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

Dr. Charles Zhu, Principal Investigator
DPM, Livonia, MI
June 10, 2015

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
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- Summary
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
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%.

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

<table>
<thead>
<tr>
<th>#</th>
<th>Milestone</th>
<th>Type</th>
<th>Due Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS 1.1</td>
<td>Si-Based Conceptual Bi-directional Charger Design Complete</td>
<td>Technical</td>
<td>3</td>
</tr>
<tr>
<td>MS 1.2</td>
<td>Si-Based Concept Bi-directional Charger Build Complete</td>
<td>Technical</td>
<td>6</td>
</tr>
<tr>
<td>MS 1.3</td>
<td>Si-Based Concept Bi-directional Charger Test</td>
<td>Technical</td>
<td>9</td>
</tr>
<tr>
<td>MS 1.4</td>
<td>A-Sample Charger Design Completed</td>
<td>Technical</td>
<td>11</td>
</tr>
<tr>
<td>DP 1</td>
<td>Analysis of the test result of the concept bidirectional charger</td>
<td>Go/No Go</td>
<td>11</td>
</tr>
</tbody>
</table>
## Prior Arts and Program Goals

<table>
<thead>
<tr>
<th></th>
<th>Prior Art</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Efficiency</strong></td>
<td>93%</td>
<td>95%</td>
</tr>
<tr>
<td><strong>Function</strong></td>
<td>Uni-directional</td>
<td>Bi-directional</td>
</tr>
<tr>
<td><strong>Power density</strong></td>
<td>0.45-0.75 kW/L</td>
<td>30% to 50% improvement</td>
</tr>
<tr>
<td><strong>Device</strong></td>
<td>Silicon</td>
<td>GaN</td>
</tr>
<tr>
<td><strong>Switching frequency</strong></td>
<td>&lt;100kHz</td>
<td>0.3-1MHz</td>
</tr>
</tbody>
</table>

- **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

<table>
<thead>
<tr>
<th>Power Device Count</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Device Type</strong></td>
</tr>
<tr>
<td>TO-247 Switch</td>
</tr>
<tr>
<td>TO-247 Diode</td>
</tr>
<tr>
<td>TO-220 Switch</td>
</tr>
<tr>
<td><strong>Total Devices</strong></td>
</tr>
</tbody>
</table>

Features
- Low Q_o
- 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.

<table>
<thead>
<tr>
<th></th>
<th>GaN HEMT</th>
<th>Si MOSFET</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transphorm TPH3205WS</td>
<td>Infineon IPB65R065C7</td>
</tr>
<tr>
<td>$R_{ds_on}$</td>
<td>63mΩ</td>
<td>58 mΩ</td>
</tr>
<tr>
<td>$C_{oss_tr}$</td>
<td>283nC</td>
<td>1,110nC</td>
</tr>
<tr>
<td>$Q_g$</td>
<td>10nC</td>
<td>64nC</td>
</tr>
<tr>
<td>$Q_{rr}$</td>
<td>138nC</td>
<td>10,000nC</td>
</tr>
</tbody>
</table>
Technical Accomplishments and Progress

• Iteration I GaN device delivery

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

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

![Diagram of a half bridge boost converter]

- 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
DE-EE0006834
Topography Candidate 2
-Selected Topology for Concept Design

**Bi-Direction AC/DC**
- Topology: PFC/Inverter

**Bi-Directional DC/DC**
- 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
Technical Accomplishments and Progress

• 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:
- $V_{in}=400\text{Vdc}$
- $V_o=240\text{VAC}$
- $P_o=3300$
- $f_s=150\text{kHz}$

![Test Waveform Diagram]

- **CH3**: GaN $I_{ds}$
- **CH2**: $V_o$
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
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