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

High-Efficiency High-Density GaN-Based 6.6kW Bidirectional On-board Charger for PEVs - 2017 Annual Merit Review Meeting

EDT067

Dr. Charles Zhu, Principal Investigator
Delta Products Corporation, Livonia, MI

April 10, 2017

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

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Contents

- Project Overview
- Project Objective
- Project Milestones
- Technical Accomplishments and Progress
    - GaN device delivery and test
    - 6.6kw GaN-based B-Sample design, build and test
    - CPES Alternative design, build and test
- Market Introduction Plan
- Responses to Previous Year Reviewer's Questions
- Partners
- Proposed Future Works
- Summary

Project Overview

Timeline

- Period 2 Start – FY16
- Period 2 Finish – FY16
- Project Finish – FY17
- 71% complete

Budget

- Total project funding DOE share – $1,487,594
- Total Period 2 funding DOE share - $565,970
- Funding received in Period 2 (FY16): $454,947

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

FY2016 Objective and Milestones

FY 2016 Objective: Technology Development and market Plan 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**
- **Design, build and test the B-Sample charger**
- **Develop and finalize market introduction plan**

#	Milestone	Type	Due Month
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
MS 3.1	Develop in-vehicle test plan	Technical	Feb. 2017
MS 3.2	Vehicle Integration	Technical	Aug 2017
MS 3.3	Conduct In-vehicle test and report	Technical	Nov 2017
MS 3.4	Completion of the in-vehicle testing	Technical	Dec 2017

Budget Period II Review Meeting

February 24, 2017,
Delta Products,
Livonia, MI

Lab Demo

Chrysler 2017 Pacifica PHEV Minivan

Contents

- ❑ Project Overview
- ❑ Project Objective
- ❑ Project Milestones
- ❑ **Technical Accomplishments and Progress**
    - ❑ GaN device delivery and test
    - ❑ 6.6kw GaN-based B-Sample design and build
    - ❑ CPES Alternative design, build and preliminary test
- ❑ Responses to Previous Year Reviewer's Questions
- ❑ Partners
- ❑ Proposed Future Works
- ❑ Summary

Technical Accomplishments and Progress

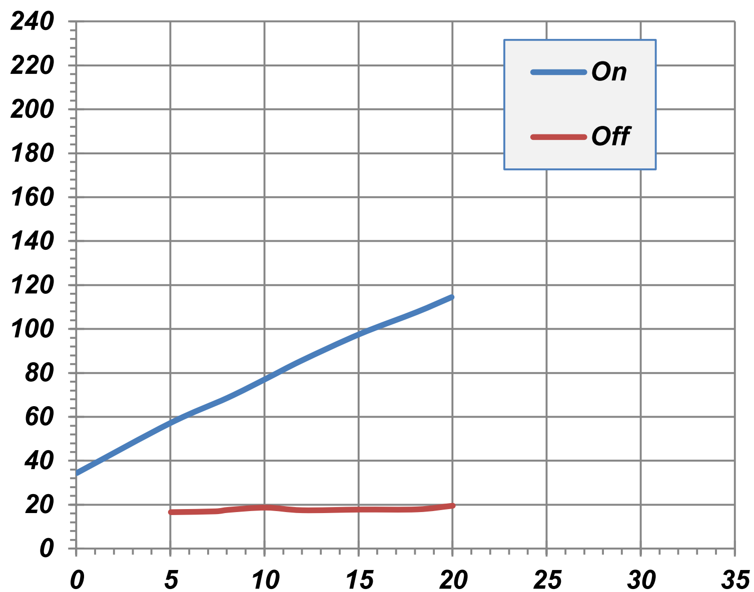
Three Iterations of GaN HEMT devices have been developed and delivered.

	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

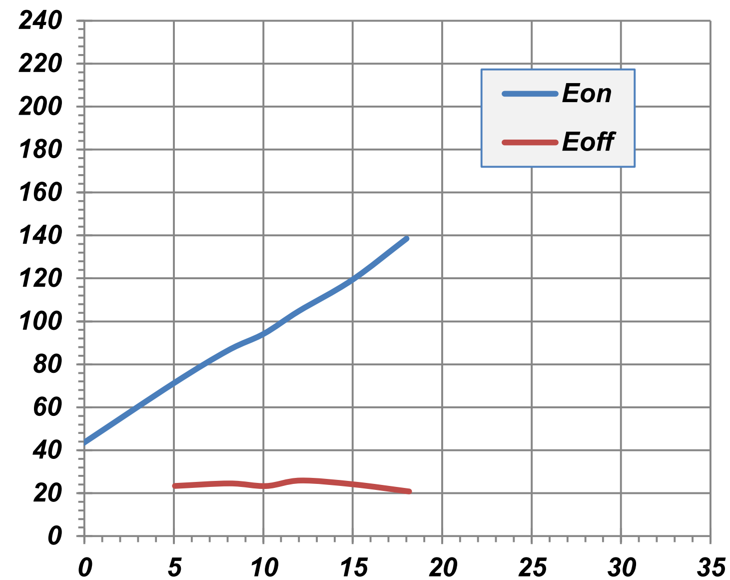
I-3 device has 33% lower Rds,on than I-2 device. Unfortunately, it also has higher charge, which will make switching performance sacrifice. Based on analysis, Delta plan to use I-2 device in A-Sample and B-Sample build.

Technical Accomplishments and Progress

Switching Losses (uJ) vs. Current (A) of I2 & I3 Devices, (Vds=400V)



I-2 Device, w/o snubber



* Not stable >18A w/o snubber

I-3 Device, w/o snubber*

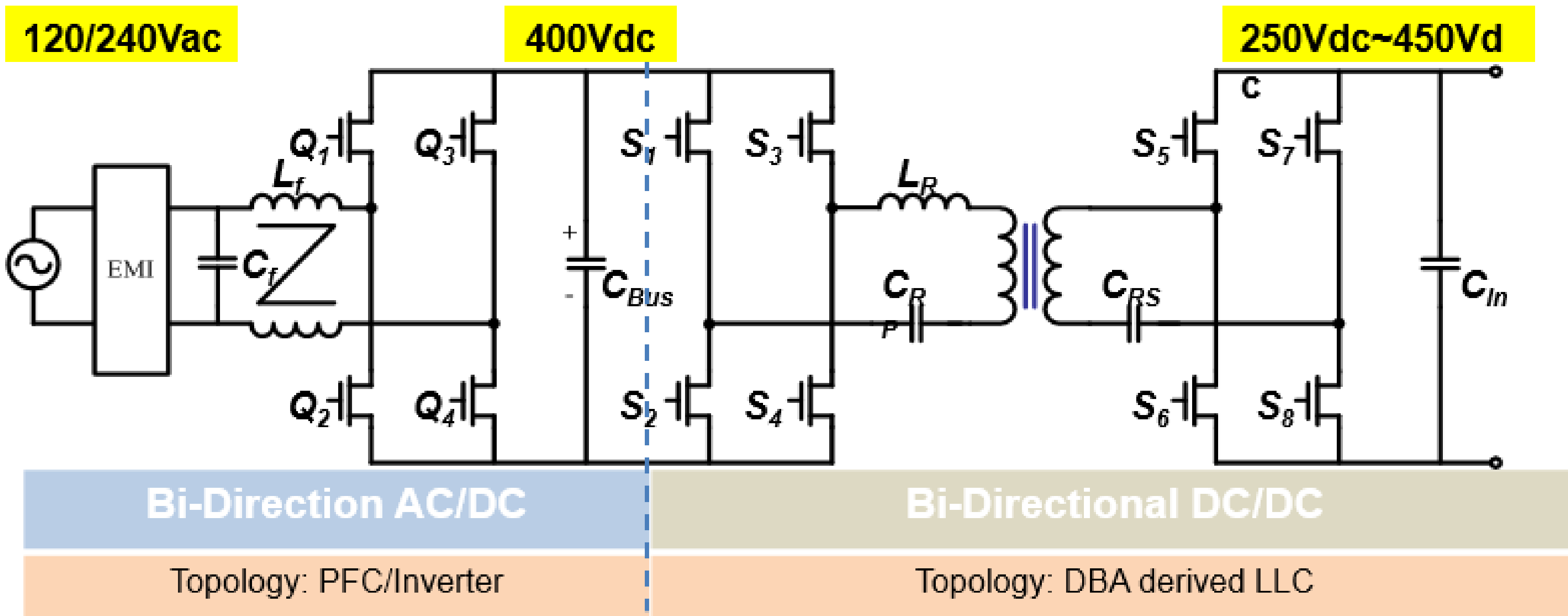
Technical Accomplishments and Progress

Parameter	Target	B-Sample Result	Production Design Feasibility
Volume	30% -50% reduction 8.1-11.4 liter	58% reduction 6.8 liter	Meet
Switching Frequency	0.3 - 1 Mega-Hertz (MHz)	DC/DC: 0.33~ 0.6MHz DC/AC: 0.3MHz	To optimize for size and efficiency trade-off
Power Efficiency	95%	95.1%	Meet
Power Rating	3.3kW at 120Vac, 6.6kW at 240Vac	3.3kW at 120Vac, 6.6kW at 240Vac	Meet
AC Voltage Range	120/240 Vac	120/240 Vac	Meet
HVDC Voltage Range	250 - 450 Vdc	250 - 450 Vdc	Meet
Nominal Battery Voltage	350 Vdc	350 Vdc	Meet
AC Line Frequency	50 - 60 Hz	50 - 60Hz	Meet
Maximum Coolant Temperature	70°C	50°C (projected from 30°C test result)	Will meet in production
Ambient Temp Range	-40 to 70°C	To be tested	Will meet in production
(CAN) Communication	Yes	Yes	Meet

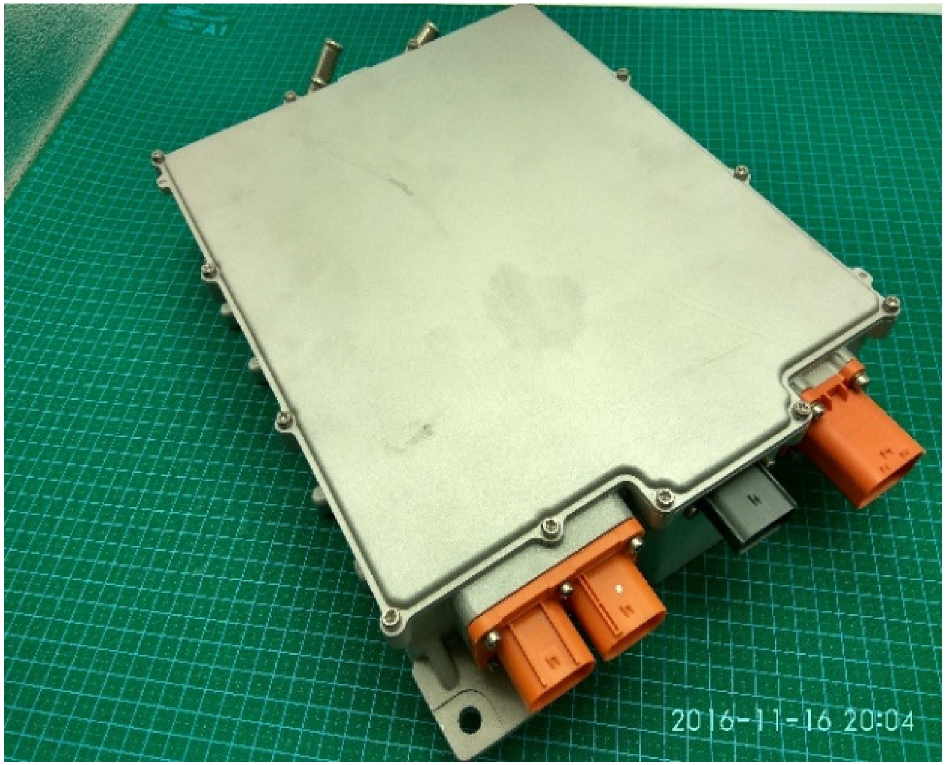
DELTA

Technical Accomplishments and Progress

Power Stage Topology (half)



Technical Accomplishments and Progress

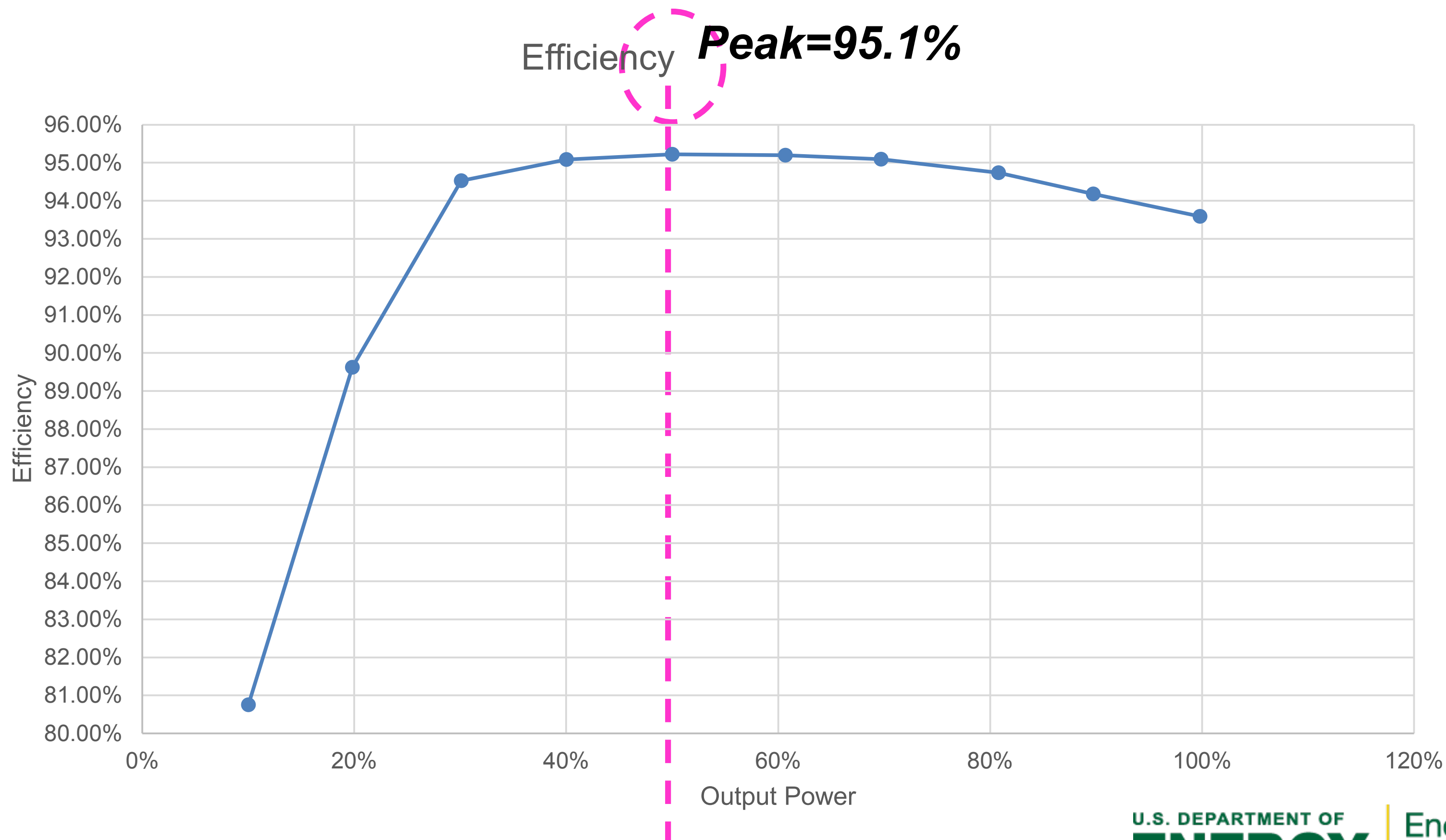


B Sample Physical parameters

- Dimension: 296x250x92mm
- Volume: 6.9 liter
- Weight: 12kg
- Water sealed design for under body installation
- Liquid Cooling

240Vac Charge Mode Efficiency

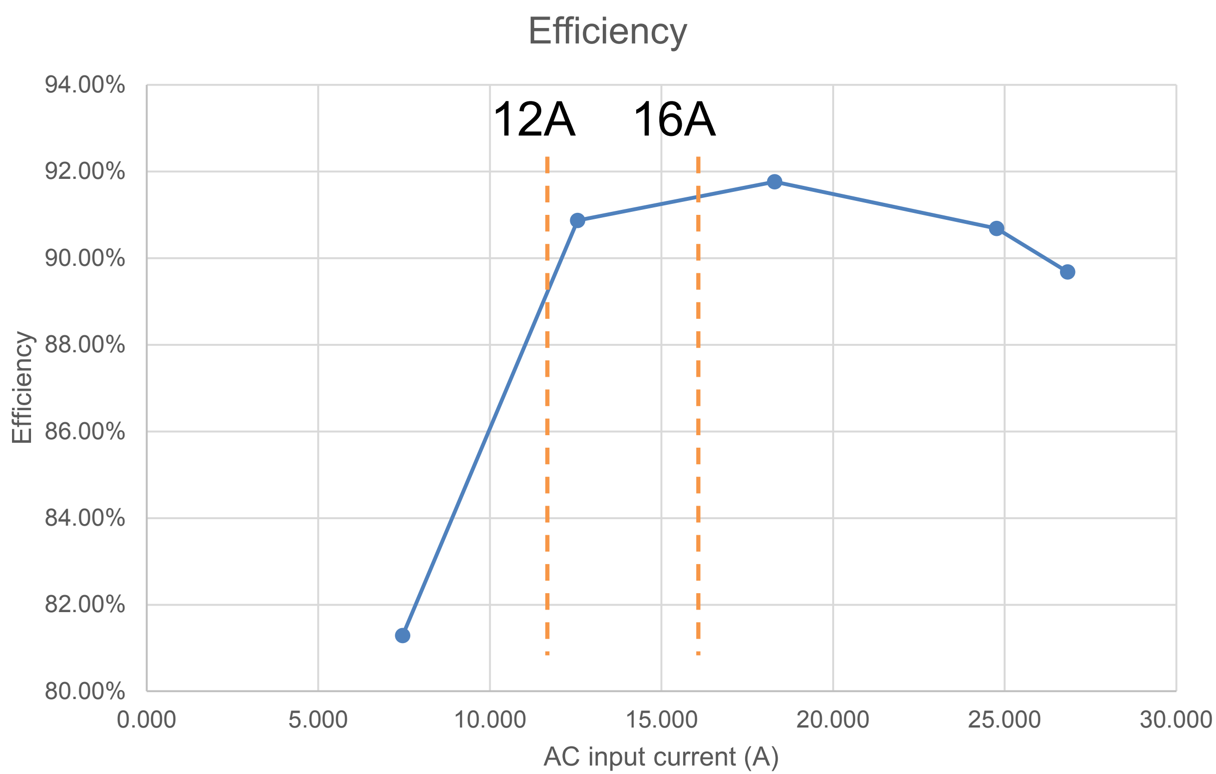
Test Condition:
30 ℃ Water Temp. 240Vac input and 350Vdc output. 100% load is 6.6kw.



Technical Accomplishments and Progress

120Vac Charge Mode Efficiency

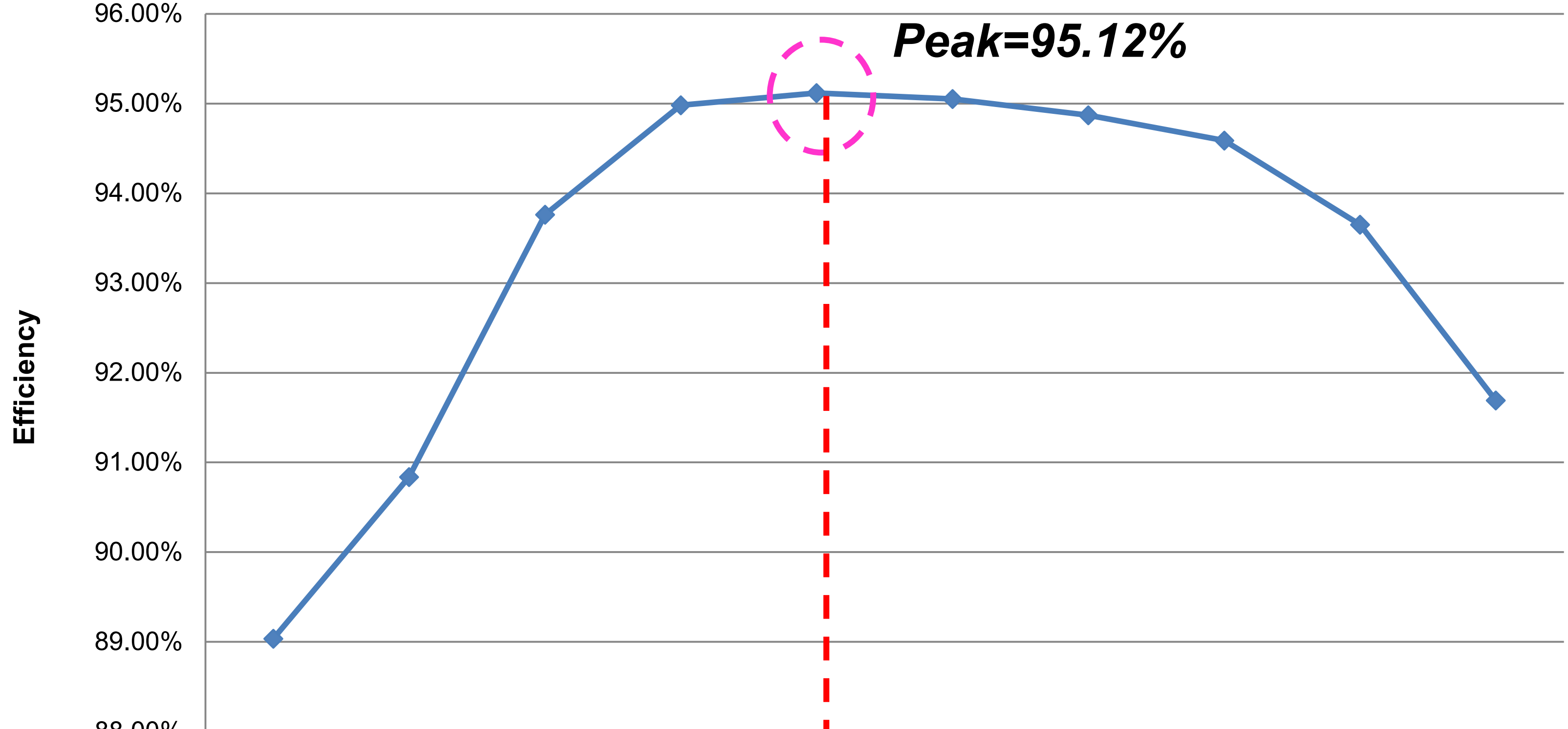
Test Condition: 30 ℃ Water Temp. 120Vac input and 350Vdc output.



Technical Accomplishments and Progress

240Vac Discharge Mode Efficiency

Test Condition:
30 ℃ Water Temp. 350Vdc input and 240Vac output. 100% load is 6.6kw.

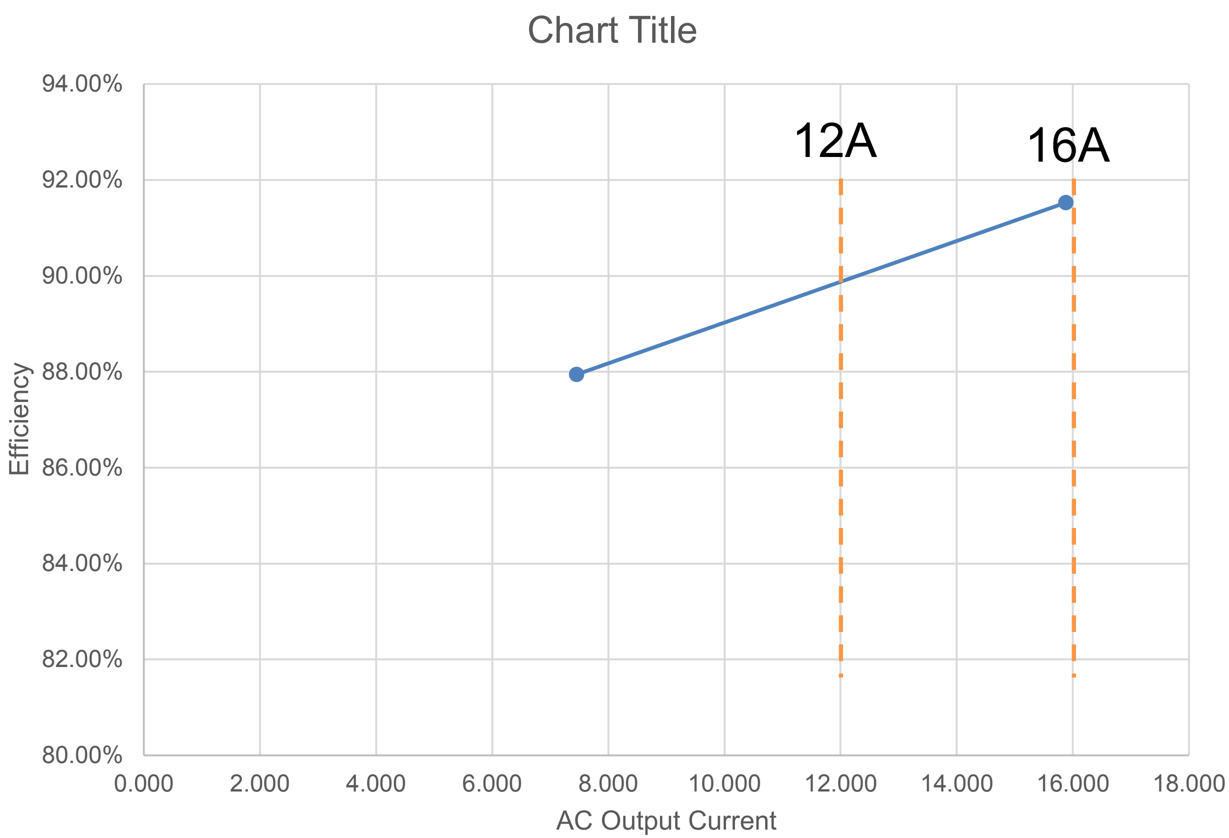


	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
350Vdc	89.04%	90.84%	93.76%	94.98%	95.12%	95.05%	94.87%	94.59%	93.65%	91.69%

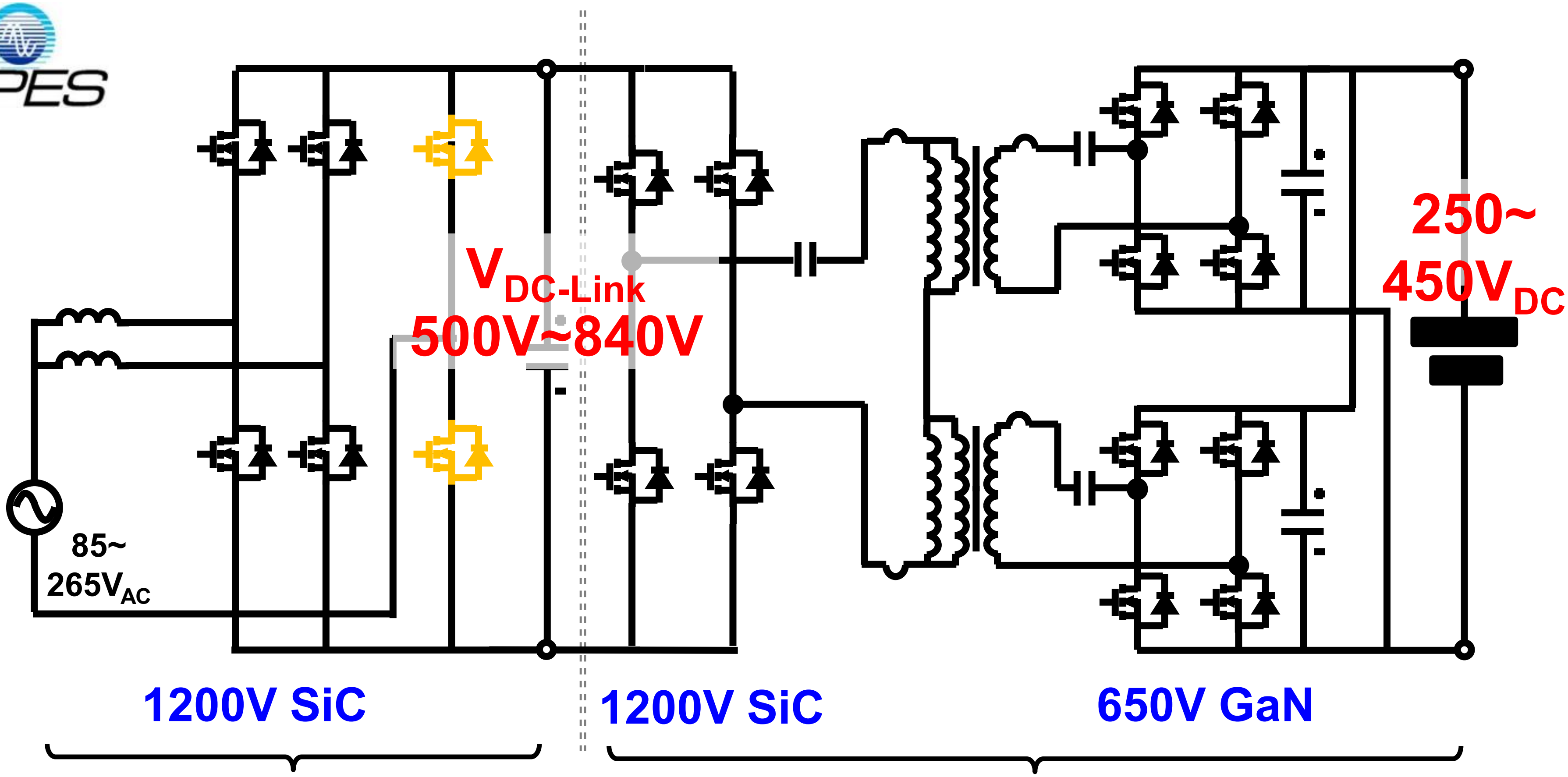
Output power

120Vac Discharge Mode Efficiency

Test Condition: 30 ℃ Water Temp. 350Vdc input and 120Vac output.



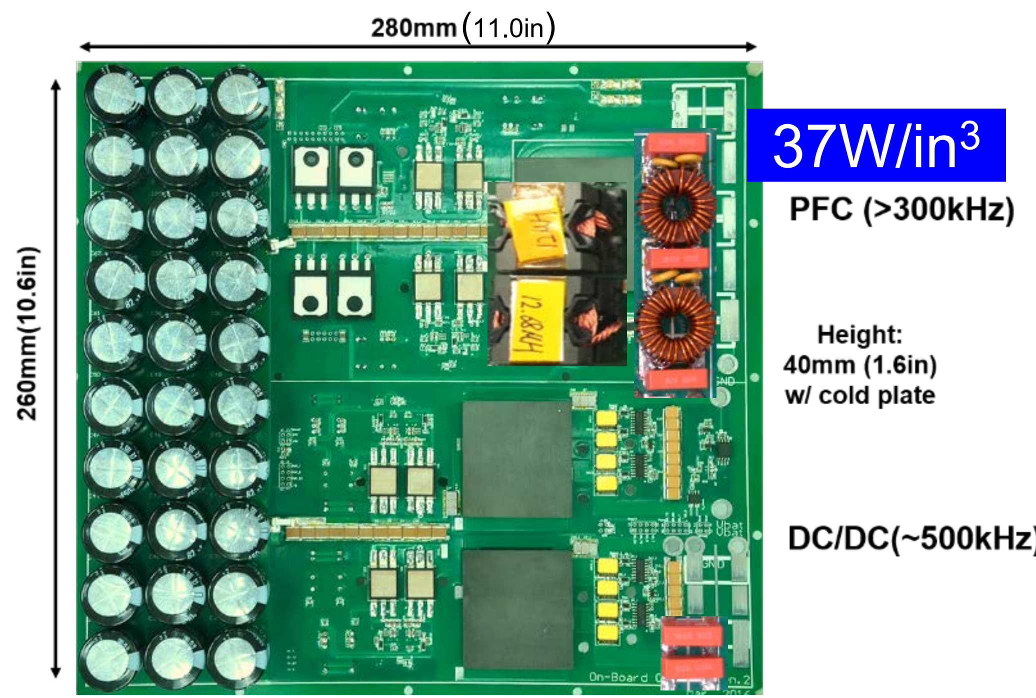
CPES Design: Variable DC-Link

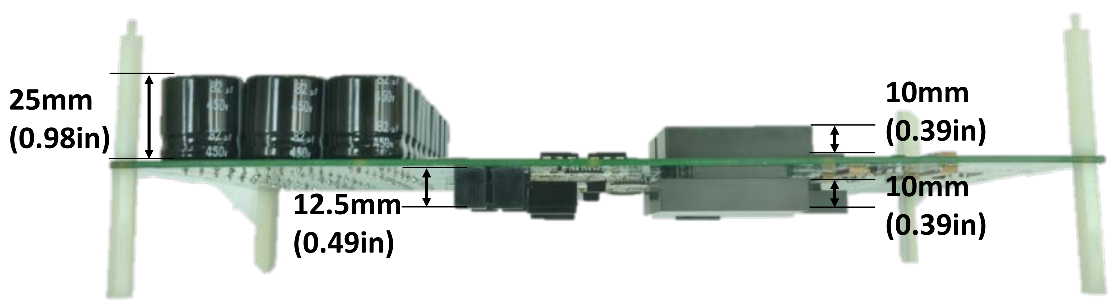


1st Stage: Totem-pole PFC
(CRM ZVS operation)

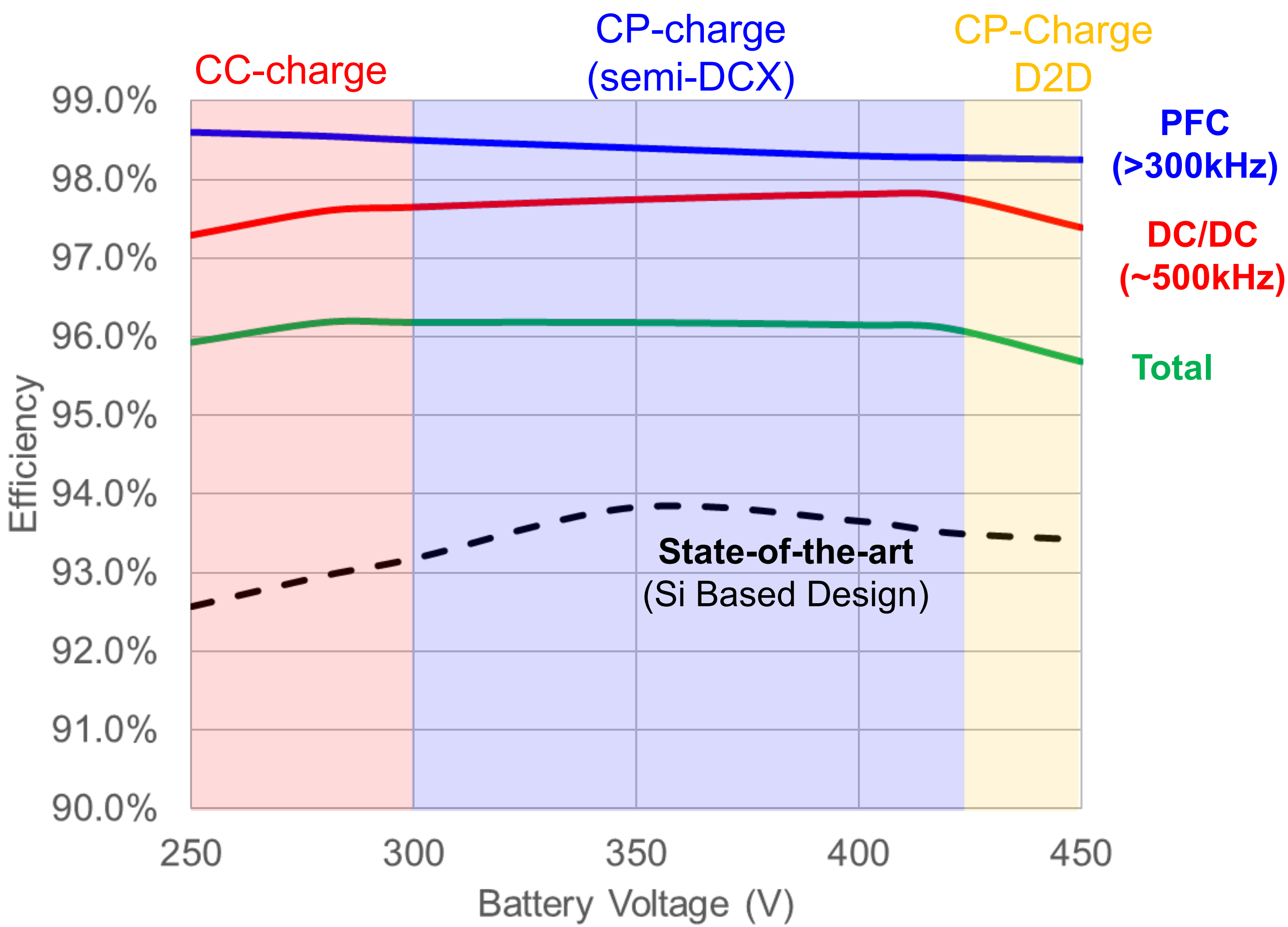
2nd Stage: CLLC
(ZVS ZCS Operation)

Hardware Prototype (PFC + DCX)

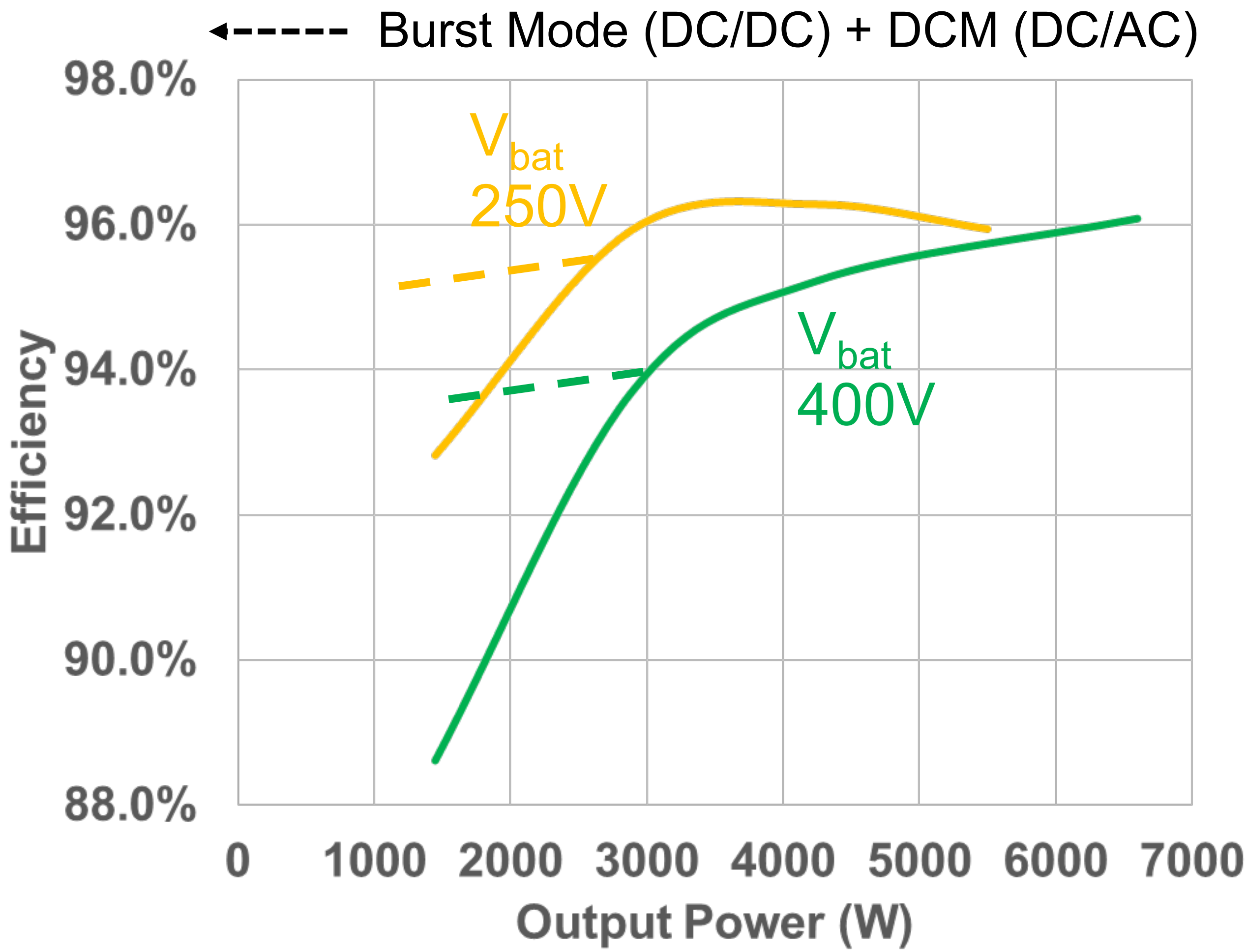




Charging Mode Efficiency (Testing Results)



Discharging Mode Total Efficiency (Testing Results)



Further improve efficiency using DCM (AC/DC) and burst mode (DC/DC)

CPES Work Summary

- A novel two stage system architecture and control are proposed
- 300kHz switching frequency for AC/DC and 500kHz for DC/DC
- ZVS is achieved for all high frequency devices
- PCB winding transformer with leakage integration
- 96.2% total system efficiency and 37W/in^3 Power density

Future Work

- Light load efficiency improvement with Burst Mode
- Implement protection function
- Implement PCB winding coupled inductor

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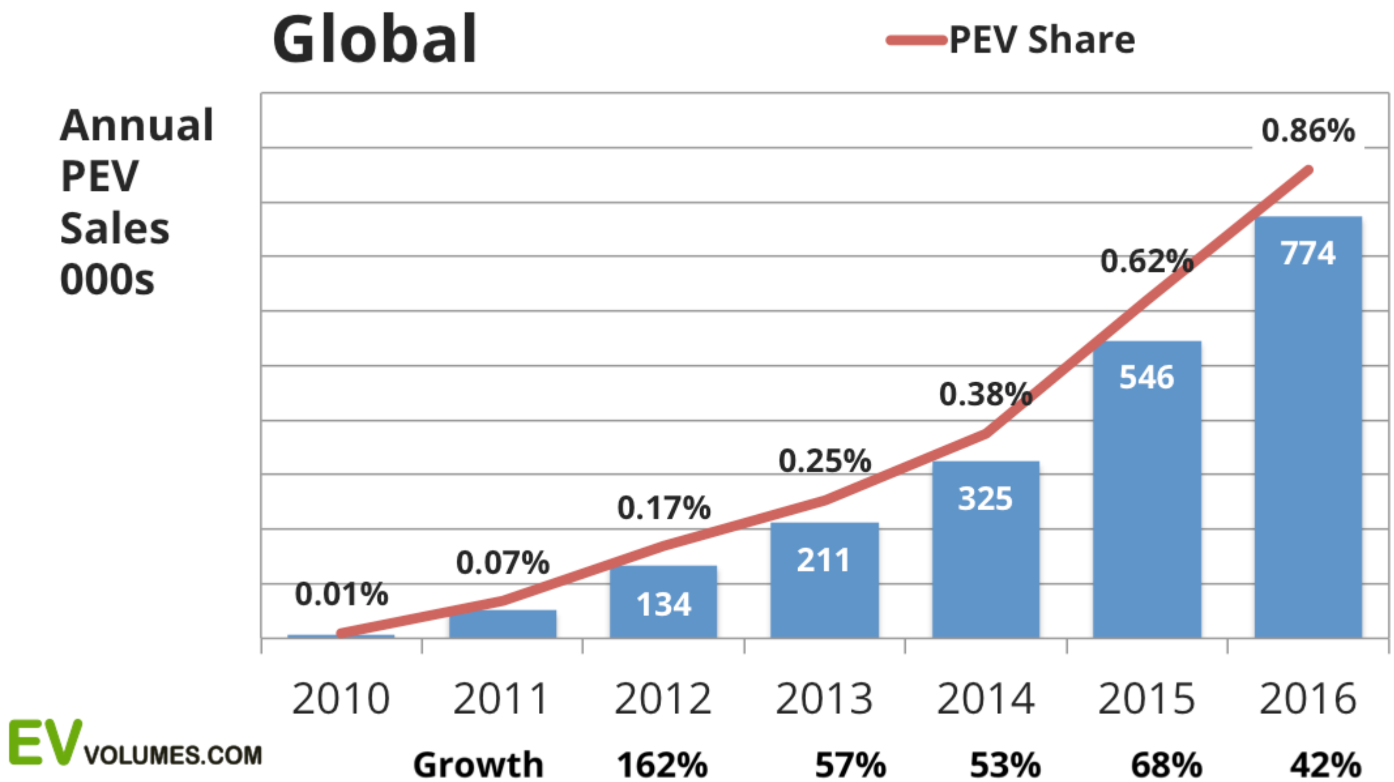
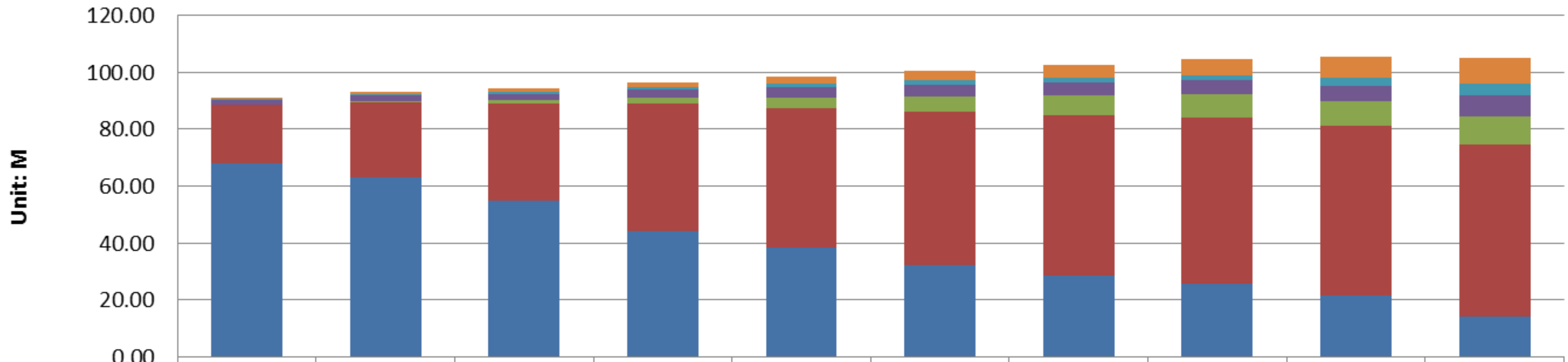
Global PEV Sales



Global Automotive Market Forecast

Vehicle Forecast by Application

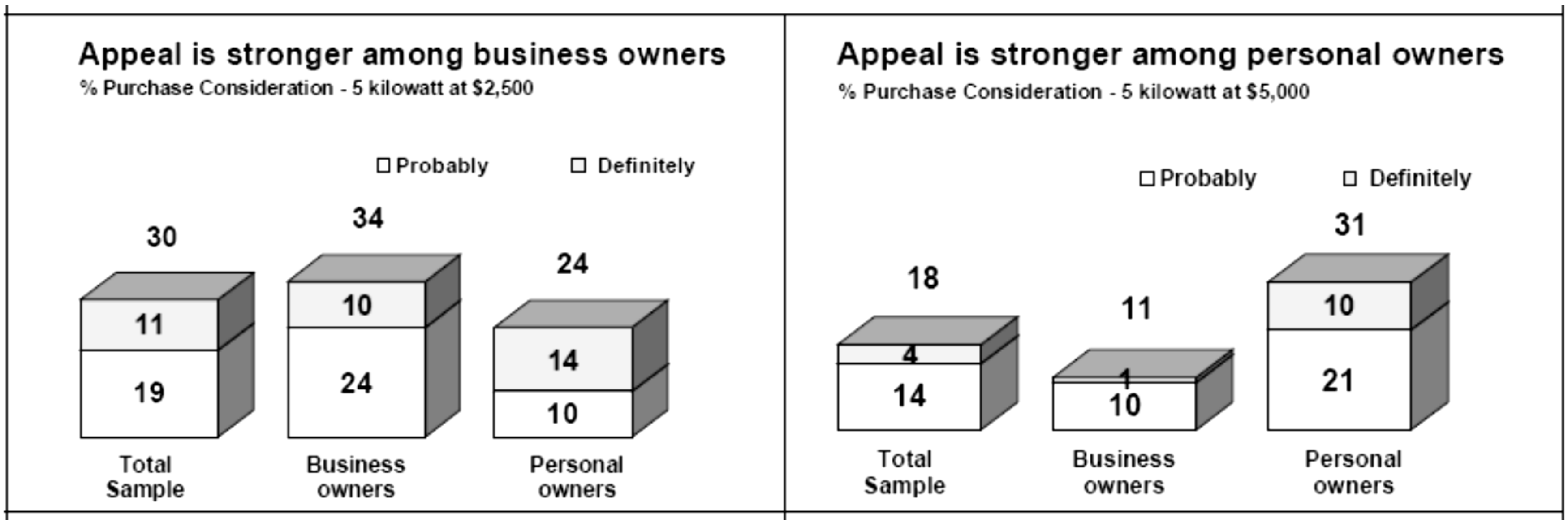


	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
BEV	0.48	0.74	1.13	1.74	2.54	3.30	4.29	5.57	7.39	9.07
PHEV	0.30	0.46	0.54	0.82	1.22	1.41	1.62	1.86	2.96	4.27
Full Hybrid	1.82	2.04	2.38	2.97	3.71	4.08	4.49	4.94	5.49	7.47
Mild Hybrid	0.00	0.19	1.00	1.98	3.44	5.35	7.20	7.83	8.45	9.60
Micro Hybrid	20.34	26.44	34.38	44.69	49.16	54.07	56.31	58.50	59.69	60.82
ICE	68.06	63.07	54.71	44.25	38.29	32.23	28.47	25.75	21.62	13.87

Source: Yole Développement(2015), IEA(2016), Frost & Sullivan(Mar. 2016), IHS (2016), Delta estimation

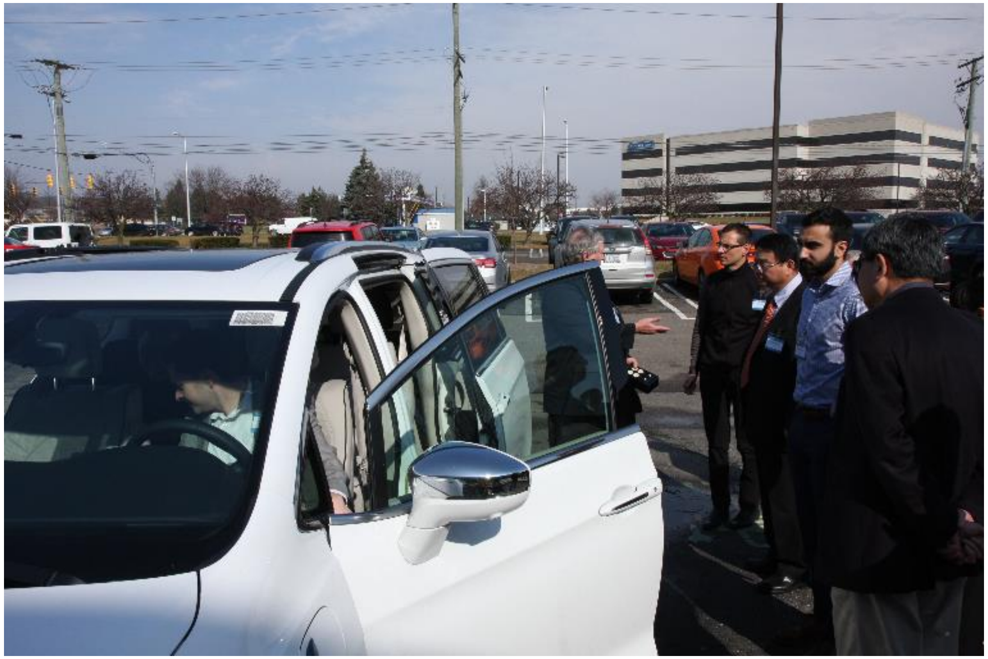
- 88M to 104M vehicle sales globally in next 10 years
- xEV will grow dramatically

AC Power Option Market Survey by FCA



34% of business owners and 24% of personal owners say they would definitely or probably choose an AC power option if offered.

Commercial Plan



- Test Vehicle: 2017 Chrysler Pacifica plug-in hybrid minivan
- Drop in replacement of RU OBCM
- Will discuss with FCA for the new feature introduction, target 2020

Jan 3, 2017 | FLAT ROCK, Mich.

Mark Fields, Ford president and CEO Announcement:

- A hybrid version of the best-selling F-150 pickup available by 2020 and sold in North America and the Middle East. The F-150 Hybrid, built at Ford's Dearborn Truck Plant, will offer powerful towing and payload capacity and operate as a mobile generator

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

Summary

- DOE Mission Support
  - Design, build and test two generations 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 A-Sample 6.6kw GaN-based OBC to verify thermal performance and packaging design
  - Designed, built and tested B-Sample 6.6kw GaN-based OBC to optimize the design with CAN control interface
  - Design, build and tested alternative OBC concept Sample with SiC/GaN devices

Proposed Future Work

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

Any proposed future work is subject to change based on funding levels

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