High Power Density AC-DC/ DC-DC/ DC-AC Conversion Techniques

Presented by HJ Chiu

Dean, Office of Industry-academia Collaboration

National Taiwan University of Science and Technology

Dec. 07, 2020

@ IEEE PECon in Malaysia

IEEE PECon 2020

POWER & ENERGY CONFERENCE

7 - 8 DECEMBER 2020

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Taiwan Tech

Outline

- Center for Power Electronic Technologies @ Taiwan Tech
- Introduction to High Power Density Converters
- High Power Density DC-DC Converter
- High Power Density Bidirectional Converter
- High Power Density PV Inverter


Xi-men-ding Shopping District


Da-dao-cheng Wharf


Taipei Songshan Airport


Taipei Arena


New Life Square Shopping District

TAIWAN TECH
National Taiwan University of Science and Technology

- Located in the most well-known university area in Taipei
- Easily accessed by Metro Rapid Transit and buses
- 10 minutes away from downtown area


Taipei Main Station


Sun Yat-sen Memorial

Eastern District of Taipei


Presidential Office Building

Chiang Kai-shek Memorial Hall


Treasure Hill Artist Village


Maokong Gondola


World University Rankings

QS World University Rankings

Year 2021	Ranked 267
Taiwan	Ranked 5

QS World University Rankings Top 50 Under 50

Year 2021	Ranked 25
Taiwan	Ranked 1

TIMES The Global University Employability Ranking

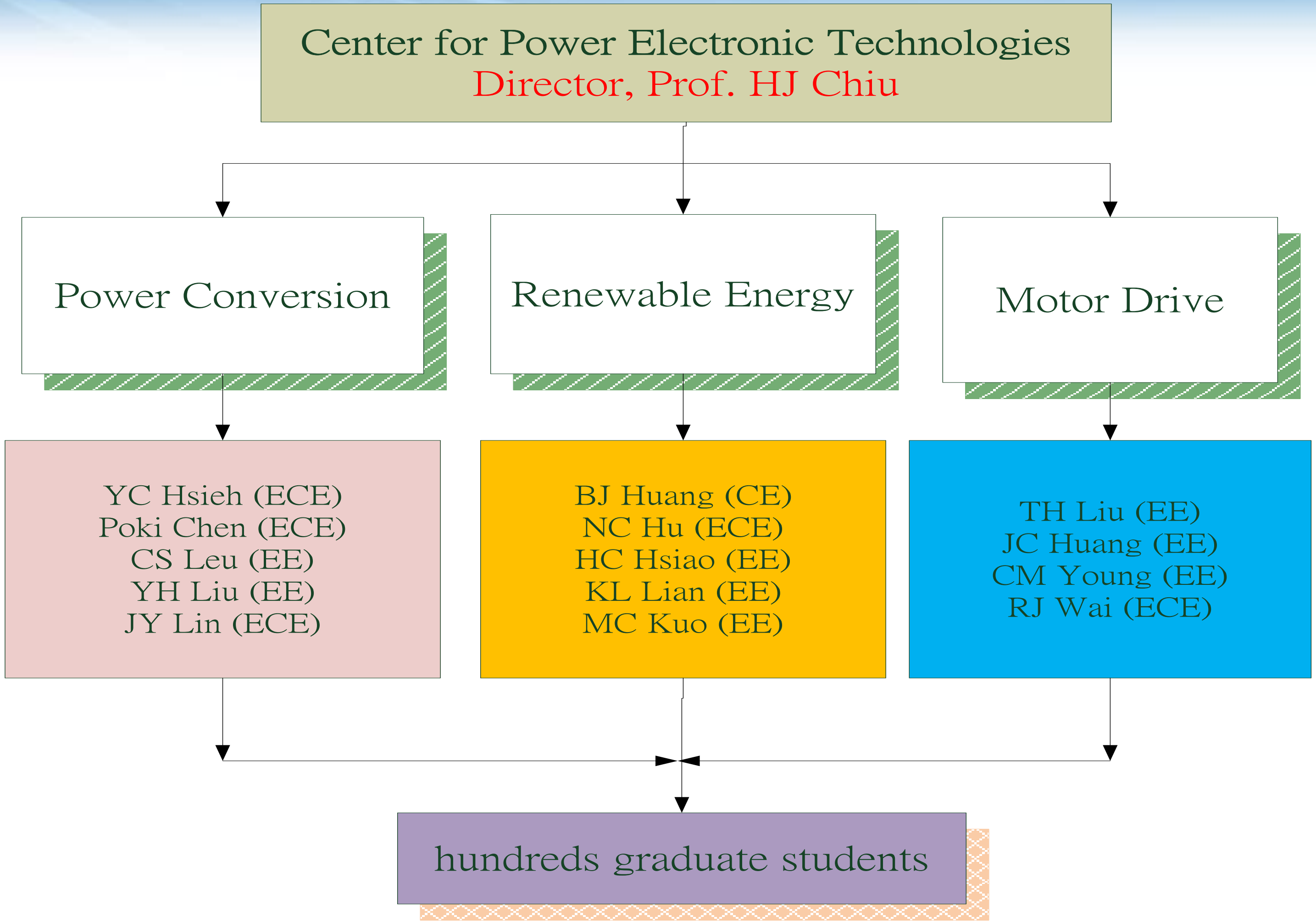
Year 2020	Ranked 82
Taiwan	Ranked 1

TIMES Higher Education Asia University Rankings

Year 2018	Ranked 42
Taiwan	Ranked 3

TAIWAN TECH
NATIONAL TAIWAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Center for Power Electronic Technologies



Research Topics

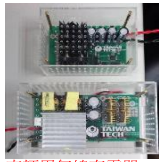

高效率伺服器電源


儀器用開架式電源


工業級直流模組


太陽能微型換流器

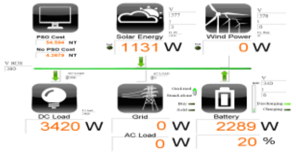
IFEC 2013 首獎



車輛用無線充電器

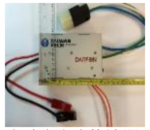
IFEC 2015 首獎

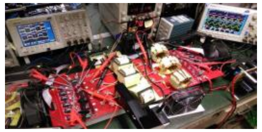

無線充電線圈

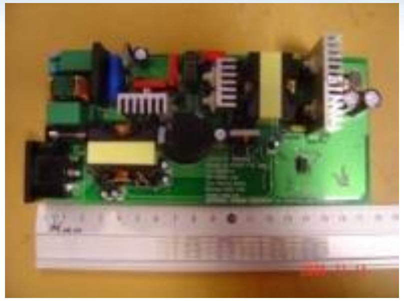

直流微電網系統


能量回收型電池測試機

Google LBC Academic Awards


高功率密度換流器


船舶用雙向直流轉換器

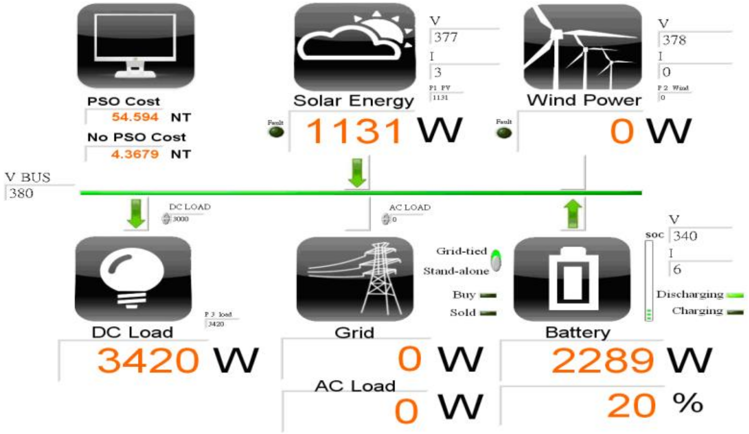


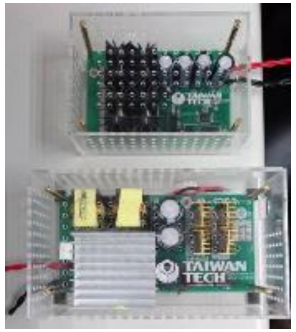
Switching Power Supplies

--Adaptor
--PC Power
--TV Power
--Server Power

Renewable Energy

--Solar Power
--Fuel Cell





Lighting Applications

--LED
--HID
--Fluorescent

Design Projects

- Funding over US$1,000,000/year supported by industry
- IC vendors: ST, TI, Infineon, ON semiconductor
- Power supply manufacturers: Delta, Lite-ON, FSP, AcBel, Meanwell
- System manufacturers: Chroma, ASUS, Gigabyte

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Achievements & Honors

Grand Prize, US$10,000

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

High Efficiency Solar Micro Inverter

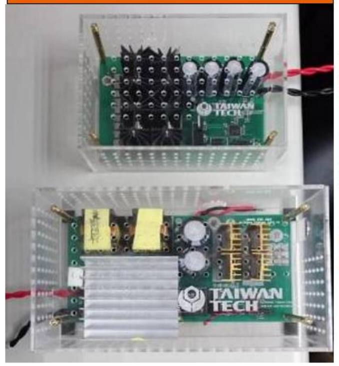
Google Little Box Challenge Academic Award, US$30,000

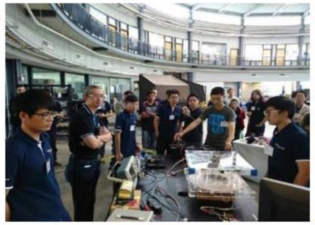
Primary Academic Institution	Principal Investigator
University of Colorado Boulder	Khurram K. Afridi
National Taiwan University of Science and Technology	Huang-Jen Chiu
Universidad Politécnica de Madrid	José A. Cobos
Texas A&M University	Prasad Enjeti
ETH Zürich	Johann W. Kolar
University of Bristol	Neville McNeill
Case Western Reserve University	Timothy Peshek
University of Illinois Urbana-Champaign	Robert Pilawa-Podgurski
University of Stuttgart	Jörg Roth-Stielow
Queensland University of Technology	Geoff Walker

Grand Prize, US$10,000

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

WPT Charging System






IEEE
Advancing Technology for Humanity
Grand Prize
2015 International Future Energy Challenge (IFEC)
Awarded to
National Taiwan University of Science and Technology

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

Pacific Asia Regional Award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Best Track Award - 1B
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International Academic Activities

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Introduction to High Power Density Converters

TAIWAN TECH

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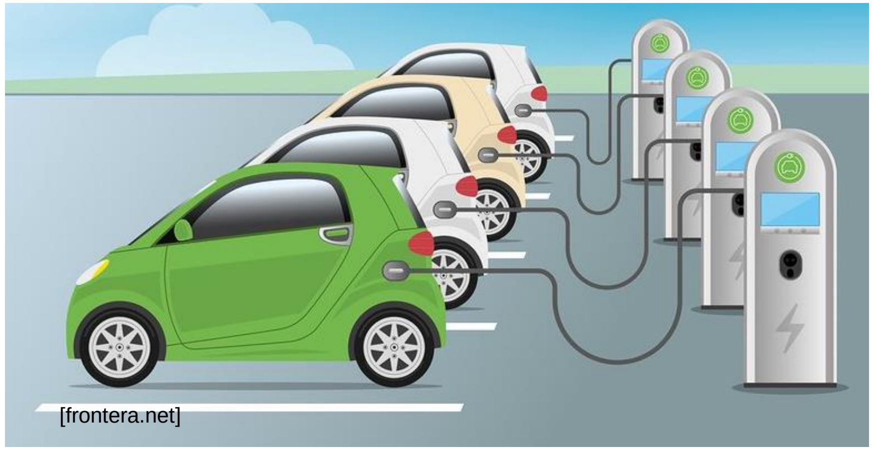
Special thanks to Prof. Yu-Chen Liu, National I-Lan University

Demand for Higher Power Density and Higher Efficiency

Data Center Power Supplies


[www.greentechmedia.com]

Electric Vehicles


[frontera.net]

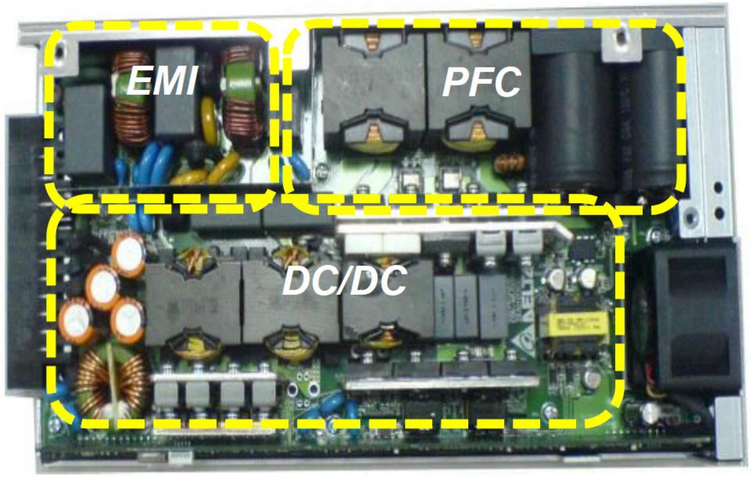
Renewable Energy Inverters

[http://blog.cet-power.com]

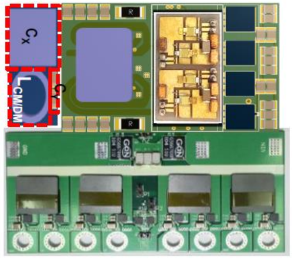
LiTTLE BOX CHALLENGE

Google | IEEE

Design Example From CPES (VT)



600V GaN based Converter



The State-of-the-Art:

Frequency: **100 KHz**
Efficiency: **96%**
Power density: **30 W/in^3**

Objectives:

Frequency: **>1MHz**
Efficiency: **> 96%**
Power density: **> 200W/in^3**
Design for Manufacturability

Wide Bandgap Devices

- **Better reverse-recovery characteristics**
- **Faster switching speeds**
- **Can reduce switching and driver loss at MHz switching**
- **Used for high-efficiency high-power-density converters**

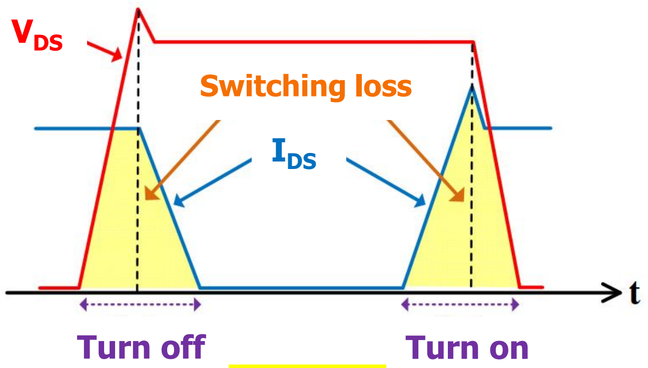
High-Frequency Converters

✓ **How high-frequency converters achieve high efficiency:**

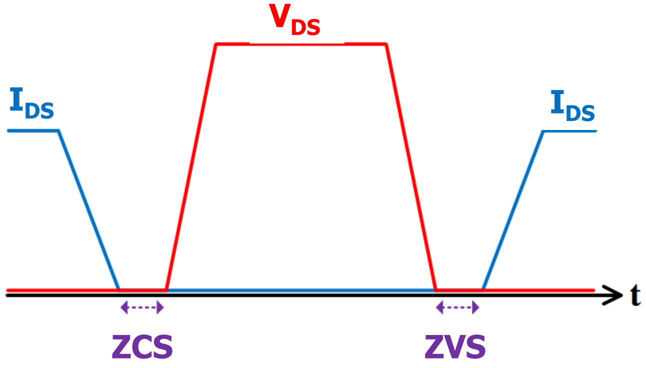
- **Soft-Switching**
- **Commonly used topologies for high efficiency**
  - **Phase-Shifted Full Bridge (PSFB) Converter**
  - **LLC Resonant Converter**

$$P_{QA,switch\_on} = \frac{1}{2} \cdot V_D \cdot I_{peak} \cdot T_{f\_\max} \cdot f_s$$

$$P_{QA,switch\_off} = \frac{1}{2} \cdot V_D \cdot I_{peak} \cdot T_{r\_\max} \cdot f_s$$



Hard Switching



Soft Switching

High-Frequency Converters

✓ **How high-frequency converters achieve high efficiency:**

- **Soft-Switching**
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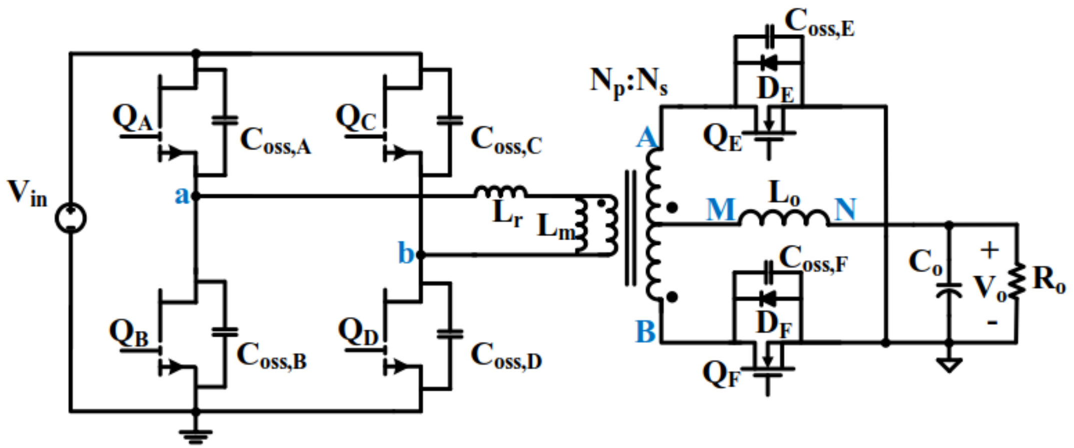


Phase Shift Full Bridge Converter

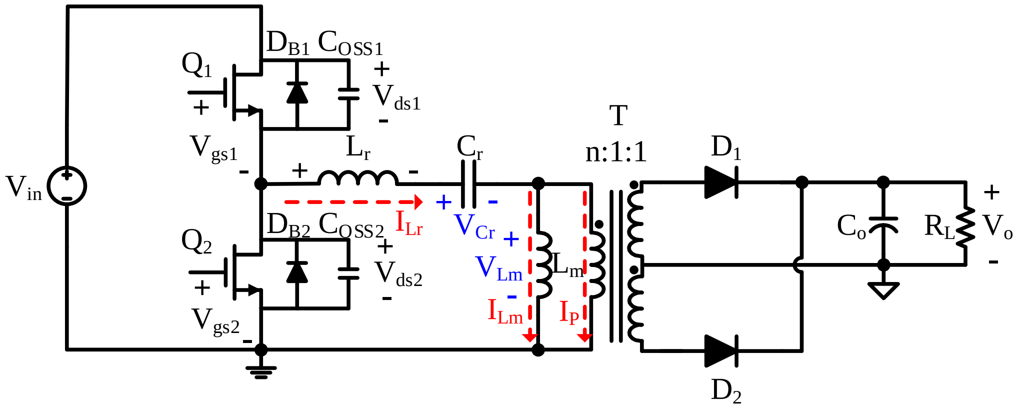
Disadvantages

- **Lagging leg cannot achieve zero voltage switching (ZVS) at light-load conditions**
- **Additional magnetic components (inductor) needed at output**

High-Frequency Converters

✓ **How high-frequency converters achieve high efficiency:**

- **Soft-Switching**
- **Commonly used topologies for high efficiency**
  - **Phase-Shifted Full Bridge (PSFB) Converter**
  - **LLC Resonant Converter**



LLC Resonant Converter

Compared with PSFB Converter

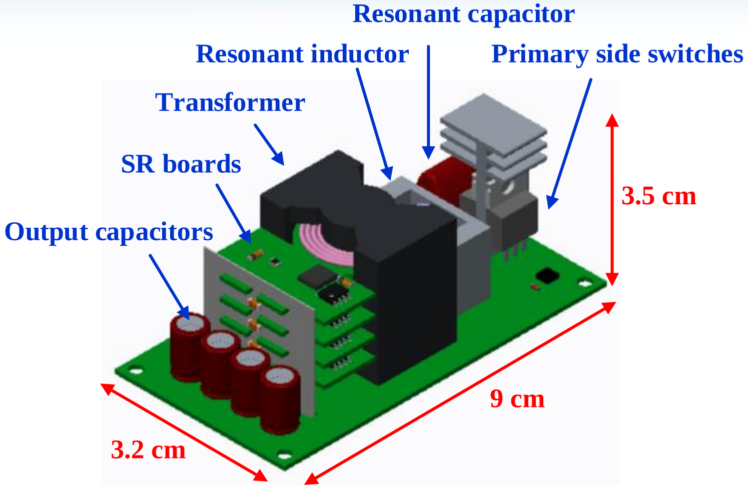
- **When resonant converter operates in LLC region, primary-side ZVS is independent of load**
- **Secondary-side ZCS achieved**
- **No extra magnetic components needed, in addition to transformer**

High-Frequency LLC Converter

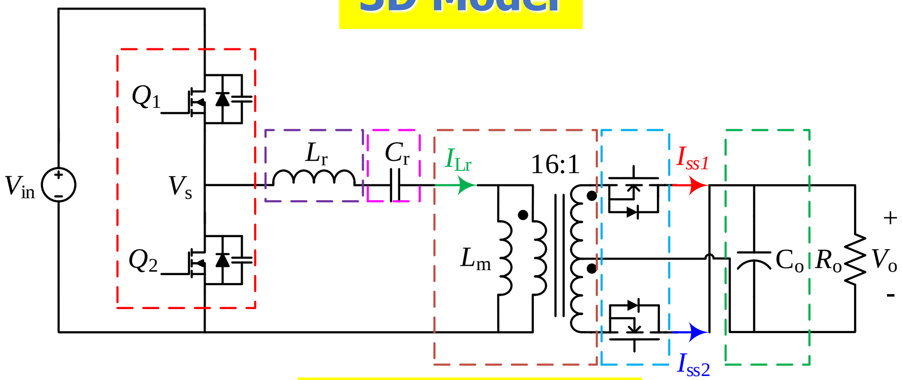
✓ 100-kHz LLC Converter

- **Specifications and Parameters**

Parameter	Value
Input Voltage	380 V
Output Voltage	12 V
Output Power	1 kW
Device	**Serial number**
Primary -side MOSFET (Q_1、Q_2)	IPP60R099C7
Secondary-side MOSFET (Q_3、Q_4)	BSC028N06NS
Core of Transformer	PQ32/30 (Material: P47)
Core of Resonant Inductor	PQI26/12 (Material: P47)
Device	**Value**
Turns Ratio	16
Magnetizing Inductor (Lm)	140 μH
Resonant Inductor (Lr)	25 μH
Resonant Capacitor (C_r)	48.2 nF
Output Capacitor (C_o)	5.96 mF



3D Model

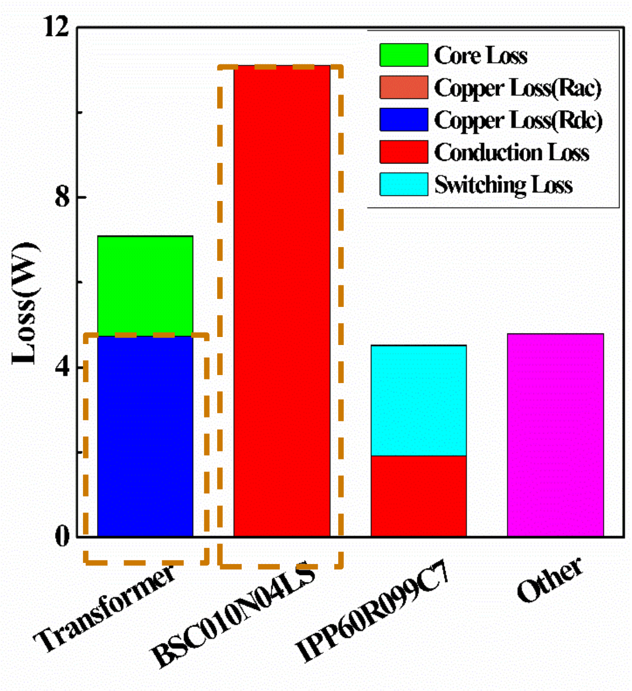


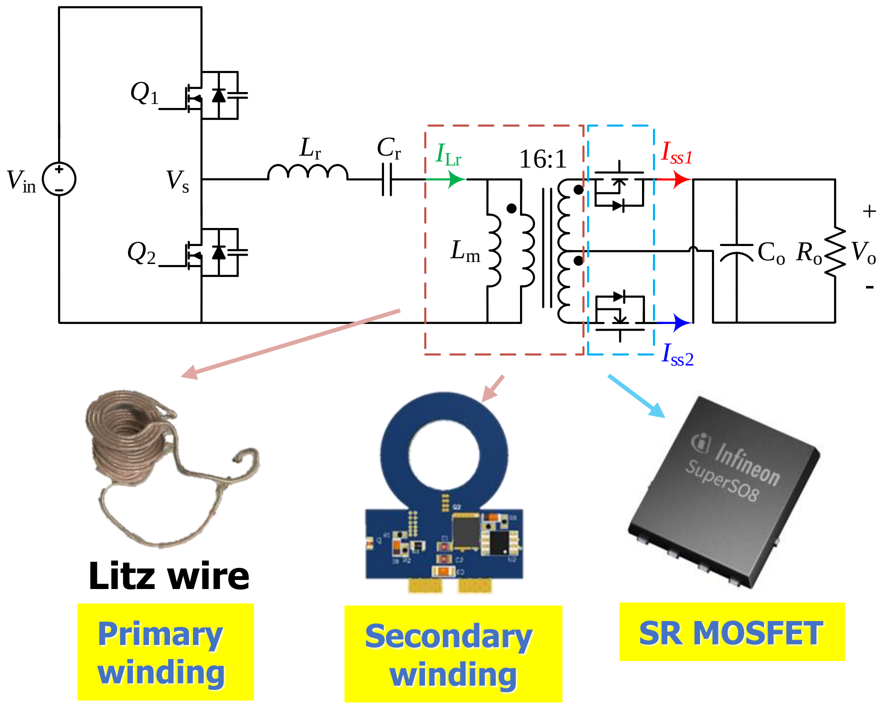
LLC Converter

High-Frequency LLC Converter

✓ 100-kHz LLC Converter Power Loss Analysis

- Main losses are **transformer copper loss** and secondary-side **switch conduction loss**

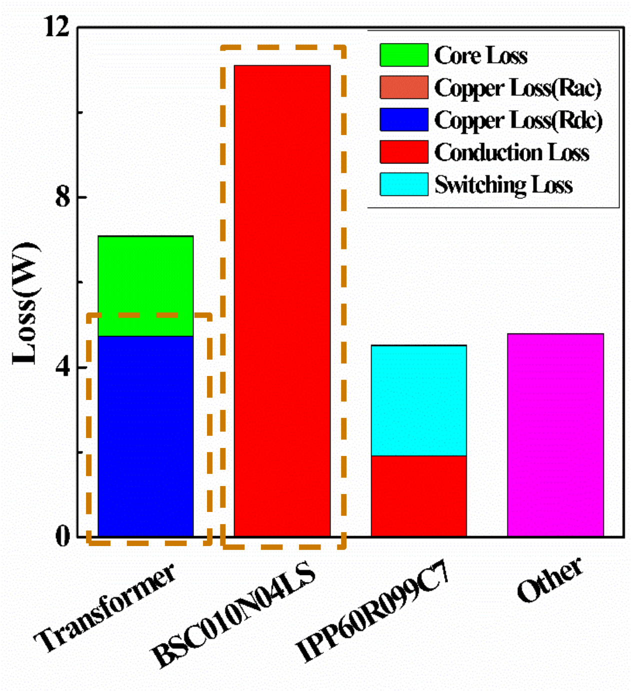


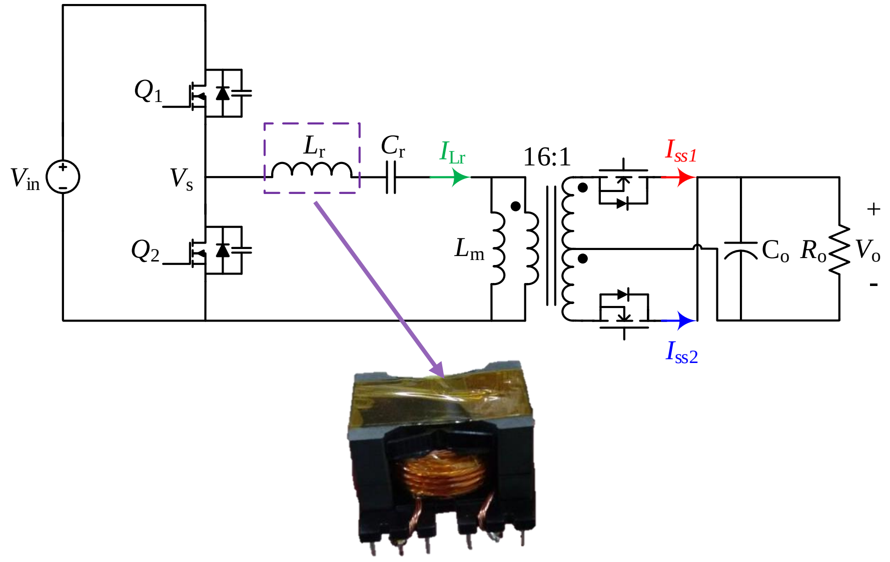


High-Frequency LLC Converter

✓ 100-kHz LLC Converter Power Loss Analysis

- Main losses are transformer copper loss and secondary-side switch conduction loss
- Others include resonant inductor loss and driver loss



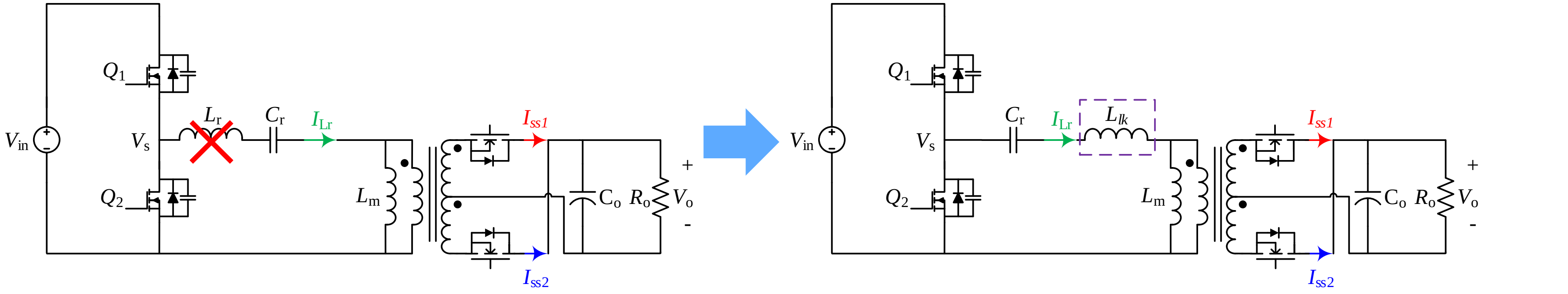


Additional Resonant Inductor

High-Frequency LLC Converter

✓ **Pros and Cons increasing frequency to 1 MHz**

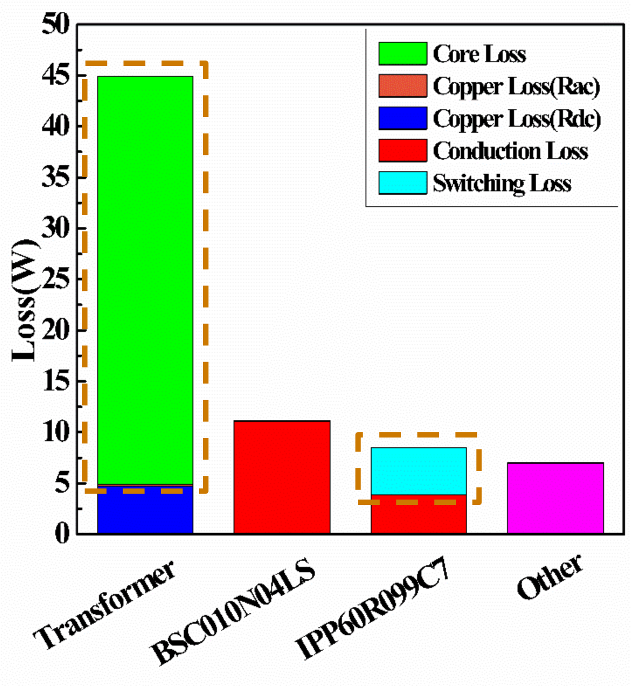
- **Advantage**
  - **Reduce transformer size**
  - **Use leakage inductance of transformer as resonant inductor**
  - **Small resonant inductance is very improves efficiency and decreases volume**
- **Disadvantage**
  - **Core loss and switching loss will increase**

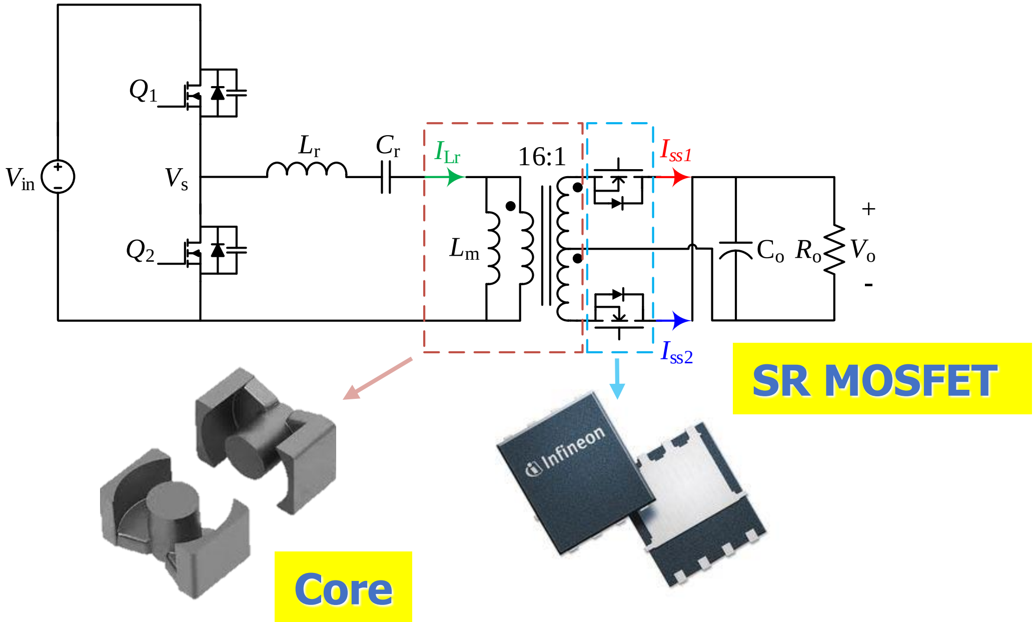


High-Frequency LLC Converter

✓ 1-MHz LLC Converter Power Loss Analysis

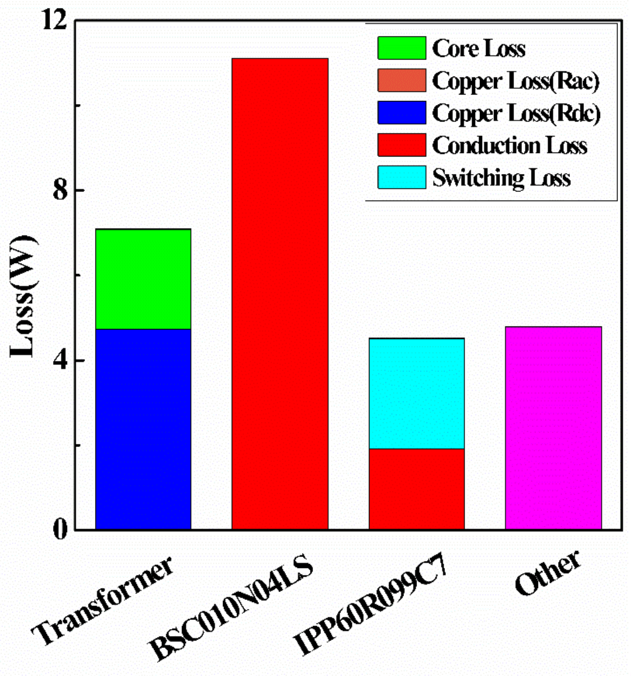
- V_{in} = 380 V, V_o = 12 V, P_o = 1 kW
- Main losses are core loss and switching loss

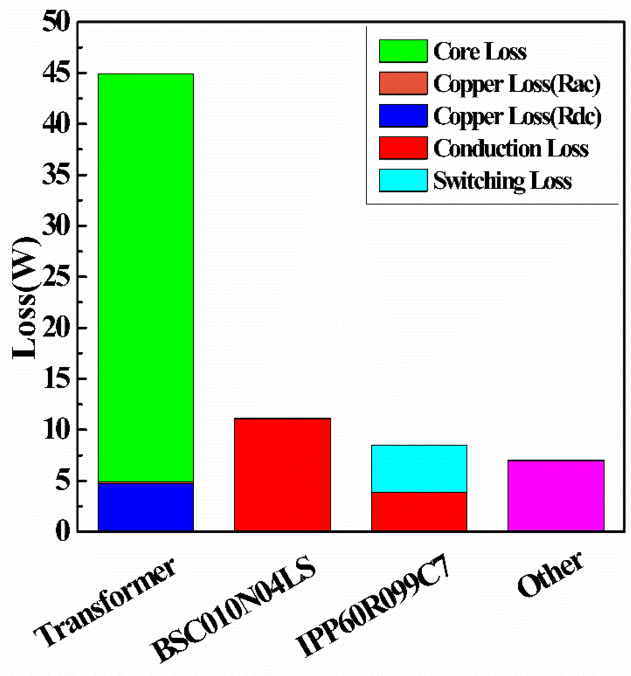




High-Frequency LLC Converter

- ✓ **Comparison of 1-MHz and 100-kHz LLC Converter**
  - **At high frequency:**
    - **Core loss increased by 37.65 W**
    - **Switching loss increased by 2.05 W**
    - **Driver loss increased by 3.88 W**





High-Frequency LLC Converter

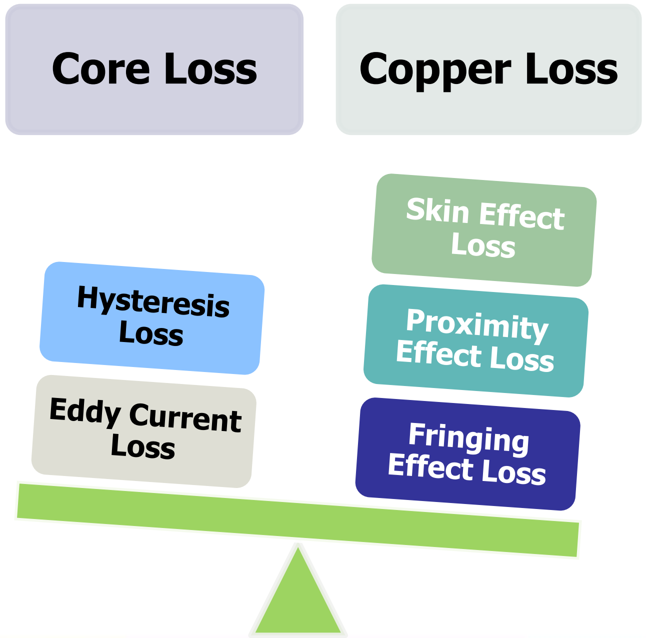
✓ 1-MHz LLC Converter Optimization

- At high frequencies, optimization of the **magnetic components** and **switching losses** are critical
- Core loss increases with switching frequency, so a **core material** suitable for high frequency applications should be utilized
- AC resistance of the magnetic coil increases with frequency, which increases copper wire loss
- Even though zero voltage switching (ZVS) is achieved on switch turn on, there is still some **turn-off loss** and **reverse-recovery loss**
- Faster switches (**wide bandgap devices**) can be used for their faster switch-off time to further reduce losses

Magnetic Component Loss

✓ **Transformer Loss**

- **Core Loss**
  Core Material, AC Flux Density, Frequency
- **Copper Loss**
  Copper thickness, MMF, Air Gap, Frequency



Copper Loss: Resistive Loss

- ✓ **Loss from DC Resistance**
  - **Related to wire length and cross-sectional area, does not depend on frequency**
- ✓ **Loss from AC Resistance**
  - **Related to switching frequency, magnetic field strength, and cross-sectional area**
  - **Skin effect: effect of eddy currents caused by current flow through the conductor itself**
  - **Proximity effect: effect of eddy currents caused by current flow through an adjacent conductor**
  - **Skin and proximity effect cause current to be unevenly distributed, increasing effective resistance**
  - **Using PCB traces reduces the skin effect since the thickness can be controlled**
  - **Thus, the proximity effect is the main source of loss in high-frequency transformers that use layer-stacked windings**

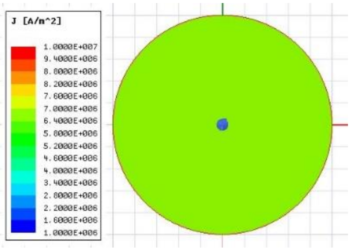
Copper Loss: Skin Effect

✓ **Skin Effect Simulation using ANSYS Maxwell 2D**

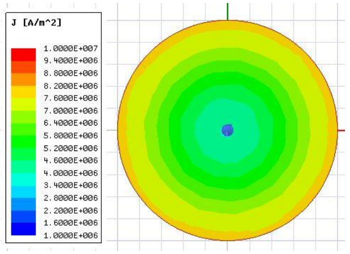
- Comparing copper loss of litz wire and PCB traces
- Conditions: 5 A of current, same cross-sectional copper area

Skin Depth

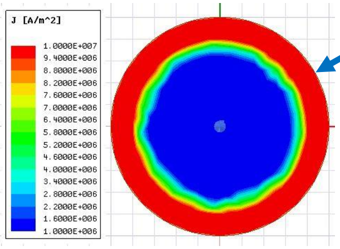
Litz Wire



0.27 W



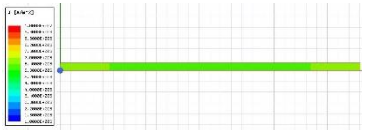
0.33 W



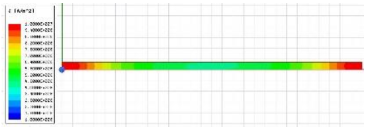
0.88 W

6 kHz — 60 kHz — 600 kHz

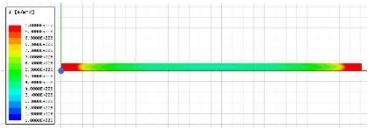
PCB trace



0.27 W



0.32 W

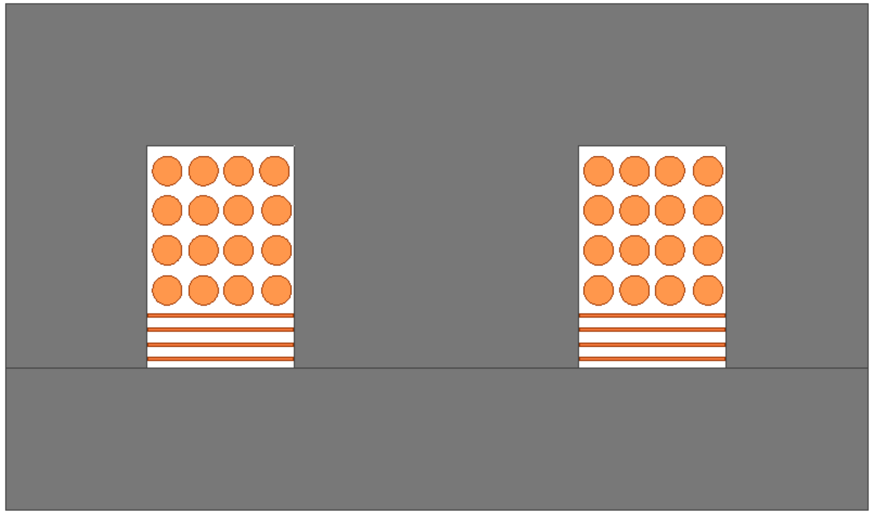


0.48 W

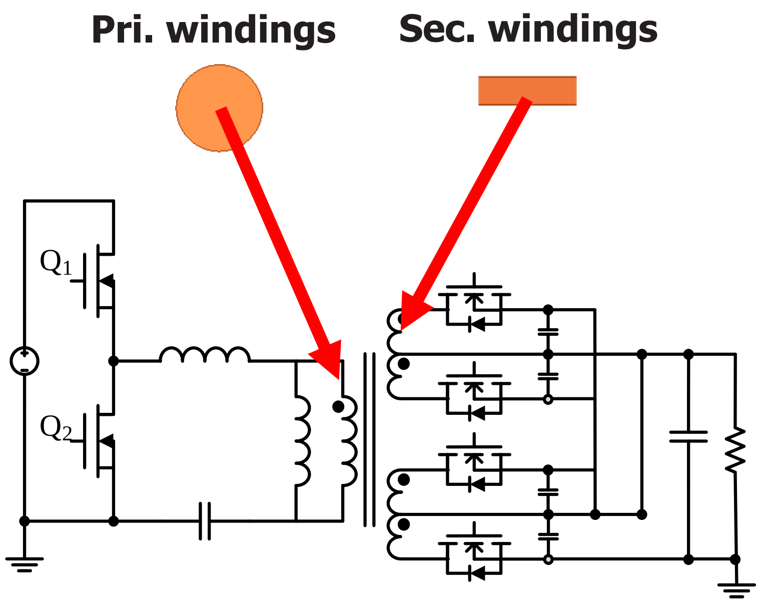
Copper Loss: Proximity Effect

✓ **Proximity effect simulation using ANSYS Maxwell 2D**

- **Transformer can be modeled in Maxwell 2D for the LLC resonant converter**
- **Copper losses can be compared for different windings**



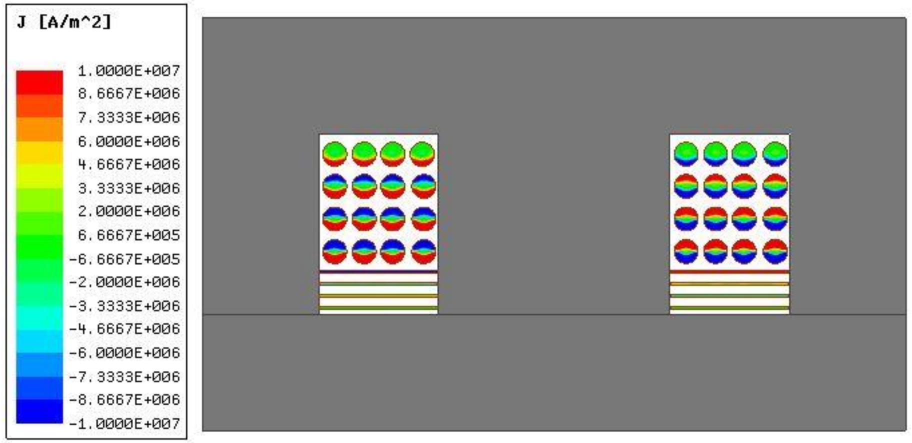
Transformer Model for Maxwell 2D

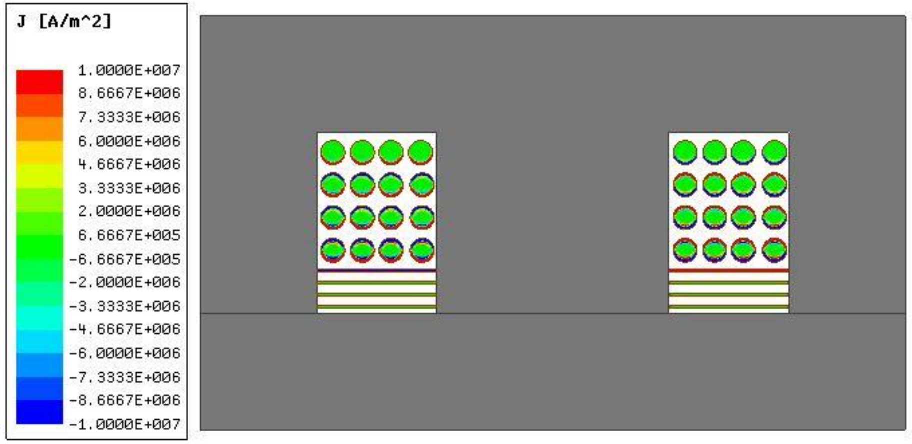


Schematic of LLC Converter

Copper Loss: Proximity Effect

✓ **Proximity effect simulation using ANSYS Maxwell 2D**
- **Case 1: Non-interleaved windings**



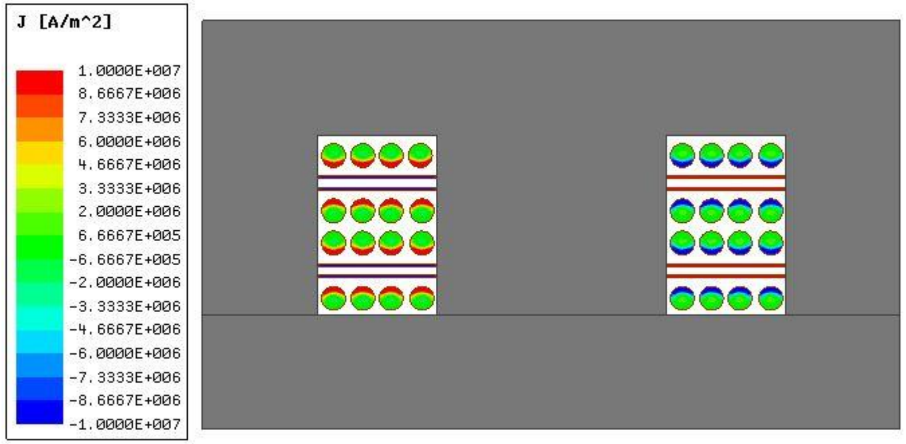


At 100 kHz, 7.22 W of loss

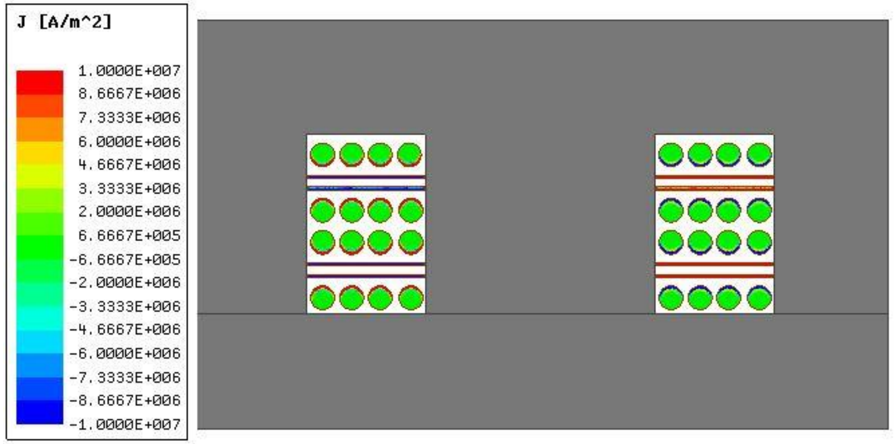
At 1 MHz, 22 W of loss

Copper Loss: Proximity Effect

- ✓ **Proximity effect simulation using ANSYS Maxwell 2D**
  - **Case 2: Partially-interleaved windings**



At 100 kHz, 1 W of loss

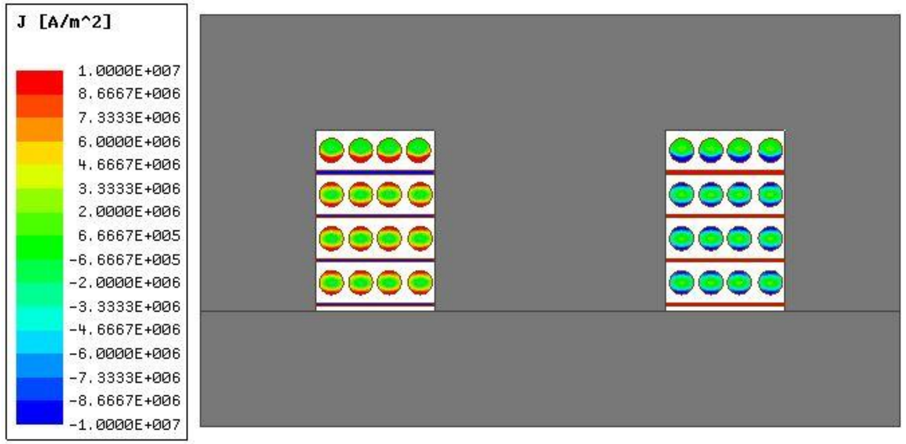


At 1 MHz, 3 W of loss

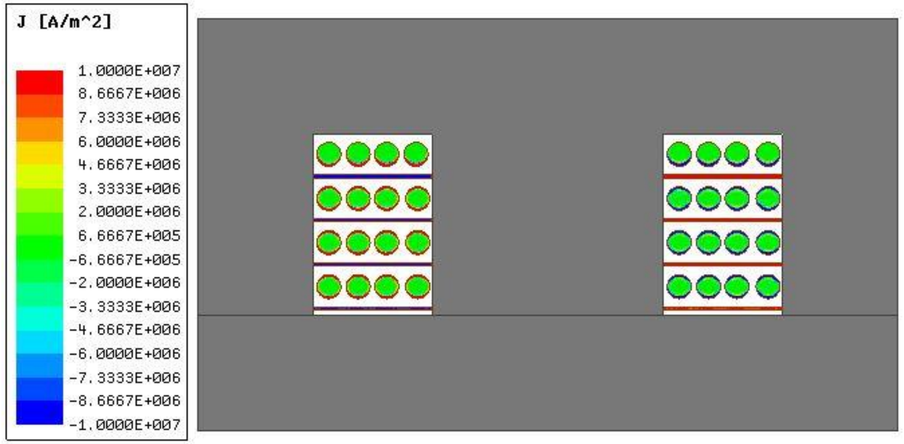
Copper Loss: Proximity Effect

✓ **Proximity effect simulation using ANSYS Maxwell 2D**

- **Case 3: Interleaved windings**



At 100 kHz, 0.8 W of loss



At 1 MHz, 1.8 W of loss

Copper Loss: Proximity Effect

✓ Comparison Summary

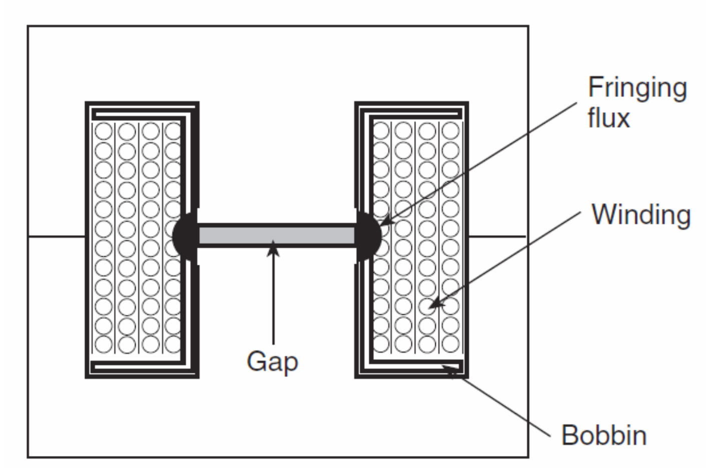
- Losses for each winding structure are summarized in the table below
- AC resistance (R_{ac}) is much higher at higher frequencies than lower frequencies
- For transformer windings, if complete interleaving is not possible, partial interleaving can still greatly reduce copper loss
- At 1 MHz and higher, complete interleaving is most effective to reduce overall copper loss

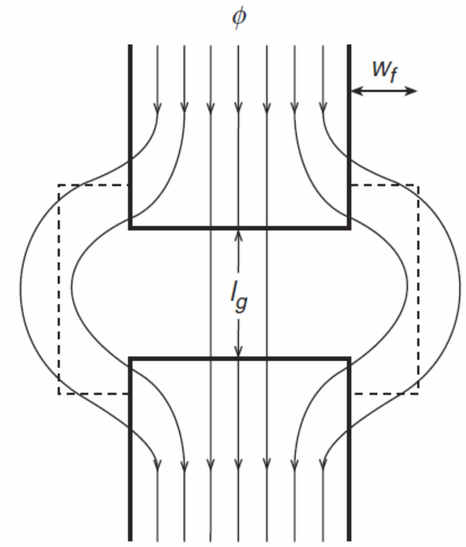
Winding Structure	100 kHz	1 MHz
Non-Interleaved	7.22 W	22 W
Partial-Interleaved	1 W	3 W
Interleaved	0.8 W	1.8 W

Copper Loss: Fringing Effect

✓ Fringing Effect Basics

- In transformer applications, an air gap can be added to reduce the attenuation of inductance caused by high DC bias
- However, increasing the air gap also increases leakage flux
- Leakage flux through the conductor can cause eddy currents to generate hot spots and further losses



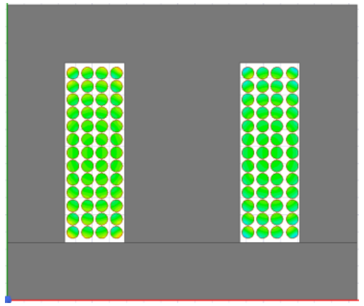


[Ref] M. K. Kazimierczuk, High-Frequency Magnetic Components, U.K., West Sussex:Wiley, 2009."

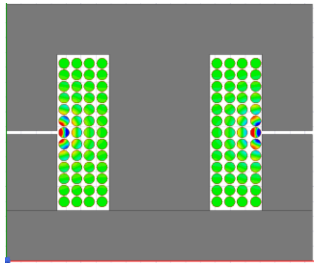
Copper Loss: Fringing Effect

✓ **Fringing effect simulation using ANSYS Maxwell 2D**

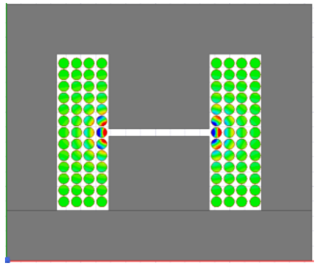
- **Transformer with air gap can be modeled in Maxwell 2D**
- **Effects of different air gaps can be compared**
- **Case 1: Litz Wire**
  - ➢ **Adding a gap at any location increases losses by 2.5 to 3.7 times**



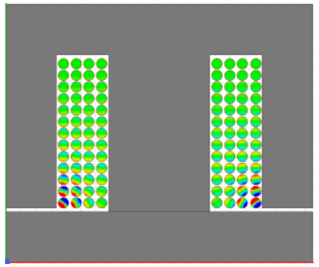
Core structure without air gap
1.53 W



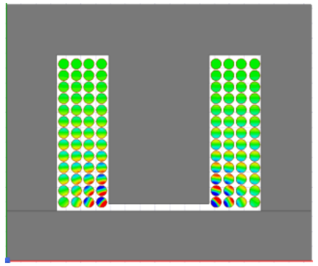
3.80 W



3.87 W



5.65 W

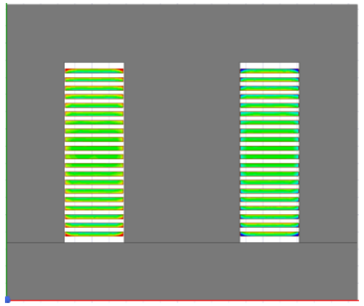


5.73 W

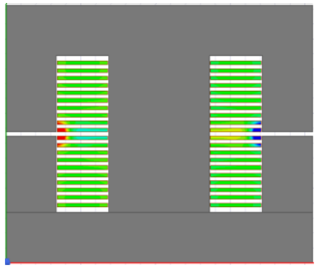
Core structure with air gap

Copper Loss: Fringing Effect

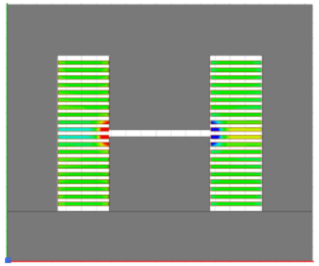
- ✓ **Fringing effect simulation using ANSYS Maxwell 2D**
  - **Case 2: PCB Windings**
    - ➢ **Adding a gap at any location increases losses by 1.6 to 2.58 times**
    - ➢ **Compared to litz wire, the PCB windings are less affected by the fringing effect**



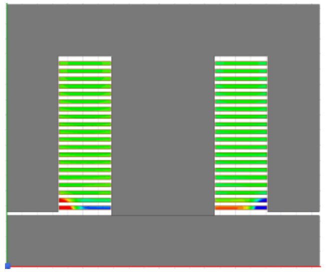
Core structure without air gap
2.07W



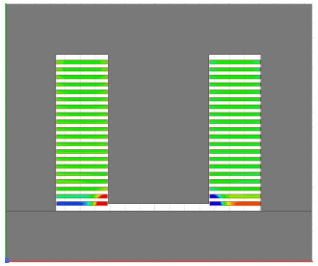
3.37W



3.5W



5.21W



5.35W

Core structure with air gap

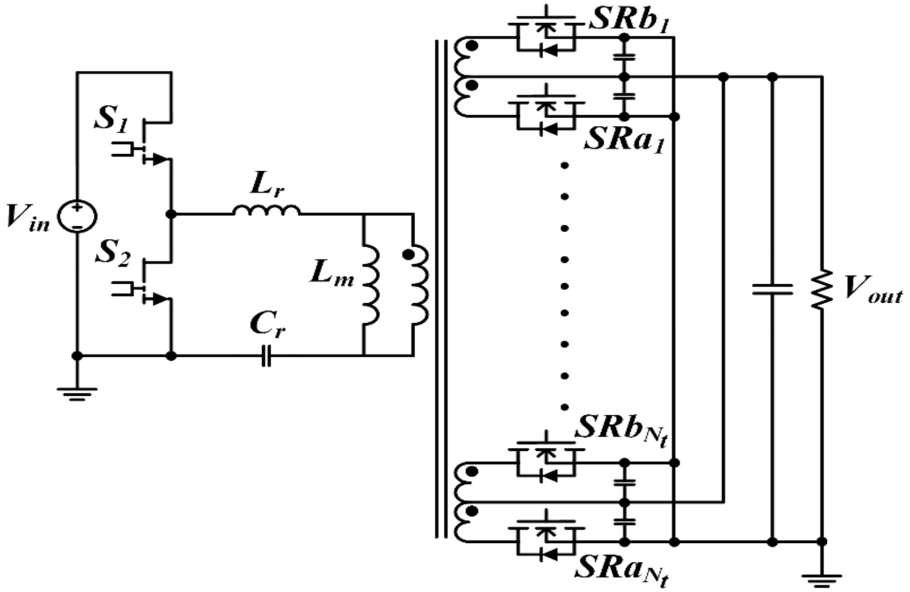
Power Loss Summary

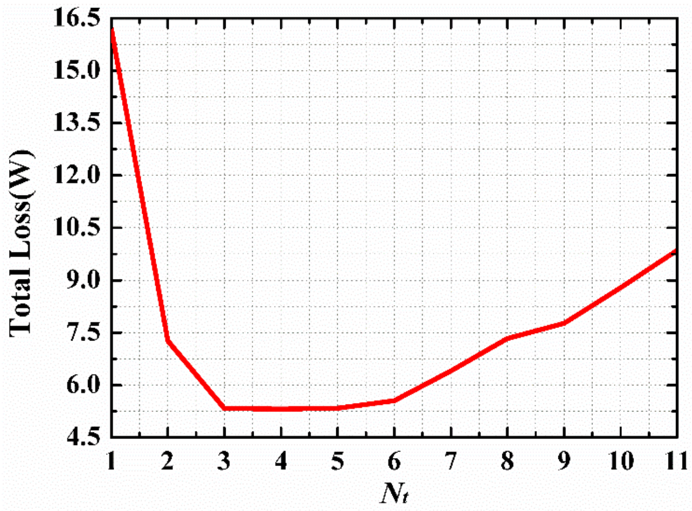
✓ **Transformer total loss**

- For transformers operating at 1 MHz, electromagnetic effects and losses are amplified
- It is important to design for reduced core and copper loss
- Core Loss
  - Eddy Current Loss: Choose an appropriate core material for high switching frequency
  - Hysteresis Loss: Considering core loss at high frequency operation, B_{max} should be designed to be less than 1000 Gauss
- Copper Loss
  - Rdc Loss: Need to consider cross-sectional area and length
  - Rac Loss
    - Skin Effect Loss: Choose an appropriate conductor thickness
    - Proximity Effect Loss: Reduce loss with interleaved windings
    - Fringing Effect Loss: Choose a proper air gap position and winding shape to reduce losses

Fractional-Turn Transformer Structure Analysis

- Specifications: V_{in}=380 V, V_o=12 V, P_o=1 kW, f_{sw}=1 MHz
- Find out the design of the best fractional-turn transformer turns ratio under this specification
- Only considers core loss and copper loss during analysis

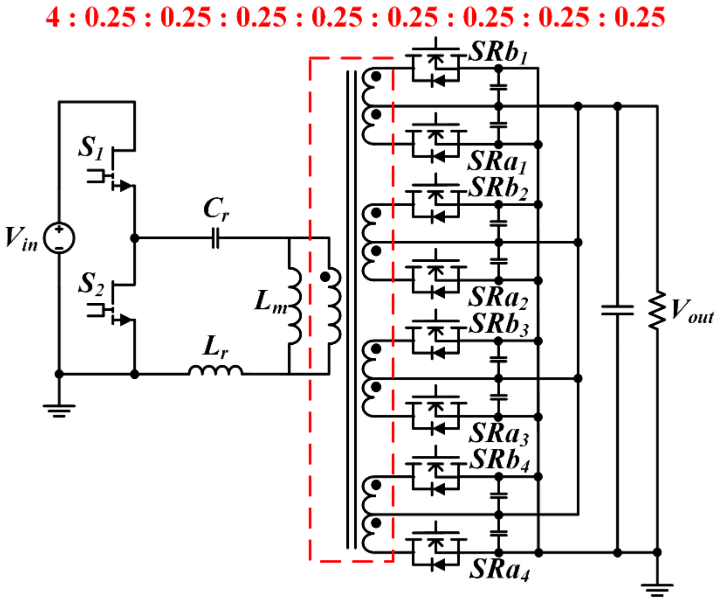




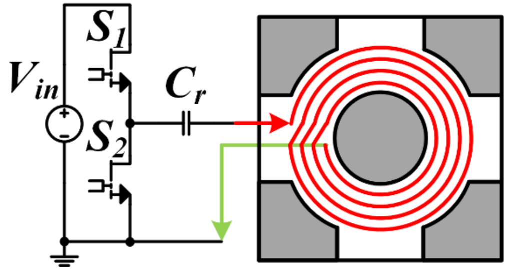
- N_t = 4 yields the minimum transformer loss
- Transformer turns ratio is 4:0.25
- 4 sets of center taps are required on the secondary side

Quarter-Turn Transformer Design

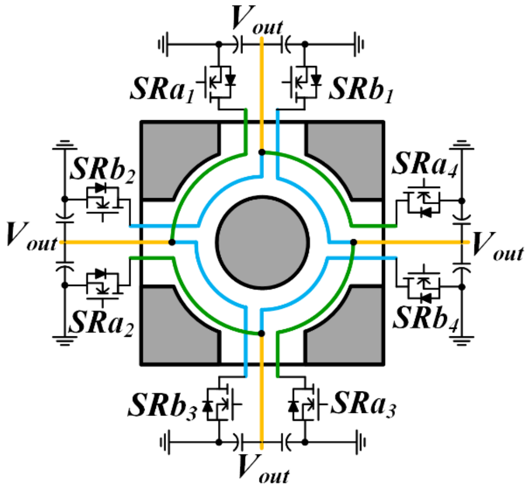
- Specifications: V_{in}=380 V, V_o=12 V
- Equivalent Turns ratio: 16:1
- Fractional-turn transformer's turns ratio: 4:0.25



Fractional-turn LLC converter



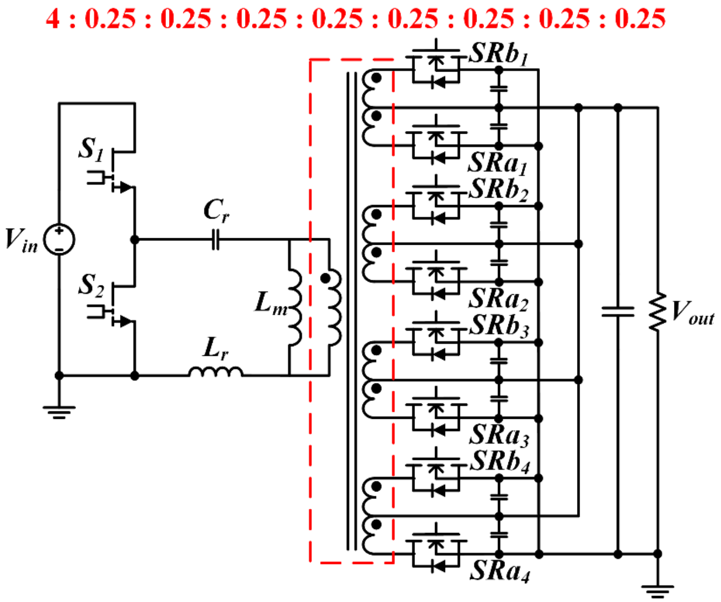
Transformer primary side wiring

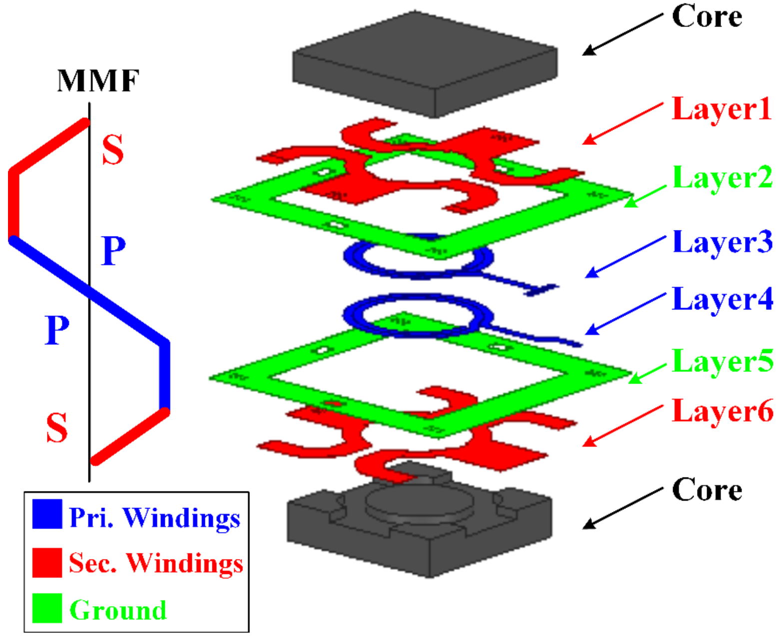


Transformer secondary side wiring

Quarter-Turn Transformer Design

- ✓ The winding layers and SRs arrangement (SPPS)
  - ☐ The primary windings are the middle layers, and the center-tapped secondary windings are the top/bottom layers
  - ☐ The SRs and capacitors are mounted directly on the secondary windings
  - ☐ In this way, the SR's termination loss is greatly reduced



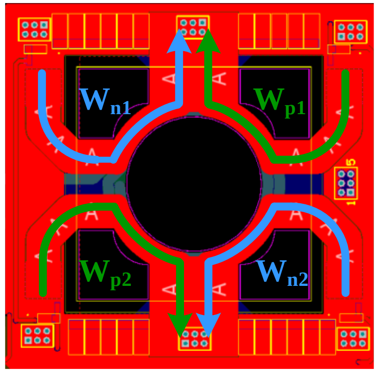


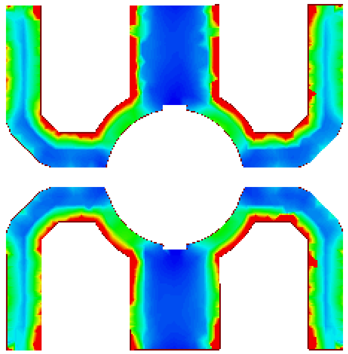
Quarter-Turn Transformer Design

✓ **Confirm the secondary current distribution using Q3D**

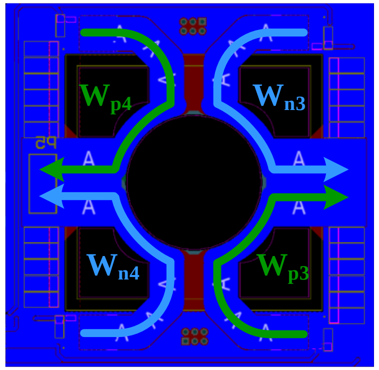
- ◻ **Except for the corners, they are evenly distributed.**

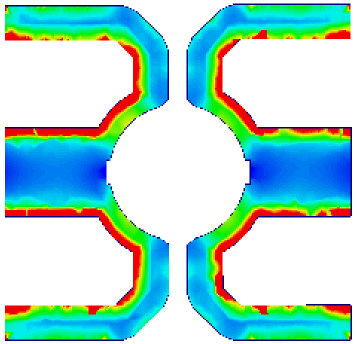
Top Layer

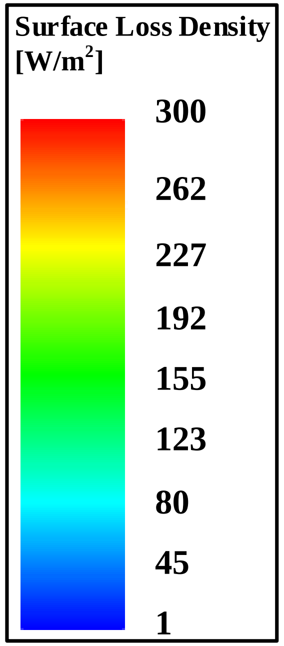




Bottom Layer

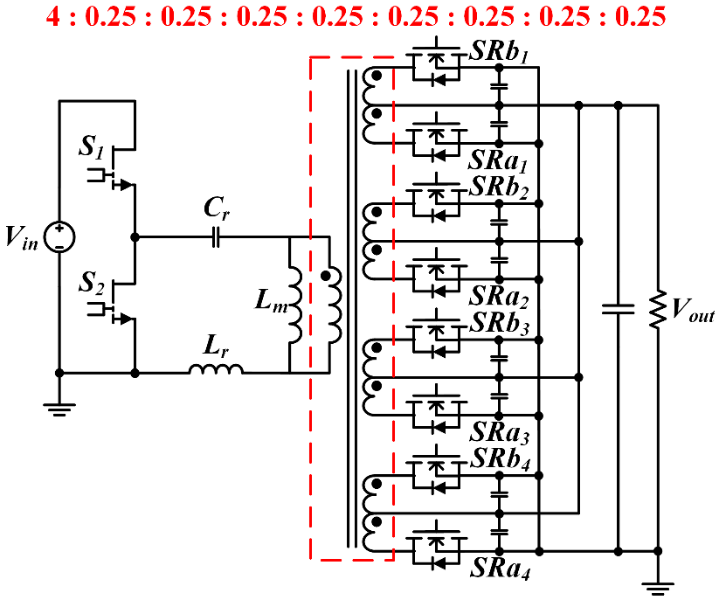


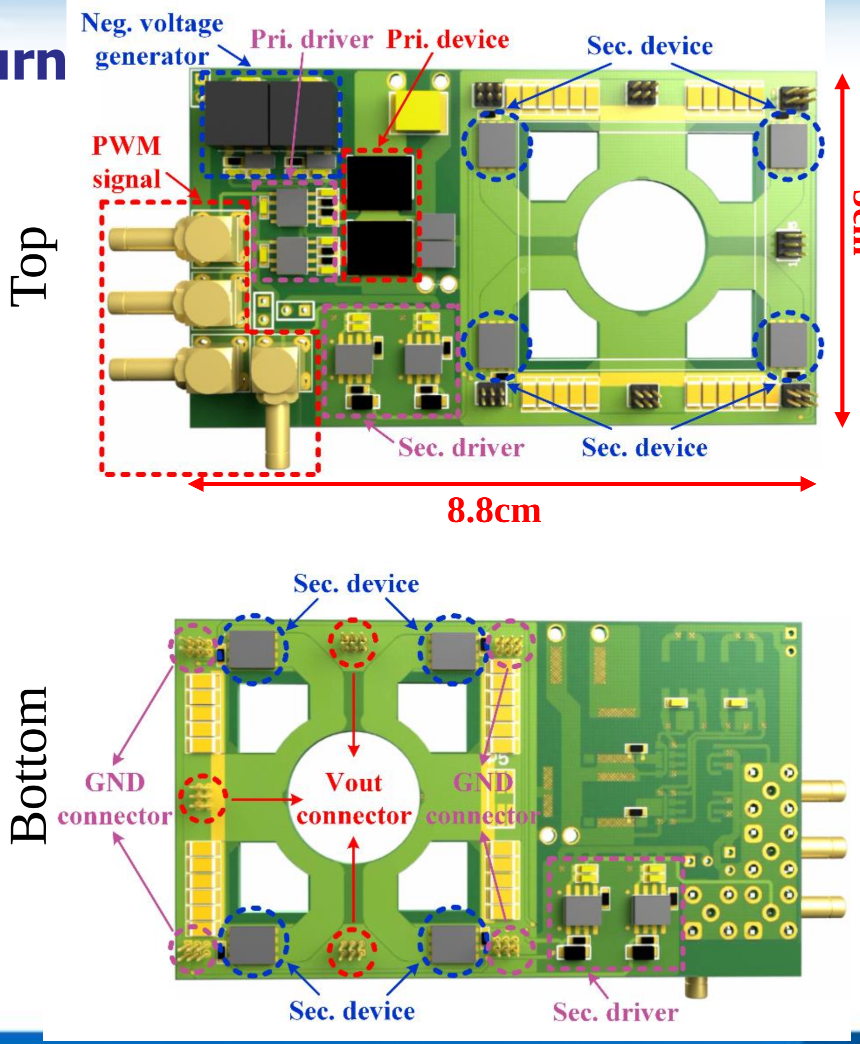




Quarter-Turn Transformer Design

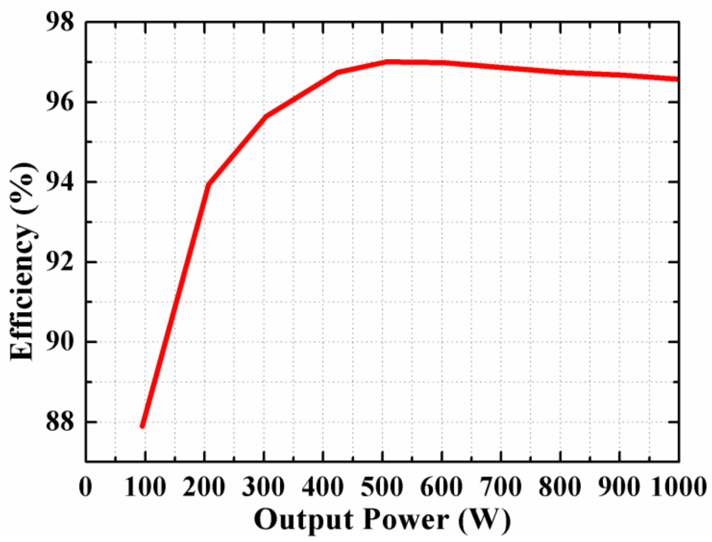
- The secondary side is a quarter turn
  - ➢ Effectively reduces copper loss
- Core height: 6mm
- Circuit volume: 26.4cm³



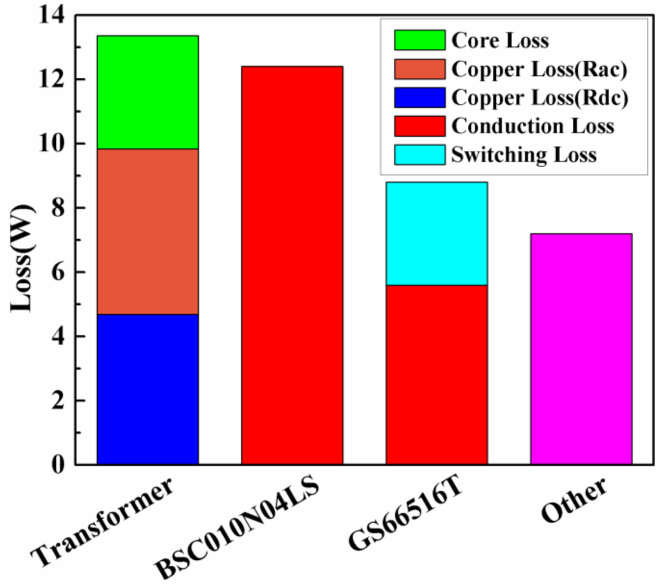


Quarter-Turn Transformer Design

✓ **Peak efficiency at half load is 97.01%**
- **Primary side switch: GS66516T**
- **Secondary side switch: BSC010N04LS**
- **Core material: 3F46**

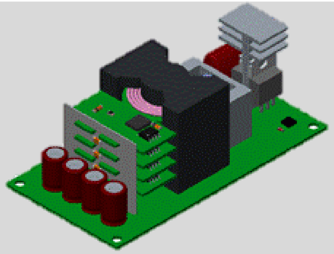
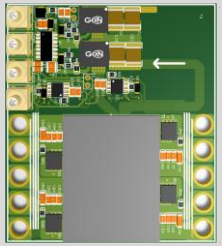
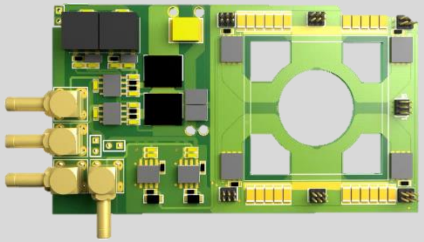


Experiment efficiency results over load range

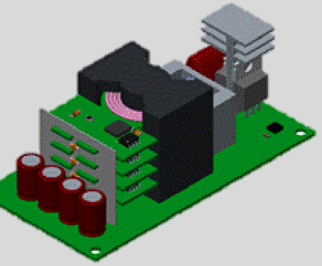
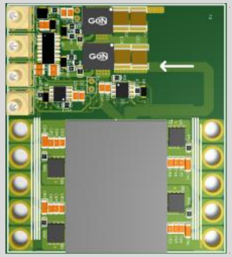
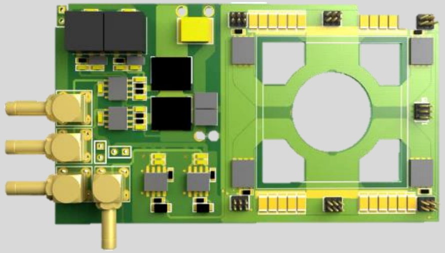


Loss analysis results at full load

Transformer Structure Comparison

Structure / Item	Stacked PCB Winding	Integrated Matrix Transformer	Quarter-Turn Transformer
PCB			
Operation Frequency	100 kHz	1 MHz	1 MHz
Circuit Size	3.2 cm * 9 cm	7 cm * 8 cm	8.8 cm * 5 cm
Height of Cores	35 mm	7 mm	6 mm
Volume	100.8 cm^3	39.2 cm^3	26.4 cm^3

Transformer Structure Comparison

Item \ Structure	Stacked PCB Winding	Integrated Matrix Transformer	Quarter-Turn Transformer
PCB			
Advantage	1. Symmetric rectifier current path 2. Shorter rectifier current path	1. High power density 2. Core loss reduction	Lowest number of secondary-side turns is a fractional turn, and secondary-side loss can be effectively reduced
Disadvantage	1. Complex design 2. Limited by iron core high 3. Higher termination loss	1. The minimum number of secondary-side turns is 1 2. Secondary-side copper loss cannot be effectively reduced	The secondary-side layout must be symmetrical, otherwise it causes current and magnetic flux imbalance

臺灣科技大學
電力電子技術研發中心
Center for Power Electronic Technologies
Taiwan Tech

High Power Density DC-DC Converter

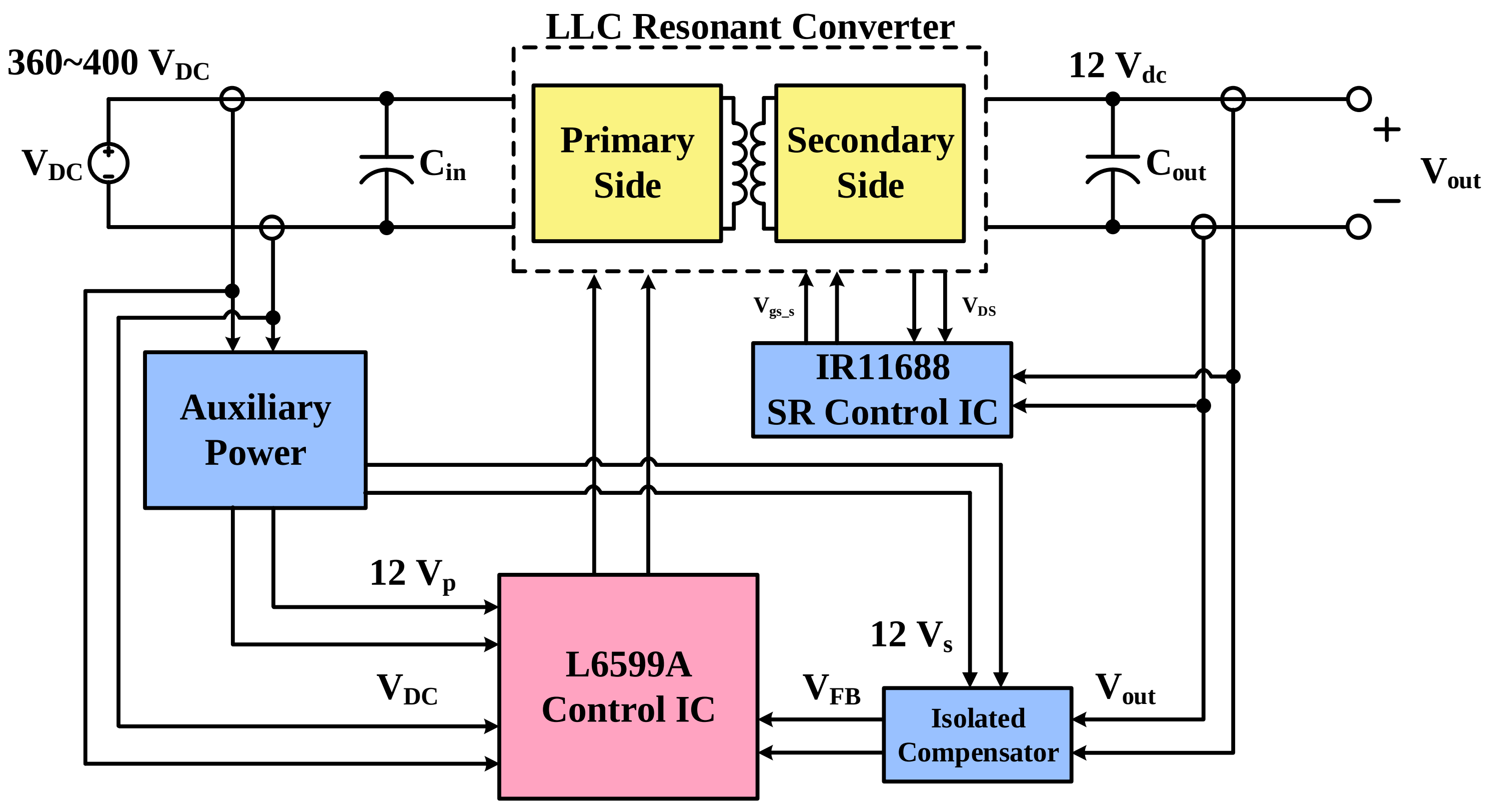
TAIWAN TECH

National Taiwan University of Science and Technology

IEEE IFEC 2017, Blacksburg

System Architecture

- Operation frequency: 120~190 kHz
- L6599A is used as control IC
- IR11688s is self-adaptive SR control IC
- L6599A is supplied by auxiliary power

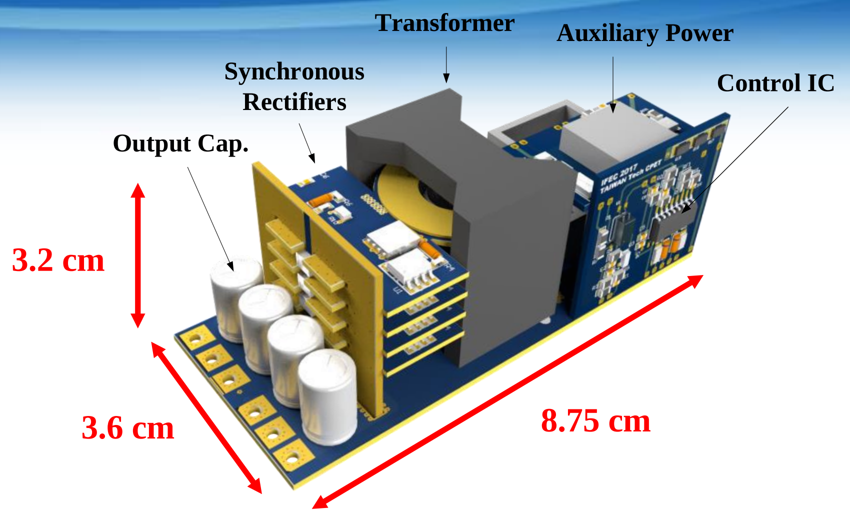


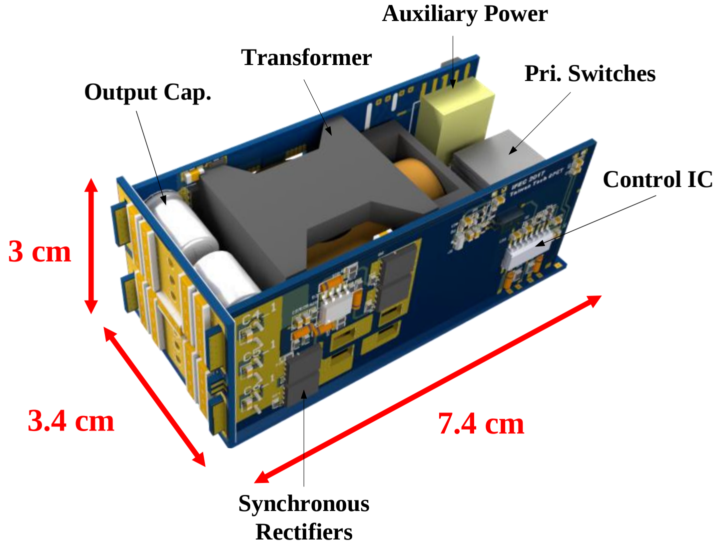
Power Density

- 1st version
  - Power Density: 7.44 W/cm^3 or 121.93 W/in^3

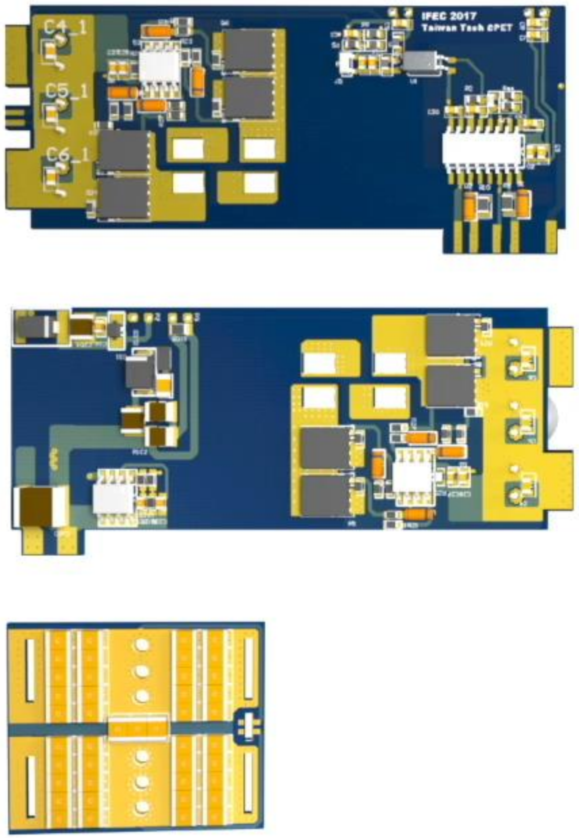
- 2nd version
  - Power Density:

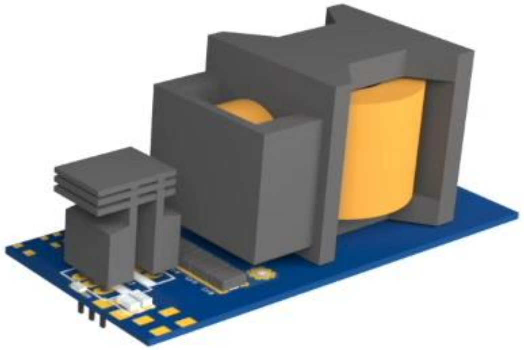
9.94 W/cm^3 or 162.88 W/in^3





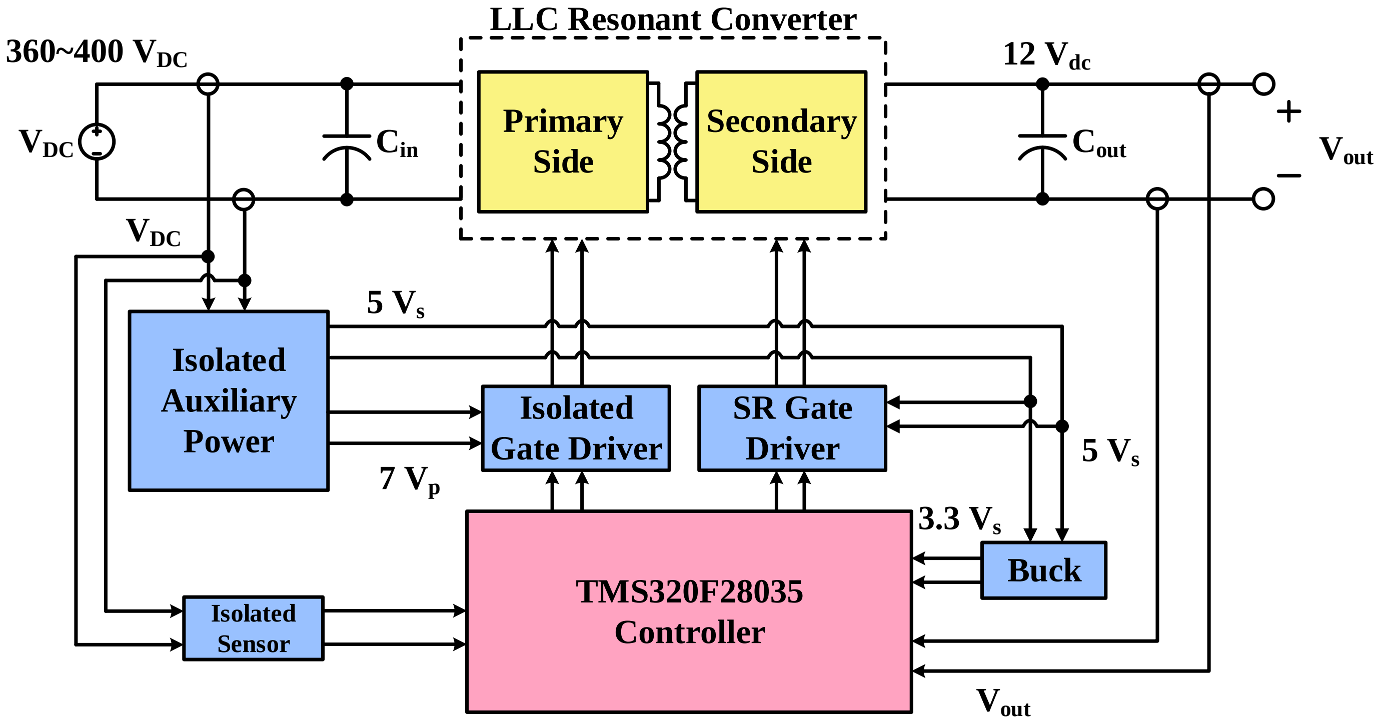
3D Demo





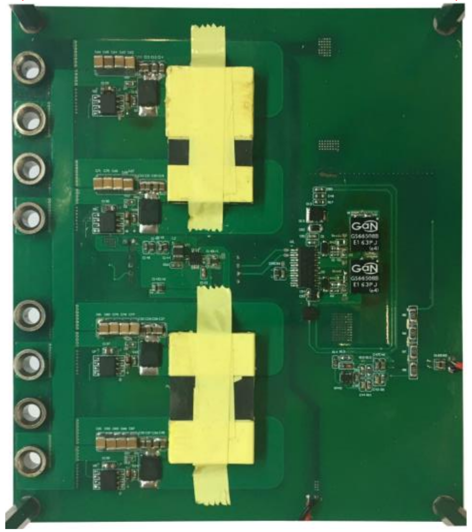
System Architecture

- Operation frequency: ~ 500 kHz
- DSP chip TMS320F28035 is used as the controller
- DSP is supplied by auxiliary power
- Tested under closed-loop control
- All GaN devices are used



Version	Power Density	Core of Transformer
1st	5.32 W/cm³ or 87.18 W/in³	31.75 ∗ 20.3 ∗ 9.5 mm³ (Material: P61)
2nd	7.93 W/cm³ or 129.97 W/in³	24 ∗ 20.3 ∗ 9.5 mm³ (Material: P61)

11.1 cm



12.7 cm

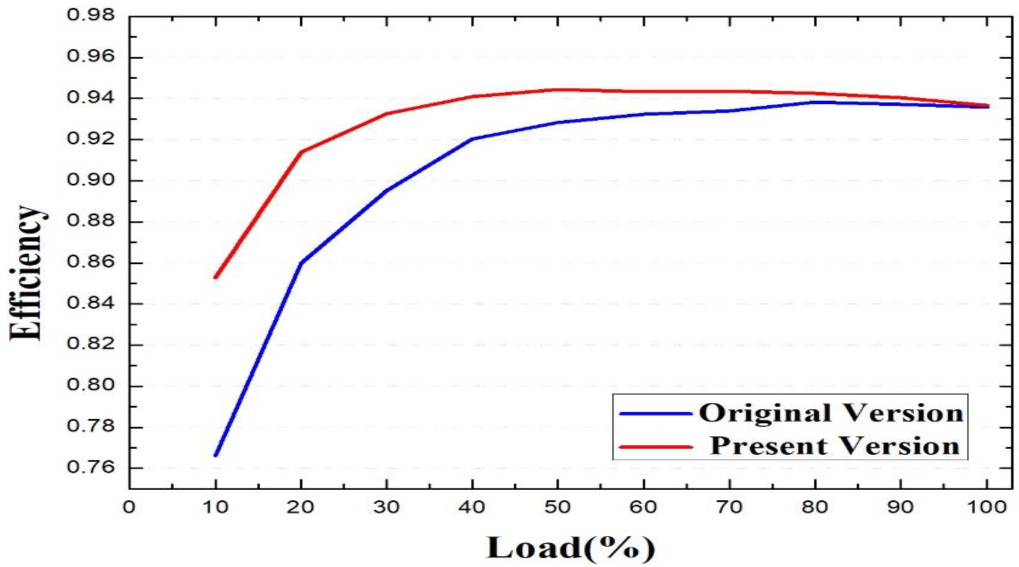
1st version (Height: 1cm)

9.6 cm

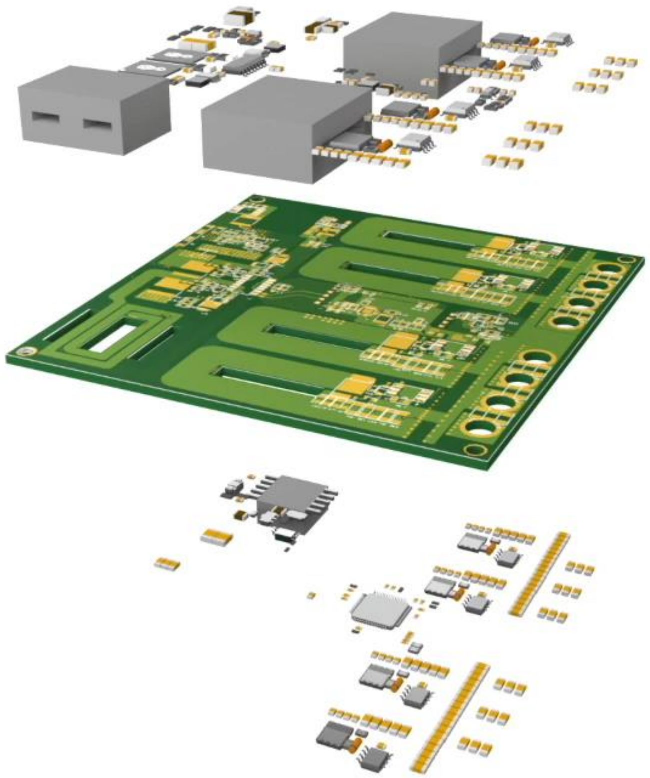
9.8 cm

2nd version(Height: 1cm)

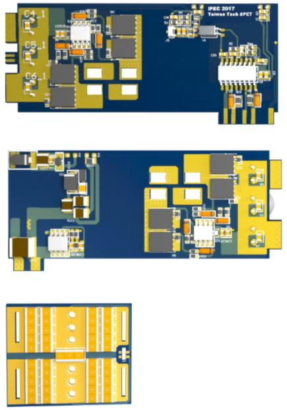
Efficiency Curve

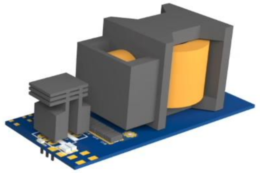


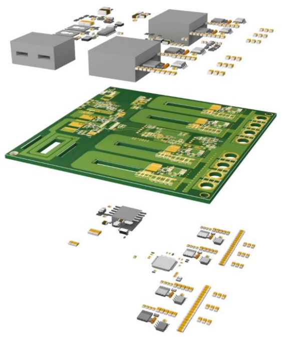
3D Demo



GaN based server power supply



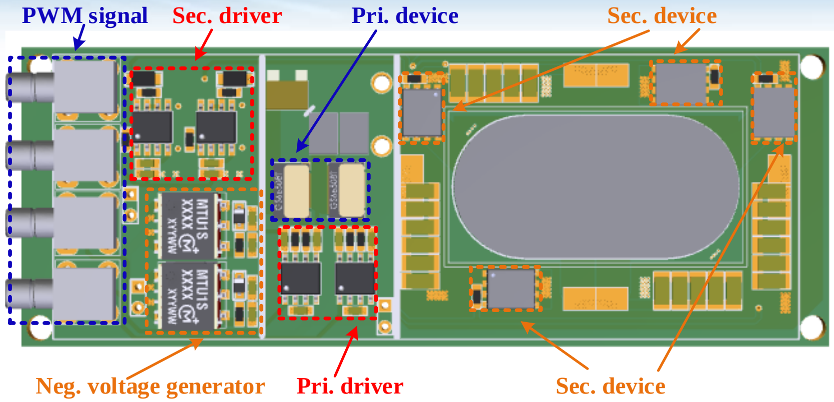




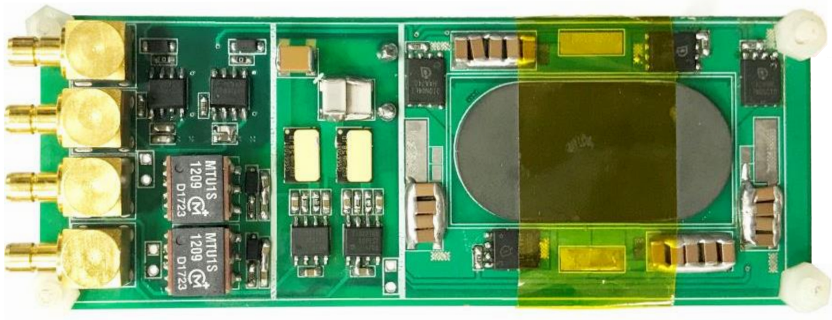
high power density/ small form factor/ digital control

GaN based server power module

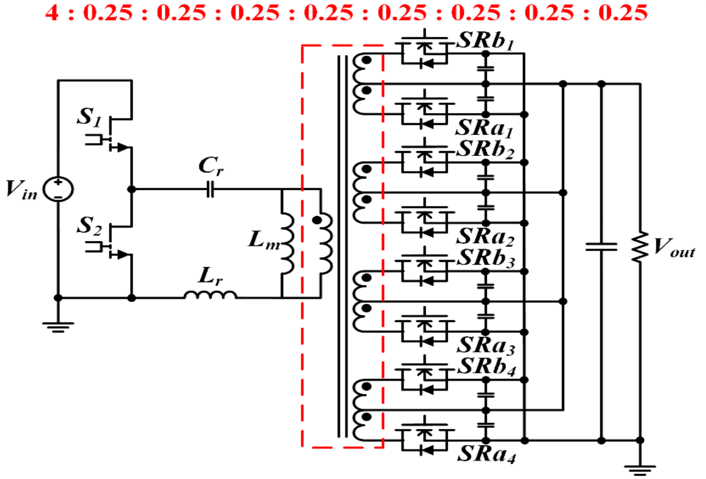
Circuit Parameters	
Input/ Output voltages	380V/12V
Output Power	800W
Switching Freq.	1MHz
Primary Switches	GS66508T
Secondary Switches	BSC0500NSi
Core Material	ML91S
Turns Ratio	16:1
Dimension	6.5cm x 3.2cm x 0.7cm

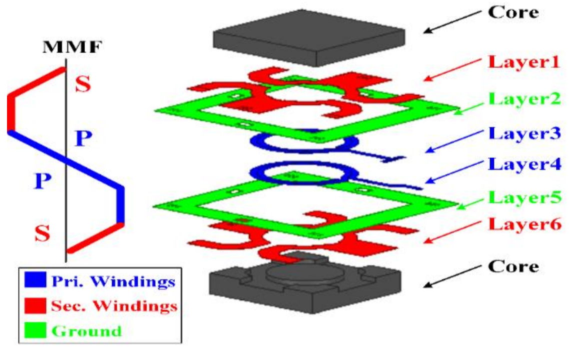


3D Layout



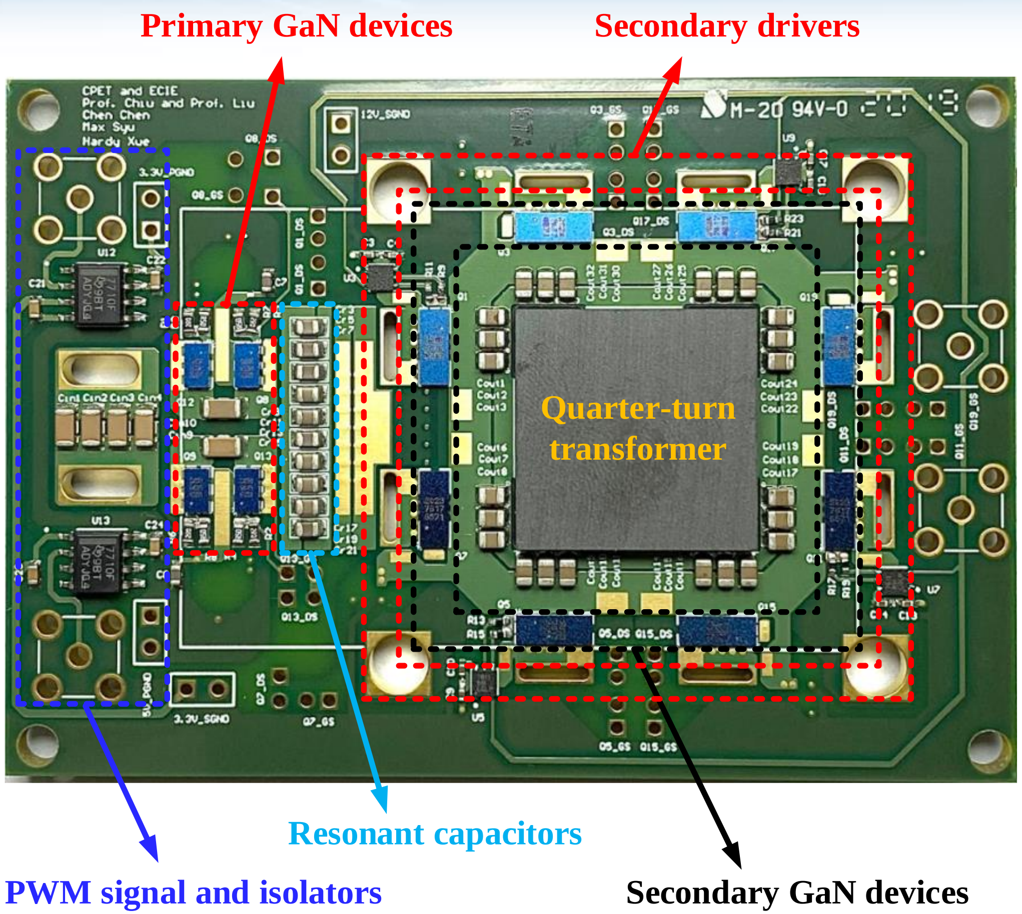
Prototype

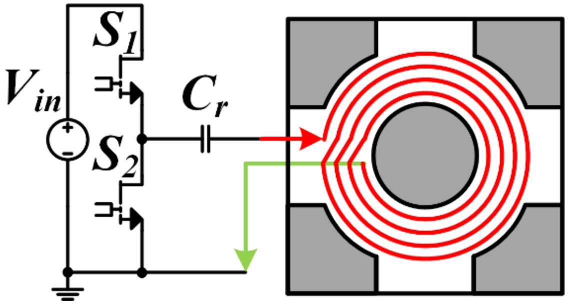


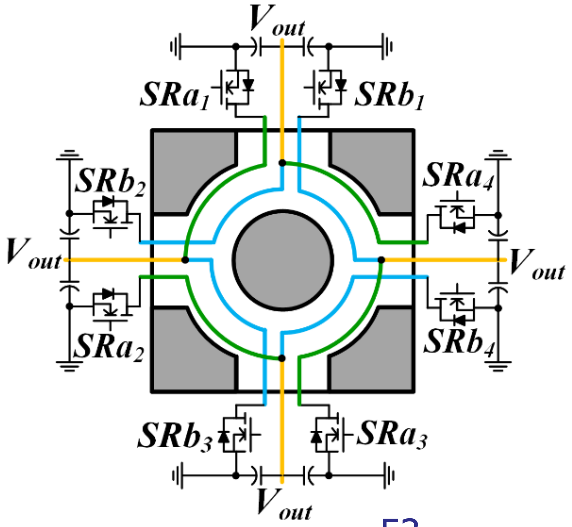


GaN based 48V DC-DC module

Circuit Parameters	
Input Voltage	48 V
Output Voltage	6 V
Output Current	190 A
Output Power	1100W
Efficiency	98%
Power Density	70 W/cm³
Transformer Turns Ratio	2 : 0.25
Core Material	P63
Primary Switches	EPC2053
Secondary Switches	EPC2023
Primary Driver IC	LM5113
Secondary Driver IC	UCC27611
Resonant Capacitance	1.05 µF
Resonant Inductance	23 nH
Magnetizing Inductance	2.4 µH

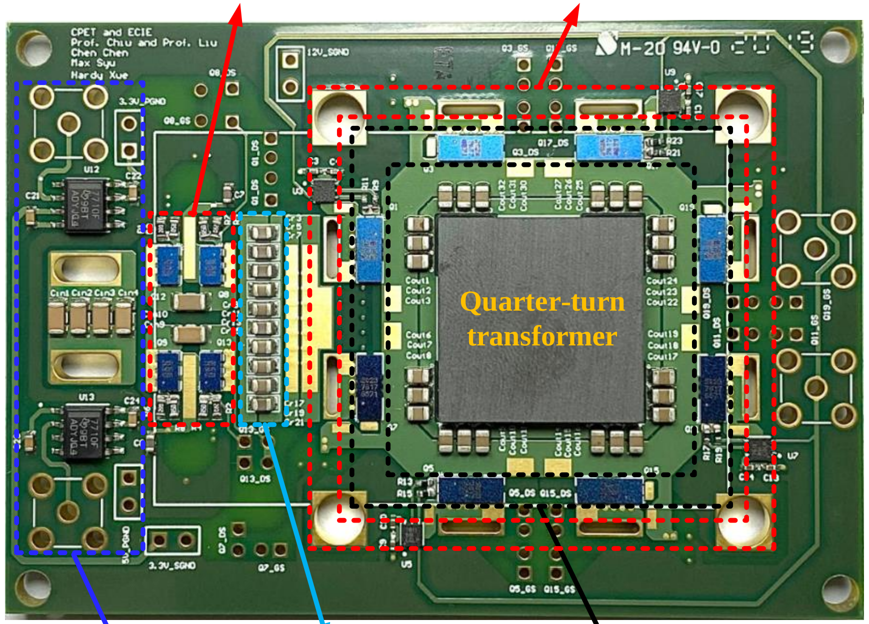




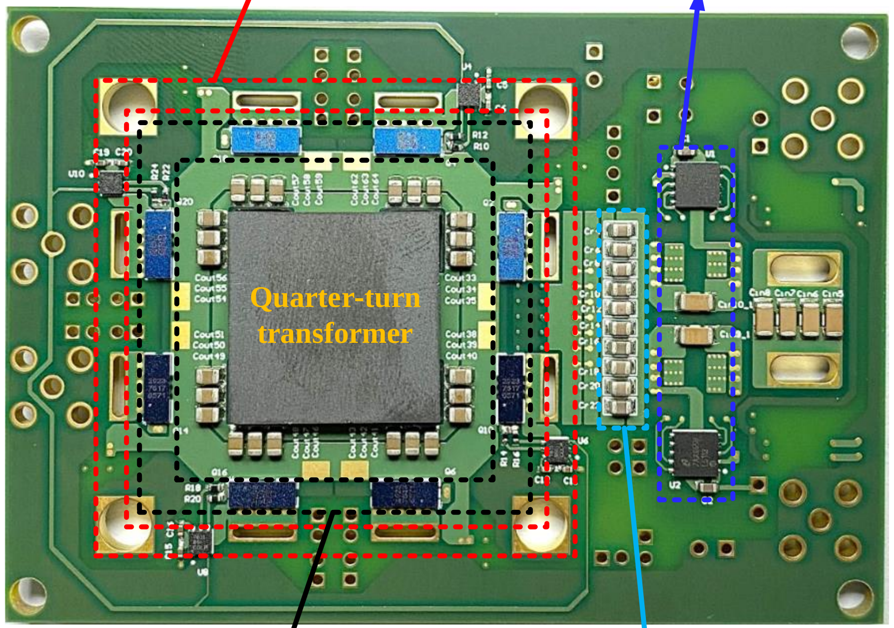


GaN based 48V DC-DC module

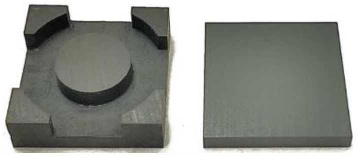
Top



Bottom

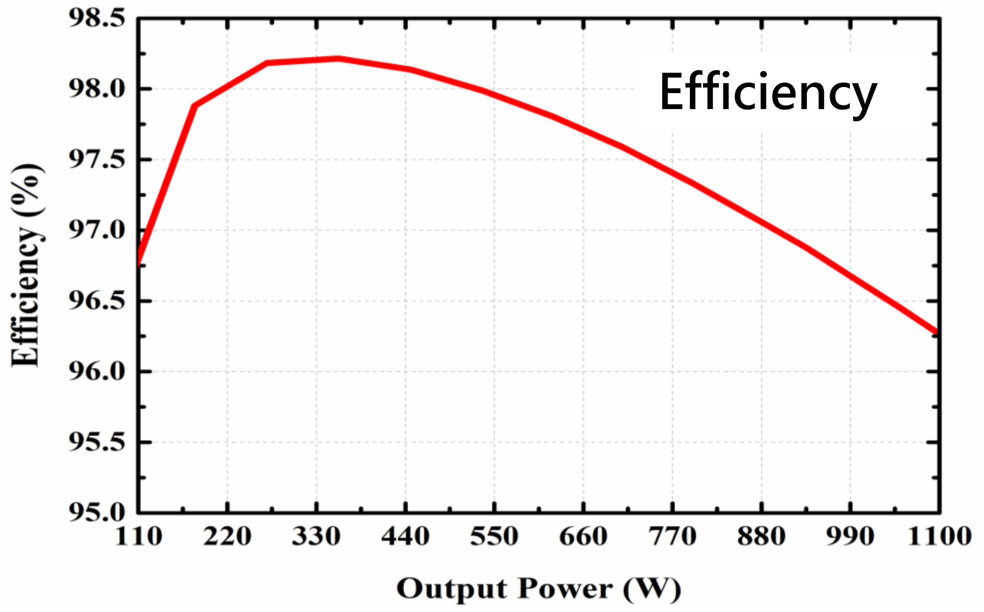


- Core Dimension：19mm x 19mm x 8.3mm
- 14-layer PCB：80.6mm x 56mm x 2.6mm

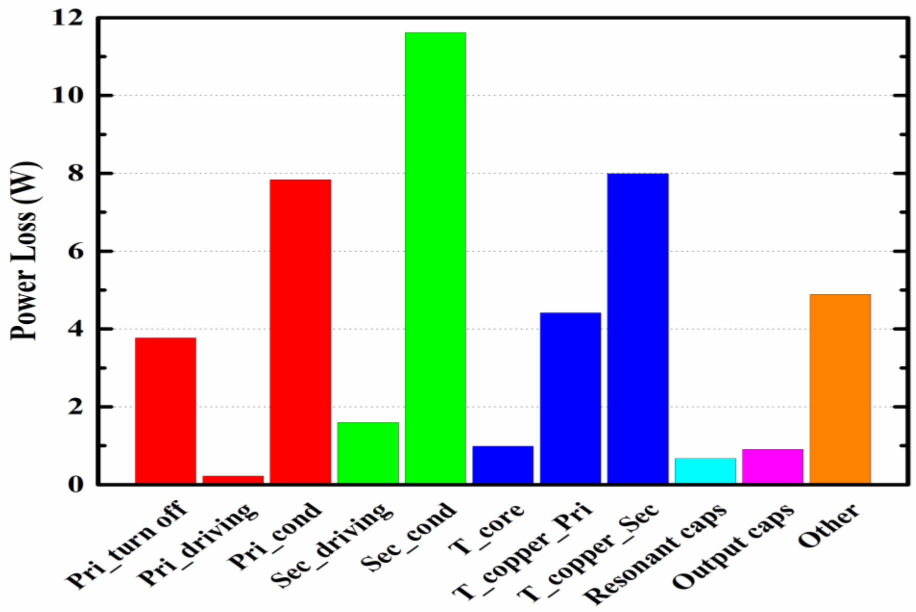


GaN based 48V DC-DC module

- Peak Efficiency **98.2%**
- Power Density **70 W/cm³**

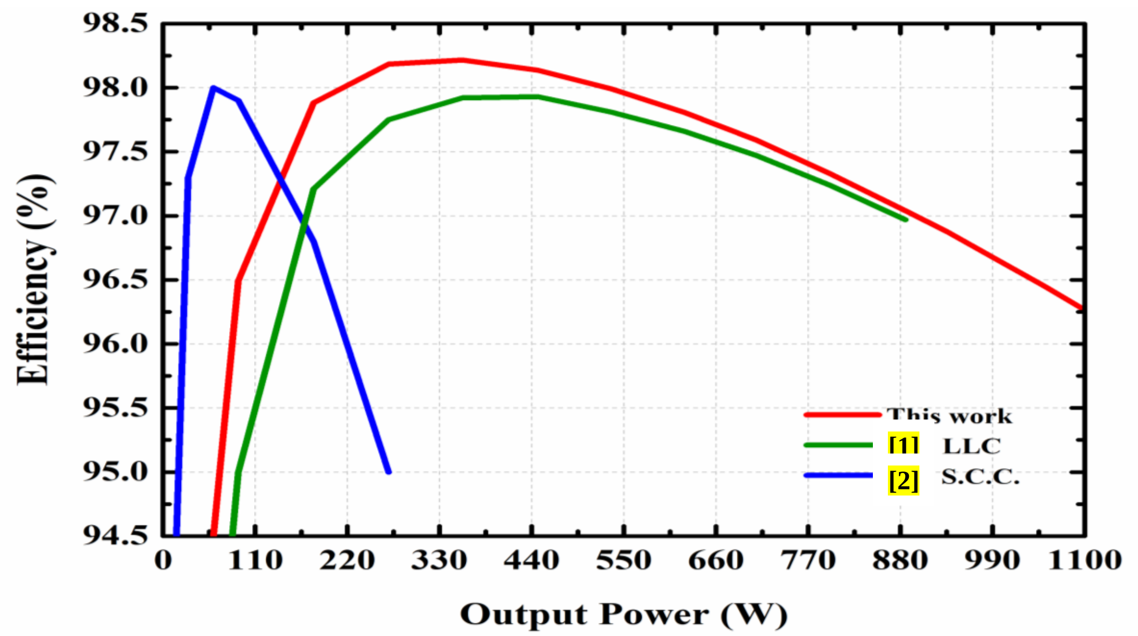


Power Losses@1100W



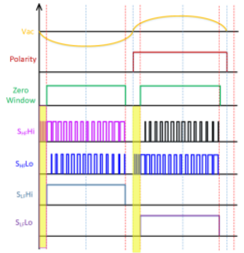
GaN based 48V DC-DC module

Circuit Spec.	This work	[1]	[2]
Topology	LLC	LLC	S.C.C.
Voltage Ratio	**48V – 6V**		
Switching Freq.	1.05 MHz	1 MHz	70 kHz
Output Power	1100 W	900 W	240 W
Power Density	70 W/cm^3	69 W/cm^3	102 W/cm^3
Peak Efficiency	98.2%	98%	98%

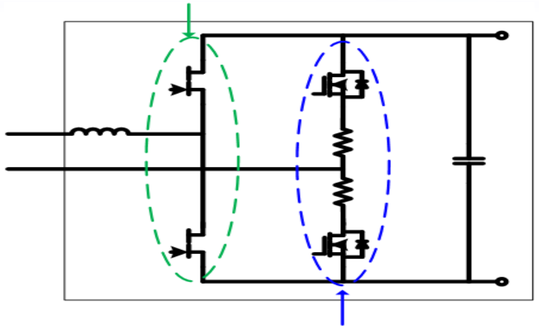


1. M. H. Ahmed, F. C. Lee and Q. Li, "Two-Stage 48V VRM With Intermediate Bus Voltage Optimization For Data Centers," in IEEE Journal of Emerging and Selected Topics in Power Electronics.
2. Z. Ye, R. A. Abramson and R. C.N. Pilawa-Podgurski, " A 48-to-6 V Multi-Resonant-Doubler Switched-Capacitor Converter for Data Center Applications," 2020 Applied Power Electronics Conference and Exposition (APEC)

GaN based totem-pole bridgeless CCM PFC

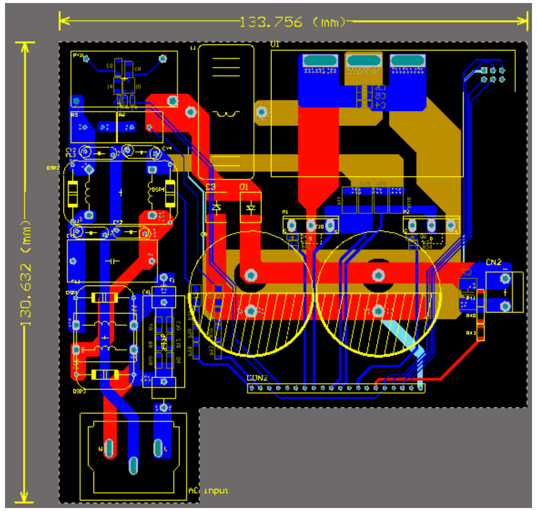


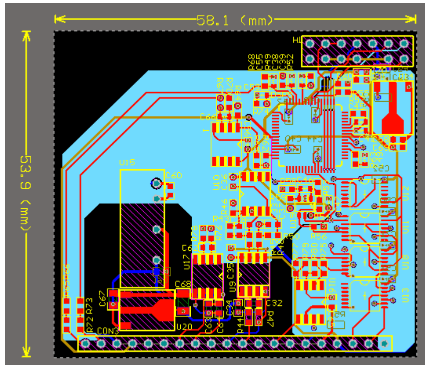
High frequency leg

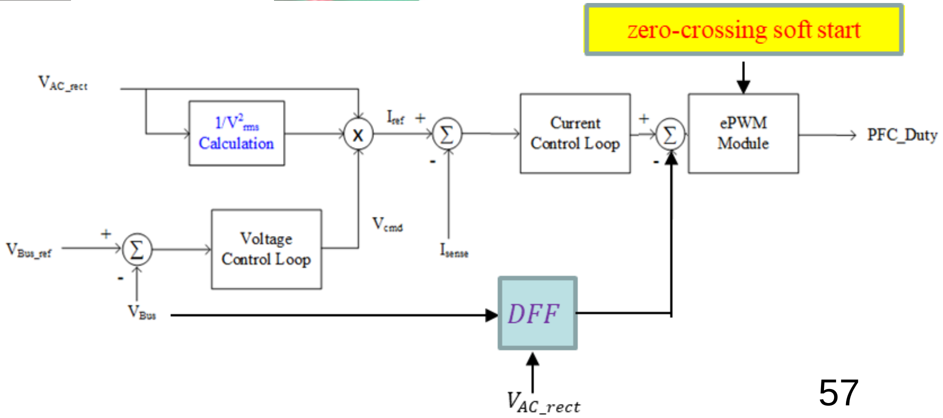


low frequency leg

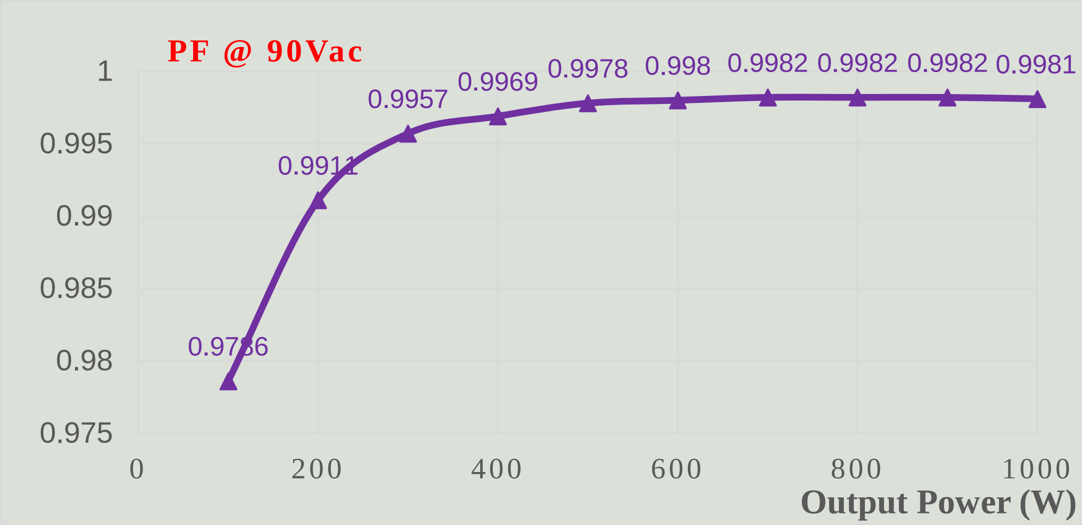
Item	Value
V_{in}	90~264Vac
Efficiency	99% @ 230Vac
Power Factor	0.99
$V_{out(max)}$	400V
Output power	1kW @ 90-132V 2.6kW @ 180-264V
Control IC	TMS320F28035
High Freq. Switches	GS66516B

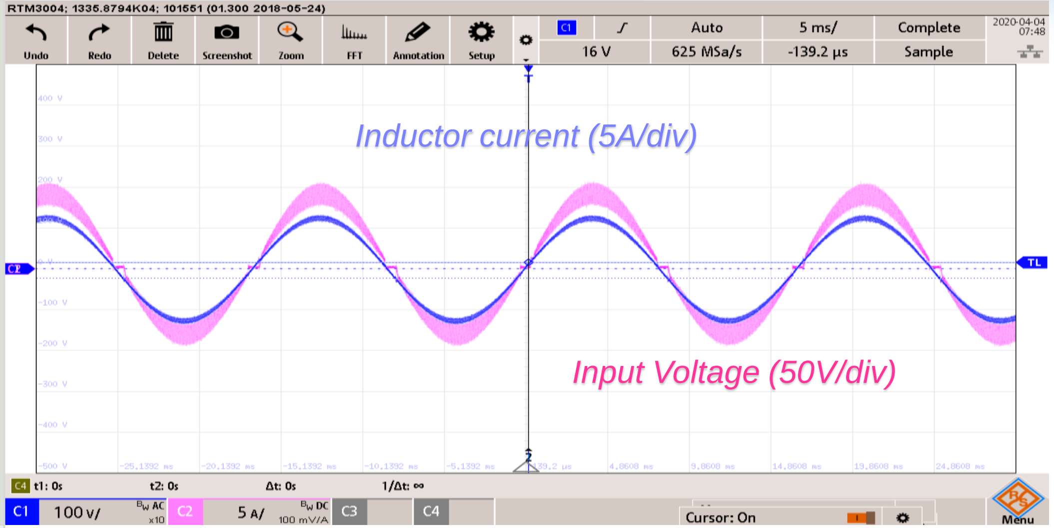


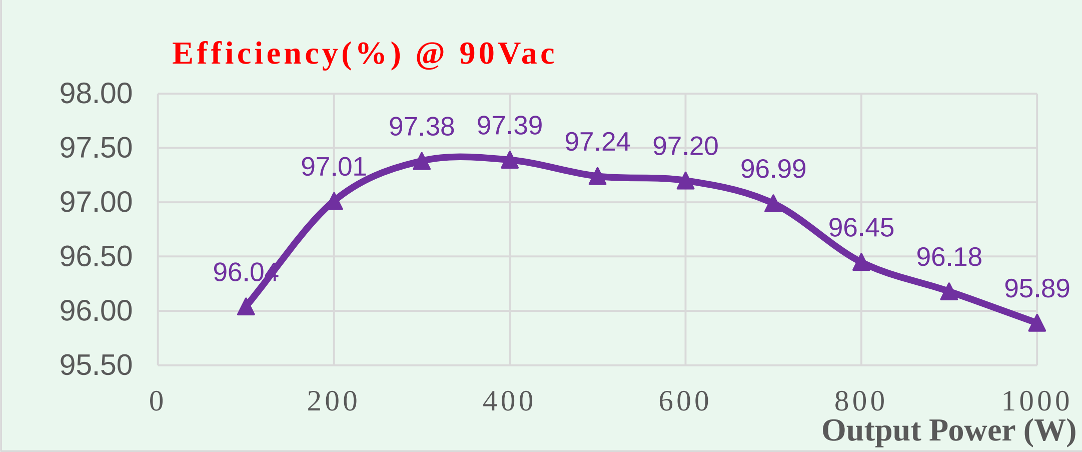


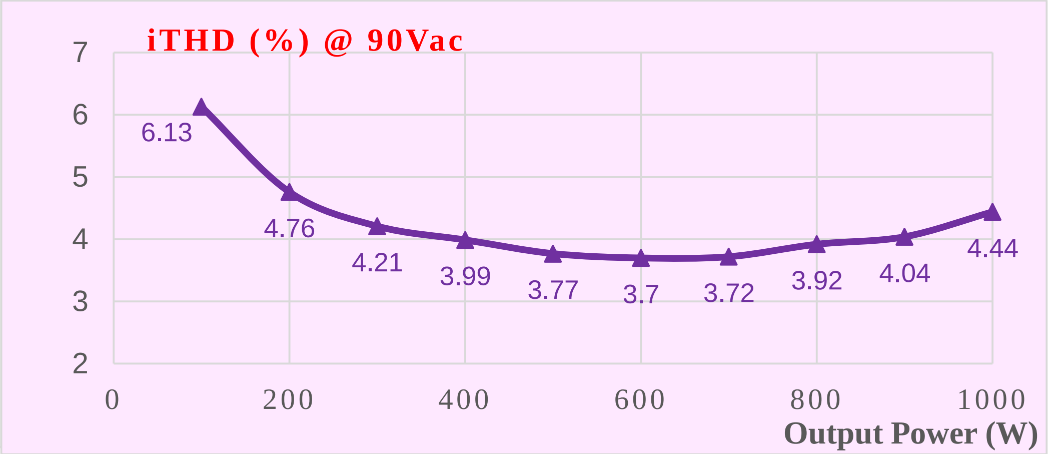


GaN based totem-pole bridgeless CCM PFC

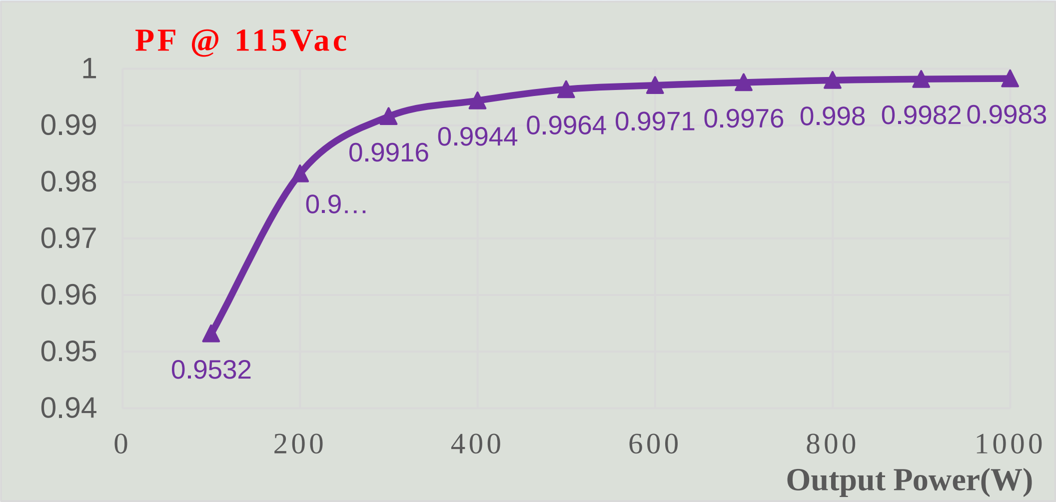


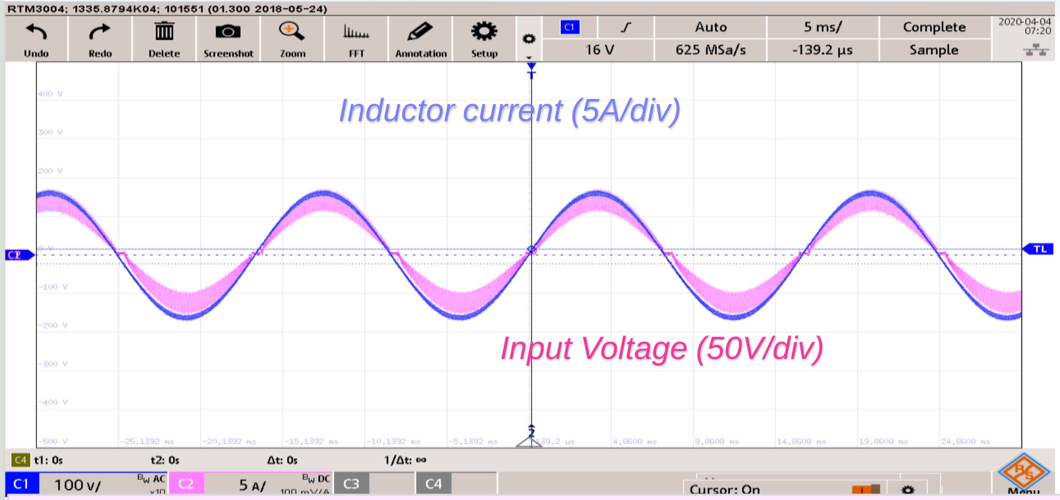


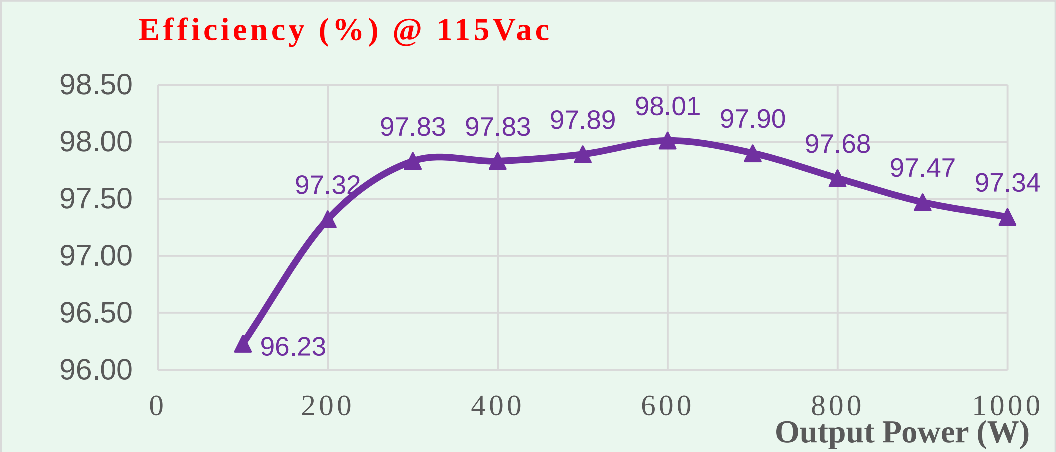


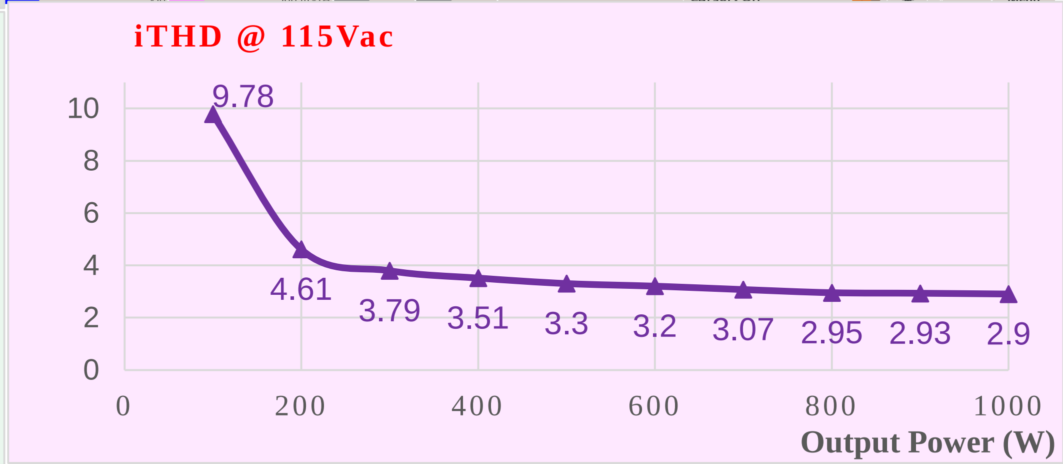


GaN based totem-pole bridgeless CCM PFC

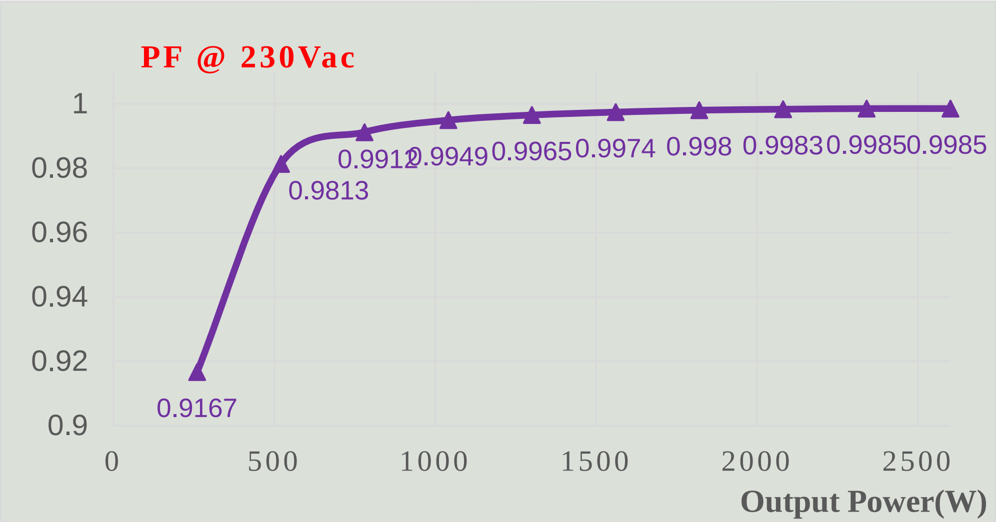


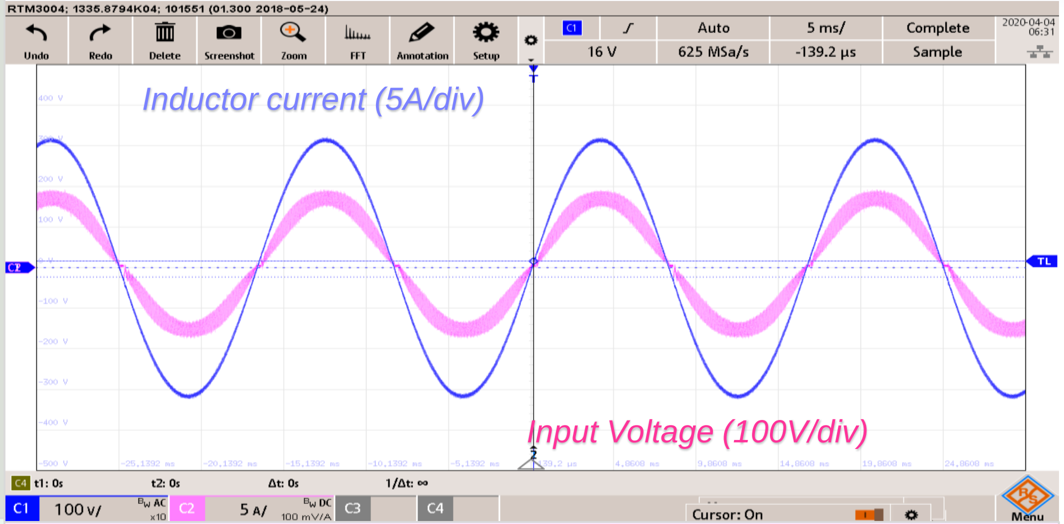


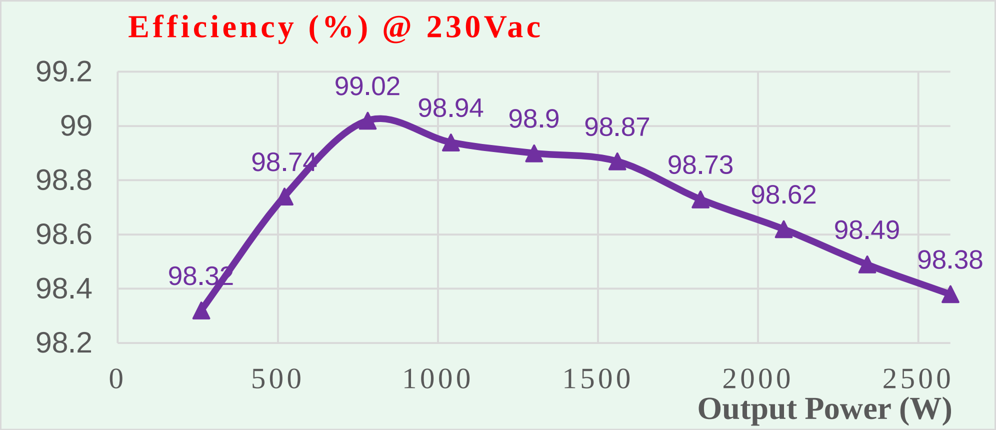


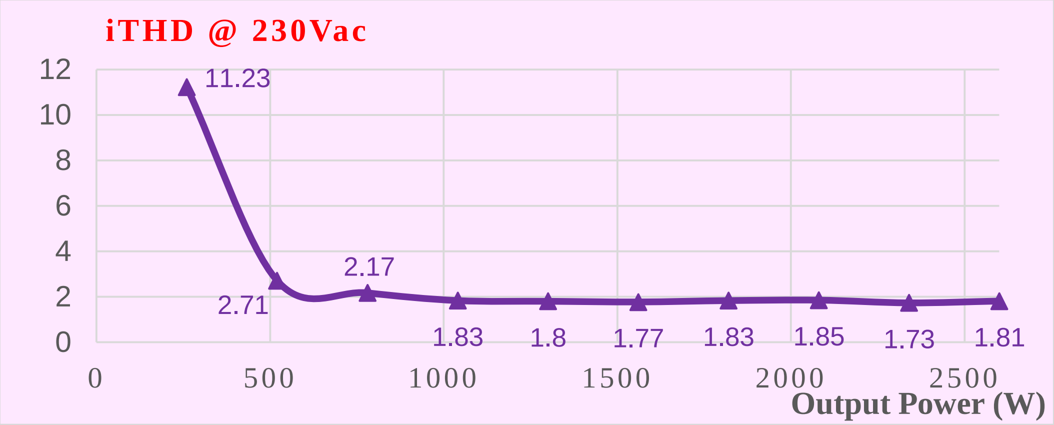


GaN based totem-pole bridgeless CCM PFC

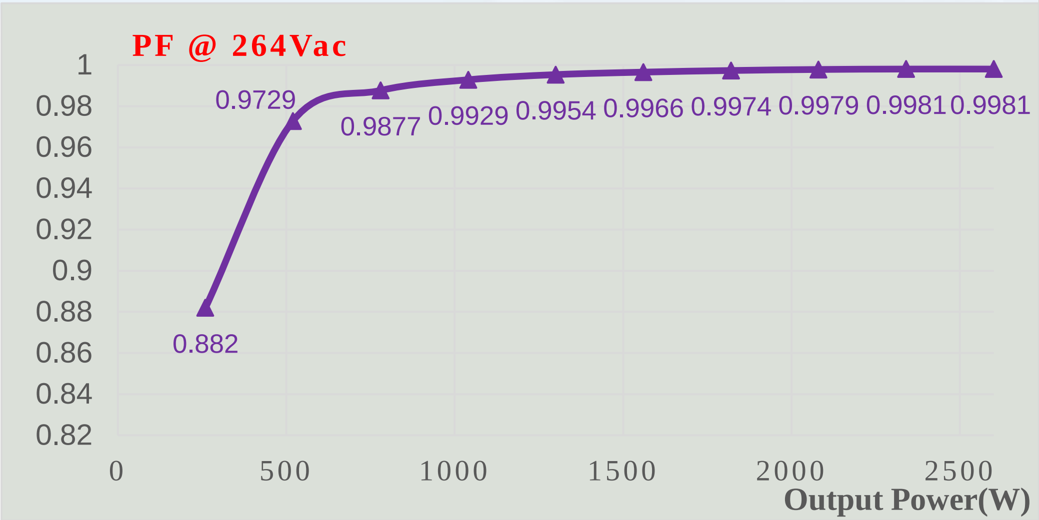


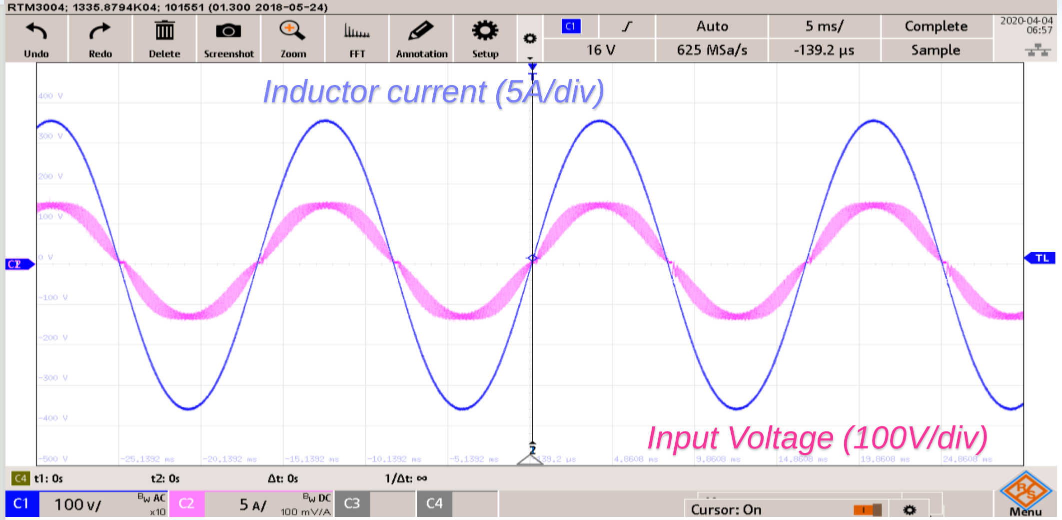


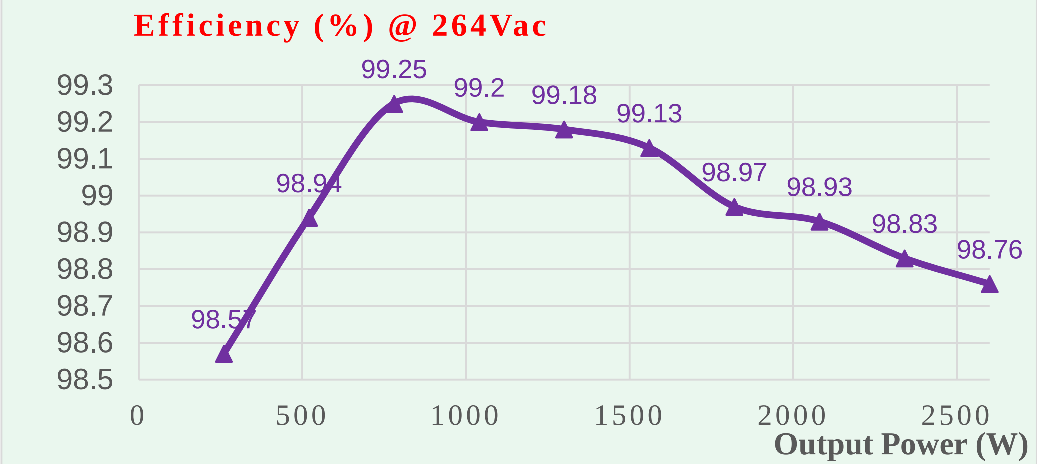


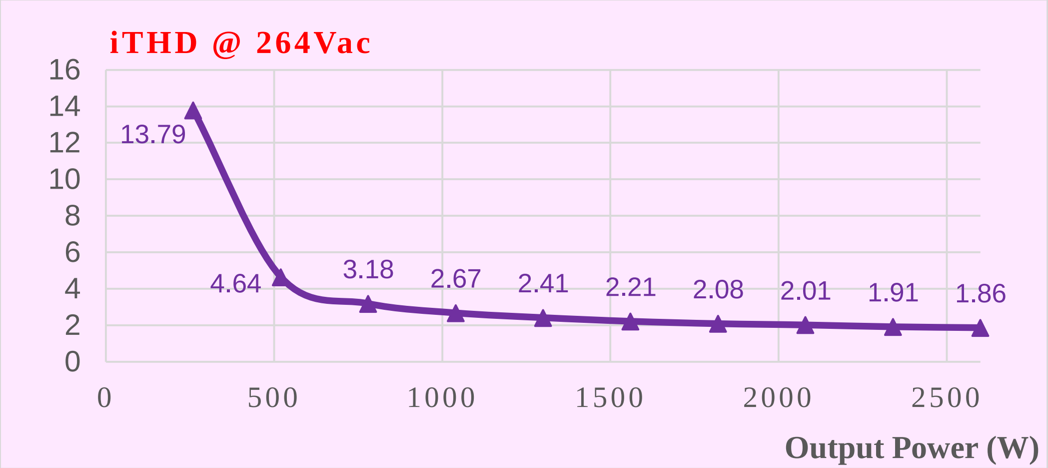


GaN based totem-pole bridgeless CCM PFC







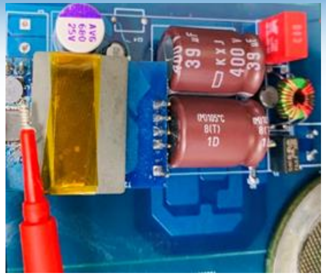


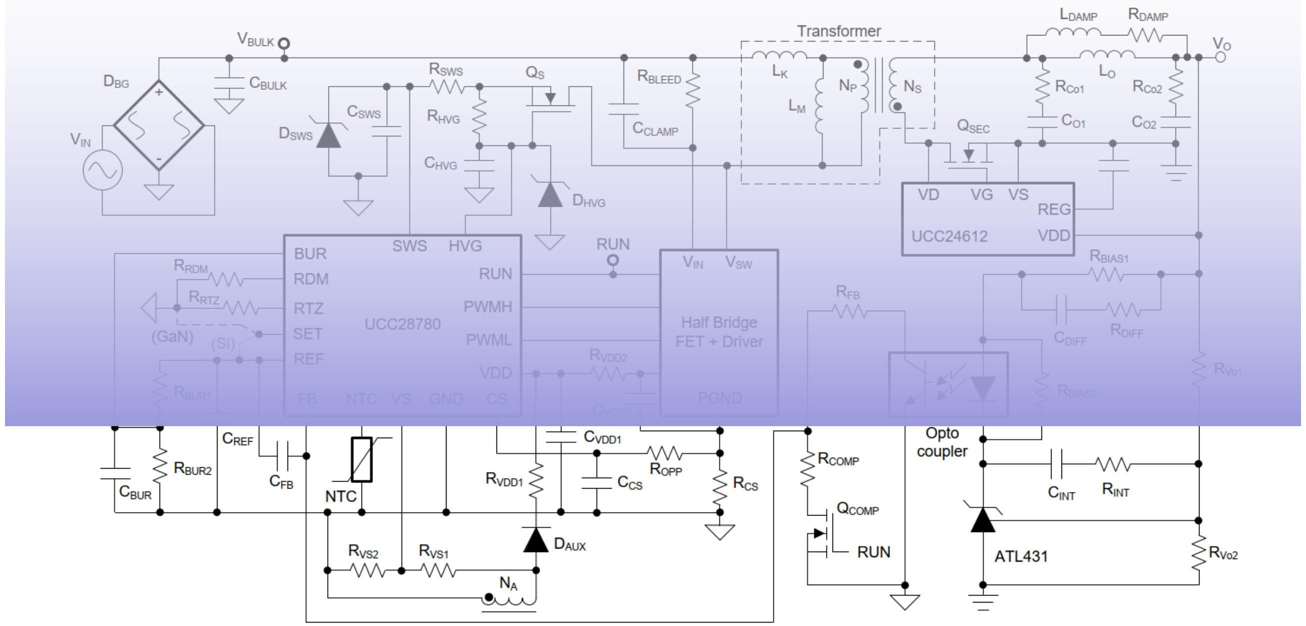
High power density GaN based adaptor

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

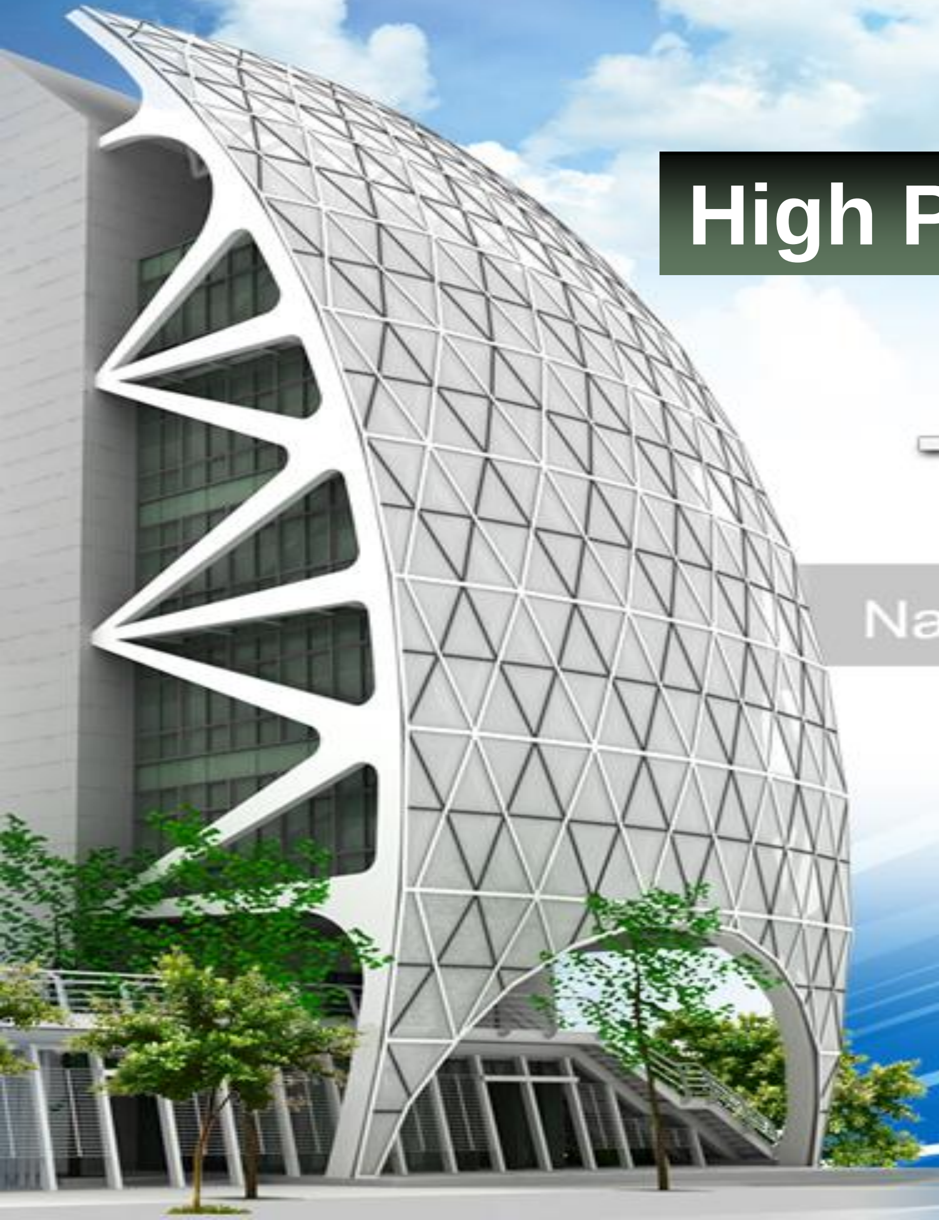
Miniaturization





臺灣科技大學
電力電子技術研發中心
Center for Power Electronic Technologies
Taiwan Tech

High Power Density Bidirectional Converters

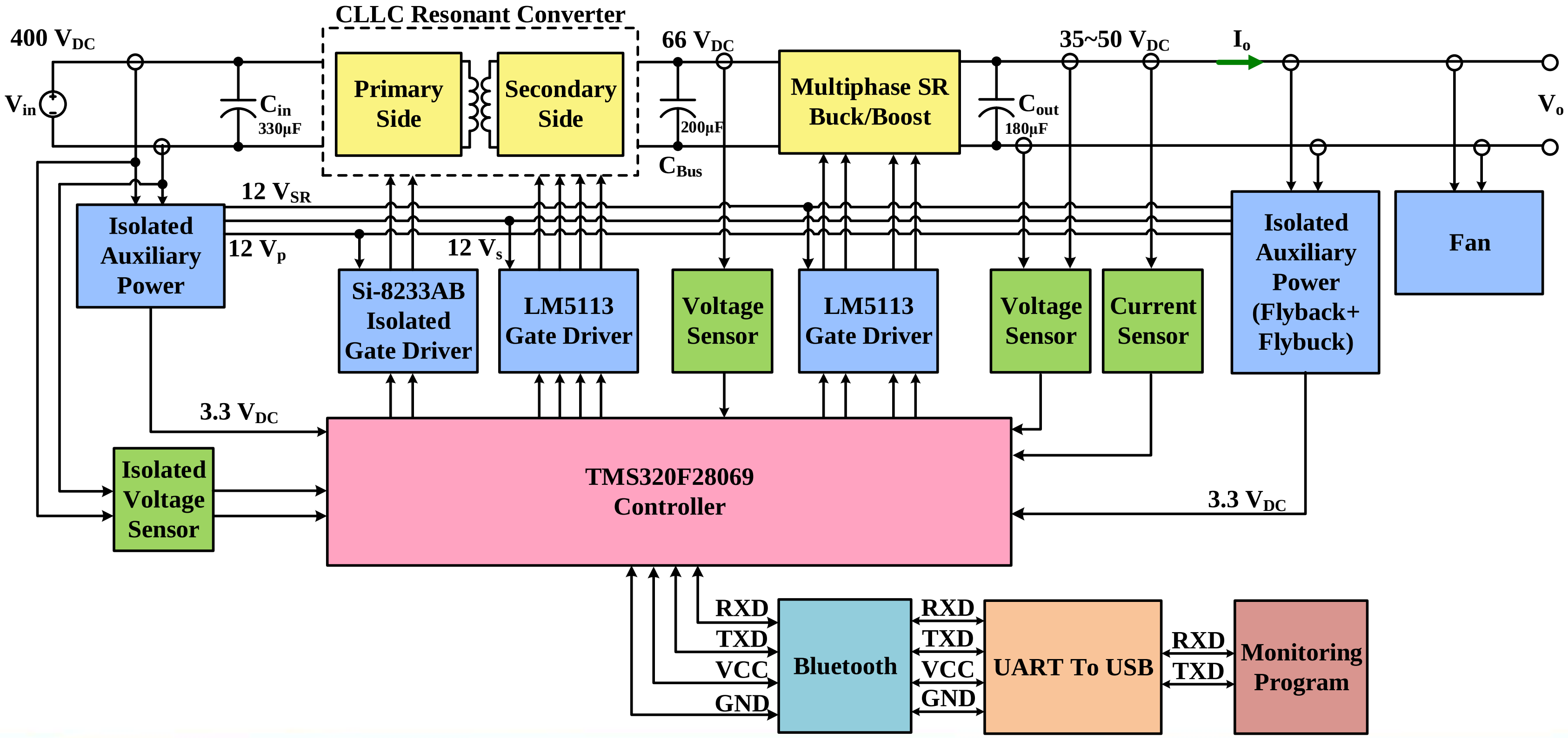


TAIWAN TECH

National Taiwan University of Science and Technology

System Architecture

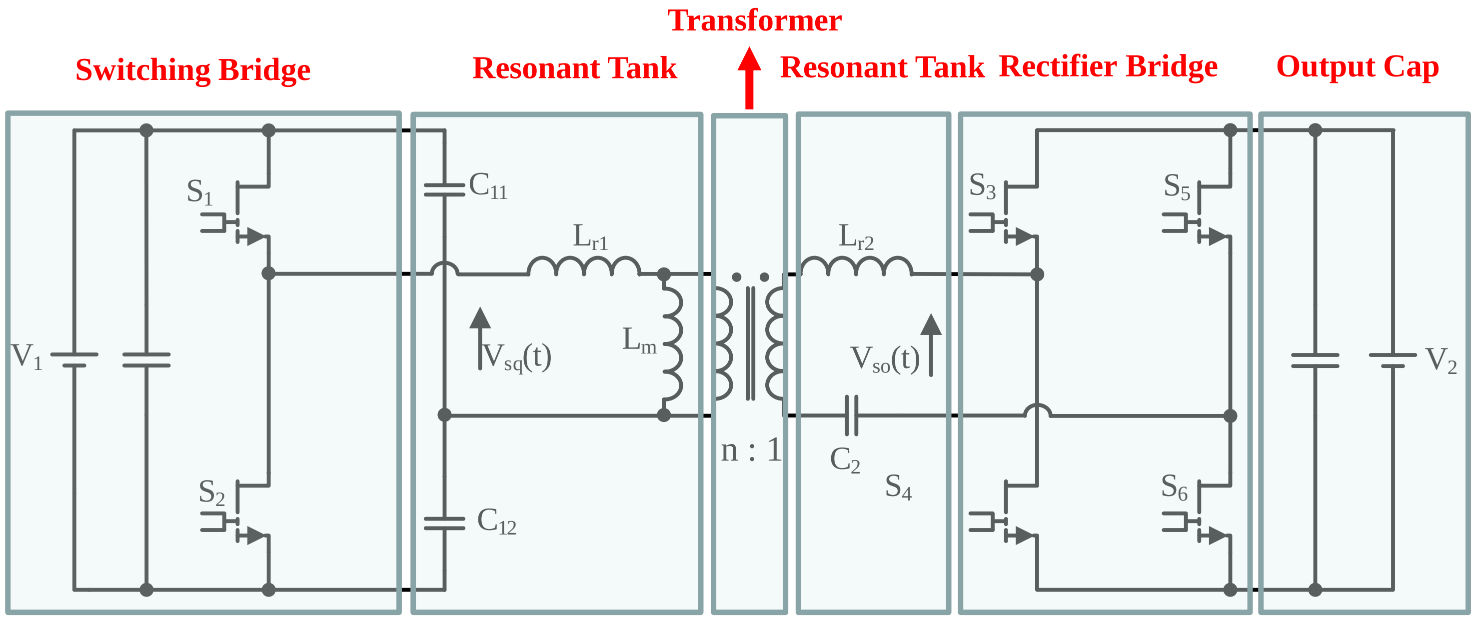
- First stage: Open-Loop CLLC resonant converter
- Second stage: Multiphase SR Buck/Boost converter
- TMS320F28069 is used as controller
- Bluetooth is used for communication



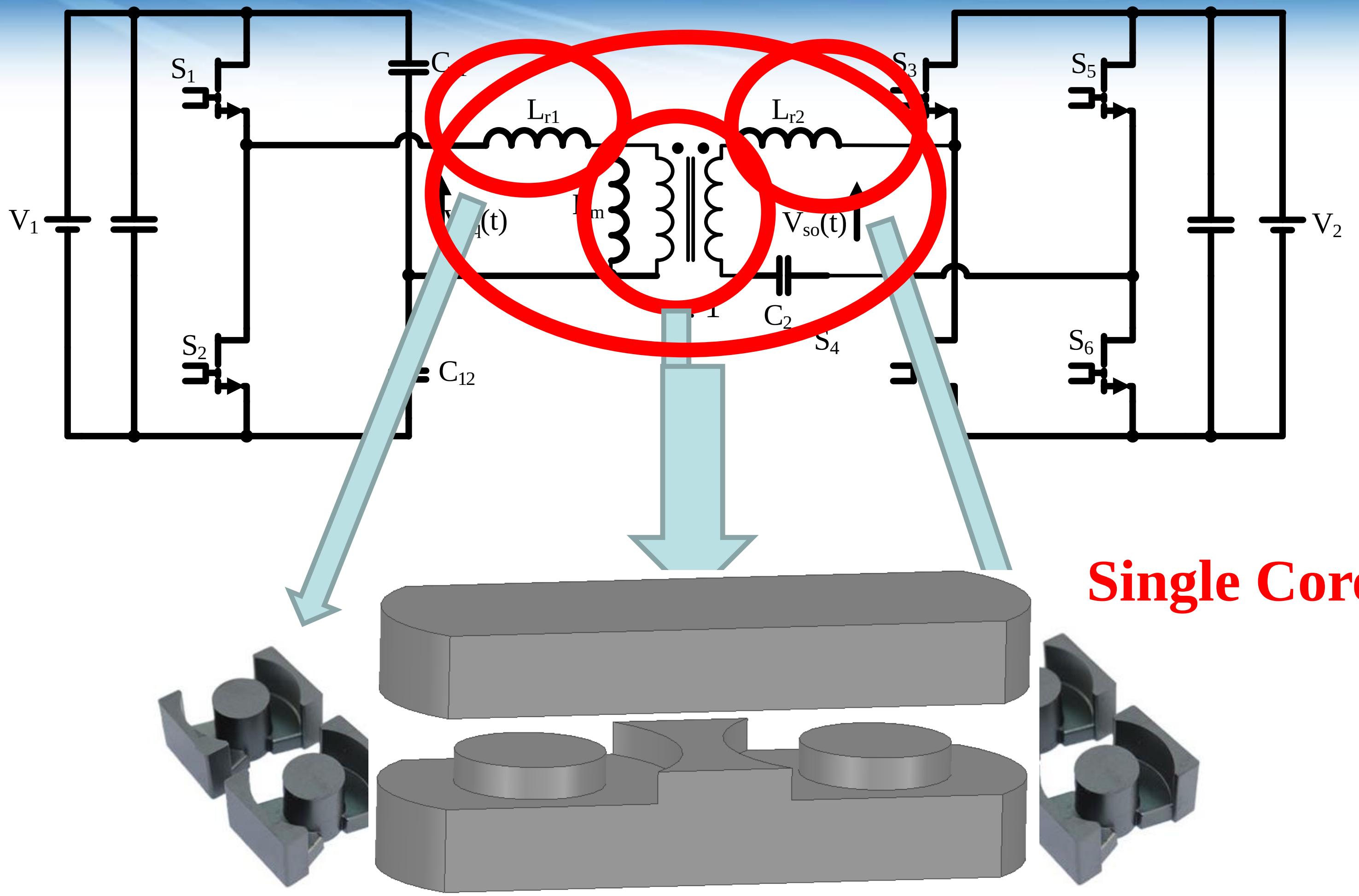
CLLC Resonant Converter

Advantages:

- **Primary side achieves ZVS over full load range**
- **Secondary side achieves ZCS in LLC region**



Transformer Design



Single Core

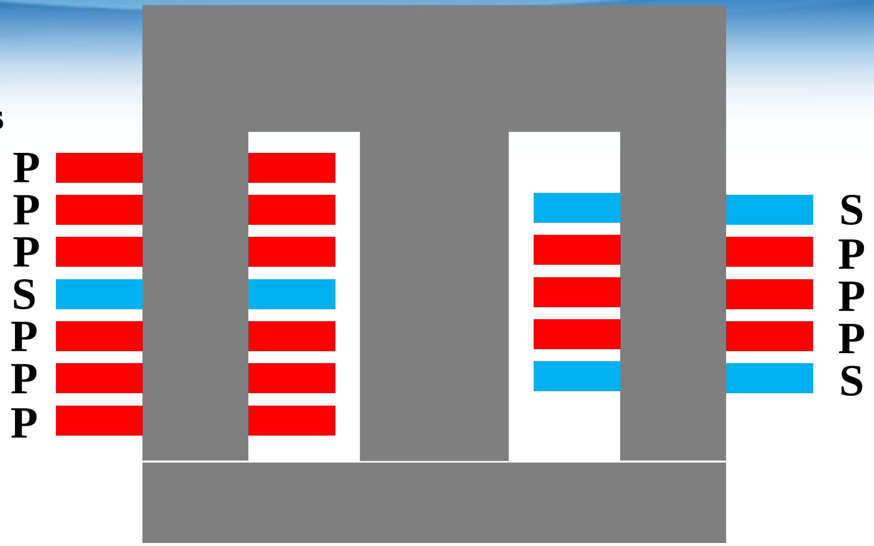
L_{r1}:PQ2620　　Transformer: EI50　　L_{r2}:PQ2620

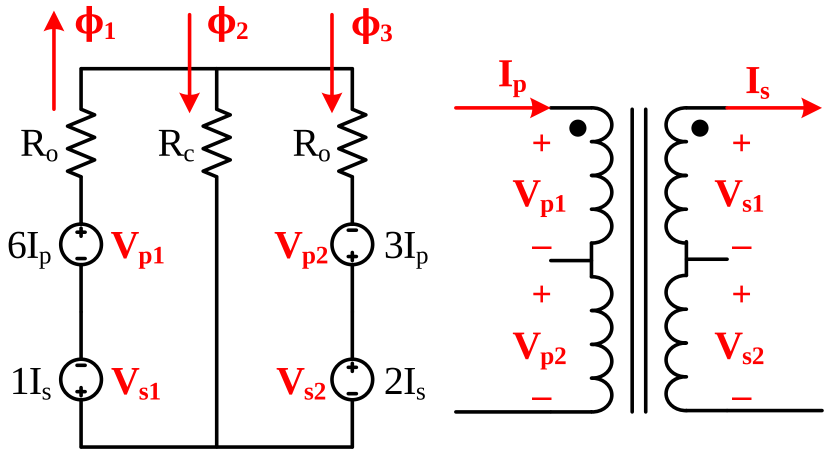
Transformer Design

✓ Transformer with controllable leakage integration

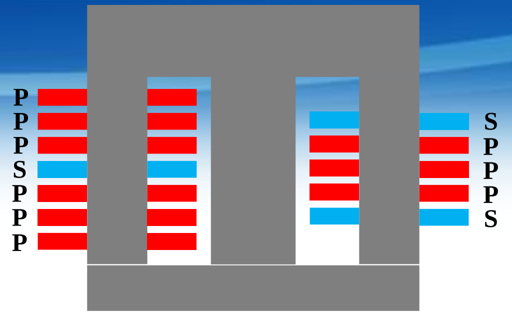
- Without primary and secondary resonant inductors
- Increasing the power density

Parameters	Inductance
Primary Side Magnetizing Inductance	$L_m = \frac{36R_o + 81R_c}{R_o(R_o + 2R_c)}$
Primary Side Leakage Inductance	$L_{lkp} = \frac{9}{R_o + 2R_c}$
Secondary side Leakage Inductance	$L_{lks} = \frac{1}{R_o + 2R_c}$





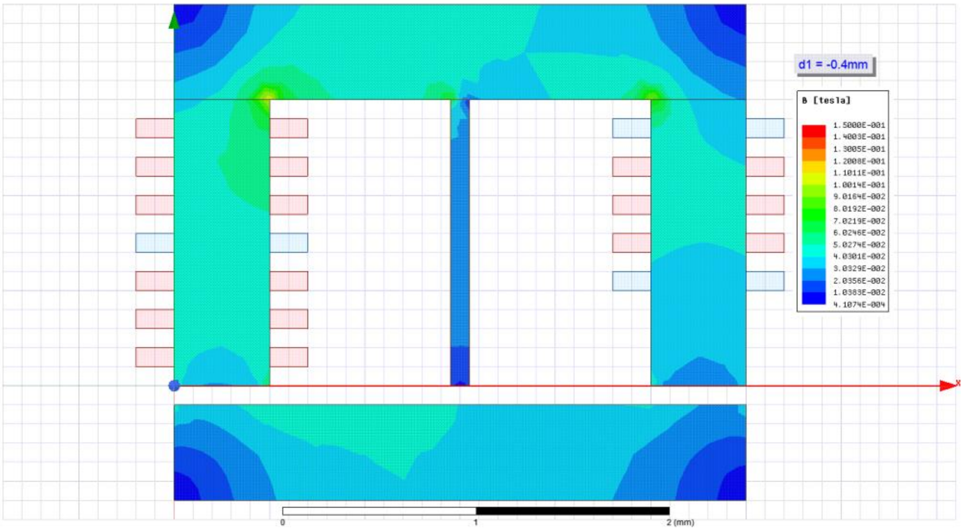
Transformer Design



✓ Transformer with controllable leakage integration

- The ratio between center leg and outer leg
- Check the coupling coefficient by MAXWELL
- Turns ratio is 9:3

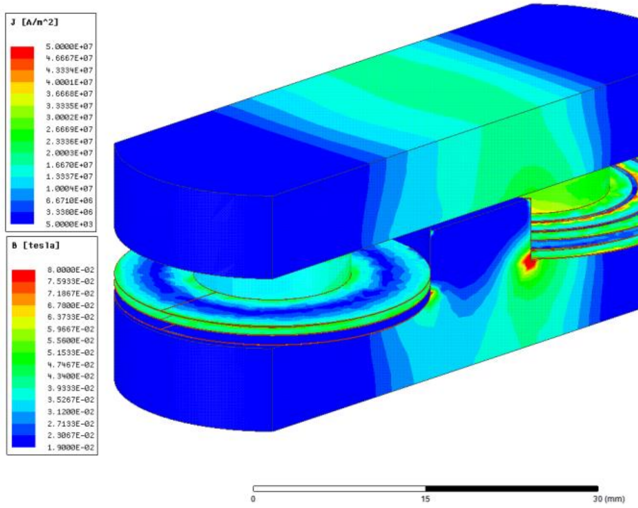
Width of Center Leg	Coupling Coefficient	L_{lkp}(μH)	L_{lks}(μH)
0.1mm	0.9291	7.08	0.871
0.2mm	0.9197	7.58	0.934
0.3mm	0.9116	8.06	0.994
0.4mm	0.9044	8.49	1.04
0.5mm	0.8981	8.89	1.98
0.6mm	0.8922	9.29	1.14
0.7mm	0.8869	9.64	1.19
0.8mm	0.8820	10.02	1.24
0.9mm	0.8774	10.40	1.29
1.0mm	0.8731	10.79	1.34

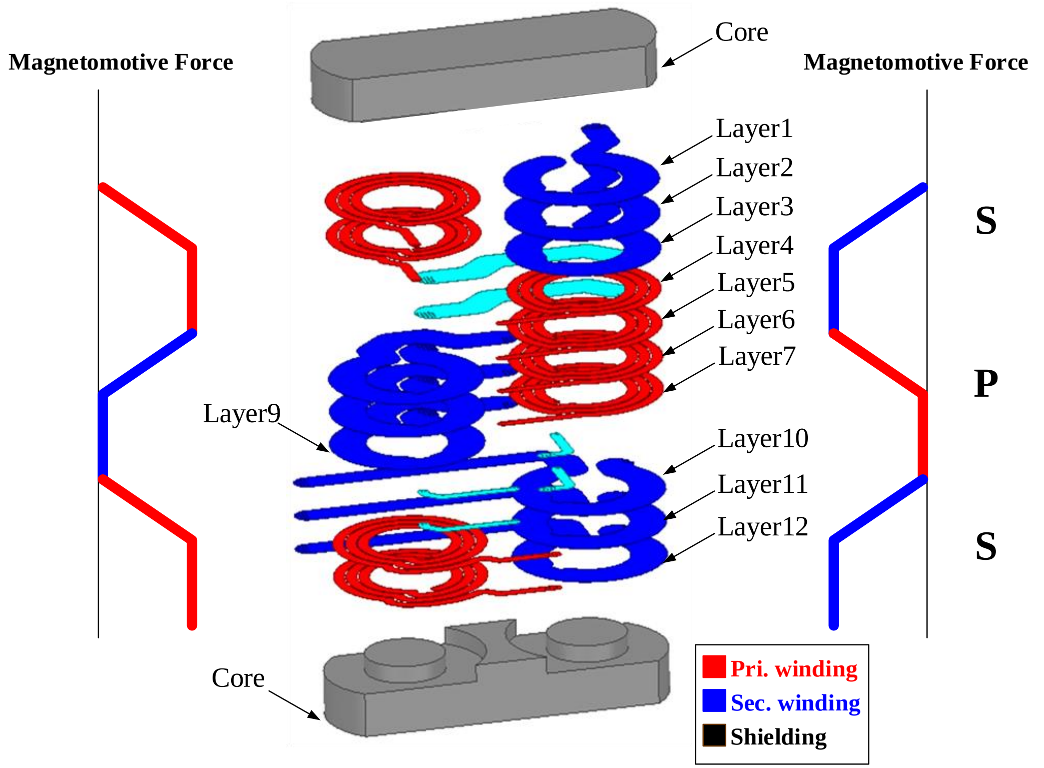


Transformer Design

✓ **Transformer with controllable leakage integration**

- **PCB winding for the transformer**
- **Interleaved structure for lower MMF**
- **Check the value of Magnetomotive Force**





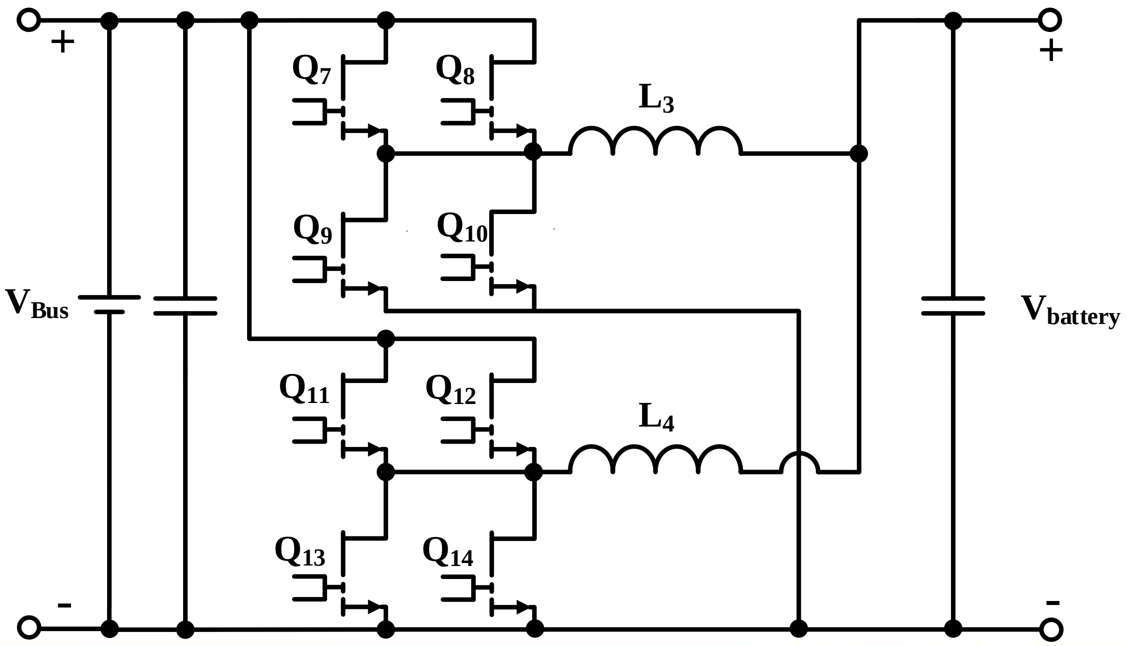
DC Buffer
Multiphase SR Buck/Boost Converter

Advantages:

- Using the output inductor can reduce the current ripple
- The Triangular Current Mode is used to achieve ZVS

Disadvantages:

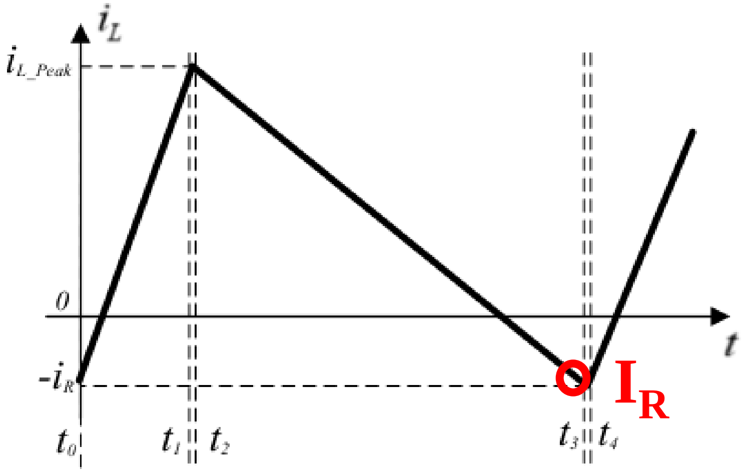
- The control method is complicated

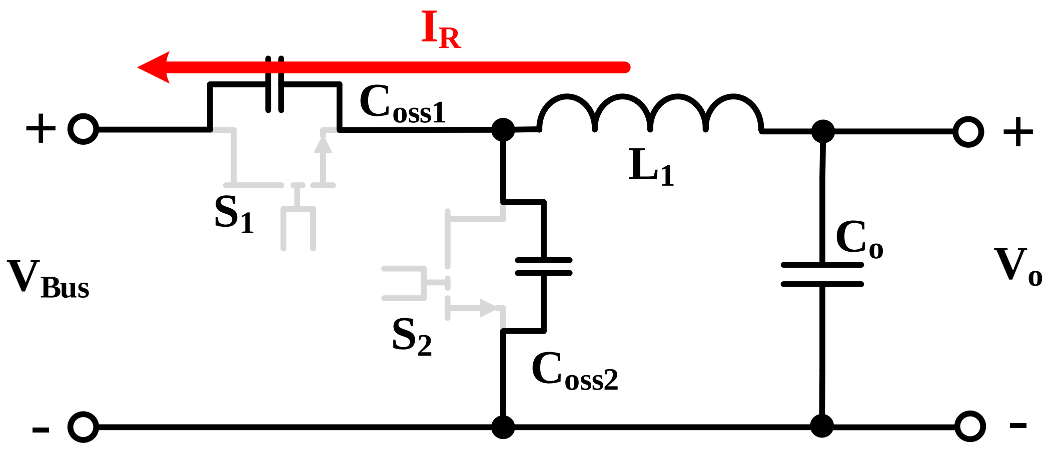


DC Buffer
Multiphase SR Buck/Boost converter

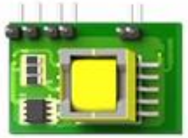
✓ **ZVS condition**

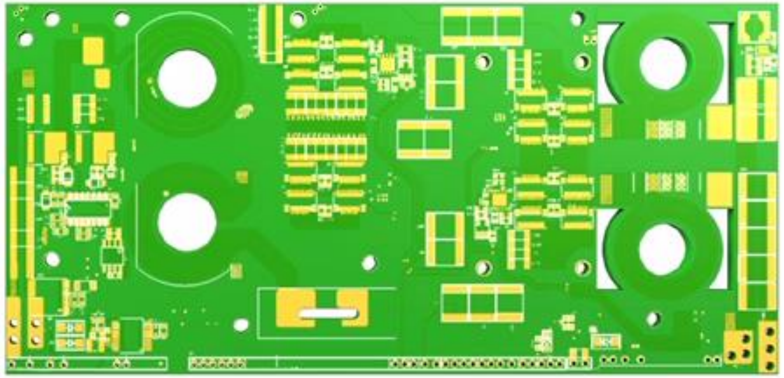
- **I_R is the key point for ZVS**
- **When I_R is large, it causes the higher conduction loss**
- **When I_R is lower, it loses the property of ZVS**
- **$Q_c = C_{oss} * V_{bus}$**





Whole System& 3D Model

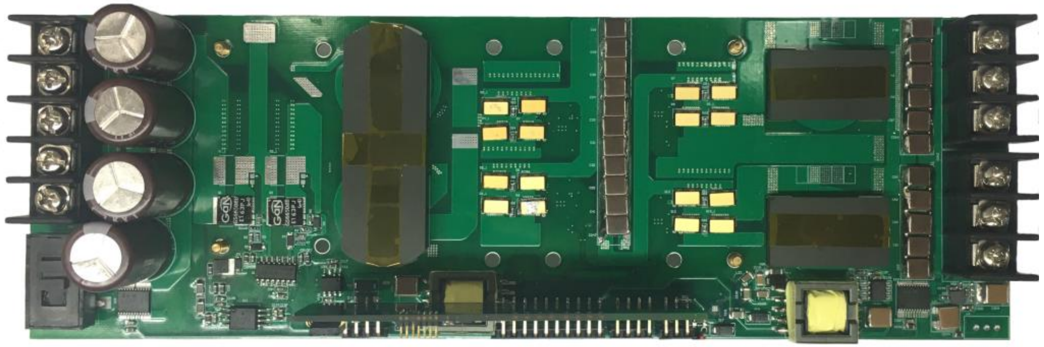




Midterm version

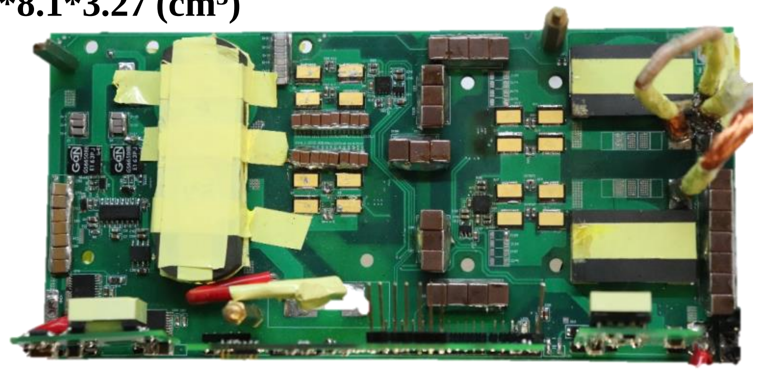
Power density: 1.6 W/cm^3

- **Six-layers PCB layout**
- **Volume: 24.93*8.1*3.27 (cm^3)**



- **Twelve-layers PCB layout**
- **Volume: 16.93*8.1*3.27 (cm^3)**

Final version



≈

Power density: 2.3 W/cm^3

Efficiency Curves: Whole System

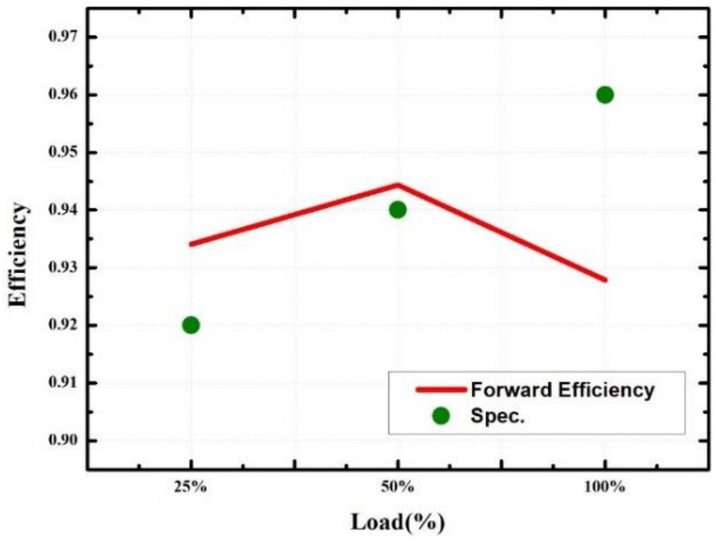
Forward Mode

- The efficiency is 93.41(V_o=48V), 94.43%(V_o=45V) and 92.78%(V_o=40V)

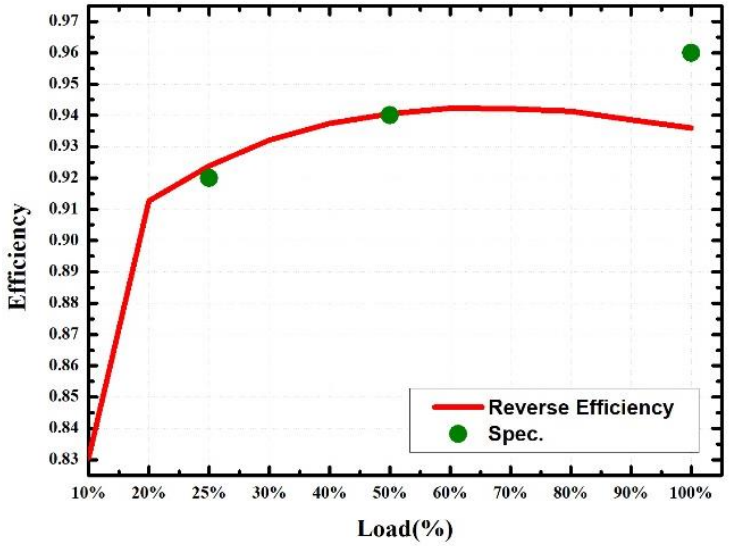
Reverse Mode

- The efficiency is 92.39%, 94.07% and 93.59% with V_{dc}=50V

Forward Mode



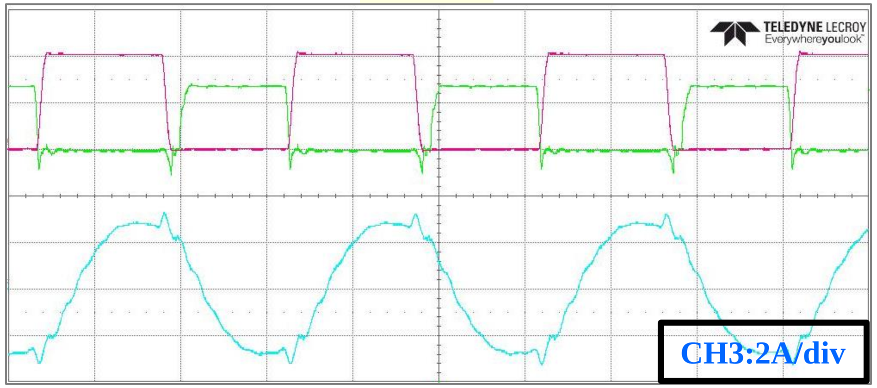
Reverse Mode



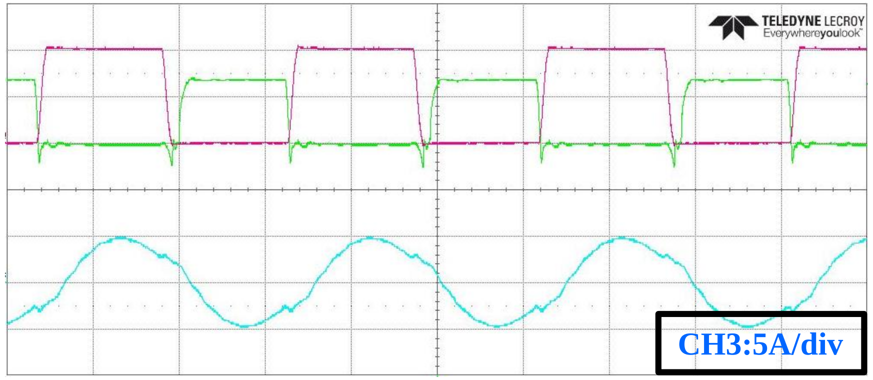
Experimental Results

- CLLC test waveform (Forward Mode)
- V_{in}=400V V_o=66V

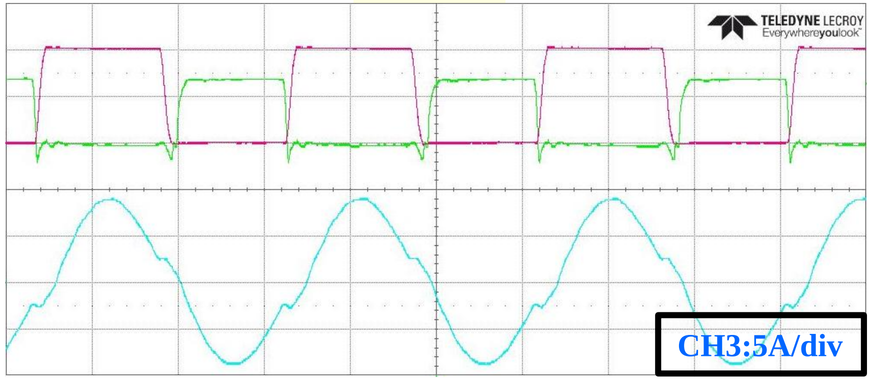
250W



500W



1000W



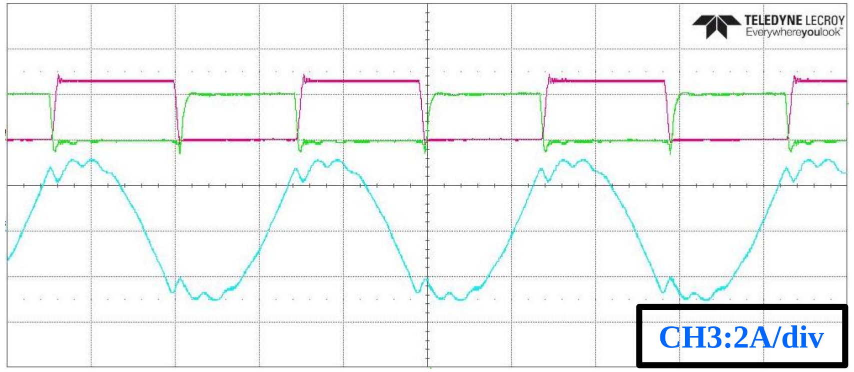
CH2:50V/div CH3:5A/div CH4:5V/div 0.5µs/div

- HV Side GaN V_{ds}
- Resonant Inductor Current
- HV Side GaN V_{gs}

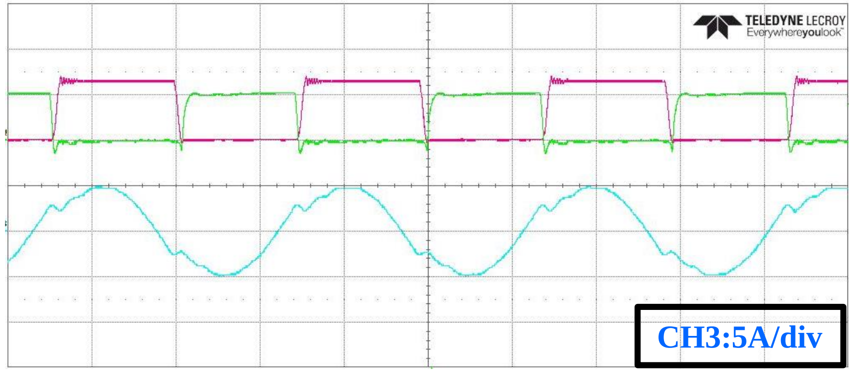
Experimental Results

- CLLC test waveform (Reverse Mode)
- V_{in}=66V V_o=400V

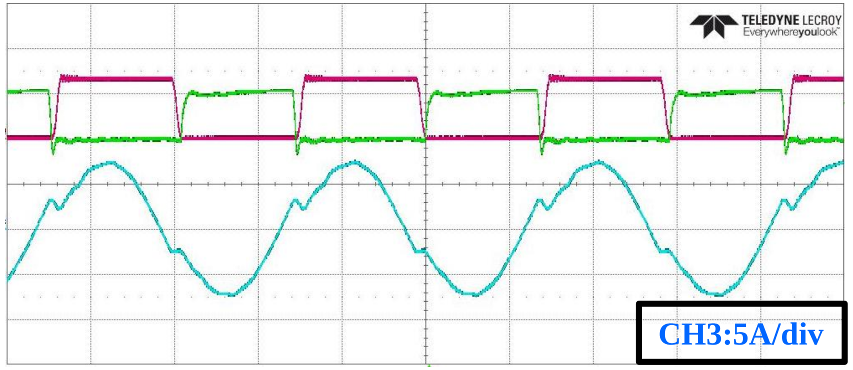
250W



500W



1000W



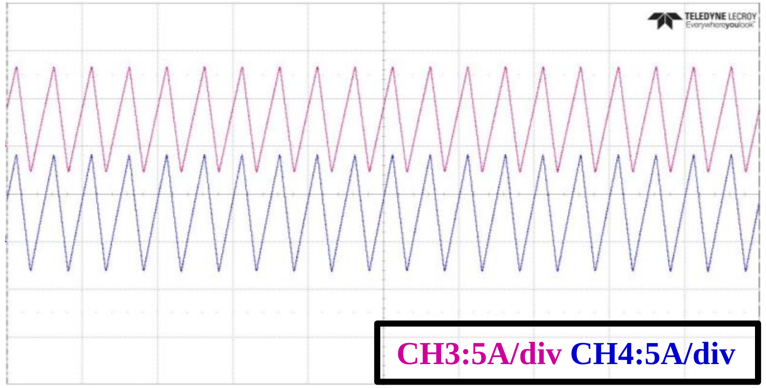
CH2:50V/div CH3:5A/div CH4:5V/div 0.5µs/div

- HV Side GaN V_{ds}
- Resonant Inductor Current
- HV Side GaN V_{gs}

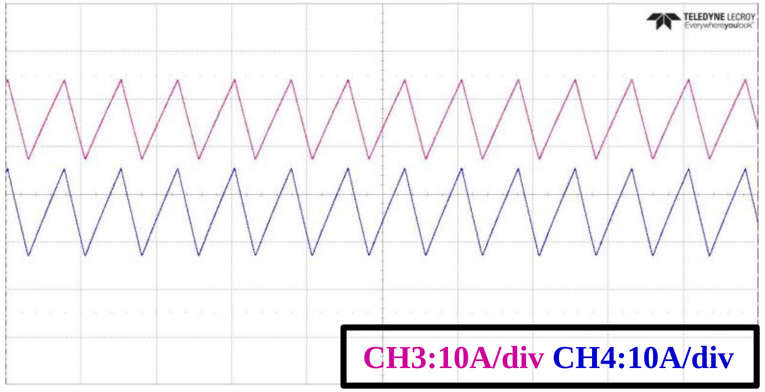
Experimental Results

- SR buck test waveform (Forward Mode)
- V_{bus}=66V V_o=40V

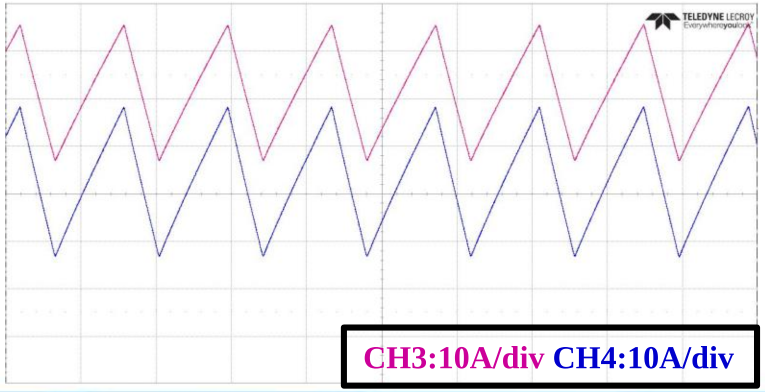
250W



500W



1000W



CH3:10A/div CH4:10A/div 2μs/div

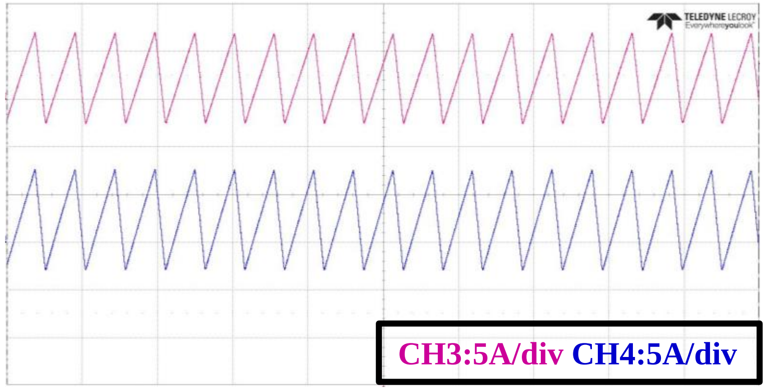
First Phase Inductor Current

Second Phase Inductor Current

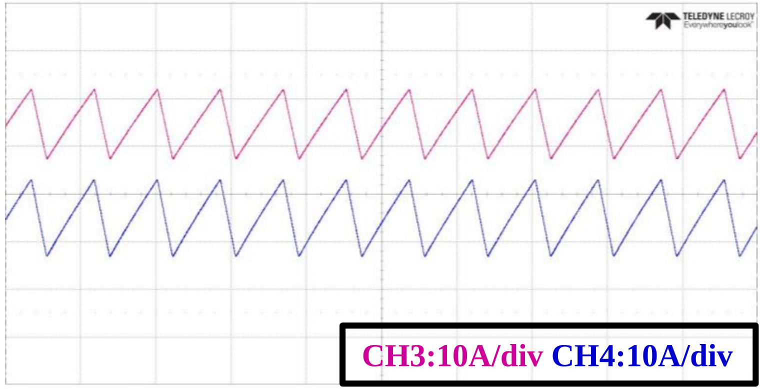
Experimental Results

- **SR buck test waveform (Forward Mode)**
- **V_{bus}=66V V_o=48V**

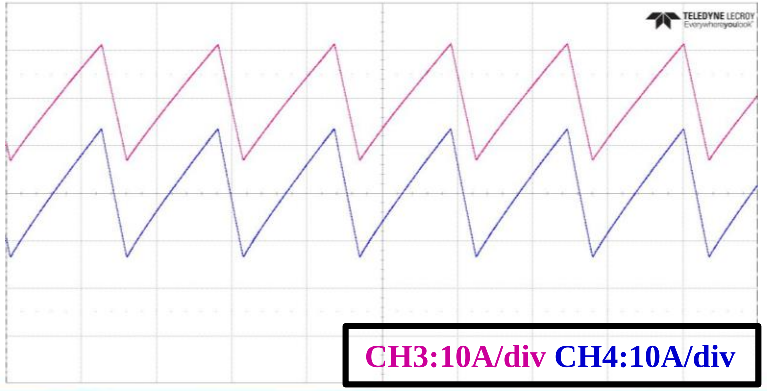
250W



500W



1000W



CH3:10A/div CH4:10A/div 2μs/div

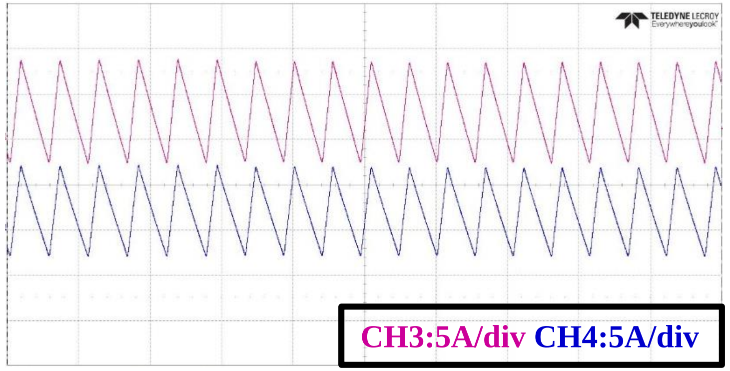
First Phase Inductor Current

Second Phase Inductor Current

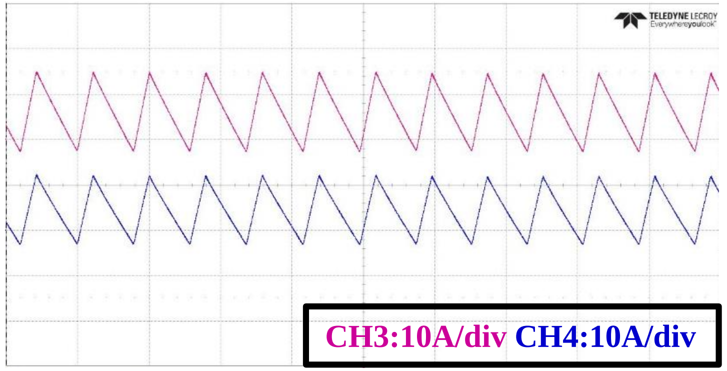
Experimental Results

- SR buck test waveform (Reverse Mode)
- V_{in}=48V V_{bus}=66V

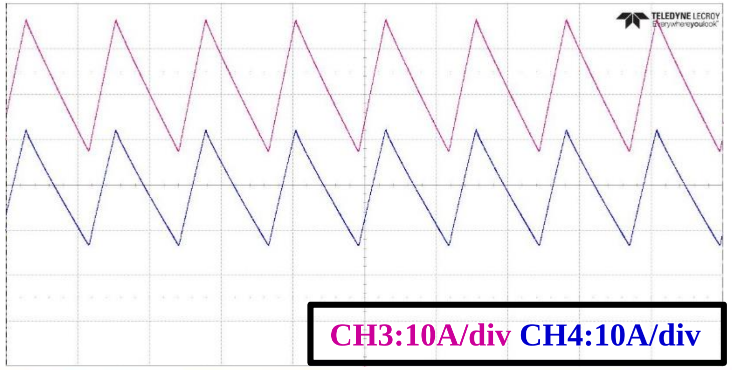
250W



500W



1000W



CH3:10A/div CH4:10A/div 2μs/div
First Phase Inductor Current
Second Phase Inductor Current

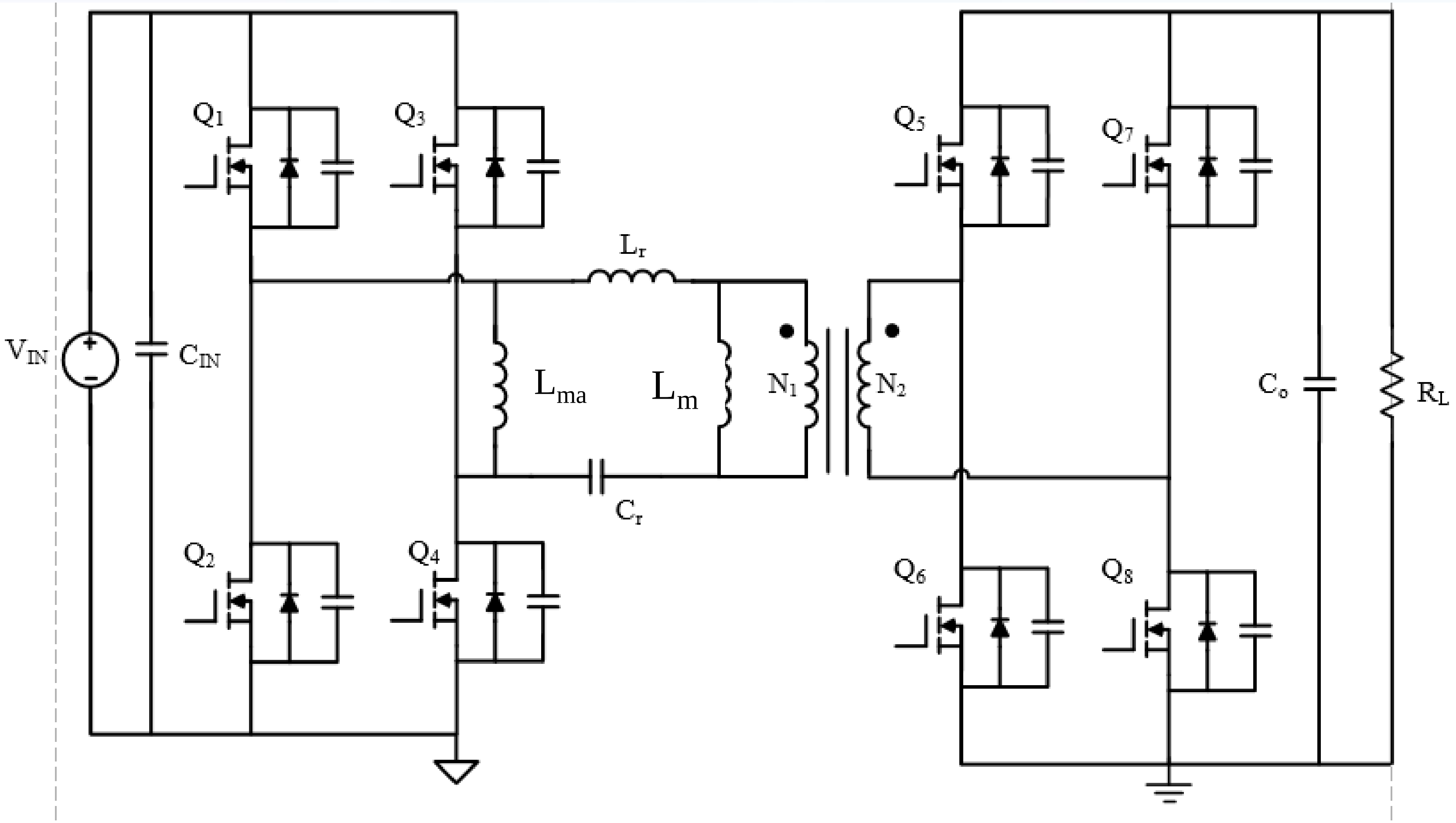
臺灣科技大學
電力電子技術研發中心
Center for Power Electronic Technologies
Taiwan Tech

SiC-based High Power Density Bidirectional DC-DC Converter

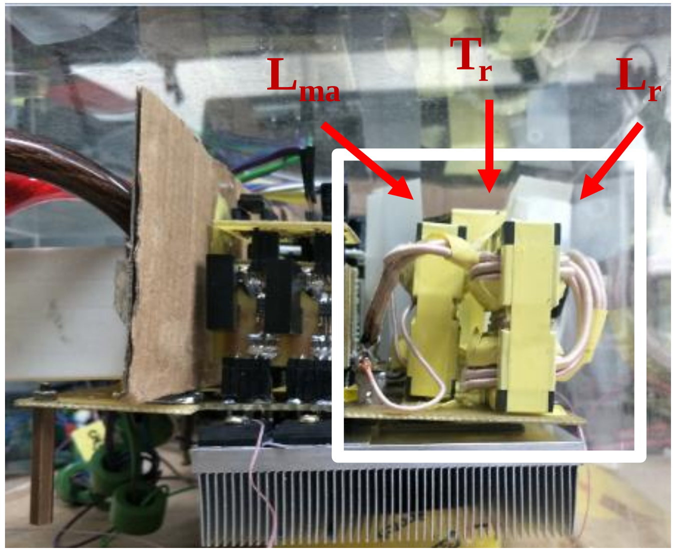
TAIWAN TECH

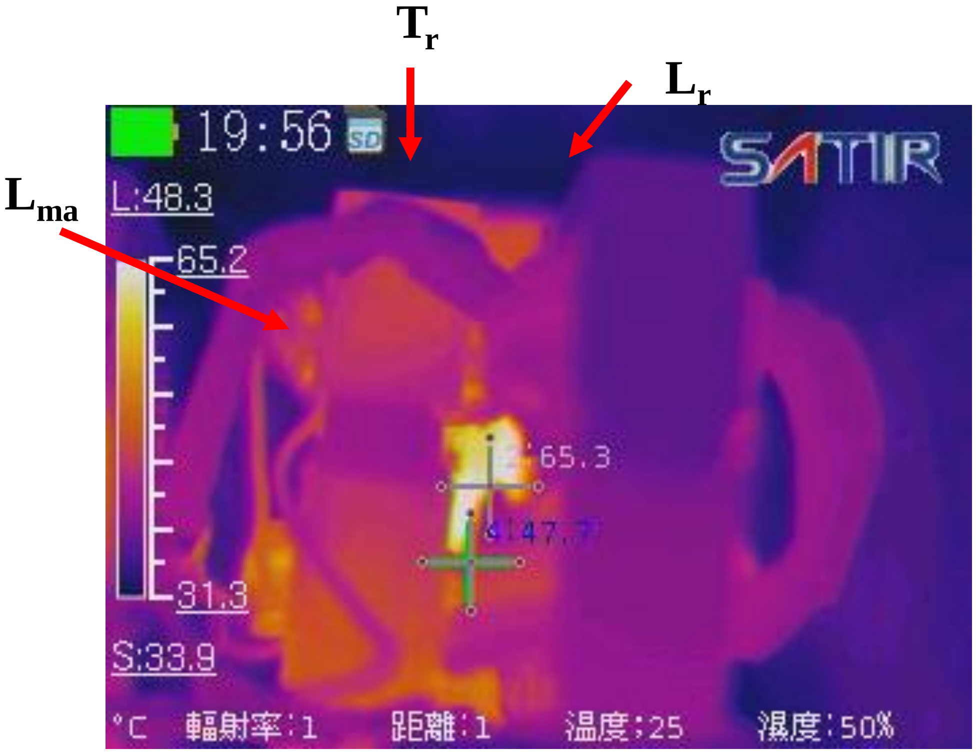
National Taiwan University of Science and Technology

DAB Bidirectional DC-DC Converter

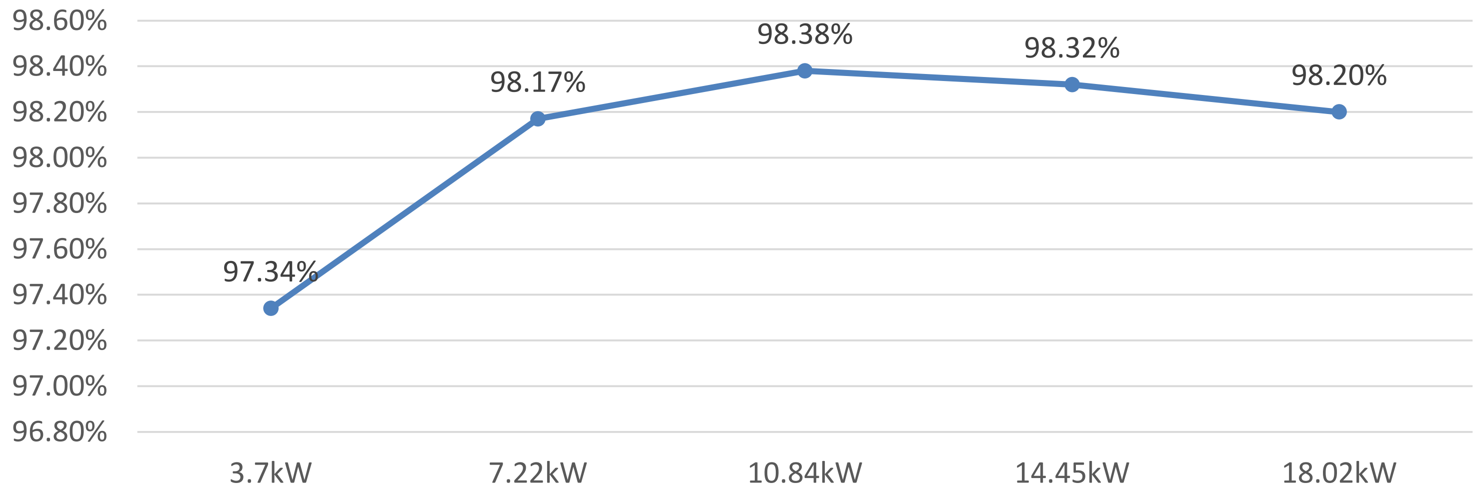


18kW/ 300kHz SiC-based HPD DAB Converter



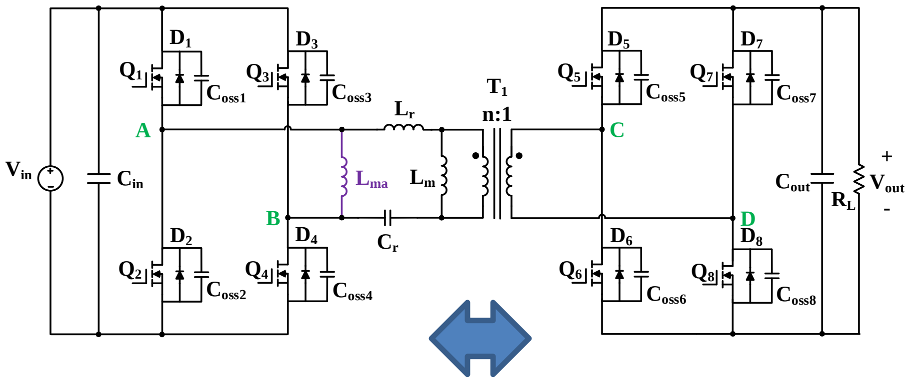


Efficiency



SiC based bidirectional power

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



臺灣科技大學 電力電子技術研發中心
Center for Power Electronic Technologies Taiwan Tech

High Power Density PV Inverter

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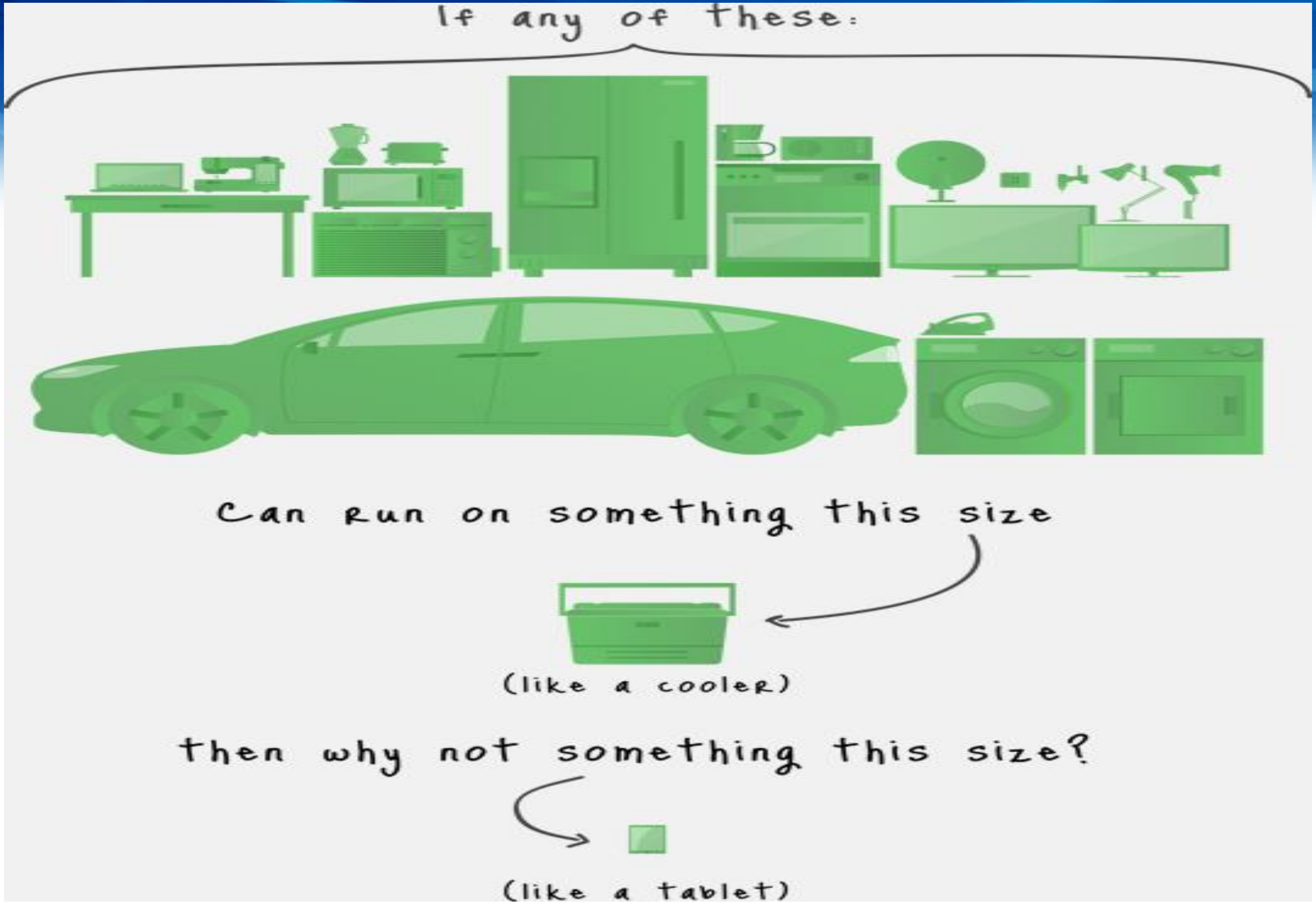
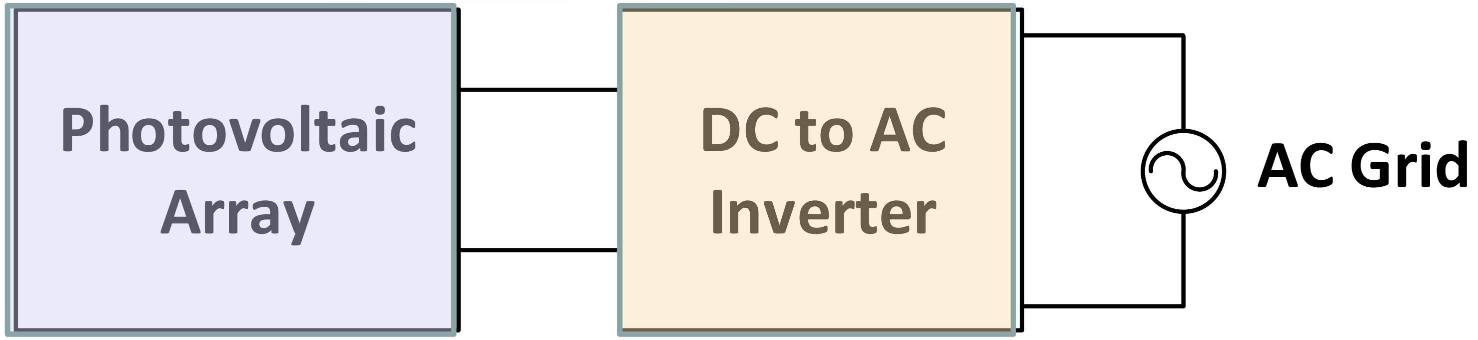
Google LBC Academic Award, 2015

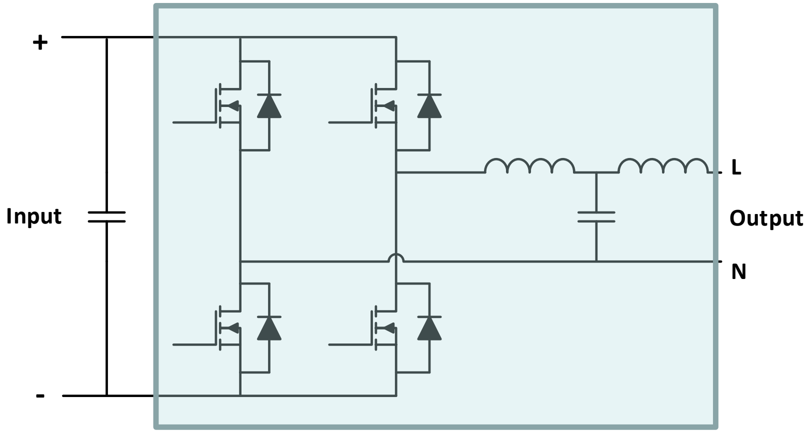

If any of these:
Can run on something this size
(like a cooler)
then why not something this size?
(like a tablet)

Google Little Box Academic Award

Primary Academic Institution	Principal Investigator
University of Colorado Boulder	Khurram K. Afridi
National Taiwan University of Science and Technology	Huang-Jen Chiu
Universidad Politécnica de Madrid	José A. Cobos
Texas A&M University	Prasad Enjeti
ETH Zürich	Johann W. Kolar
University of Bristol	Neville McNeill
Case Western Reserve University	Timothy Peshek
University of Illinois Urbana-Champaign	Robert Pilawa-Podgurski
University of Stuttgart	Jörg Roth-Stielow
Queensland University of Technology	Geoff Walker

Photovoltaic Inverters

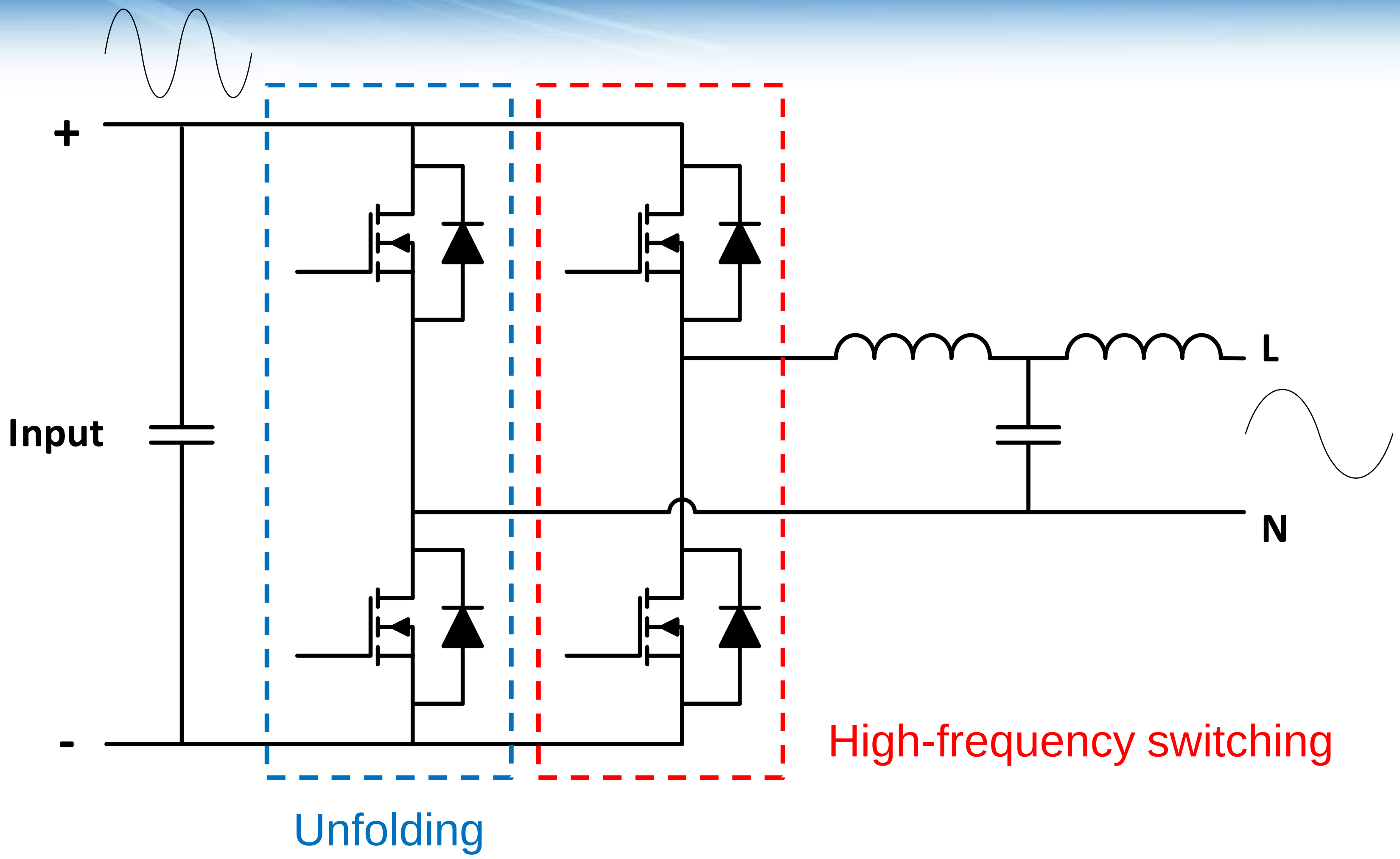




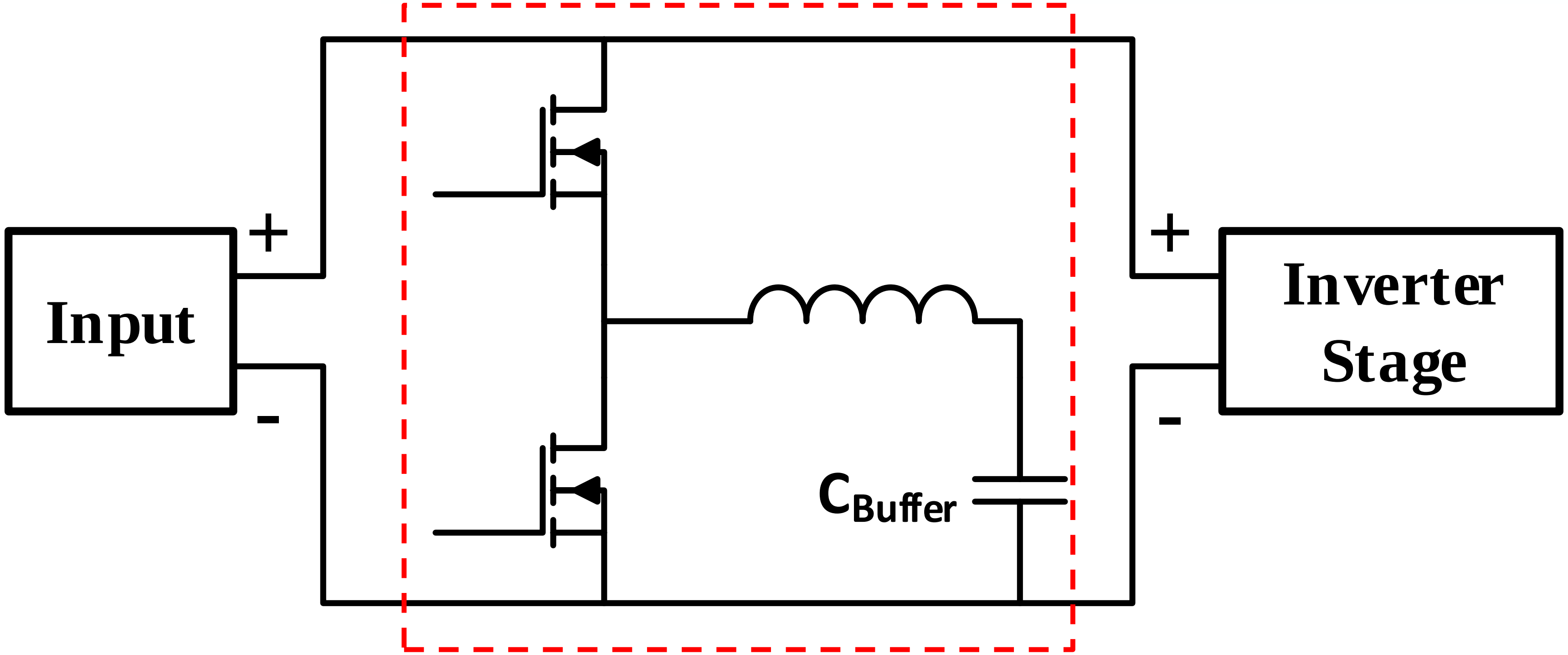
LBC Specifications

Parameter	Requirement	Comment
Maximum load	2 kVA	Load will be adjusted so that at most 2 kVA is sourced at 240 V RMS AC output at 60 Hz
Power density	> 50 W/in^3	In accordance with maximum load and volume requirements
Volume	< 40 in^3	Require rectangular enclosure, max dimension 20 in., min 0.5 in.
Voltage input	450 V DC, 10 Ω Resistor	See voltage source description
Voltage output	240 +/- 12 V AC	Single phase. See description below
Frequency output	60 +/- 0.3 Hz	Single phase
Power factor of load	0.7-1	Leading and lagging, load description below
Voltage output THD+N	< 5%	Total harmonic distortion+noise

Inverter Topology

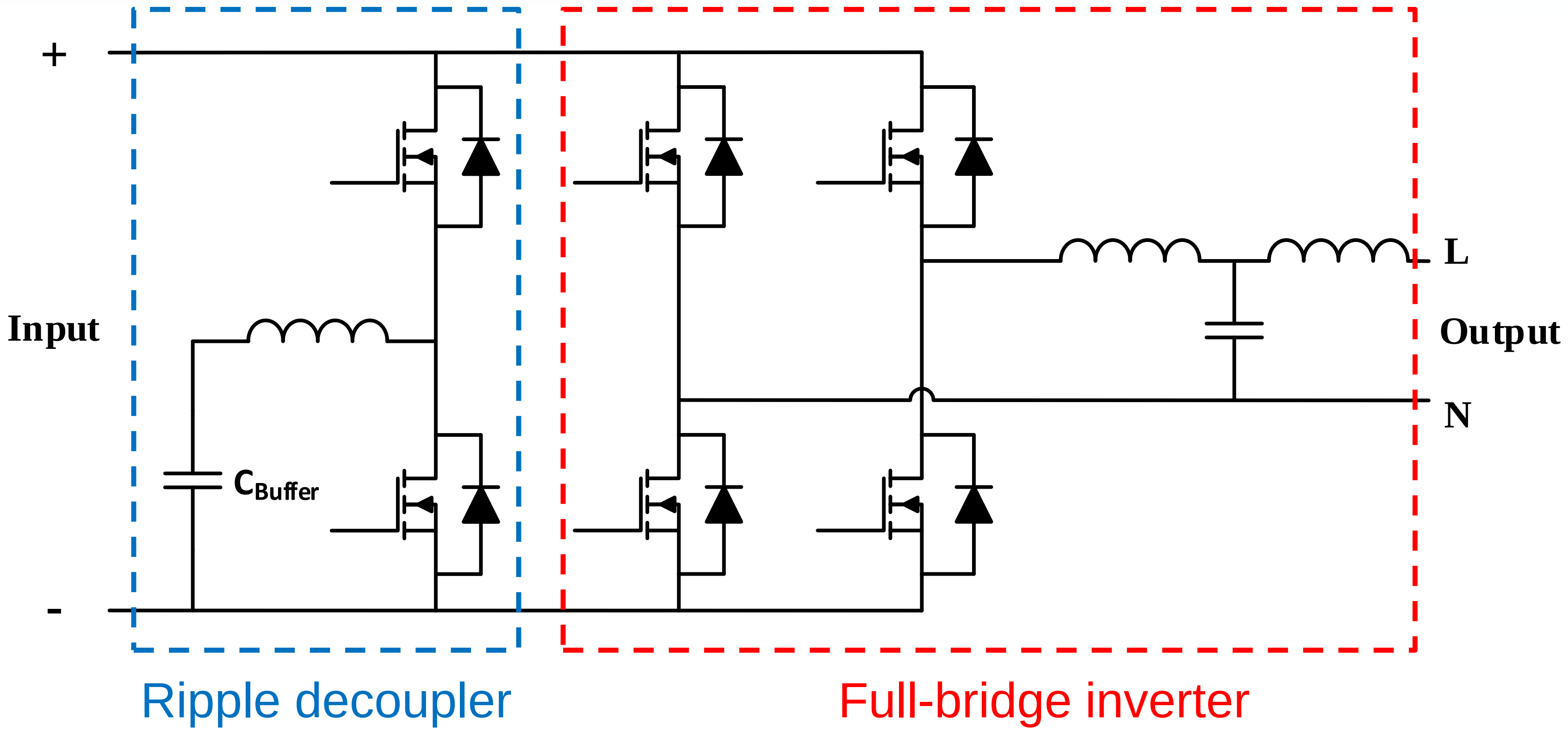


Parallel Ripple Decoupler Topology

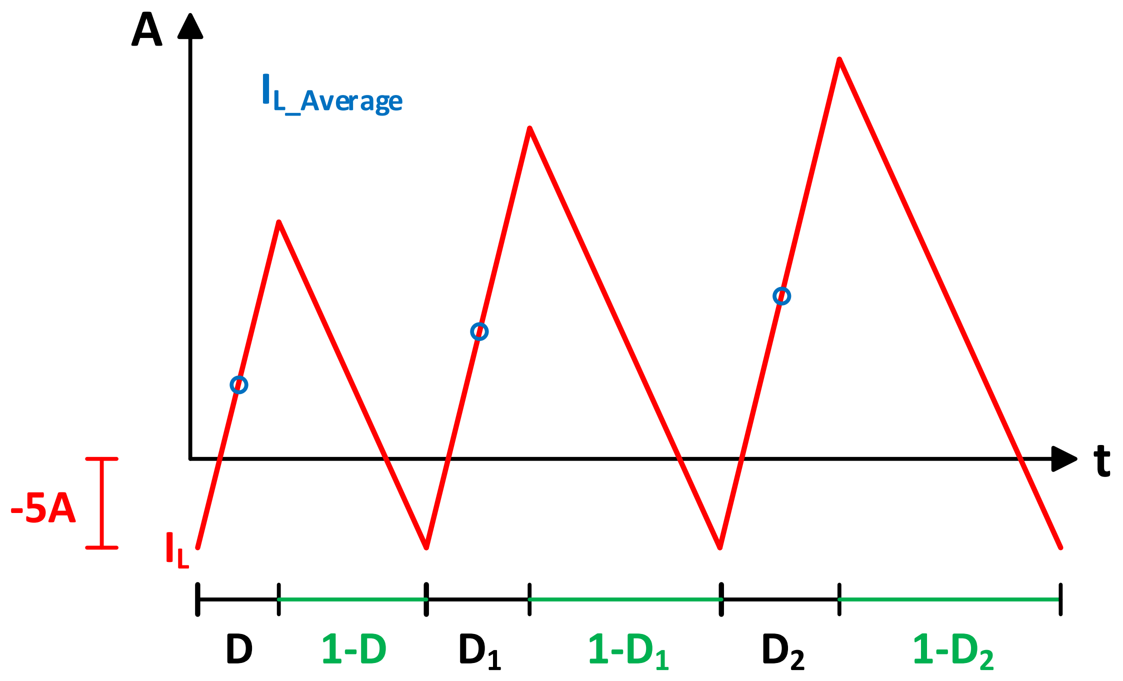


Input 450 V, 2 kW → C_{Buffer} > 70 μF
Voltage stress < input voltage (450 V)

Overall Power Stage



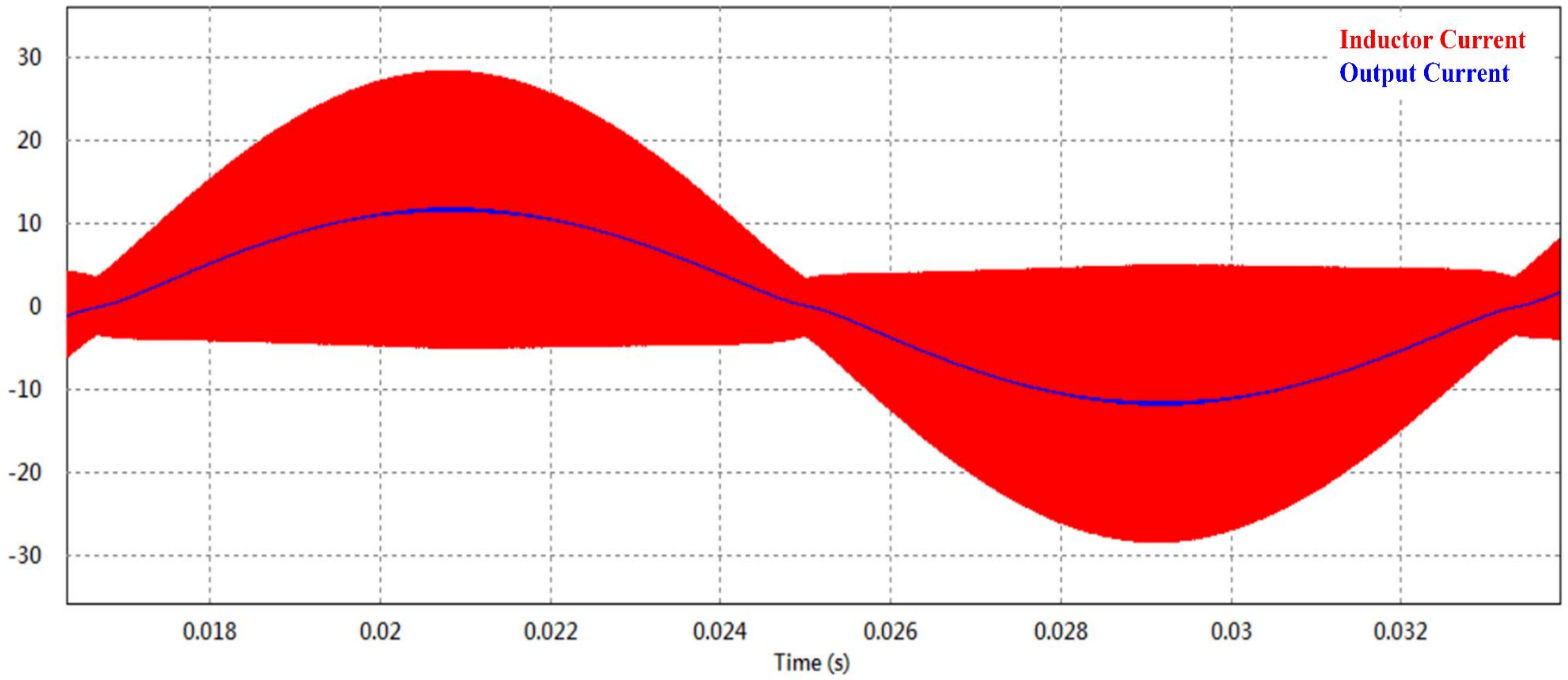
Reverse Current Control



✗ Without reverse current control it may cause high RMS current

✓ Maintain reverse current to a fixed value

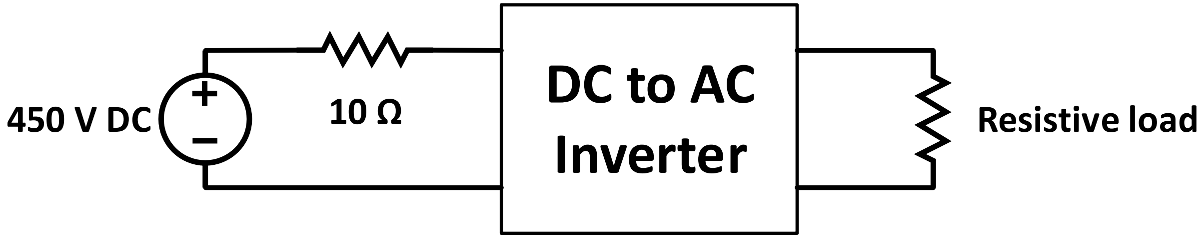
Inverter Inductor Current



Set reverse-current as 5 A

Circuit Specifications

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



Thansphorm TPH3205WS GaN HEMT are used as power switches

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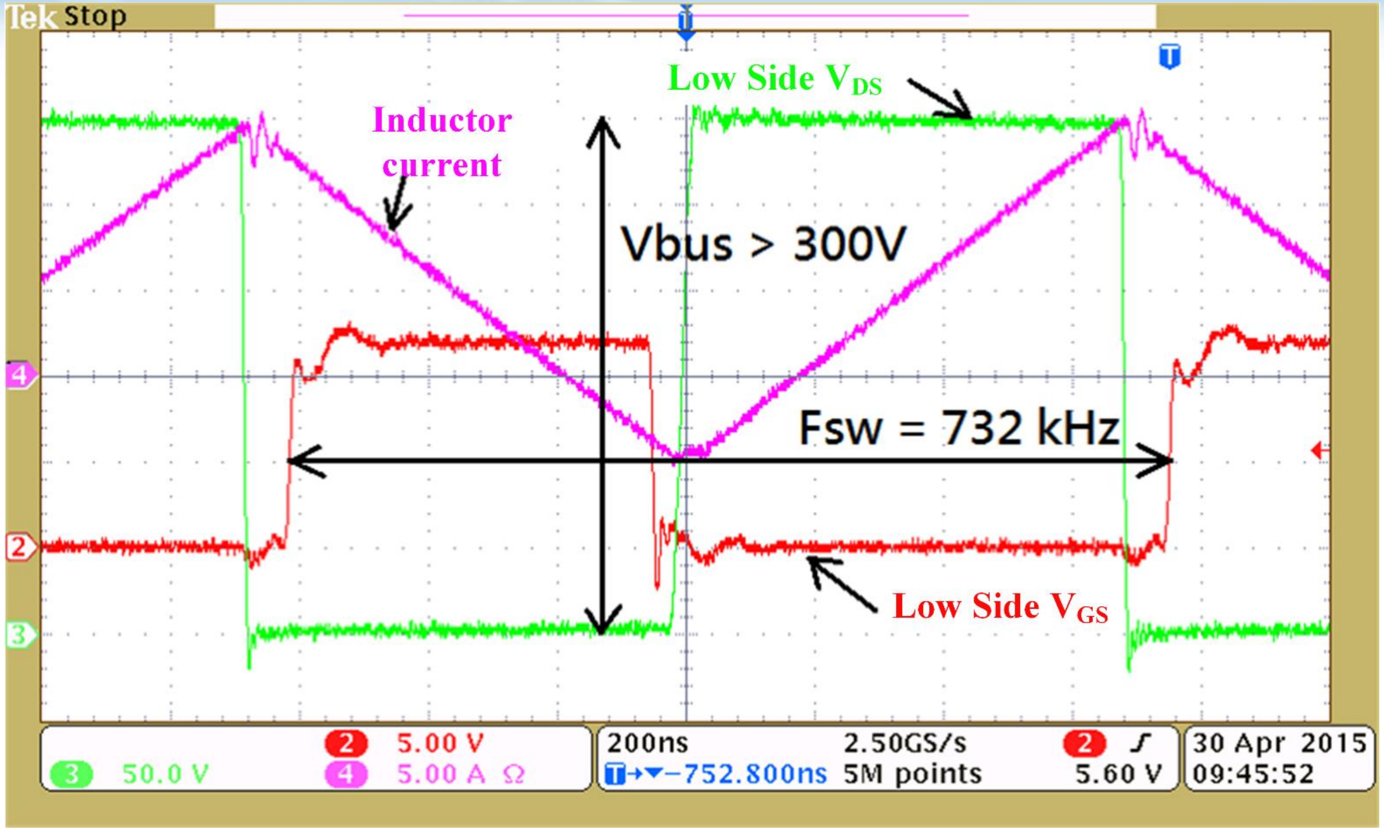
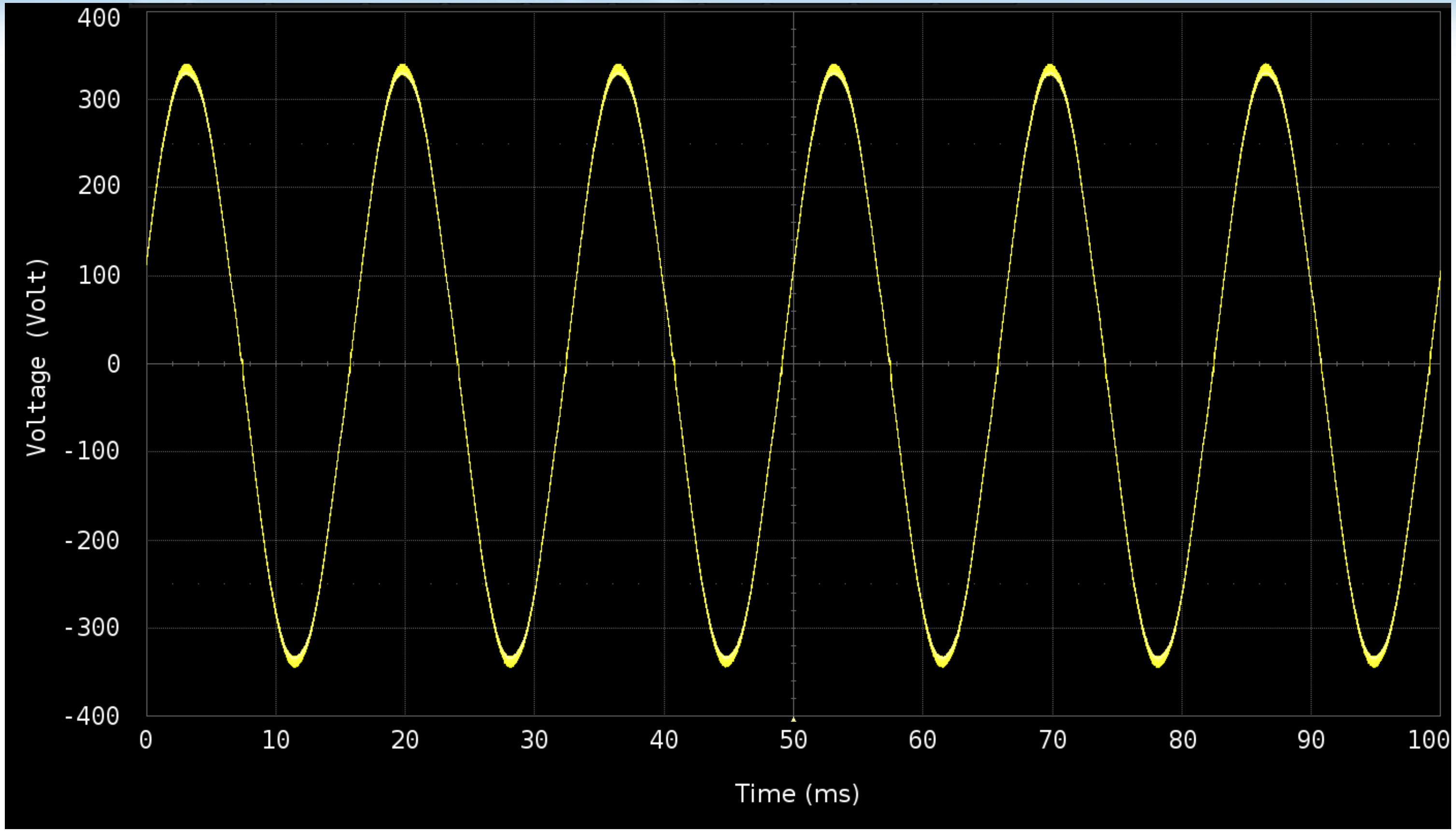
Reverse-Current Control



CH2
CH3
CH4

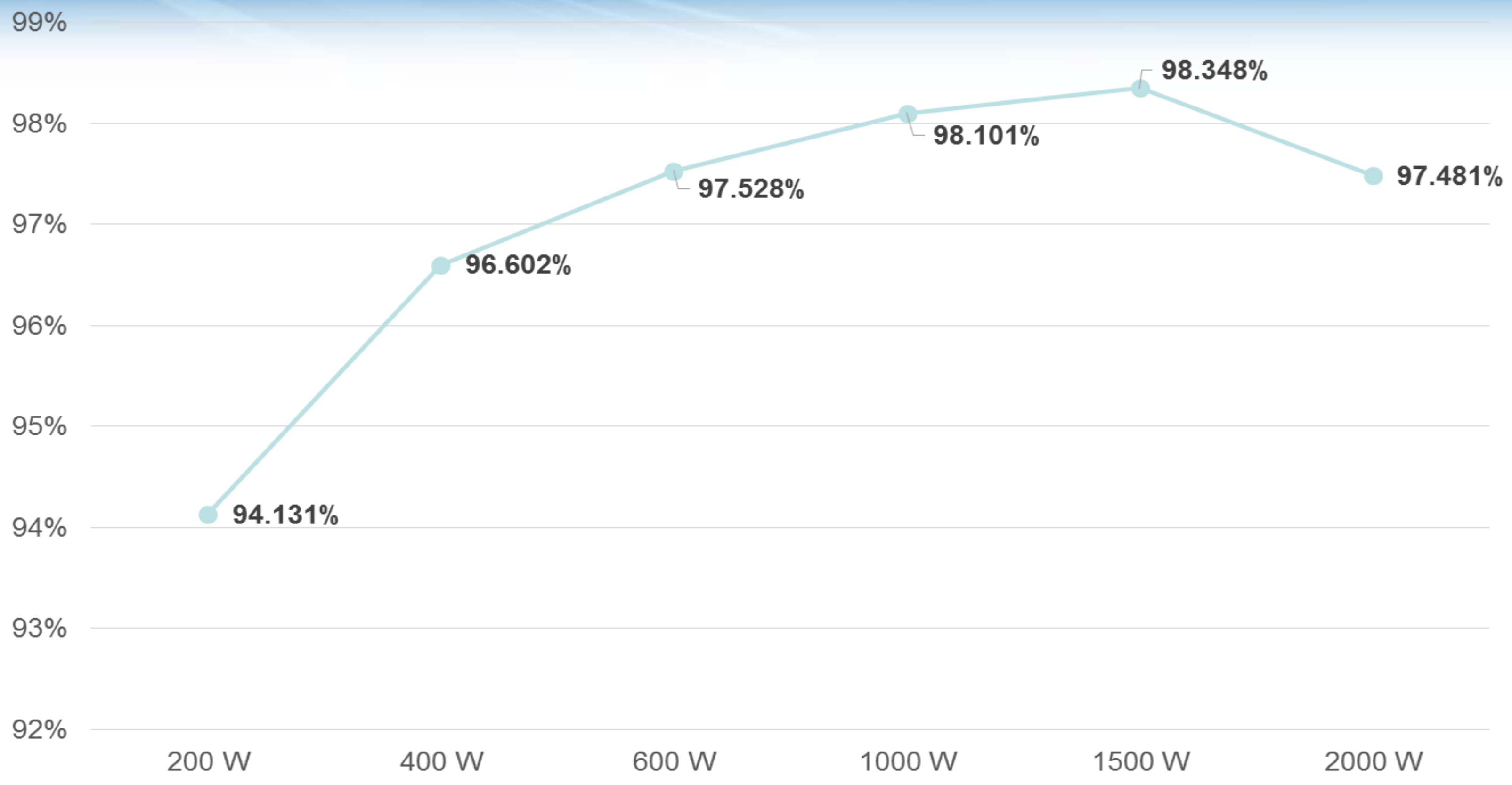
Set reverse-current as 5 A   Controller: TI TMS320F28035

Output Voltage Waveform



@ 2000 W

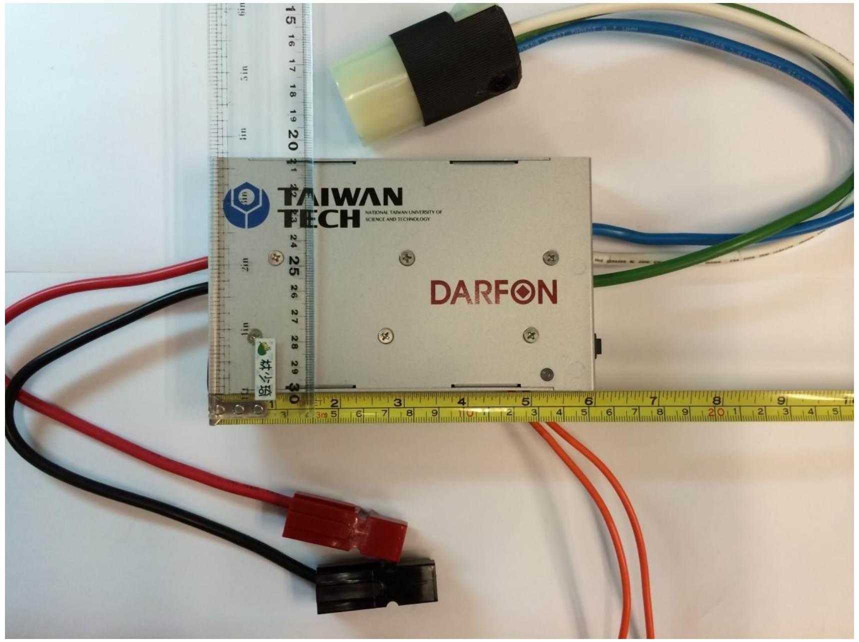
Overall Efficiency



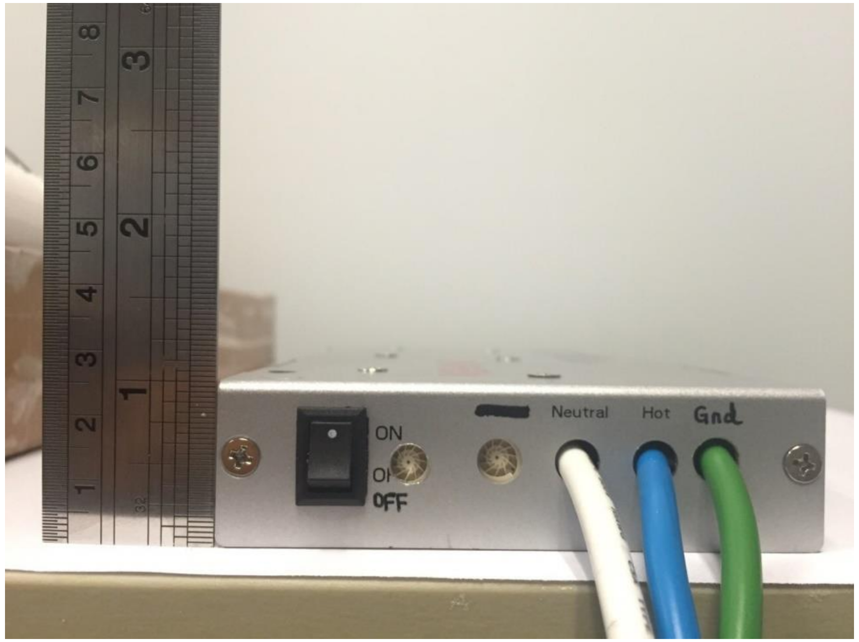
DC/ AC efficiency (CEC): 96.5 %

Power Density

Top View



Side View



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

Google Little Box Academic Award

Google granted US$30,000 award for research of high power density PV inverters

Thank you for your attention!