High-Efficiency High-Density GaN-Based 6.6kW Bidirectional On-board Charger for PEVs - 2015 Annual Merit Review Meeting

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DPM, Livonia, MI

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DE-EE0006834

Contents

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Overview

Timeline

- Start – FY14
- Finish – FY17
- 8.3% complete

Budget

- Total project funding DOE share – $1,487,593
- Funding received in FY14: $0
- Funding for FY15: $588,738

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

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

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FY2015 Objective and Milestones

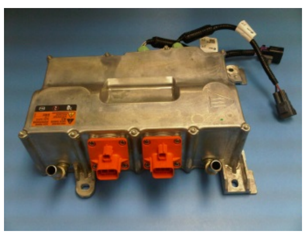
FY 2015 Objective: Technology Design and Development

- Developing prototypes of GaN device.
- Developing advanced circuit for GaN device application.
- Topology selection and evaluation for DC/DC stage, with comparison among topologies in performance, size and cost.
- Designing and building one concept bi-directional OBC.
- Designing the first generation of GaN-based OBC.

#	Milestone	Type	Due Month
MS 1.1	Si-Based Conceptual Bi-directional Charger Design Complete	Technical	3
MS 1.2	Si-Based Concept Bi-directional Charger Build Complete	Technical	6
MS 1.3	Si-Based Concept Bi-directional Charger Test	Technical	9
MS 1.4	A-Sample Charger Design Completed	Technical	11
DP 1	Analysis of the test result of the concept bidirectional charger	Go/No Go	11

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)

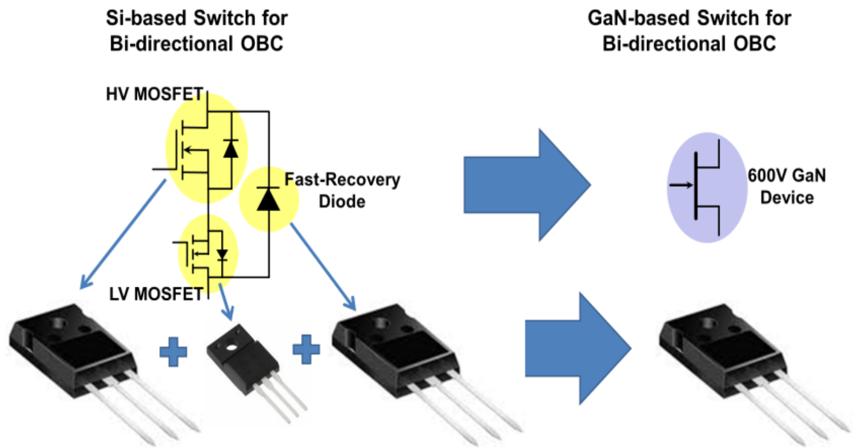
Delta
OBCM
(6.6kW)

TDK
OBCM
(6.6kW)

Panasonic
OBCM
(6.6kW)

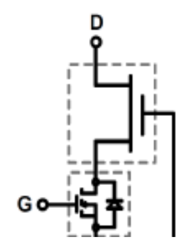
Delta
Solar Inverter
(5kW)

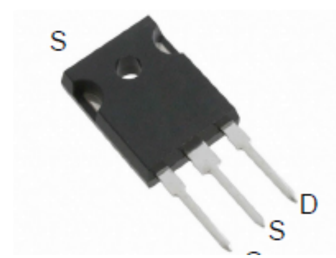
Approach
– Reduce number of switching devices



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	1,110nC
Q_g	10nC	64nC
Q_{rr}	138nC	10,000nC

Technical Accomplishments and Progress

- Iteration I GaN device delivery

transphorm TPH3205WS

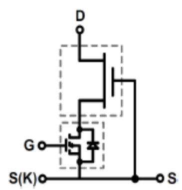
Preliminary

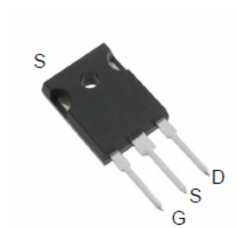
PRODUCT SUMMARY (TYPICAL)	
V_{DS} (V)	600
$R_{DS(on)}$ (mΩ)	63
Q_{rr} (nC)	138

GaN Power
Low-loss Switch

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

Applications
- Compact DC-DC converters
- AC motor drives
- Battery chargers
- Switch mode power supplies





TO-247 3L Package

Absolute Maximum Ratings (T_C=25 °C unless otherwise stated)

Symbol	Parameter	Limit Value	Unit
$I_{D25°C}$	Continuous Drain Current @T_C=25 °C	34	A
$I_{D100°C}$	Continuous Drain Current @T_C=100 °C	24	A
I_{DM}	Pulsed Drain Current (pulse width:100 µs)	140	A
V_{DSS}	Drain to Source Voltage	600	V
V_{TDS}	Transient Drain to Source Voltage [a]	750	V
V_{GSS}	Gate to Source Voltage	±18	V

G S D G K S D*D*

- 180 pc of samples delivered in two types of packages
- Initial application test completed
- 3-pin package is chosen for future delivery

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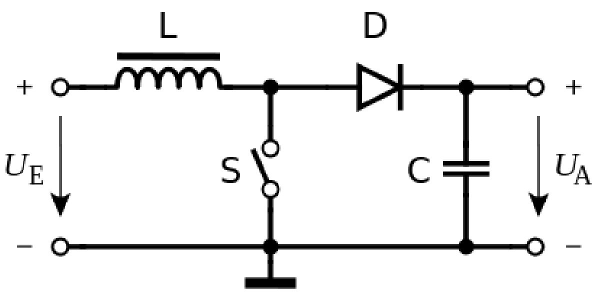
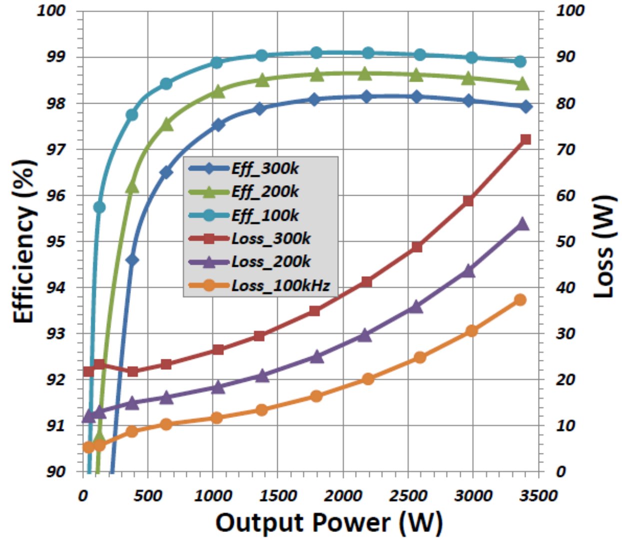
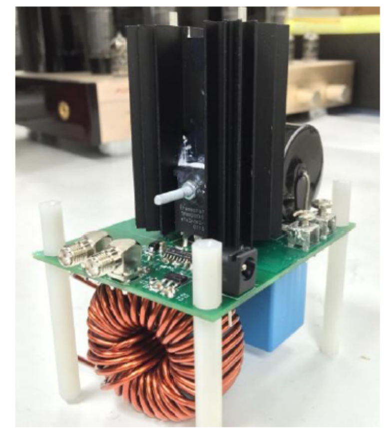
Technical Accomplishments and Progress

- **TPH3205ws Sync-rec Boost Converter Efficiency Test**



Half bridge boost converter, syn-rec, 240V:400V
(Expect same result from 400V:240V)



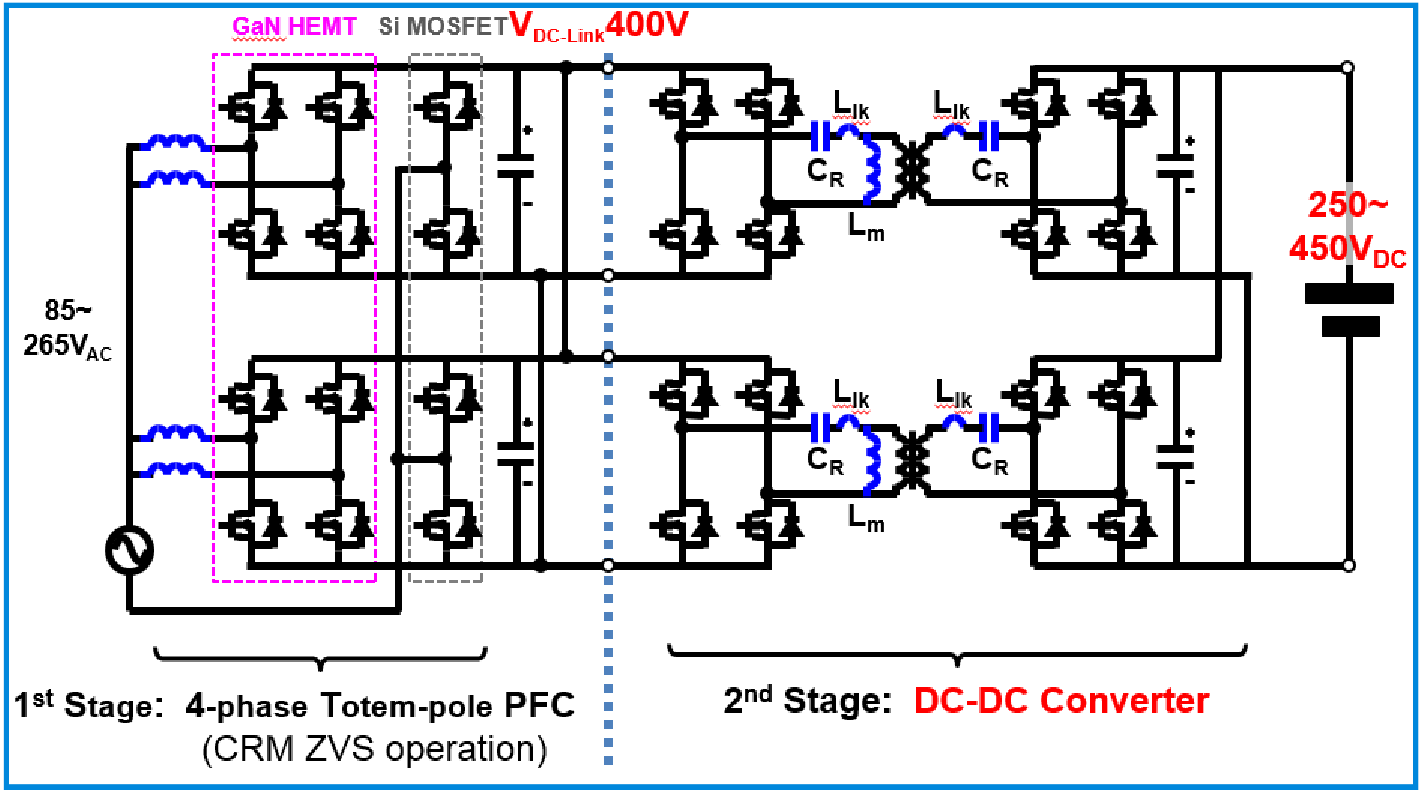


2 device on 1 heat sink: R_{th}=1.27 C/W.
Inductor: L=268uH dcr=20mohm

- Data taken after equilibrium. All converter losses included.
- Peak Eff. >99% obtained at 100kHz (98.9% at 3.4kW)
- Peak Eff. >98% obtained at 300kHz (97.9% at 3.4kW)

Note: test data provided by Transphorm

Topology Candidate 1
– Totem Pole PFC + LLC DC-DC



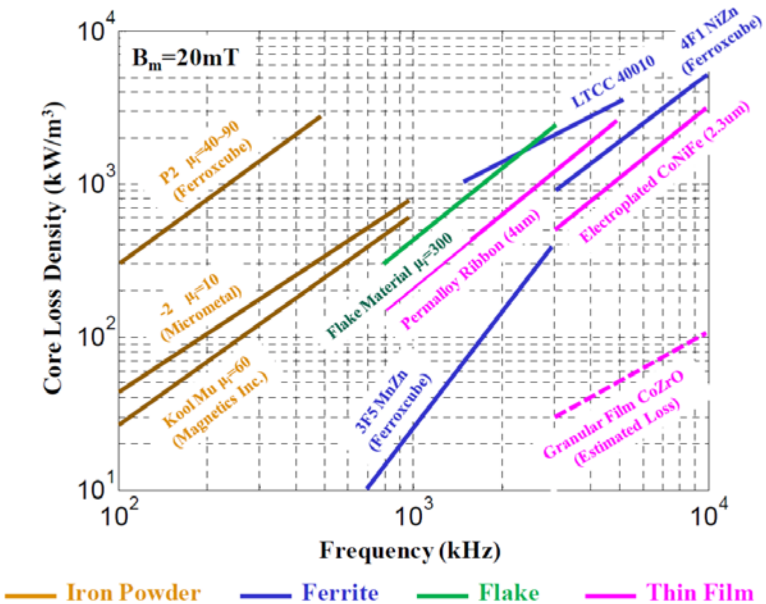
PROs
- Soft switching AC/DC
- High efficiency DC/DC

CONs
- Realizing soft switching in DC/AC is a challenge
- Control method is complicated

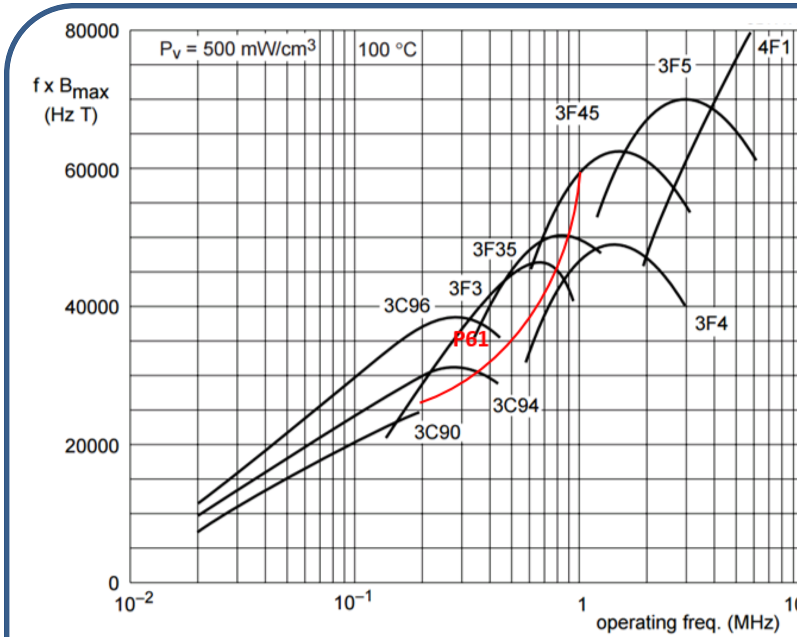
This is Plan B – CPES will continue research of the Totem-pole PFC/inverter

Technical Accomplishments and Progress

- **High frequency Magnetics**



- In the 500 KHz ~ 2MHz range, MnZn ferrite material has the lowest core loss density.



- When compared with 3F45, 3F35 and 3F4, the new material P61 from ACME has the lowest core loss.

Research done provided by CPES

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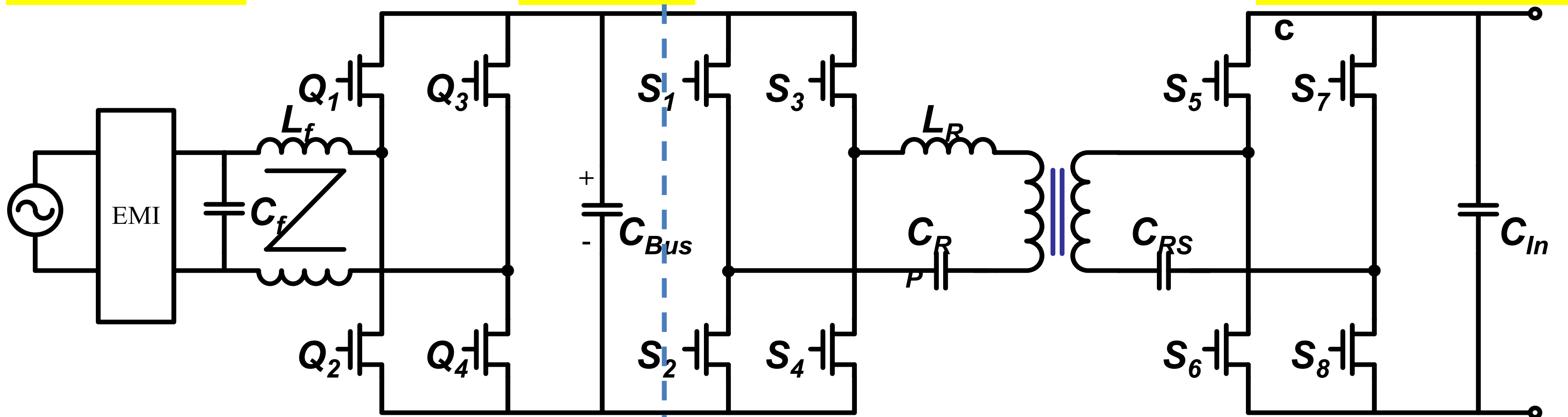
Topology Candidate 2
-Selected Topology for Concept Design



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

PROs

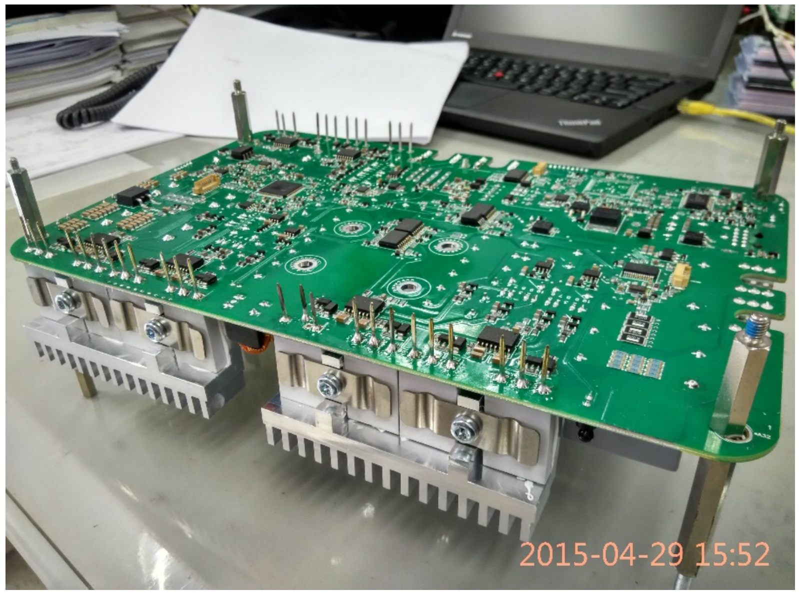
- Mature DC/AC design
- Soft switching DC/DC

CONs

- Higher loss of DC/AC due to hard switching

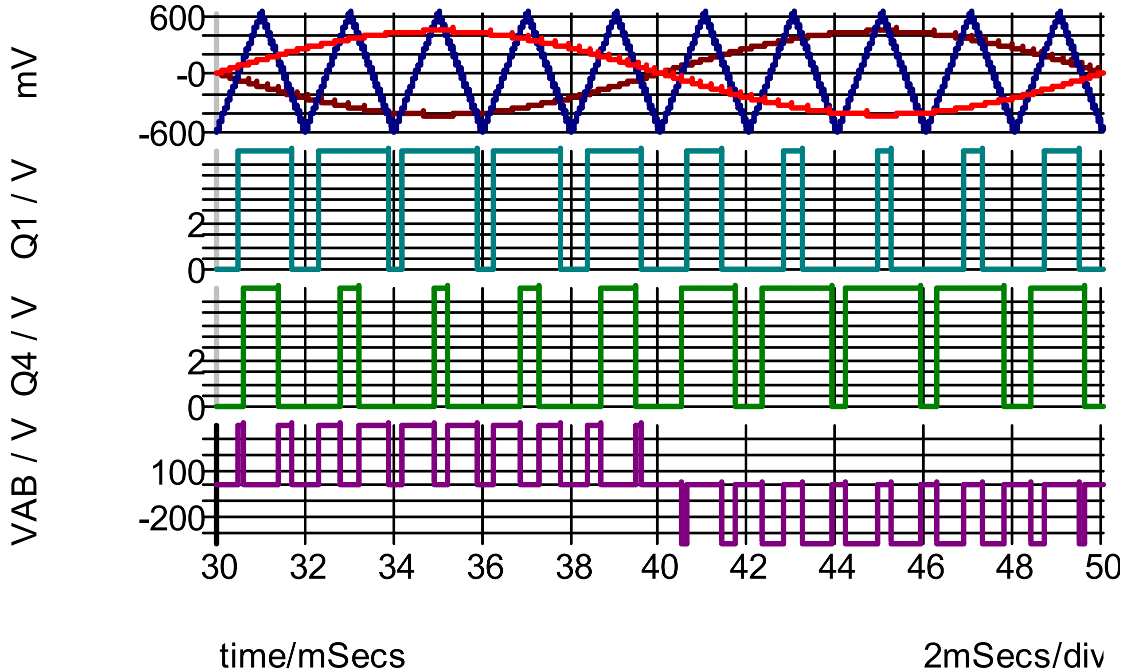
This is Plan A – Delta will build concept prototype with this topology

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



Technical Accomplishments and Progress

- **DC/AC inverter control**



Unipolar modulation

Technical Accomplishments and Progress

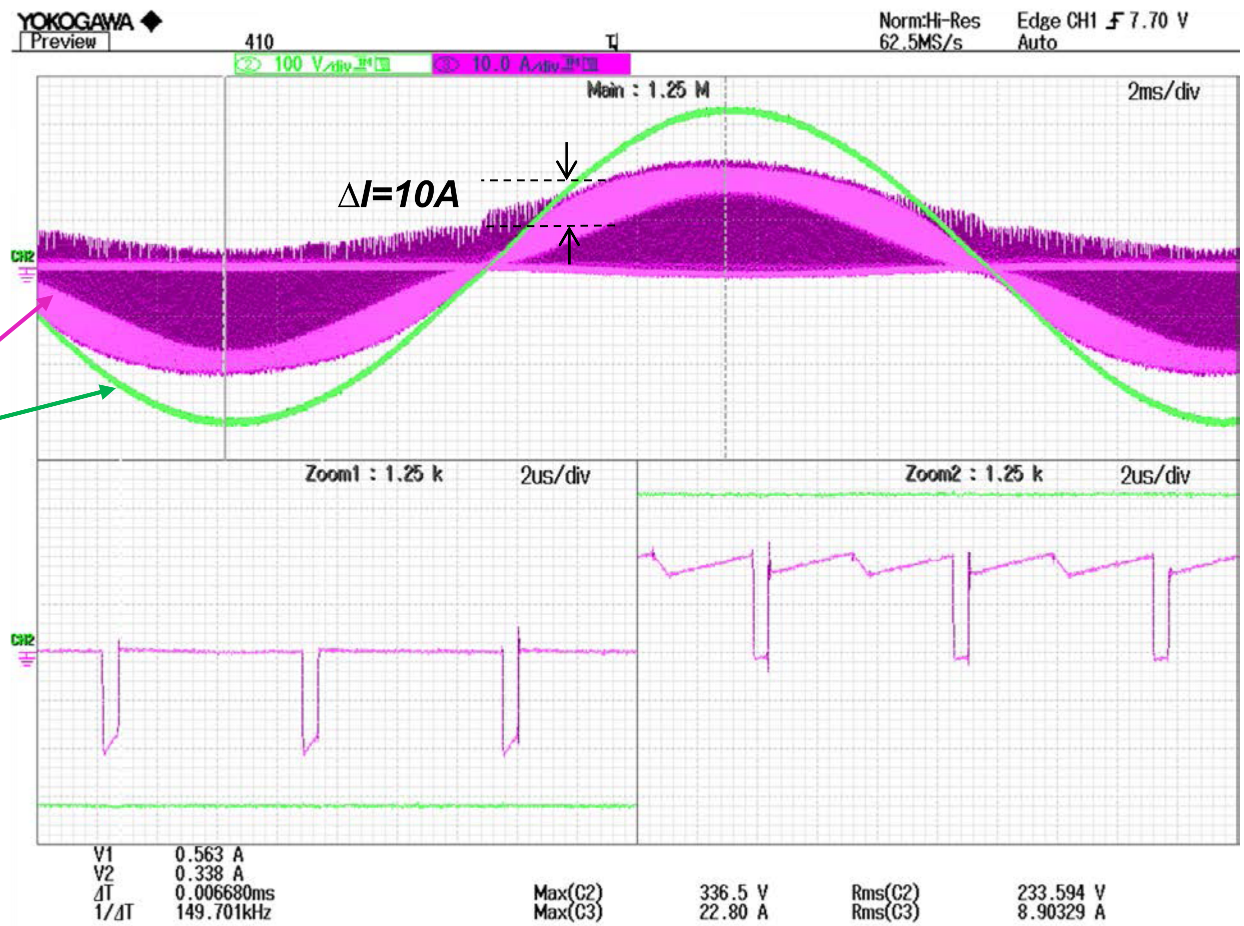
- **DC/AC inverter test waveforms**

Test condition:

- Vin=400Vdc
- Vo=240VAC
- Po=3300
- fs=150kHz

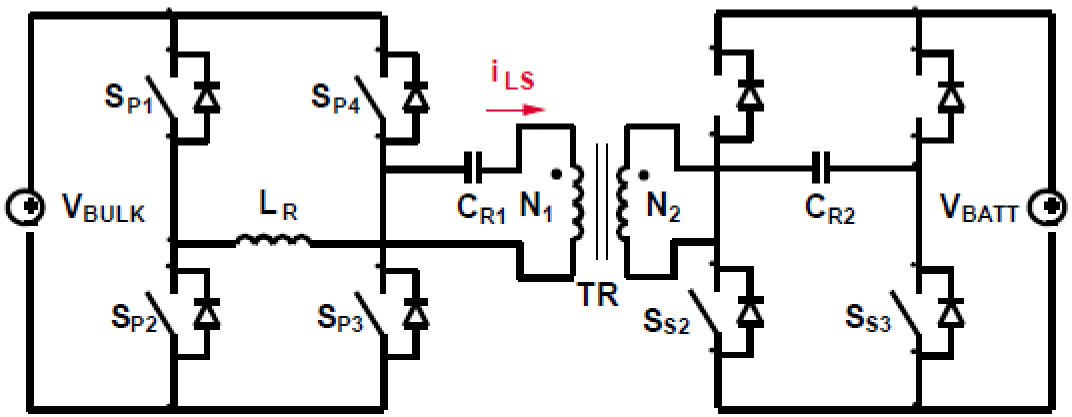
CH3: GaN Ids

CH2: Vo



Technical Accomplishments and Progress

- **Novel DC/DC Stage Topology**



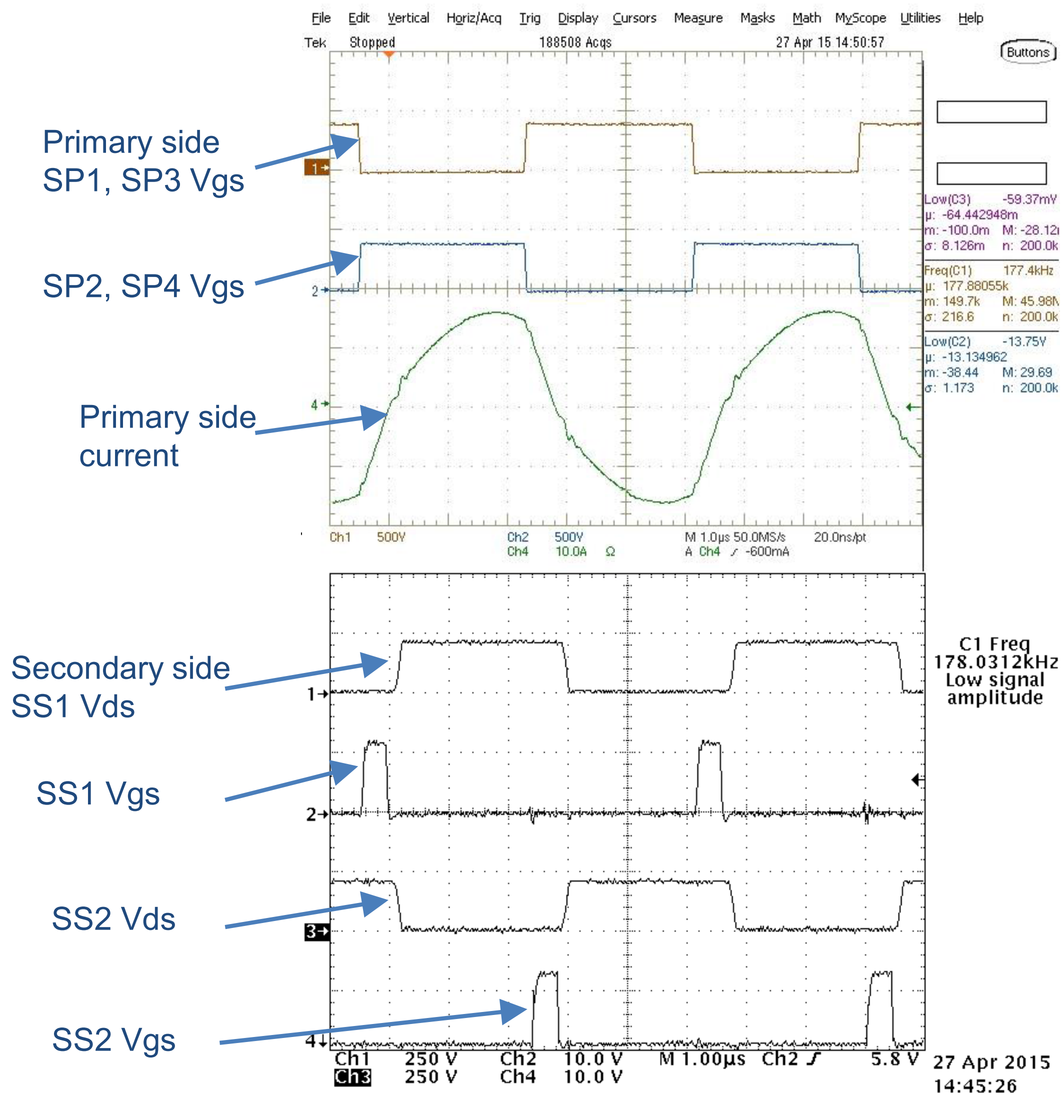
- Both sides are full bridge
- Soft switching on both sides
- Secondary side time-delay control provides multiple benefits:
  - better current sharing in paralleled power stages
  - Step up capability
  - narrow switching frequency range
  - high efficiency across the output voltage range

Technical Accomplishments and Progress

- **Novel DC/DC Stage Waveforms (Vin=400V, Vout=200V)**

The secondary side boost function is not needed when Vout < 280V

The secondary side drive has no additional on time



Technical Accomplishments and Progress

- **Novel DC/DC Stage Waveforms (Vin=400V, Vout=320V)**

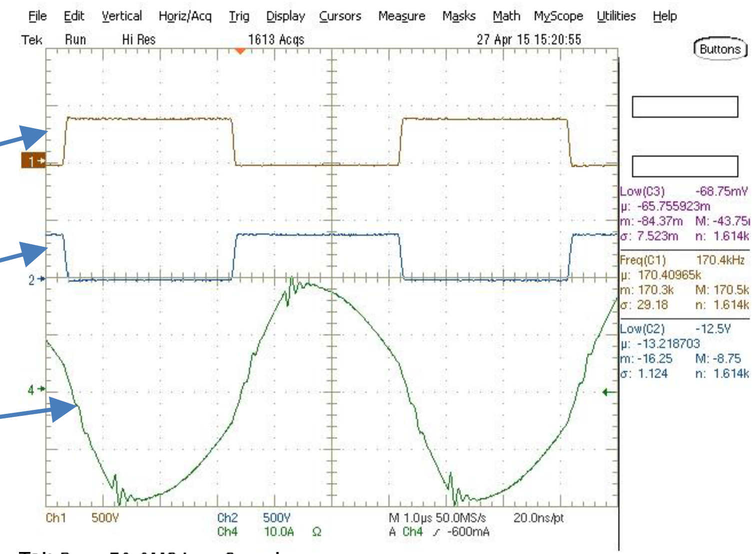
The secondary side boost function is needed when Vout > 280V

The secondary side drive has additional on time

Primary side SP1, SP3 Vgs

SP2, SP4 Vgs

Primary side current

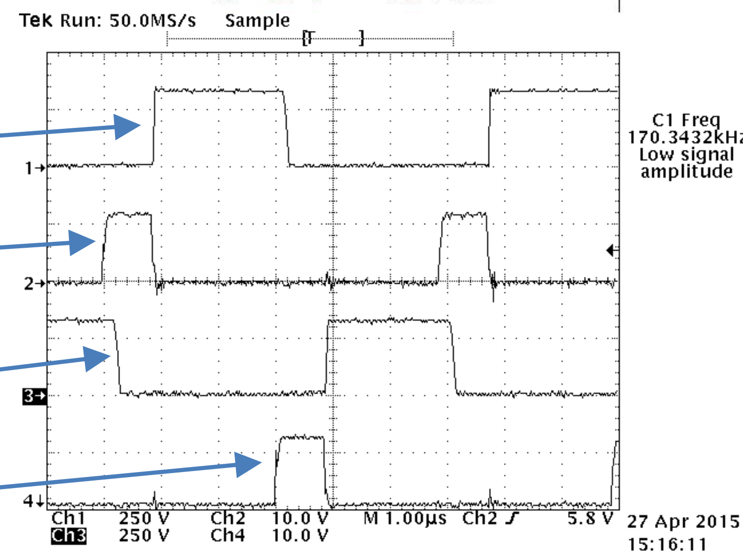


Secondary side SS1 Vds

SS1 Vgs

SS2 Vds

SS2 Vgs



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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 2015
  - Develop two iterations of improved GaN device.
  - Design and build one concept bi-directional OBC.
  - Design the first generation of GaN-based OBC.

- FY 2016
  - Continue development of GaN devices and advanced circuit for GaN device application.
  - Build and test two generations of GaN-based OBCs.
  - 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
  - Design and build one concept bi-directional OBC.
  - Design 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 GaN device.
  - Developed new soft switching technology for DC/DC
  - Compared and selected topologies of AC/DC stage and DC/DC stage
  - Simulated and experimented AC/DC stage and DC/DC stage
  - Completed 3.3kw concept bi-directional OBC schematic design
- Future Work
  - Build 6.6kw bi-directional OBC samples
  - Test OBC in vehicle
  - Create commercial plan