U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

High-Efficiency High-Density GaN-Based 6.6kW Bidirectional On-board Charger for PEVs - 2016 Annual Merit Review Meeting

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DPM, Livonia, MI
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EDT067

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DE-EE0006834

Contents

Project Overview

Timeline

- Period 1 Start – FY14
- Period 1 Finish – FY15 (extended for 3 mo., no cost)
- Project Finish – FY17
- 38% complete

Barriers

- Parasitic parameters in GaN device and PCB restricts the switching frequency
- Topology and control Scheme for bi-directional power flow
- Thermal design to remove heat
- High frequency magnetics
- GaN device cost

Budget

- Total project funding DOE share – $1,487,594
- Total Period 1 funding DOE share - $588,741
- Funding received in Period 1 (FY14 and 15): $519,849

Partners

- Transphorm
- CPES at Virginia Tech
- Fiat Chrysler Automobiles

Project Objective

The objective of this project is to design, develop, and demonstrate a 6.6kw isolated bi-directional On-Board Charger (OBC) using Gallium Nitride (GaN) power switches in a vehicle capable of achieving the specifications identified in Table 1, below. The developed OBC will reduce size and weight when compared to commercially existing Silicon (Si) based OBC products in automobiles by 30%-50%.

Parameter	Requirement
Switching Frequency	0.3 - 1 Mega-Hertz (MHz)
Power Efficiency	95%
Power Rating	3.3 kilo-Watt (kW) at 120 Volts Alternating Current (VAC), 6.6kW at 240 VAC (Auto sensing depending on AC input voltage)
Plug-In VAC	120/240 VAC
High Voltage (HV) Battery Voltage Range	250 - 450 Voltage Direct Current (VDC)
Nominal Battery Voltage	350 VDC
AC Line Frequency	50 - 60 Hz
Maximum Coolant Temperature	70°Celcius (C)
Ambient Temp Range	-40 to 70°C
Controller Area Network (CAN) Communication	Yes

FY2015 Objective and Milestones

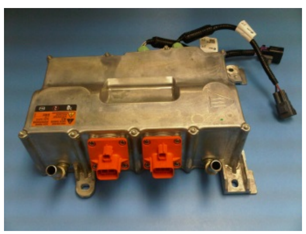
FY 2015 Objective: Technology Design and Development

- **Design, build and test Iteration III GaN device**
- **Iteration III GaN device switching performance evaluation**
- **Advanced circuit development for GaN device application**
- **Build and test the A-Sample charger**

#	Milestone	Type	Due Month
MS 1.1	Si-Based Conceptual Bi-directional Charger Design Complete	Technical	March 2015
MS 1.2	Si-Based Concept Bi-directional Charger Build Complete	Technical	June 1015
MS 1.3	Si-Based Concept Bi-directional Charger Test	Technical	Sept. 2015
MS 1.4	A-Sample Charger Design Completed	Technical	Nov. 2015
DP 1	Analysis of the test result of the concept bidirectional charger	Go/No Go	Nov. 2015
MS 2.1	Build the A-Sample charger	Technical	Feb. 2016
MS 2.2	Test the A-Sample charger and report	Technical	May 2016
MS 2.3	Design the B-Sample charger	Technical	June 2016
MS 2.4	Test the B-Sample charger and report	Technical	Dec 2016
DP 2	Completion of the B-Sample charger prototype build	Go/No Go	Nov 2016

Prior Arts and Program Goals

	Prior Art	Goal
Efficiency	93%	95%
Function	Uni-directional	Bi-directional
Power density	0.45-0.75 kW/L	30% to 50% improvement
Device	Silicon	GaN
Switching frequency	<100kHz	0.3-1MHz



Delta OBCM (3.3kW)

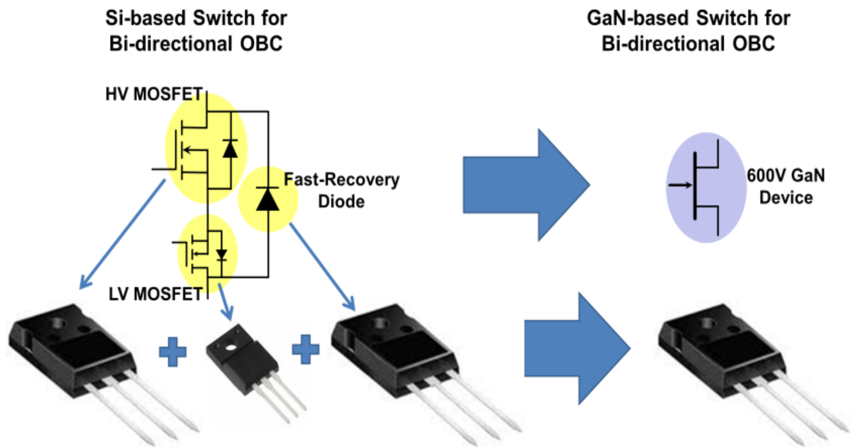
Delta OBCM (6.6kW)

TDK OBCM (6.6kW)

Panasonic OBCM (6.6kW)

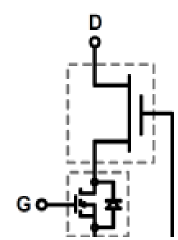
Delta Solar Inverter (5kW)

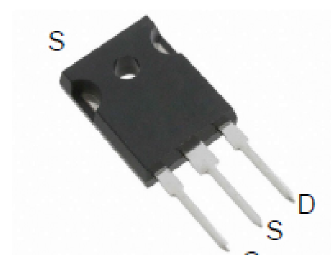
Approach
– Reduce number of switching devices



Power Device Count		
Device Type	Si-based	GaN-based
TO-247 Switch	28	24
TO-247 Diode	24	0
TO-220 Switch	24	0
Total Devices	76	24

Features
- Low Q_{rr}
- Free-wheeling diode not required
- Quiet Tab™ for reduced EMI at high dv/dt
- GSD pin layout improves high speed design
- RoHS compliant
- High frequency operation





Approach – Increase switching frequency

- Approximately 30% of the volume of OBC is taken by magnetic components and capacitors.
- Increasing switching frequency will reduce the size and cost of these components.
- GaN device has lower switching loss, thus allow higher switching frequency.

	GaN HEMT	Si MOSFET
	Transphorm TPH3205WS	Infineon IPB65R065C7
R_{ds_on}	63mΩ	58 mΩ
C_{oss_tr}	283nC	1110nC
Q_g	10nC	64nC
Q_{rr}	138nC	10000nC

Technical Accomplishments and Progress

Three Iterations of GaN HEMT devices have been developed and delivered.

	Iteration I	Iteration II	Iteration III
PN	TPH3205WS	TPH3205WSA	TPH3207WS
Quantities delivered	180	550	190
Rds,on	63mΩ	52mΩ	35mΩ
Co_tr	283pF	247pF	430pF
Qg	10nC	19nC	28nC
Qrr	138nC	136nC	175nC

I-3 device has 33% lower Rds,on than I-2 device. Unfortunately, it also has higher charge, which will make switching performance sacrifice. Delta plan to do performance comparison between I-2 and I-3 devices on A-Sample OBC.

Technical Accomplishments and Progress

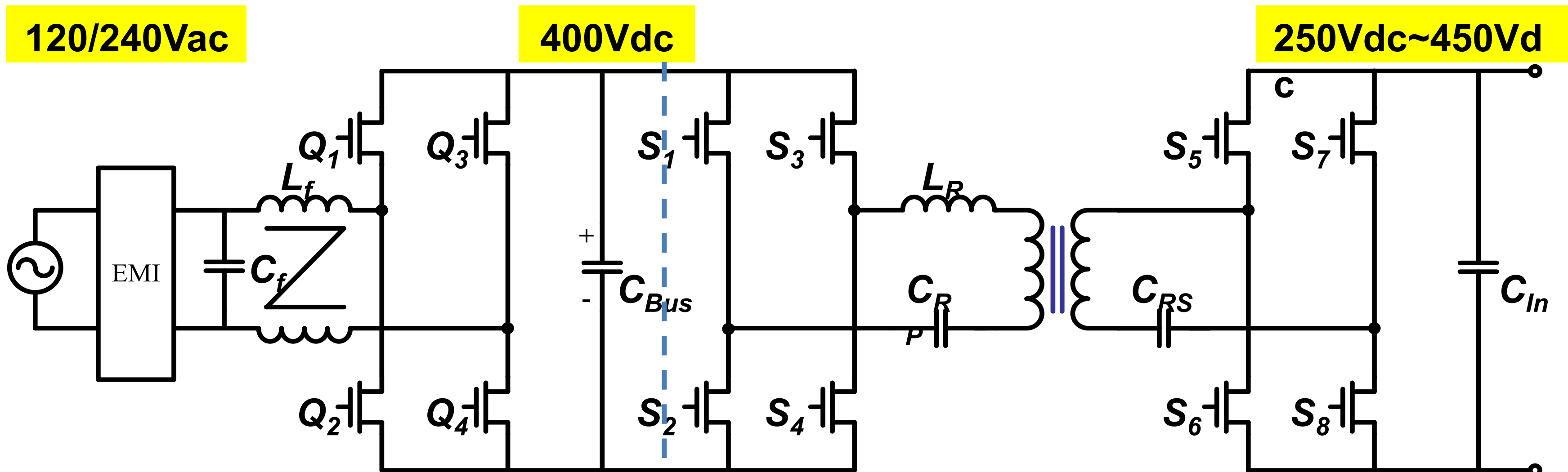
Transphorm conducted qualification tests on the Iteration II GaN HEMT device.

transphorm	Review Specification		
Document #:	700254	Revision:	1
Process Owner:	Ronald Barr	Effective Date:	Nov. 11, 2015
Title:	**Qualification Report TPH3205WS**		

a) AEC-Q101: Stress Test Qualification for Automotive Grade Discrete Semiconductors
b) JESD47: Stress-Test Driven Qualification of Integrated Circuits
c) MIL-PRF-38535: Performance Specification-Integrated Circuits Manufacturing General Specification for Department of Defense
d) JESD22-A108C: High Temperature Reverse Bias (HTRB)
e) JESD22-A110D: Highly Accelerated Temperature and Humidity Stress Test (HAST)
f) JESD22-A104D: Temperature Cycle (TC)
g) JESD22-A122: Power Cycle (PC)
h) JESD22-A103C: High Temperature Storage Life (HTSL)
i) JESD22-A115B: Electrostatic Discharge Machine Model
j) JS-001-2012: Electrostatic Discharge Human Body Model
k) MIL-STD-883E, 2007.2 Condition A: Vibration Variable Frequency
l) MIL-STD-883E, 2002.3 Condition A: Mechanical Shock

DELTA

Selected Topology for Concept Design



Bi-Direction AC/DC	Bi-Directional DC/DC
Topology: PFC/Inverter	Topology: DBA derived LLC

PROs

- Mature DC/AC design
- Soft switching DC/DC

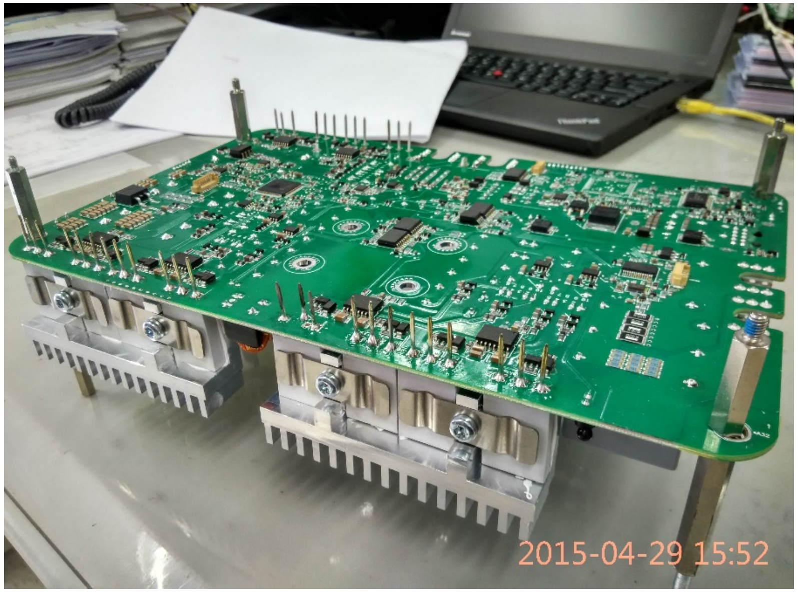
CONs

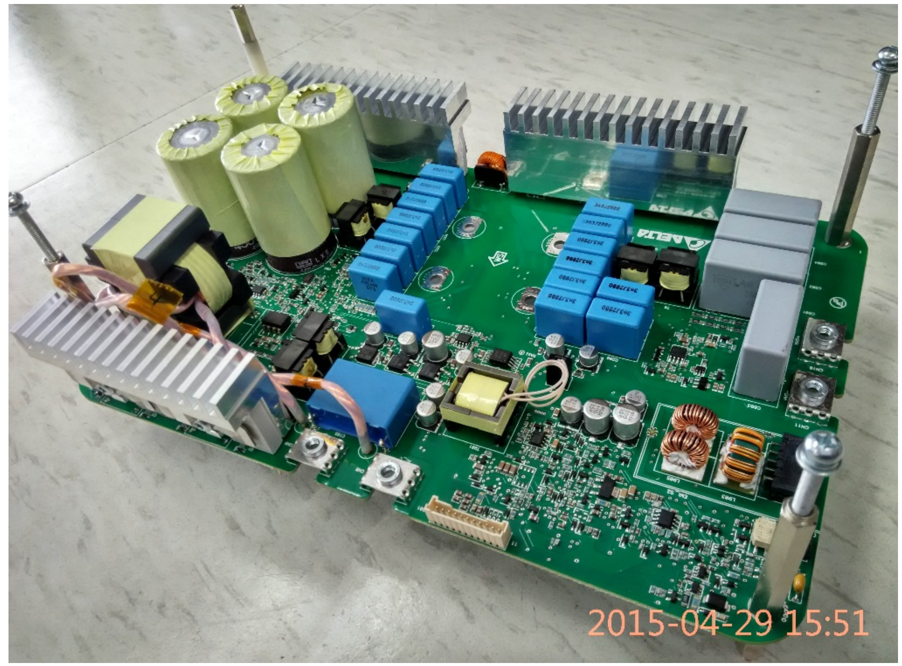
- Higher loss of DC/AC due to hard switching

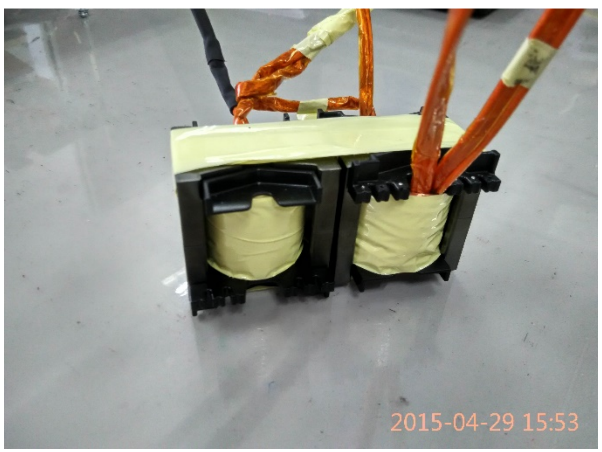
This is Plan A – Delta design OBC with this topology

Technical Accomplishments and Progress

- **3.3kW bi-directional charger concept prototype PCB**

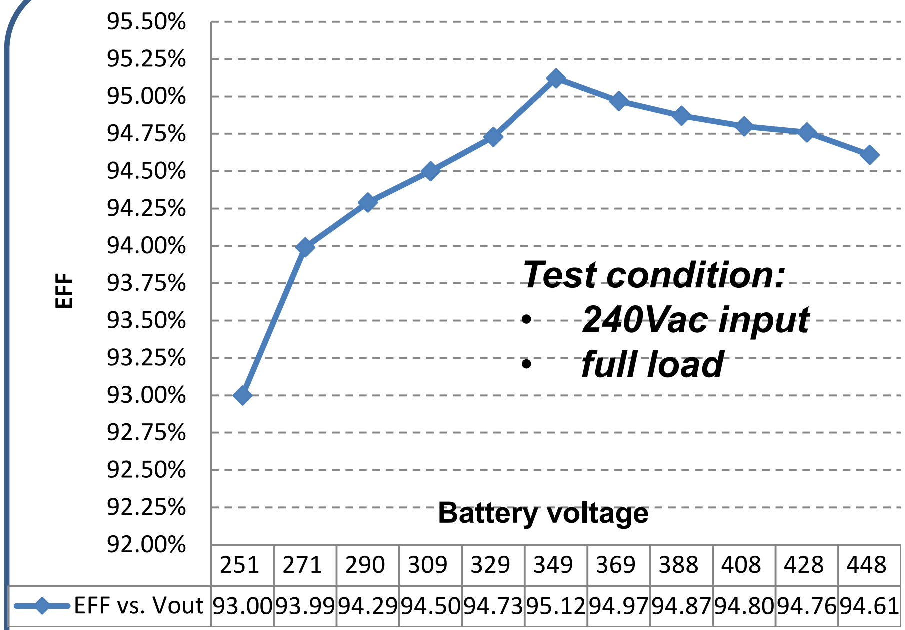




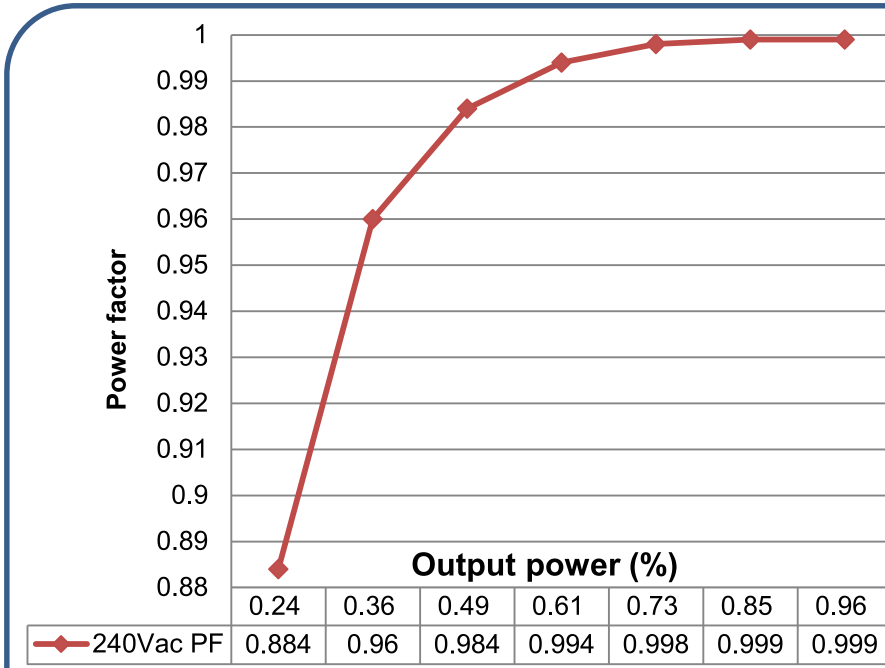


Technical Accomplishments and Progress

- **3.3kw GaN-based Concept OBC Test Result**



Charger Mode Efficiency



Charger Mode Power Factor

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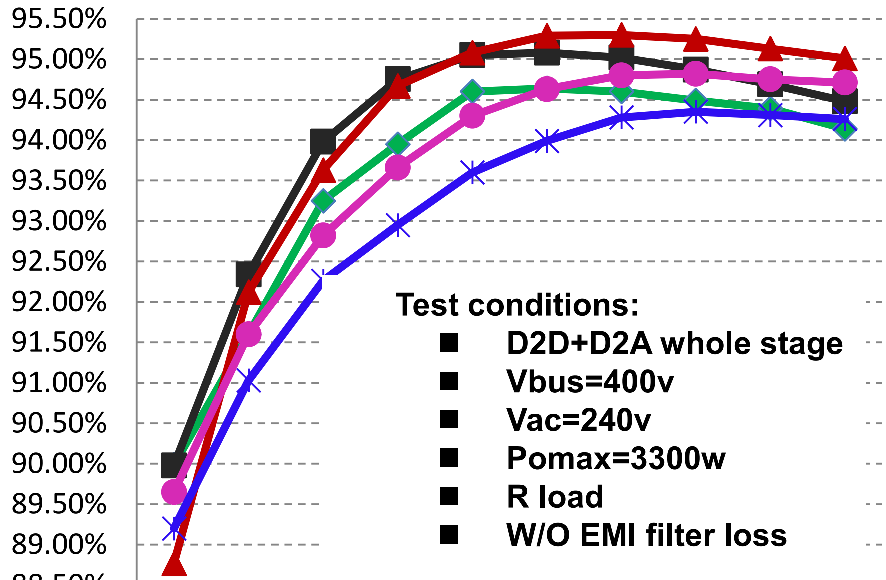
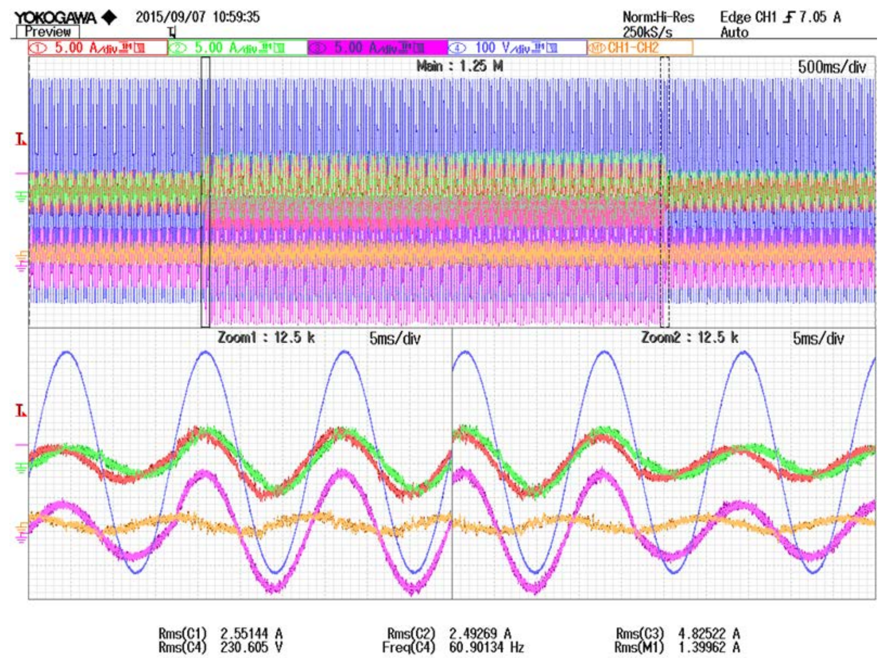
Technical Accomplishments and Progress

- **3.3kw GaN-based Concept OBC Test Result**



	10%	20%	30%	40%	50%	60%	70%	80%	90%	100 %
250Vbat	89.99	91.60	93.25	93.95	94.60	94.64	94.60	94.49	94.39	94.14
300Vbat	89.98	92.34	93.98	94.75	95.05	95.08	95.02	94.87	94.69	94.48
350Vbat	88.77	92.12	93.63	94.67	95.08	95.29	95.30	95.25	95.13	95.01
400Vbat	89.65	91.60	92.82	93.66	94.30	94.63	94.80	94.82	94.75	94.71
450Vbat	89.20	91.03	92.26	92.95	93.60	93.99	94.28	94.35	94.31	94.26

Inverter Mode Efficiency

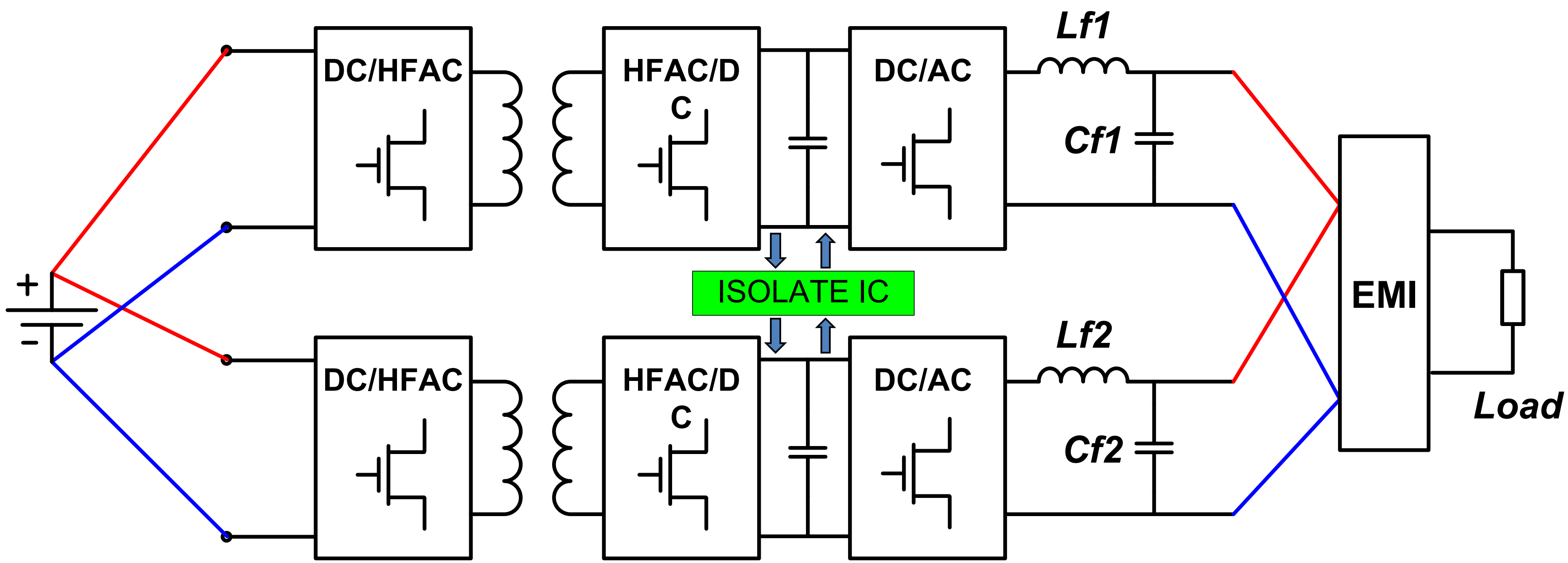


CH1:Iac of S1; CH2: Iac of S2; CH3: Iac; CH4:Vac

Inverter Load jump
600W→1500W→600W

Technical Accomplishments and Progress

- **A-Sample Design**

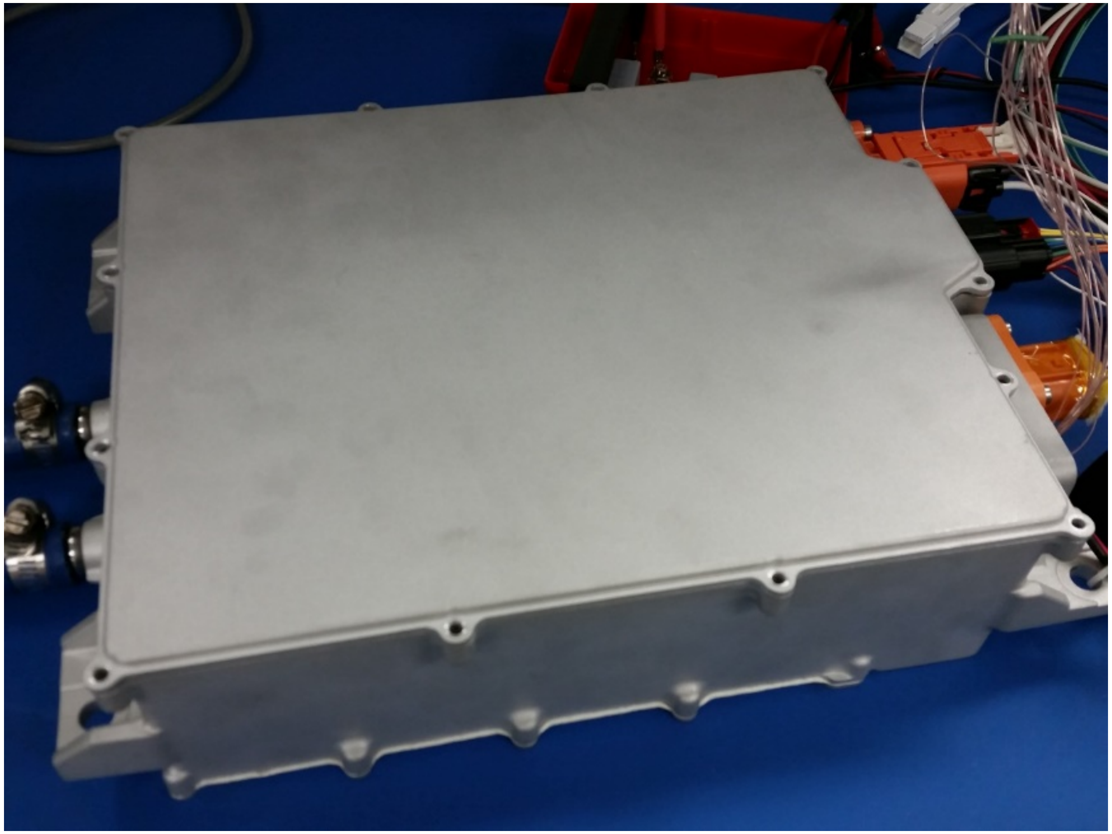


Parallel of two 3.3kw modules

- **The synchronous signal and AC side sensing signal are isolated**
- **Use droop control to reduce circulating current**

Technical Accomplishments and Progress

- **6.6kw A-Sample OBC**



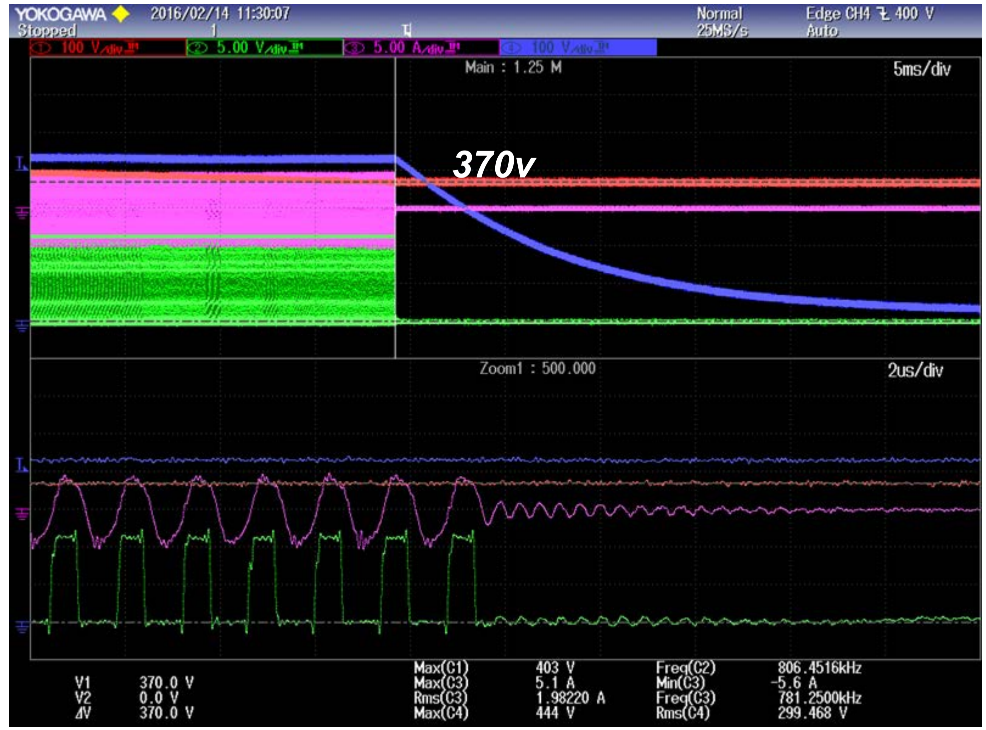
Picture of A-Sample prototype
Dimension: 296x250x75mm)

Technical Accomplishments and Progress

- **Charger Mode Soft Start**

Test condition: Vbus=400v; Vbat=450v; Po=1kw

Ch1:Vbus, Ch2:Vgs_Q1011, Ch3:Ip, CH4: Vbat



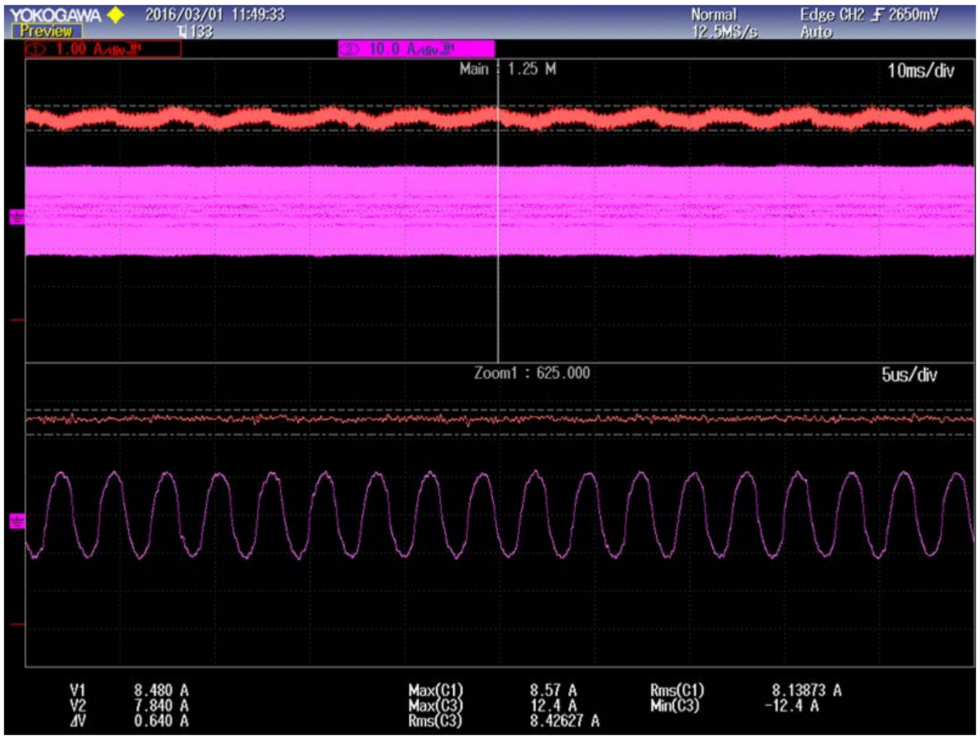
- The power on set point is 380v and the power off set point is 370v.
- The max frequency is limited at 800khz.

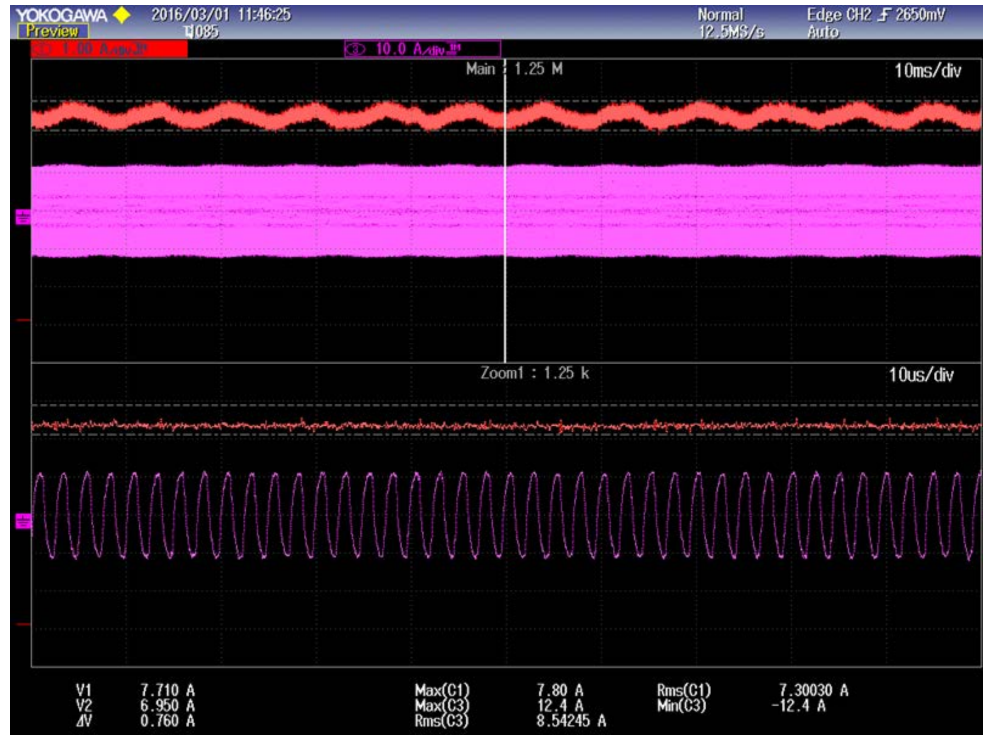
Technical Accomplishments and Progress

- **Inverter Mode Battery Side Current Ripple**

Test condition: Vbat=400v/450v; Vac=240v; R load

400v input 3.3kw *CH1:Ibat_ripple CH3: resonant current* 450v input 3.3kw





- The battery side output current ripple is lower than 10%.

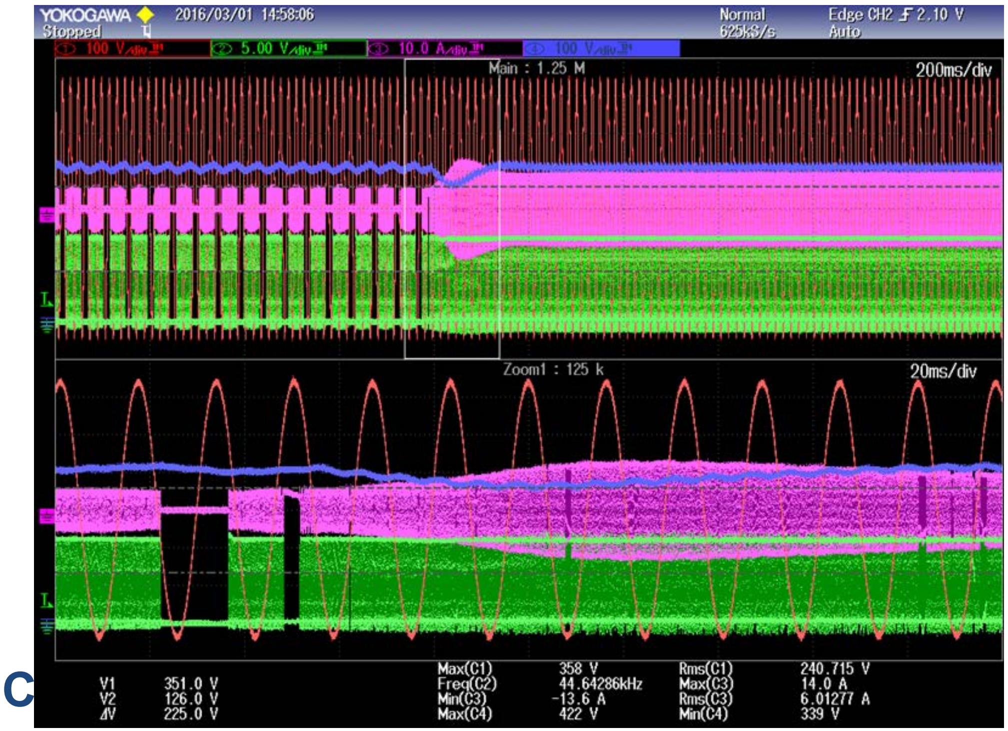
Technical Accomplishments and Progress

- **Inverter Mode Dynamic Load Response**

Test condition: Vbat=450v; Vac=240v; R load

CH1:Vac Ch2:Vgs-D2D, CH3: resonant current, Ch4: Vbus

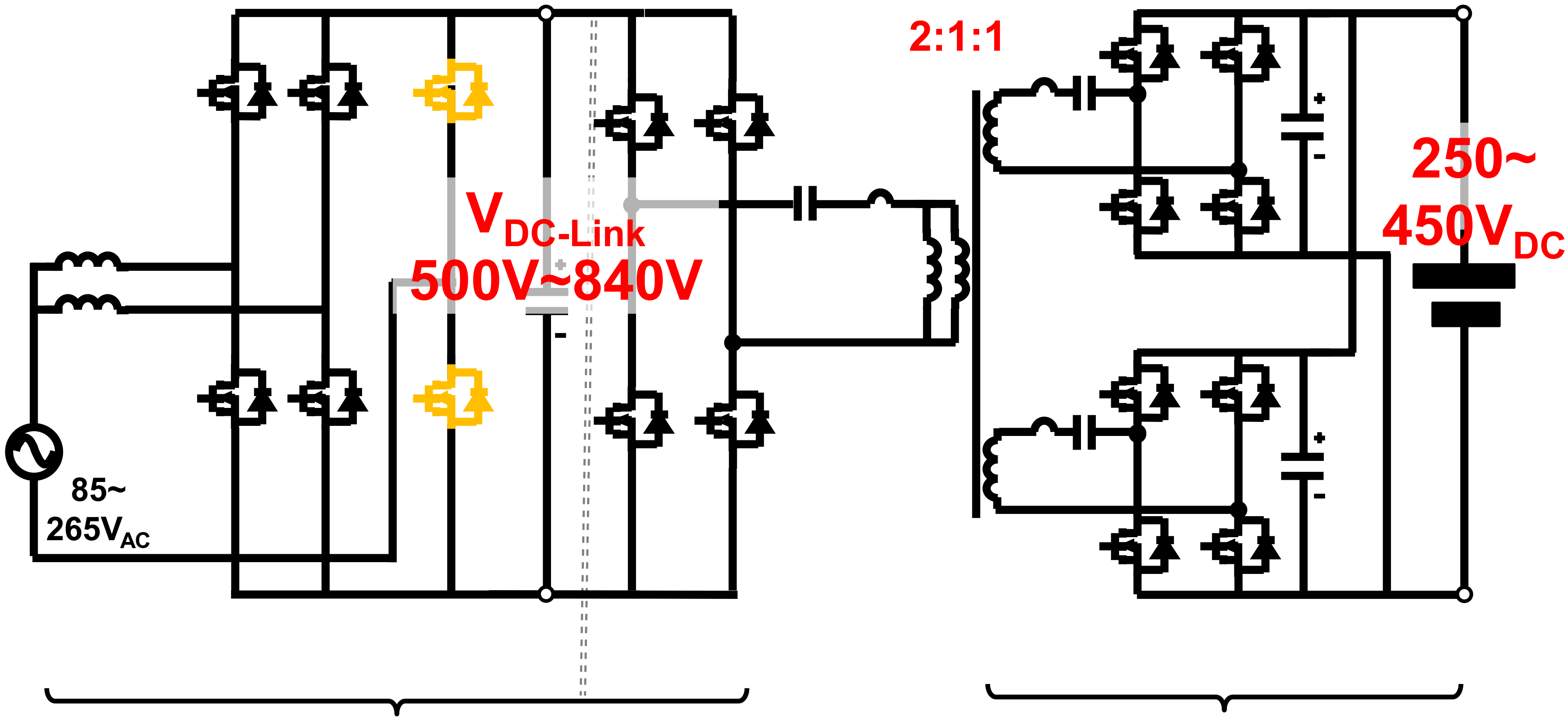
0w-→1800w



900w-→2700w

Technical Accomplishments and Progress

- **CPES alternative Topology (PFC + Semi-DCX)**



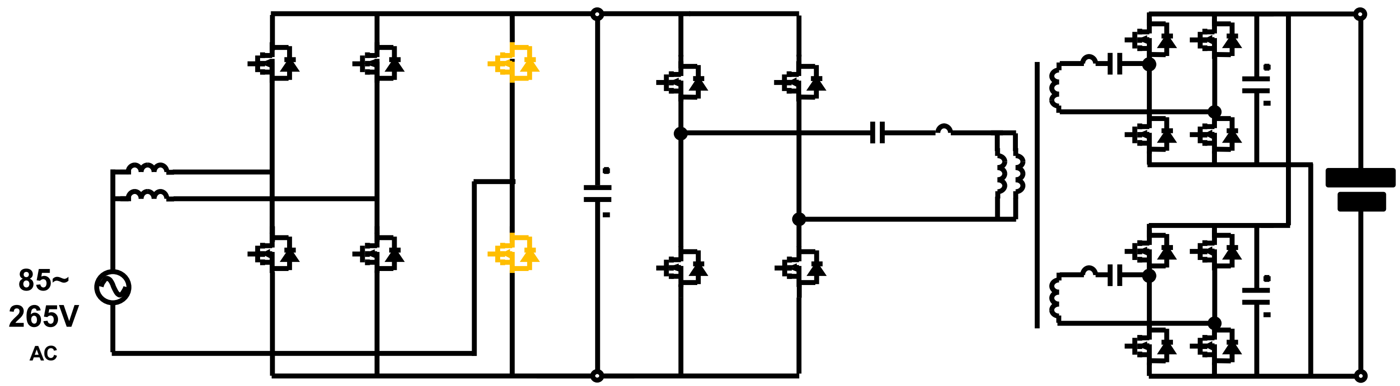
1st Stage: Totem-pole PFC
(CRM ZVS operation)
1200V SiC Device

2nd Stage: CLLC
(**Almost fixed frequency**)
600V GaN Device

Developed by CPES

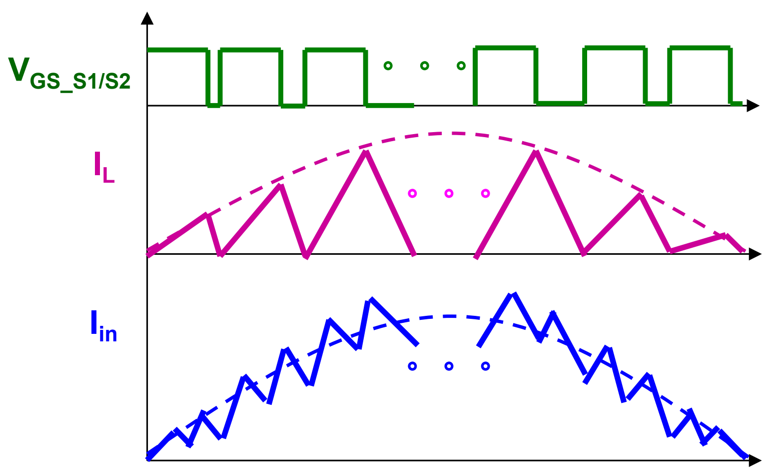
Technical Accomplishments and Progress

- **CPES alternative Topology (PFC + Semi-DCX)**



CRM operation to achieve ZVS

Resonant Converter to achieve ZVS



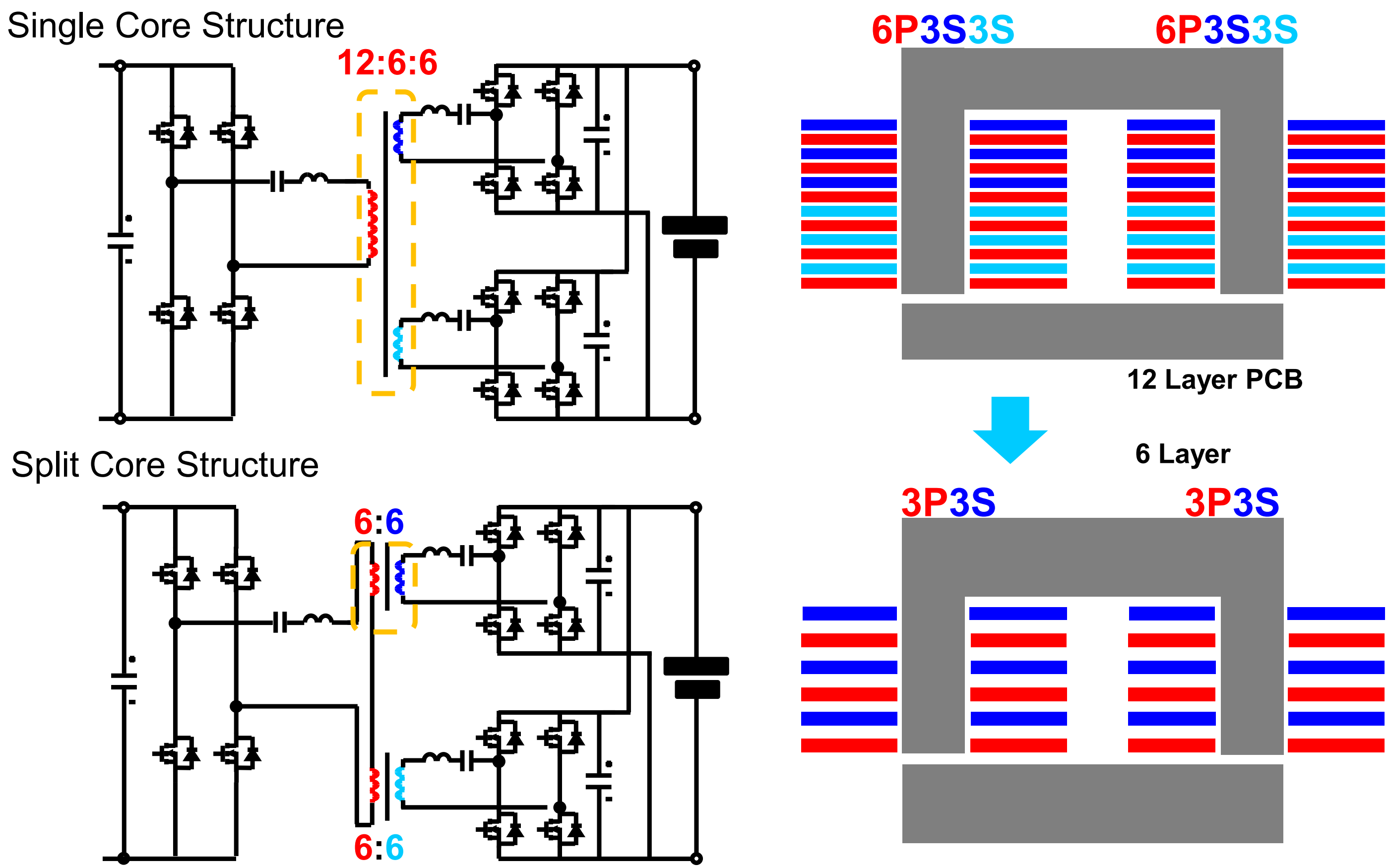
- ➢ **All fast switch can achieve soft switching**
- ➢ **Large current ripple can be compensated by two phase interleave**

Soft Switching to Eliminate Turn on Loss

Developed by CPES

Technical Accomplishments and Progress

- **CPES alternative Topology (PFC + Semi-DCX)**



Split core structure can reduce the required number of PCB layers

Developed by CPES

Technical Accomplishments and Progress

- **CPES alternative Topology (PFC + Semi-DCX)**

PFC (>300kHz) **DC/DC(~500kHz)**

420mm

270mm(10.6in)

Height: 40mm (1.6in) w/ cold plate

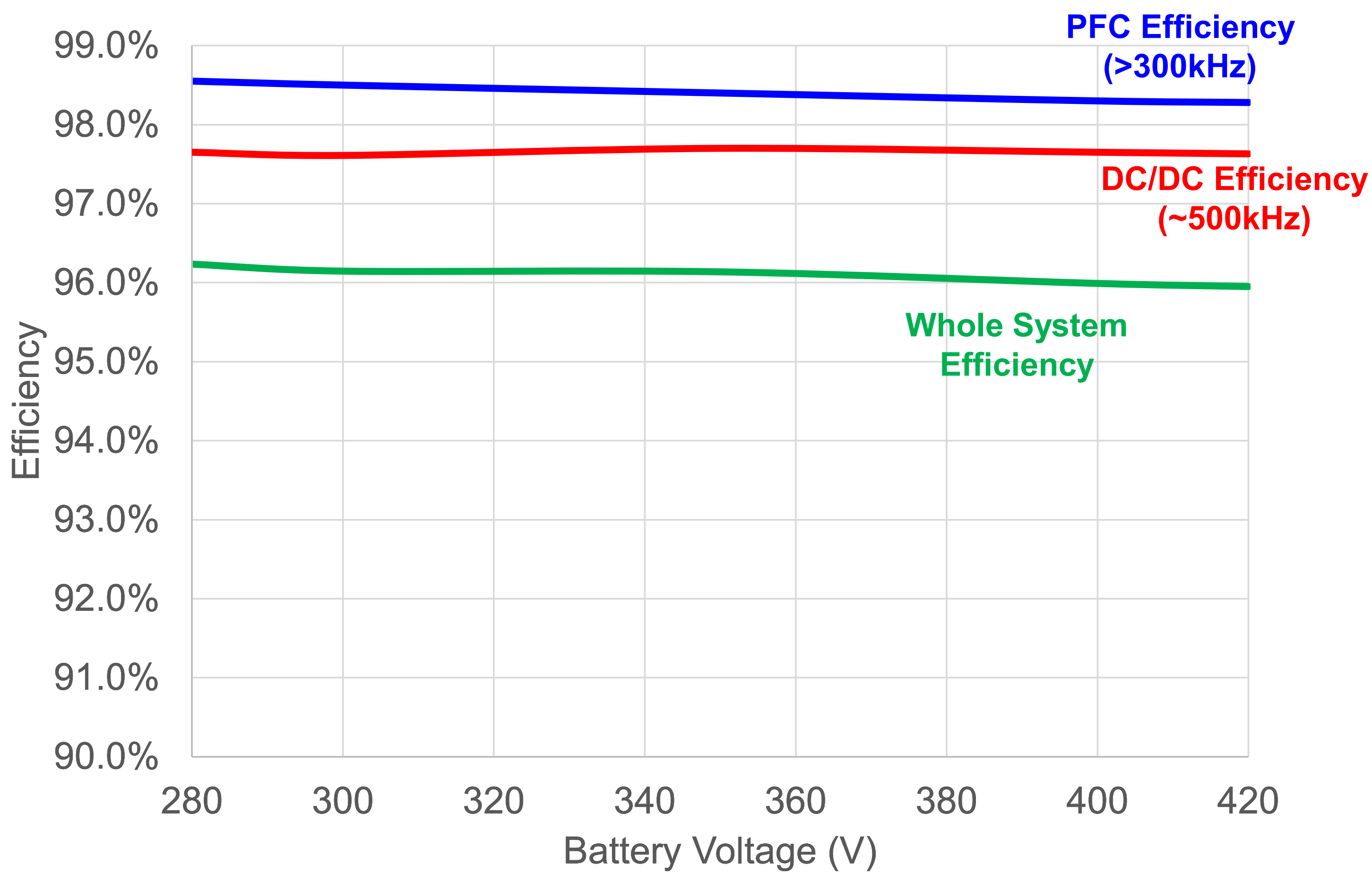
24W/in^3->32W/in^3
0.1% Efficiency Drop

Change to electrolytic cap: 32W/in^3>38W/in^3

Developed by CPES

Technical Accomplishments and Progress

- **CPES alternative Topology (PFC + Semi-DCX)**



Over 96% efficiency is achieved over the whole battery voltage range

Developed by CPES

Partners/Collaborators

Delta Products Corporation (Primary Recipients)

Administrative responsible to DOE, single point of contact
Technical direction and program management
Timing and deliverables, budget control
OBCM Prototypes development and testing, system integration
Commercialization

Transphorm, Inc.

High frequency GaN device development
GaN device characterization and qualification

CPES at Virginia Tech

GaN device in circuit evaluation
High frequency circuit topology selection and evaluation
High-frequency magnetic components development

FCA US LLC

Vehicle integration and testing
Commercialization

Proposed Future Work

- Remainder of FY 2016
  - Compare performance of Iteration III and Iteration II Device in PBC modules
  - Test A-Sample GaN-based OBCs
  - Develop B-Sample GaN-based OBC
  - Develop and finalize market introduction plan at device level and charger level.
  - Confirm host vehicle and integration plan.

- FY2017
  - Develop vehicle test plan.
  - Vehicle integration.
  - Test the OBC in vehicle.

Summary

- DOE Mission Support
  - Test and test one concept bi-directional OBC.
  - Design and build the first generation of GaN-based OBC.
- Approaches
  - Reduce switching devices from 76 Si devices to 24 GaN devices
  - Increase switching frequency to reduce passive components size
  - Develop software switching technology to reduce switching loss
- Technical Accomplishment
  - Developed and evaluated three iterations of GaN devices.
  - Designed, built and tested concept 3.3kw GaN-based OBC to verify architecture and high frequency switching circuit
  - Designed and built A-Sample 6.6kw GaN-based OBC to verify thermal performance and packaging design
  - Developed alternative topology with SiC/GaN devices

Summary

- Future Work
  - Test A-Sample 6.6kw OBC samples
  - Design, build and test B-Sample OBC samples
  - Test prototype of PFC + Semi-DCX topology
  - Test OBC in vehicle
  - Create commercial plan

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