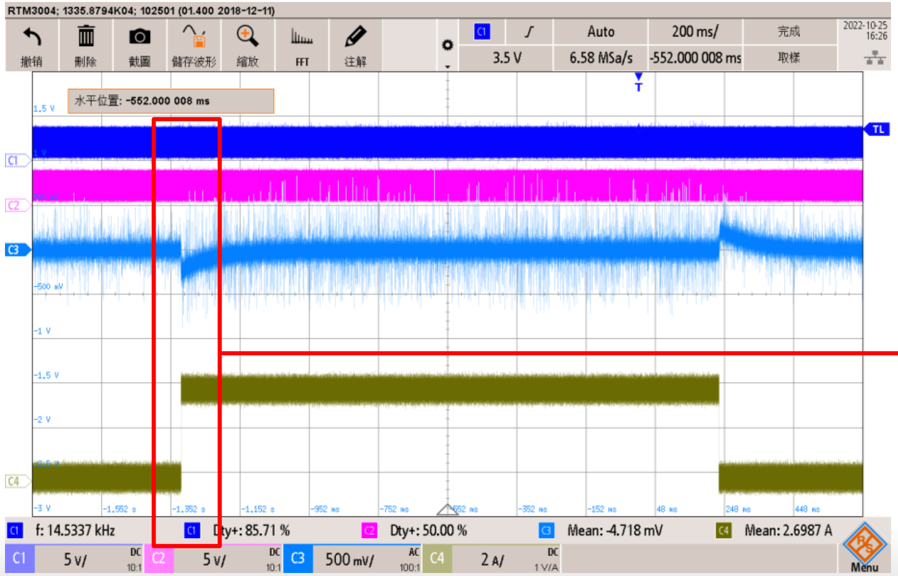
$I_O = 0A\text{-}4A/10\mu s$

Result：

Charging cycle $D_1 = 75.31\ \%$;

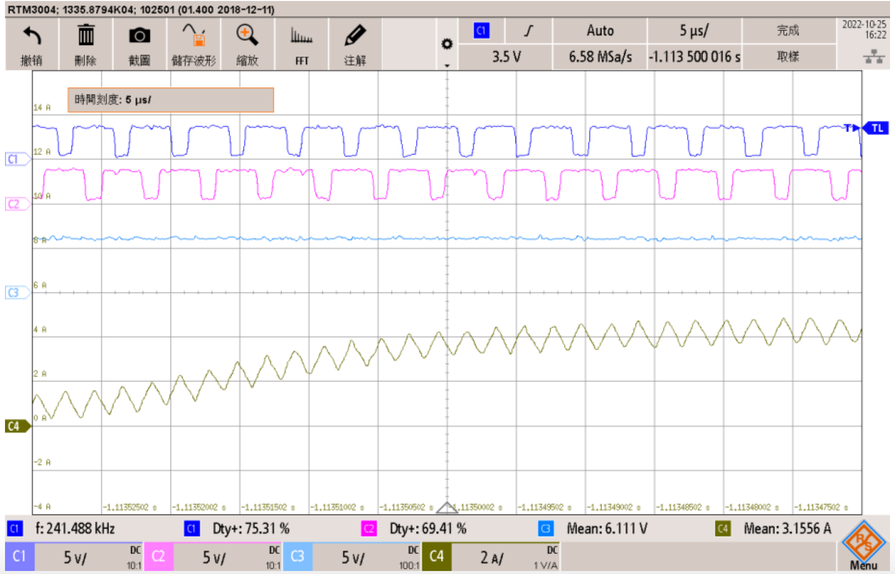
Discharge cycle $D_2 = 69.41\ \%$

Q1
Q2
V_{CF}
I_L



Zoom in

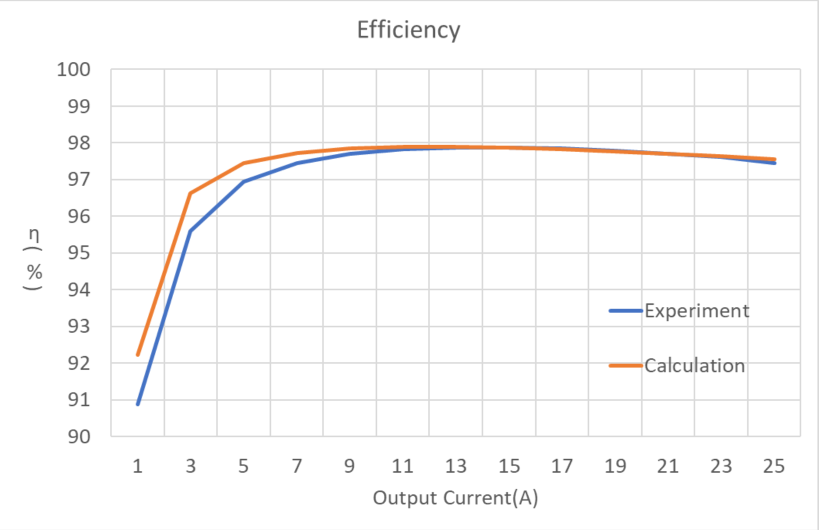
Q1
Q2
V_{CF}
I_L

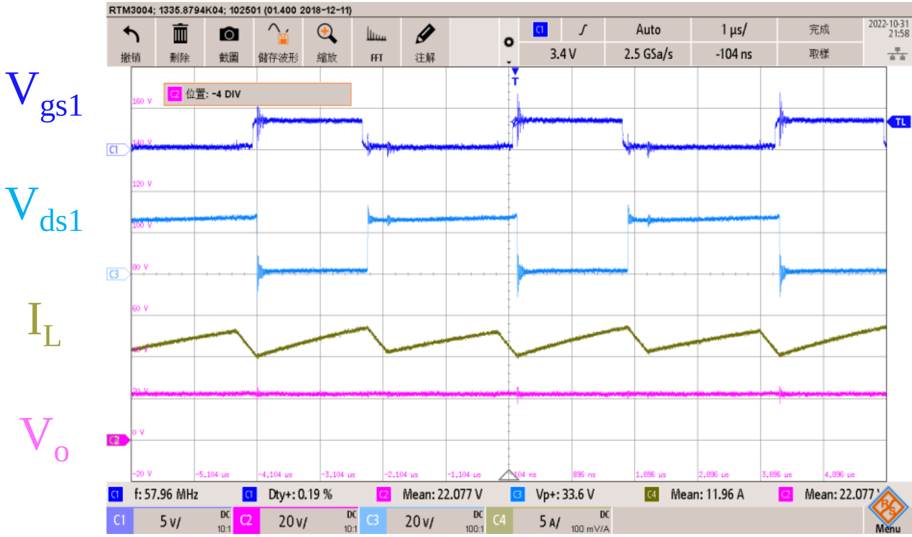


Efficiency Measurement (48V to 20V)

V_{in}(V)	V_O(V)	I_O(A)	Efficiency(%)	
			Exp	*Cal*
48.09	20.56	1	90.88	92.23
48.07	20.42	3	95.60	96.63
48.04	20.38	5	96.95	97.44
48.01	20.29	7	97.44	97.73
47.99	20.23	9	97.70	97.85
47.96	20.19	11	97.83	97.89
47.93	20.15	13	97.88	97.89
47.87	20.11	15	97.88	97.86
47.85	20.08	17	97.85	97.83
47.82	20.03	19	97.79	97.77
47.80	19.99	21	97.71	97.71
47.77	19.95	23	97.61	97.64
47.74	19.89	25	97.44	97.56

- Test condition : V_{in} = 48 V; V_o = 20 V; D = 41.7%; f_{sw} = 240 kHz
- $V_{ds(max)}$ of Q1 is 34V, spike is about 10V and didn't over the voltage stress 80V.
- Peak efficiency is 97.88% at load 13A~15A.





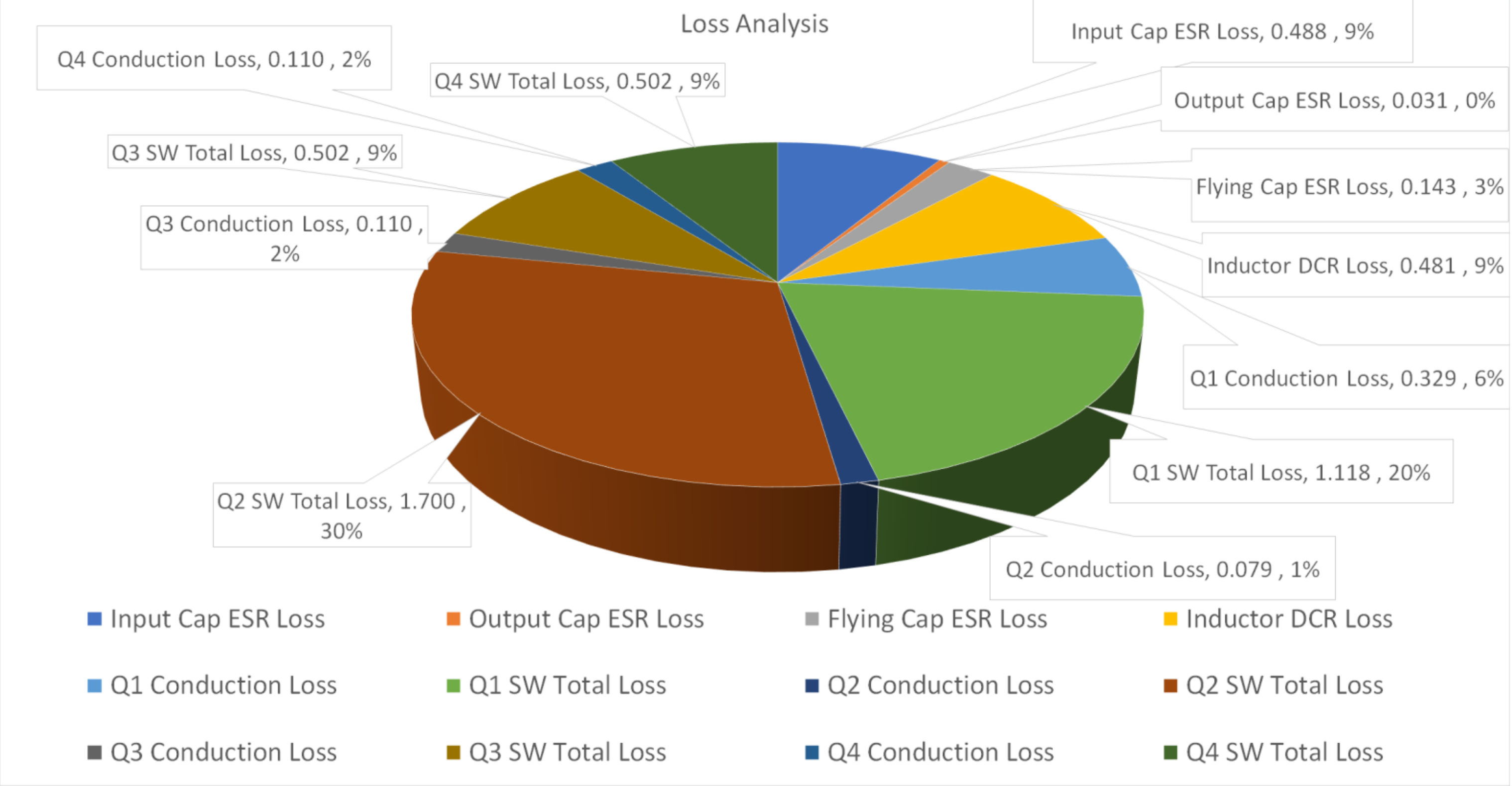
Test condition: I_o=12A

48Vin/ 20Vout Loss Distribution @Peak Efficiency

- Switching loss is a major part of the total loss because of hard switching.

V_{in}(V)	V_O(V)	I_O(A)	Efficiency(%)	Loss(W)
47.93	20.15	13	97.88	5.67

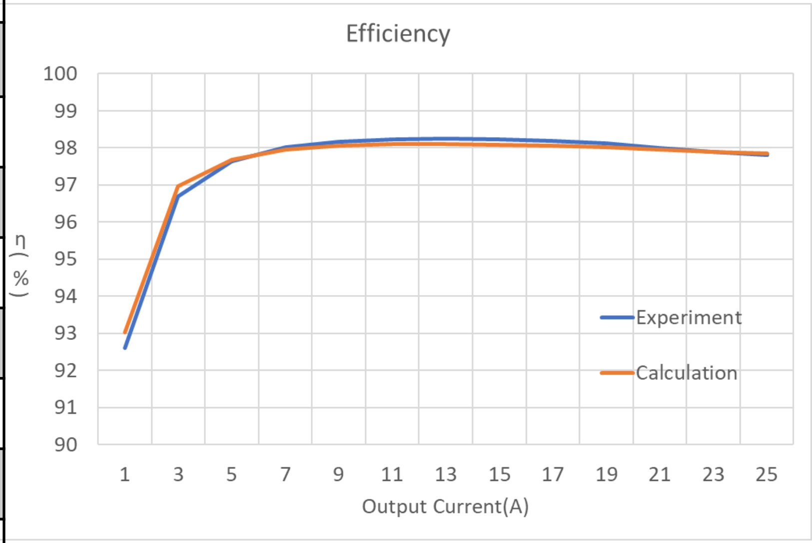
Loss Item	Loss(W)	Proportion(%)
MOS Switching	3.822 W	68.33 %
Capacitors Conduction	0.662 W	11.83 %
MOS Conduction	0.628 W	11.23 %
Inductor Conduction	0.481 W	8.60 %
Total Loss	5.593 W	100%

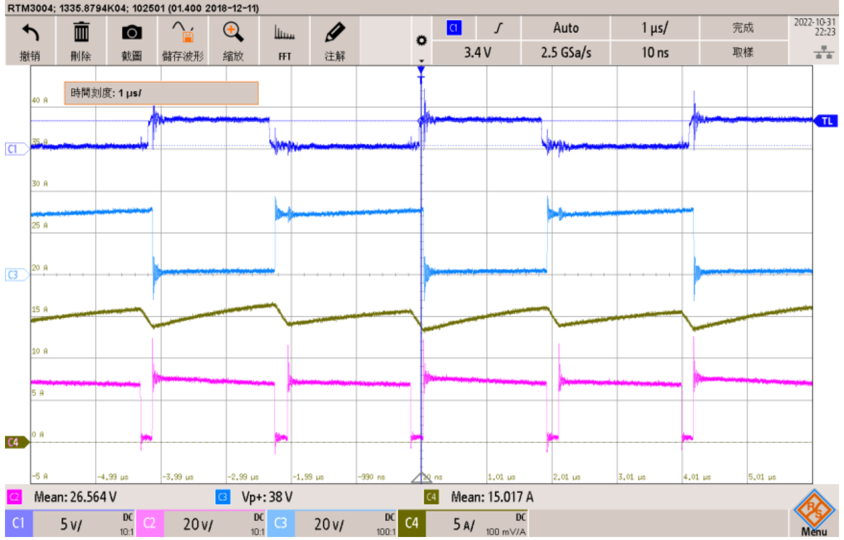


Efficiency Measurement (54V to 24V)

$V_{in}(V)$	$V_O(V)$	$I_O(A)$	***Efficiency(%)***	
			Exp	*Cal*
54.08	24.94	1	92.61	93.03
54.06	24.76	3	96.70	96.97
54.02	24.67	5	97.64	97.69
53.99	24.63	7	98.02	97.96
53.96	24.55	9	98.17	98.07
53.94	24.49	11	98.23	98.11
53.90	24.44	13	98.25	98.11
53.86	24.39	15	98.23	98.09
53.83	24.34	17	98.19	98.05
53.80	24.27	19	98.12	98.01
53.77	24.25	21	98.00	97.96
53.74	24.19	23	97.89	97.90
53.72	24.15	25	97.80	97.84

- Test condition : V_{in} = 54 V; V_o = 24 V; D = 44.4%; f_{sw} = 240 kHz
- $V_{ds(max)}$ of switch is 38V, spike is about 11V and didn't over the voltage stress 80V.
- Peak efficiency is 98.25% at load 13A.



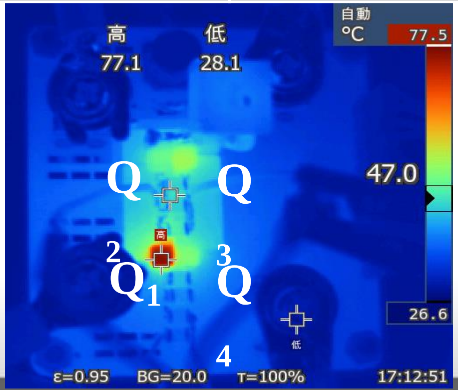


Test condition: I_o=15A

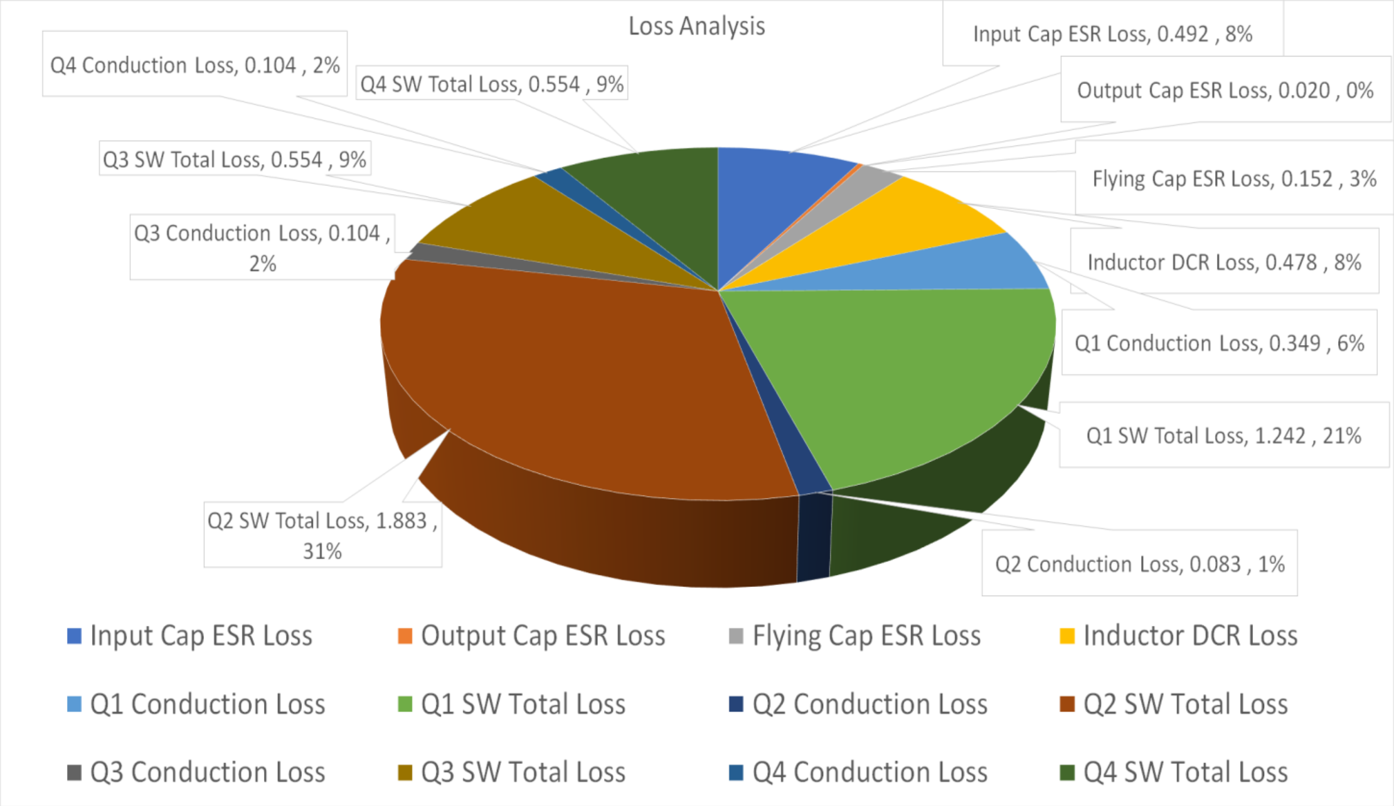
54Vin/ 24Vout Loss Distribution @Peak Efficiency

V_{in}(V)	V_O(V)	I_O(A)	Efficiency(%)	Loss(W)
53.90	24.44	13	98.25	5.66

Loss Item	Loss(W)	Proportion(%)
MOS Switching	4.233 W	70.37 %
Capacitors Conduction	0.663 W	11.02 %
MOS Conduction	0.641 W	10.65 %
Inductor Conduction	0.478 W	7.94 %
Total Loss	6.015 W	100%



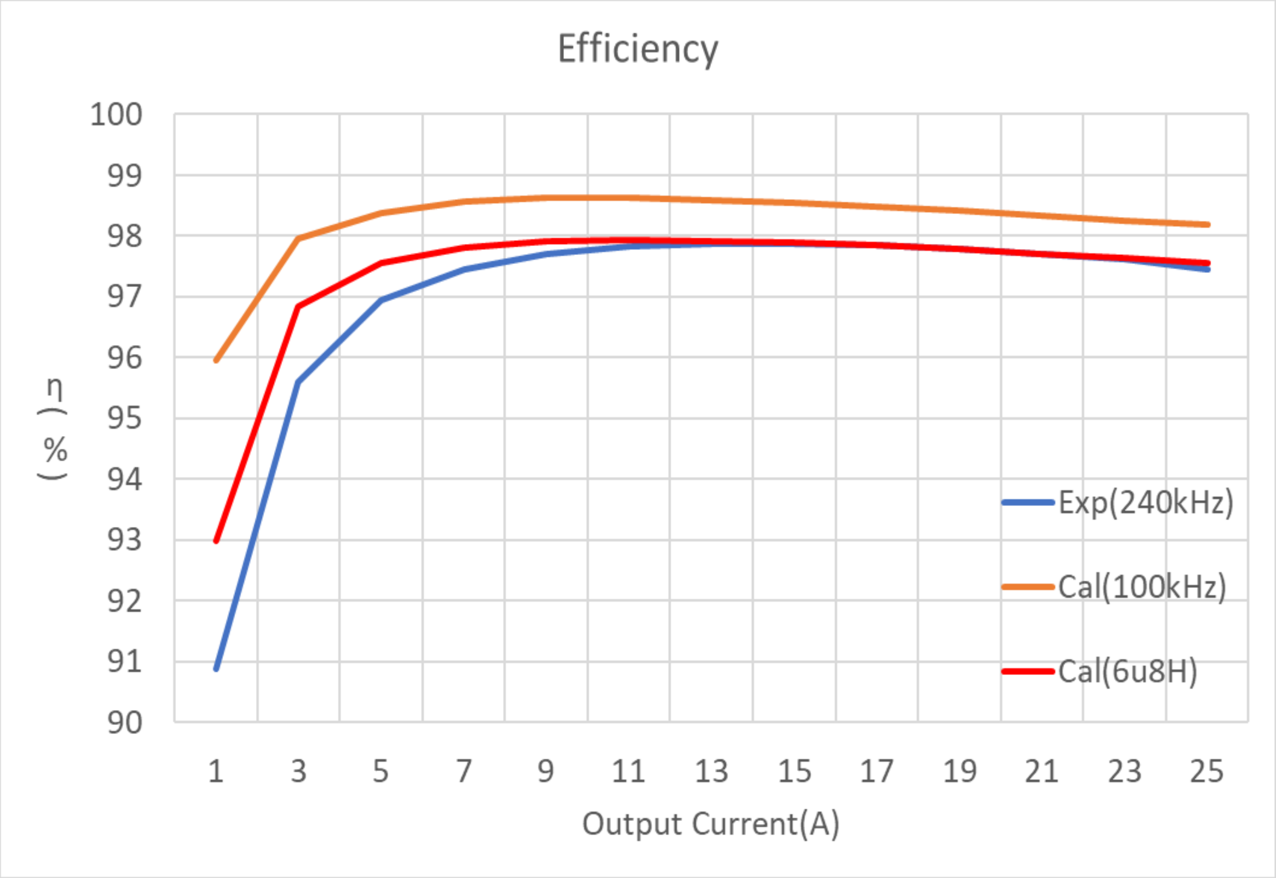
Switching loss is a major part of the total loss because of hard switching.



Summary of Optimizing Efficiency

Due to previous loss estimation, most of the losses are generated by switching loss. It can be optimized by these two direction :

- Increasing the inductance: lower the switching current point to decrease the RMS current.
- Lower the switching frequency: reduce the switching period but it require higher inductor saturation current and doubled the flying capacitance.



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- Aug. 31, 2023: Final paper submission

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