Benchmarking EV and HEV Technologies

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Project ID: EDT006

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Overview

Timeline

- Start – FY16
- End – FY18

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY16: $ 600K

Barriers

- Integrating custom ORNL inverter-motor-controller with OEM components.
  - Optimizing controls for non-linear motors throughout operation range.
- Intercepting, decoding, and overtaking OEM controller area network (CAN) signals.
- Adapting non-standard motor shaft and assembly to dynamometer and test fixture.
- This project helps with program planning and the establishment and verification of all DOE 2022 targets.

Partners

- ORNL Team members
  - Lixin Tang
  - Curt Ayers
  - Randy Wiles
  - Steven Campbell
  - Zhenxian Liang
  - Andy Wereszczak
- ANL
- NREL

Project Objective and Relevance

- **Overall Objective:** The core function of this project is to confirm power electronics and electric motor technology status and identify barriers and gaps to prioritize/identify R&D opportunities
  - Assess design, packaging, and fabrication innovations during teardown of sub-systems
    - Identify manufacturer techniques employed to improve specific power and/or power density
    - Perform compositional analysis of key components
      - Facilitates trade-off comparisons (e.g. magnet strength vs coercivity) and general cost analysis
  - Examine performance and operational characteristics during comprehensive test-cell evaluations
    - Establish realistic peak power rating (18 seconds)
    - Identify detailed information regarding time-dependent and condition-dependent operation
  - Compile information from evaluations and assessments
    - Identify new areas of interest
    - Evaluate advantages and disadvantages of design evolutions
    - Compare results with other EV/HEV technologies and DOE targets
- **FY16 Objectives**
  - Complete 2014 Honda Accord HEV dynamometer testing.
  - Complete teardown of BMW i3 inverter assembly and electric motor.

Milestones

Date	Milestones and Go/No-Go Decisions	Status
December 2015	Go/No-Go decision: Identify vehicle subsystems that meet EDT benchmarking criterion.	Go.
March 2016	Milestone: Determine core functionality and general design approach of HEV/EV subsystems.	Complete.
June 2016	Milestone: Perform initial testing on HEV/EV subsystems.	On Track.
September 2016	Milestone: Complete benchmarking tests of selected subsystem and assess design characteristics and operation with respect to 2022 DOE targets.	On Track.

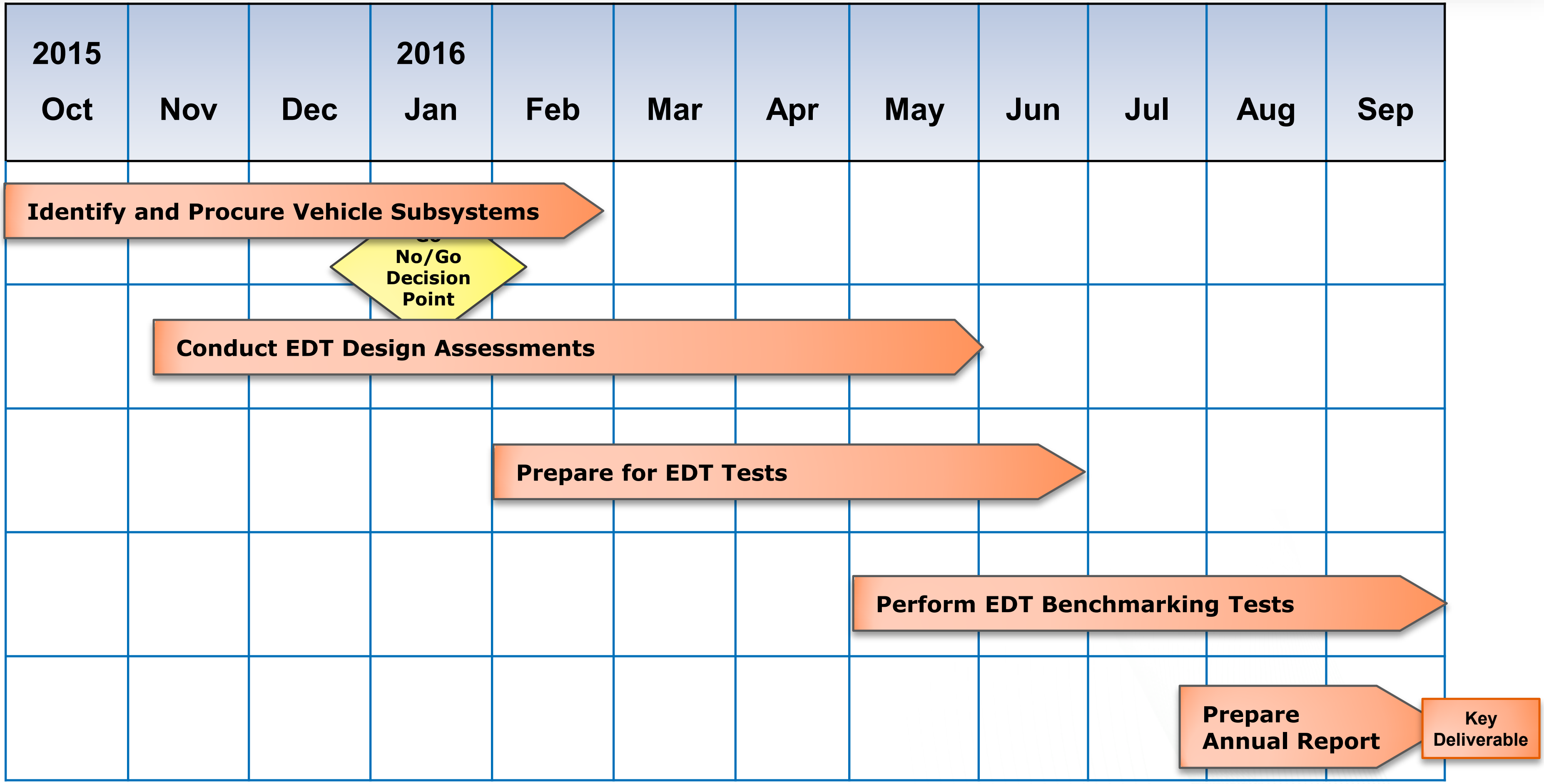
Approach/Strategy

- Provide status of select EV and HEV technologies through assessment of design, packaging, fabrication, and performance during comprehensive testing
  - Compare results with other EV and HEV technologies
  - Confirm or provide feedback on VTO targets
  - Identify new areas of interest
  - Evaluate advantages and disadvantages of design changes, i.e., complexity of 3rd generation Prius PCU cooling system
- Foster collaborations with U.S. DRIVE Electrical and Electronics Tech Team (EETT) and Vehicle Systems Analysis Tech Team (VSATT)
- Publish test results and conclusions for open discussion

Approach/Strategy

- Obtain and publish detailed information on state-of-the-art technologies and their progression:
  - Design and functional assessments
    - Magnet and capacitor characteristics
    - Power control unit and electric motor design and packaging
    - Converter (e.g. boost, DC-DC, charger, etc.) design and packaging
    - Mass, volume, and power capabilities of various subsystems
    - Material quantities (e.g. copper mass, NdFeB mass and composition, etc)
    - Power density and specific power
  - Operational characteristics
    - Efficiency maps for motor, inverter, converter, and charger
    - Impact of temperature limits, speed, etc. upon capabilities
    - Continuous duration
      - Time-dependent and condition-dependent information especially important as technologies progress to long duration operation, such as electric vehicles EVs
      - 55 kW for 2 seconds, 2 minutes, or 2 hours?

FY16 Tasks to Achieve Key Deliverable



Go No/Go Decision Point: Identify vehicle subsystems that meet EDT benchmarking criterion.

Key Deliverable: Annual report with findings from benchmarking assessments.

Accomplishments – Previous FYs

- Compared progressing technologies - 2004 Prius, 2006 Accord, 2007 Camry, 2008 LS 600h, 2010 Prius, 2011 Sonata, 2012 Sonata generator, 2012 LEAF, 2013 LEAF charger, 2013 Camry PCU, 2014 Accord, and BMW i3.

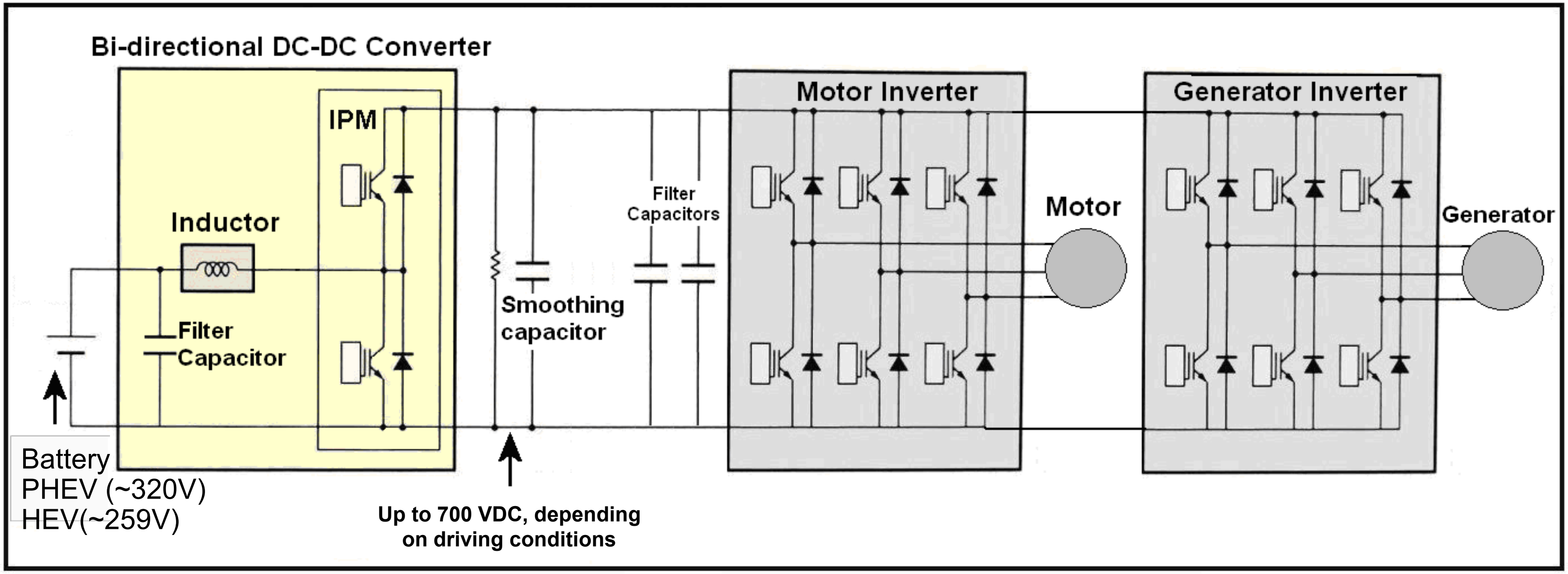
Component & Parameter	2022 DOE Targets	2012 Leaf (80 kW)	2012 Sonata HSG 23 (8.5 kW)	2011 Sonata (30 kW)	2010 Prius (60 kW)	2008 LS600h Lexus (110 kW)	2007 Camry (70 kW)	2013 Camry (105 kW)	2004 Prius (50 kW)
Motor									
Peak power density, kW/L	**5.7**	**4.2**	**7.42** (2.7)	**3.0**	**4.8**	**6.6**	**5.9**		**3.3**
Peak specific power, kW/kg	**1.6**	**1.4**	**1.9** (0.7)	**1.1**	**1.6**	**2.5**	**1.7**		**1.1**
Inverter									
Excludes generator inverter (parenthetical values exclude boost converter mass/volume for Toyota Vehicles)									
Peak power density, kW/L	**13.4**	**5.7**	**5.6** (2.0)	**7.3**	**5.9** (11.1)	**10.6** (17.2)	**7.4** (11.7)	**12.7** (19.0)	**4.5** (7.4)
Peak specific power, kW/kg	**14.1**	**4.9**	**5.4** (2.0)	**6.9**	**6.9** (16.7)	**7.7** (14.9)	**5.0** (9.3)	**11.5** (17.2)	**3.8** (6.2)

Note: All power density and specific power levels in table are not apples-to-apples. (e.g. LEAF and Sonata have continuous capability near their published rated power)

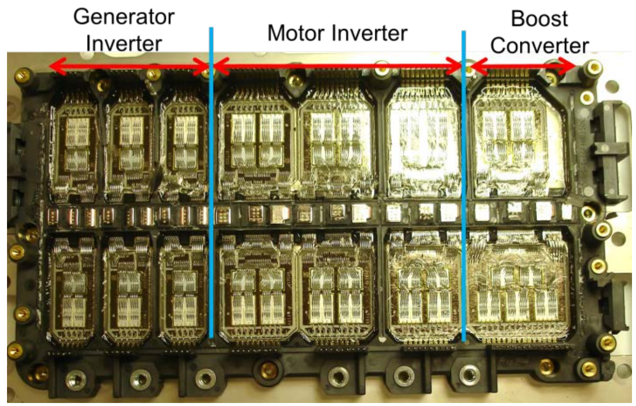
FY16 Accomplishments – 2014 Accord

Electrical schematic of Accord hybrid system

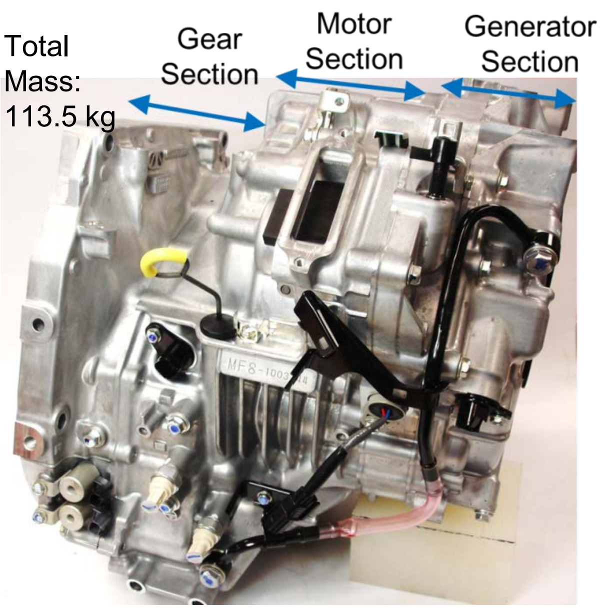
Converter/Inverter system similar to Toyota system



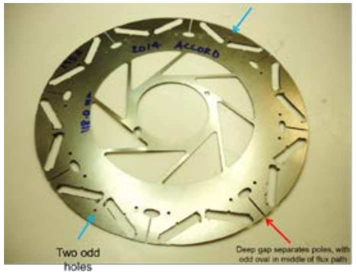
FY16 Accomplishments – 2014 Accord



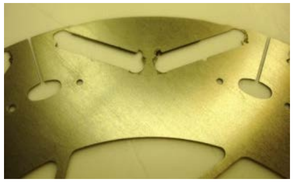
- Number of IGBTs
  - Motor inverter:
    - 2 per switch
  - Generator inverter:
    - 1 per switch
  - Boost converter:
    - 3 lower switch
    - 2 upper switch
- Capacitor assembly
  - Battery input
    - 411 uF, 370Vdc
  - Boosted DC link
    - 1,125 uF, 700 Vdc



- Generator and Motor stator and rotor laminations appear to be identical
  - Stator OD: 29.13 cm
  - Rotor OD: 19.5 cm
- Motor specifications
  - Stack length: 6.17 cm (1.64 times generator: 3.762cm)
  - Rotor mass: 11.8 kg
  - Stator mass: 20.8 kg
  - Total magnet mass: 1.24 kg

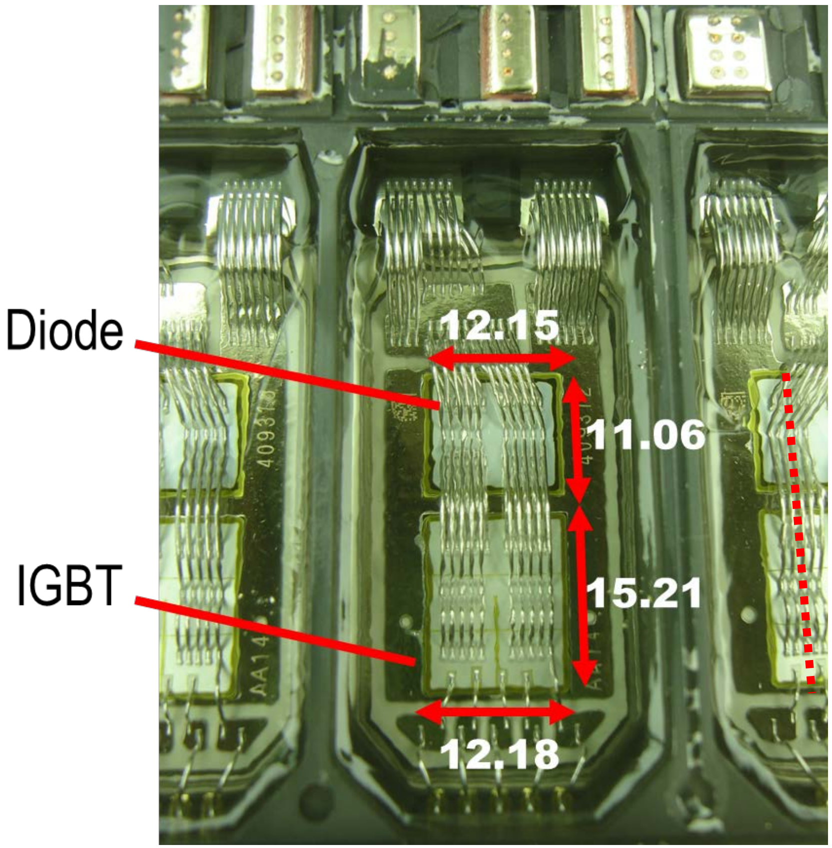


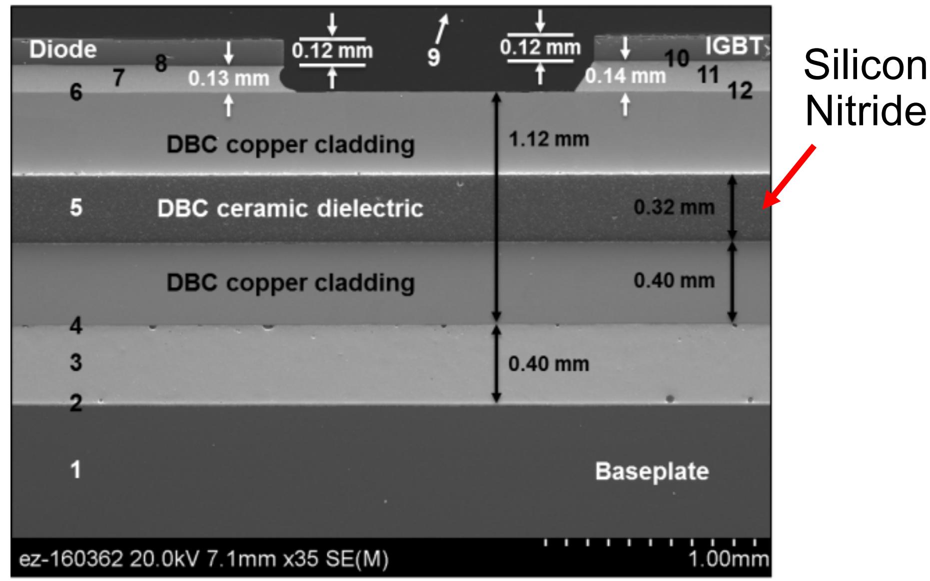
2014 Accord rotor lamination



FY16 Accomplishments – 2014 Accord

Cross-section and compositional analysis of power module





1. Baseplate
2. Baseplate plating
3. Solder - Baseplate/DBC
4. DBC plating
5. Ceramic in DBC
6. DBC plating
7. Solder - DBC/Diode
8. Diode plating
9. Wire (not shown)
10. IGBT plating
11. Solder - DBC/IGBT
12. DBC plating (same as #6)

FY16 Accomplishments – 2014 Accord

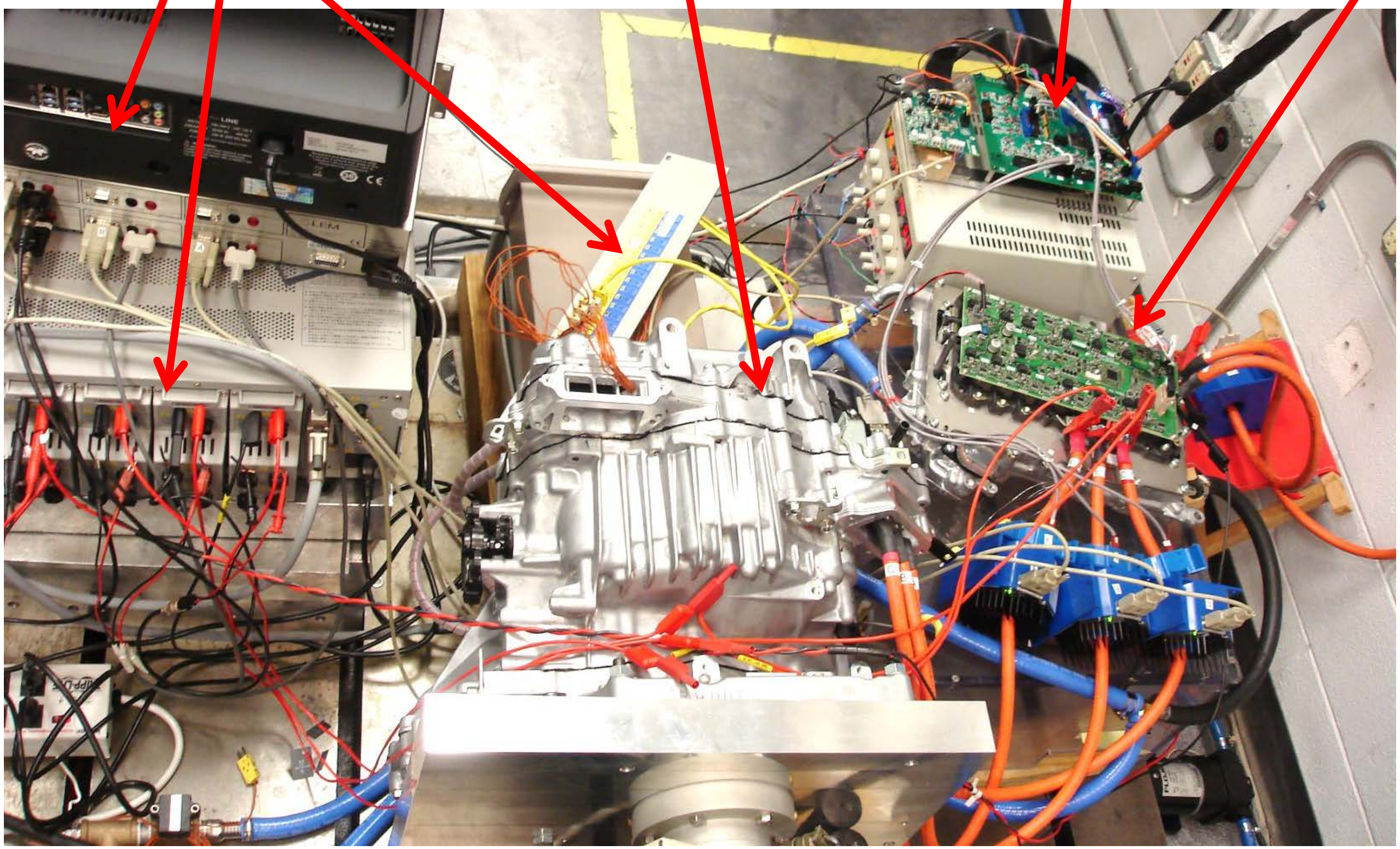
Accord Hybrid Inverter and Motor on Dynamometer

Power analyzers and other data acquisition equipment

Accord Motor/Transmission

ORNL Controller

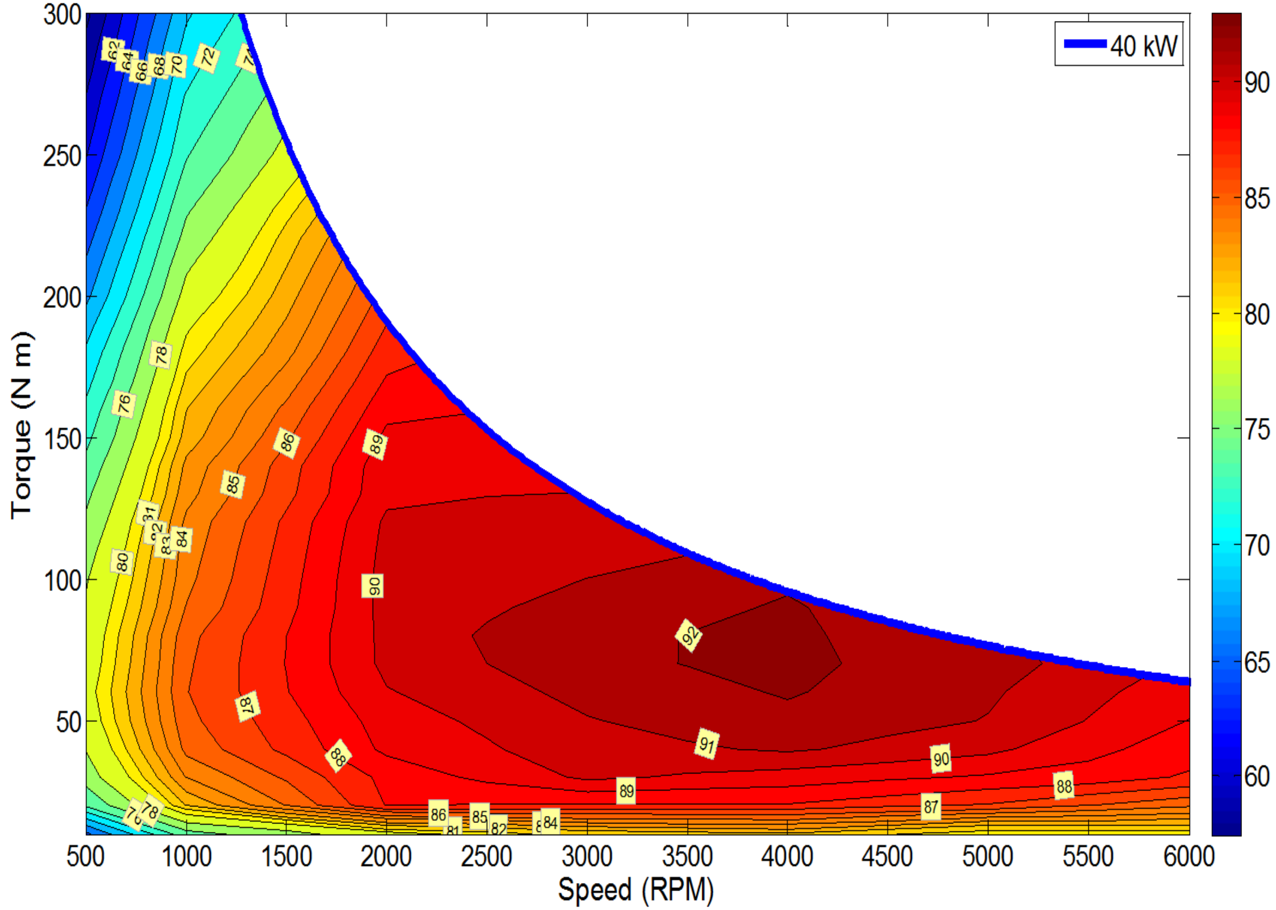
Accord Inverter



FY16 Accomplishments – 2014 Accord

Motor/Inverter Efficiencies at 300VDC

- Combined efficiency reaches above 92%



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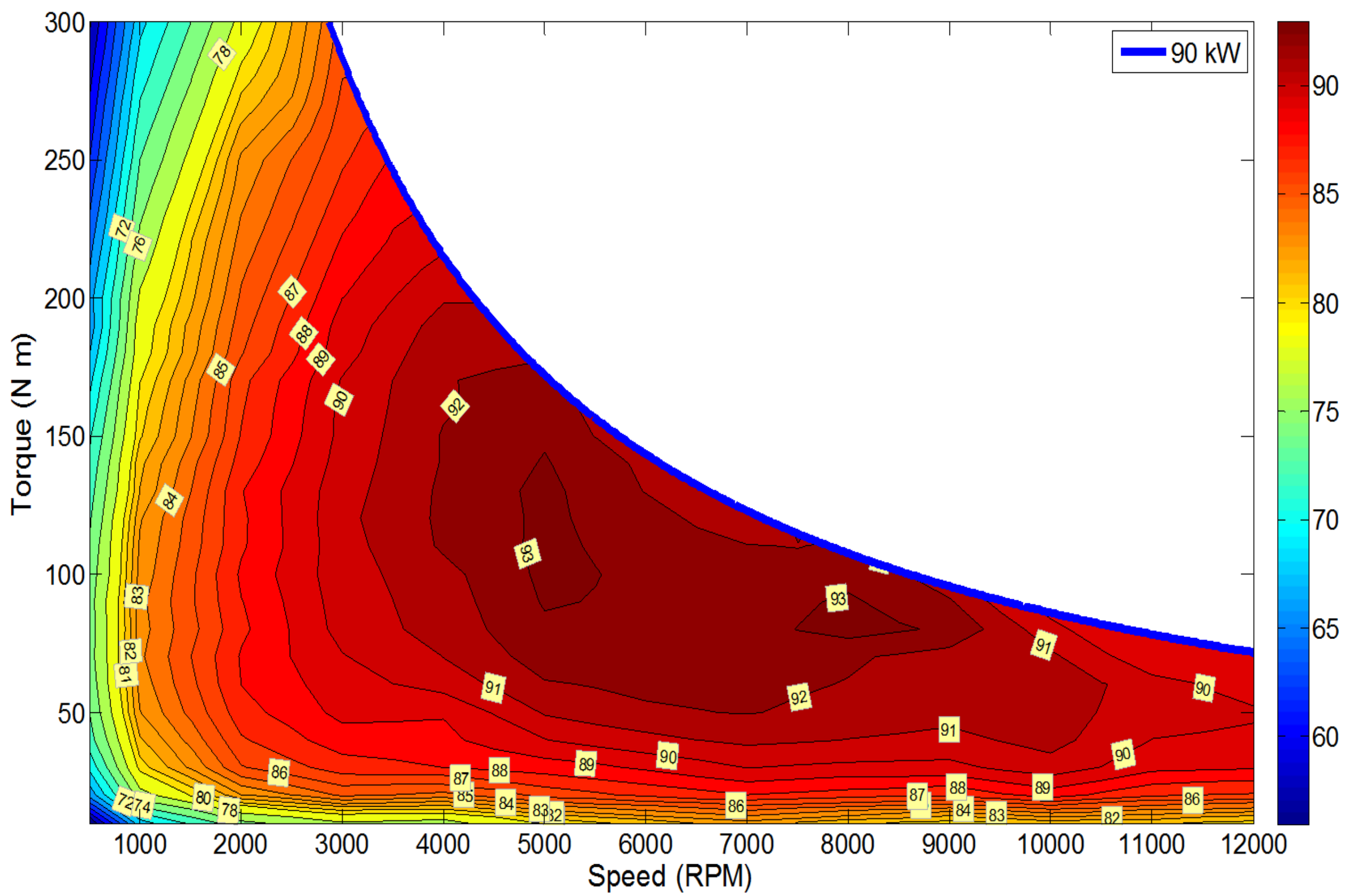
FY16 Accomplishments – 2014 Accord

Motor/Inverter Efficiencies at 500VDC

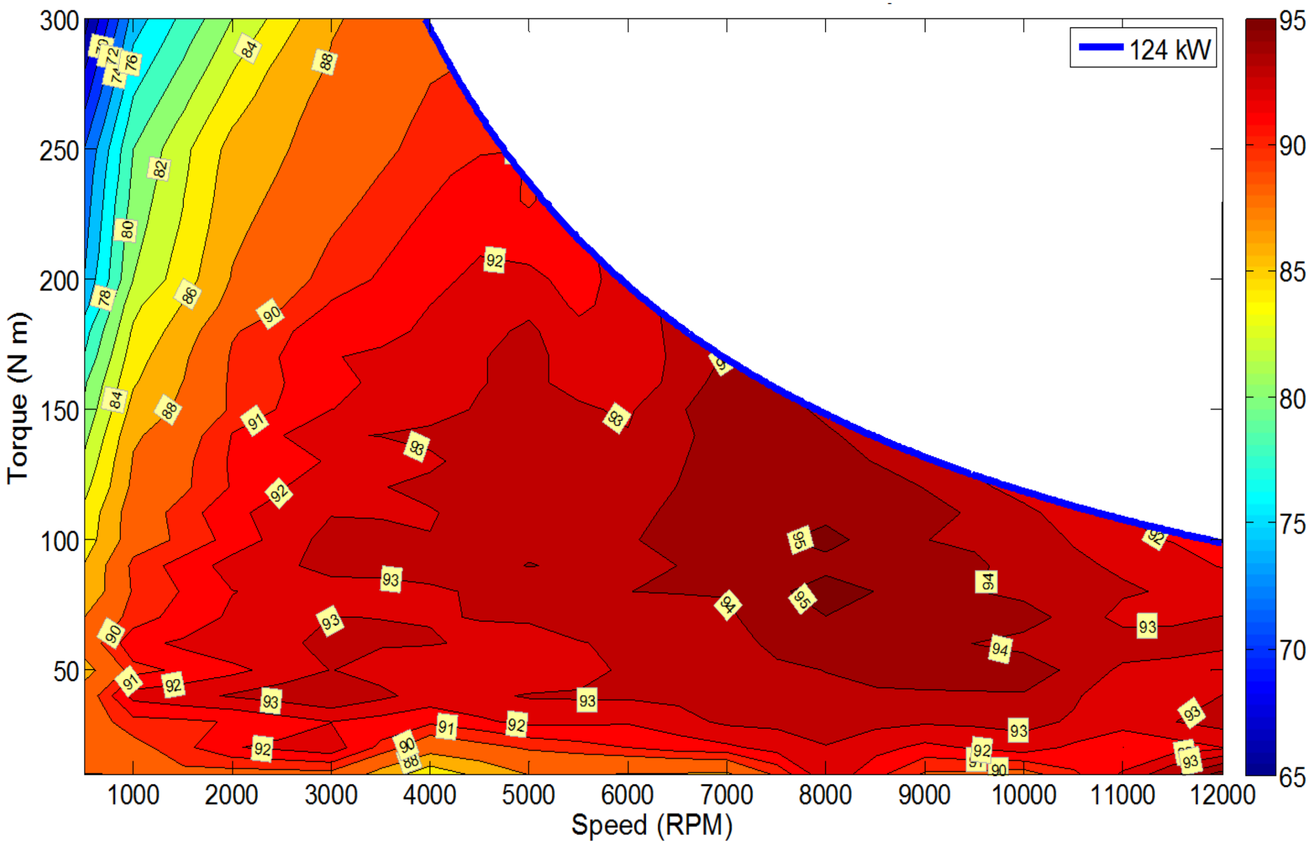
- Combined efficiency reaches above 93%



FY16 Accomplishments – 2014 Accord

Motor Efficiencies at 700VDC

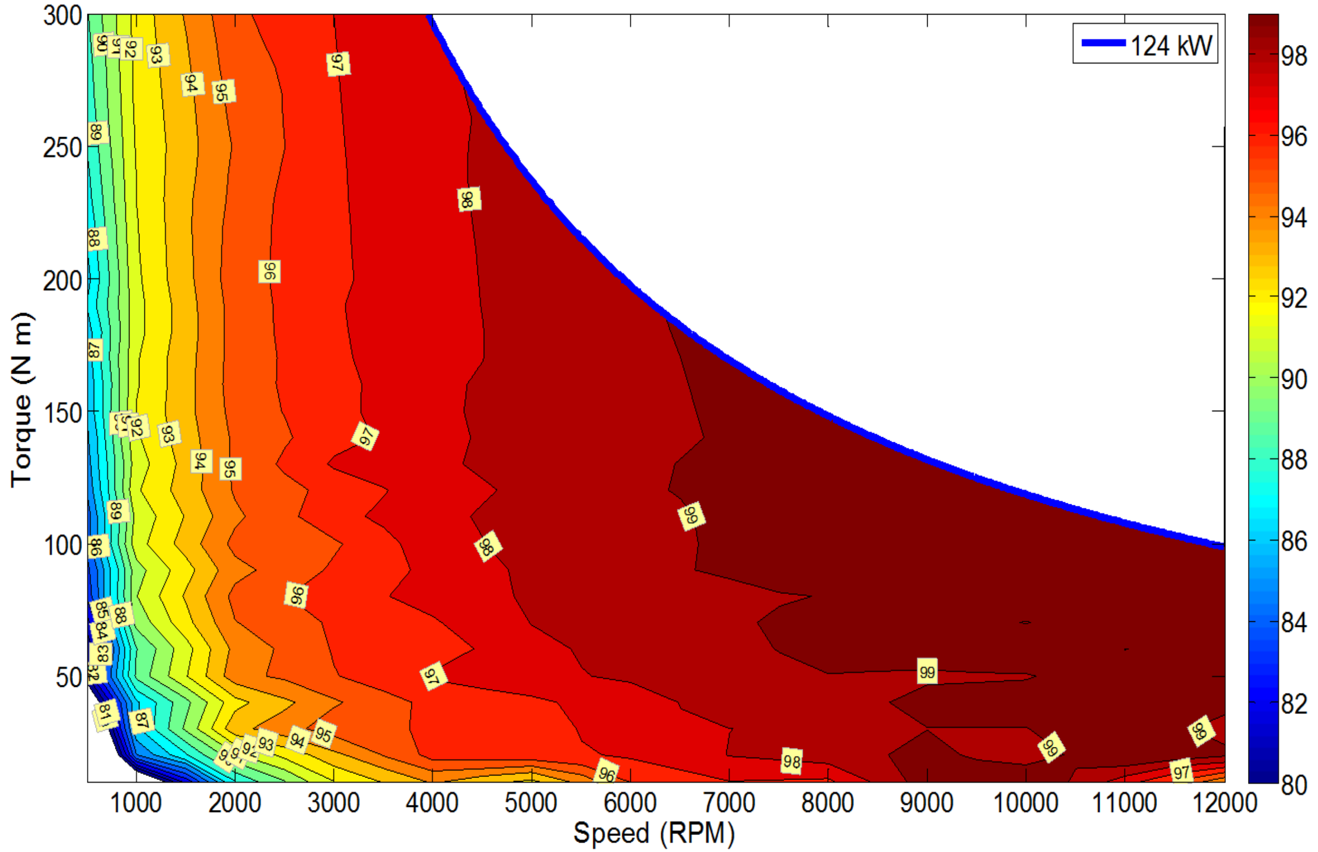
- Motor efficiency reaches above 94%



FY16 Accomplishments – 2014 Accord

Inverter Efficiencies at 700VDC

- Inverter efficiency reaches above 99%



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FY16 Accomplishments – 2014 Accord

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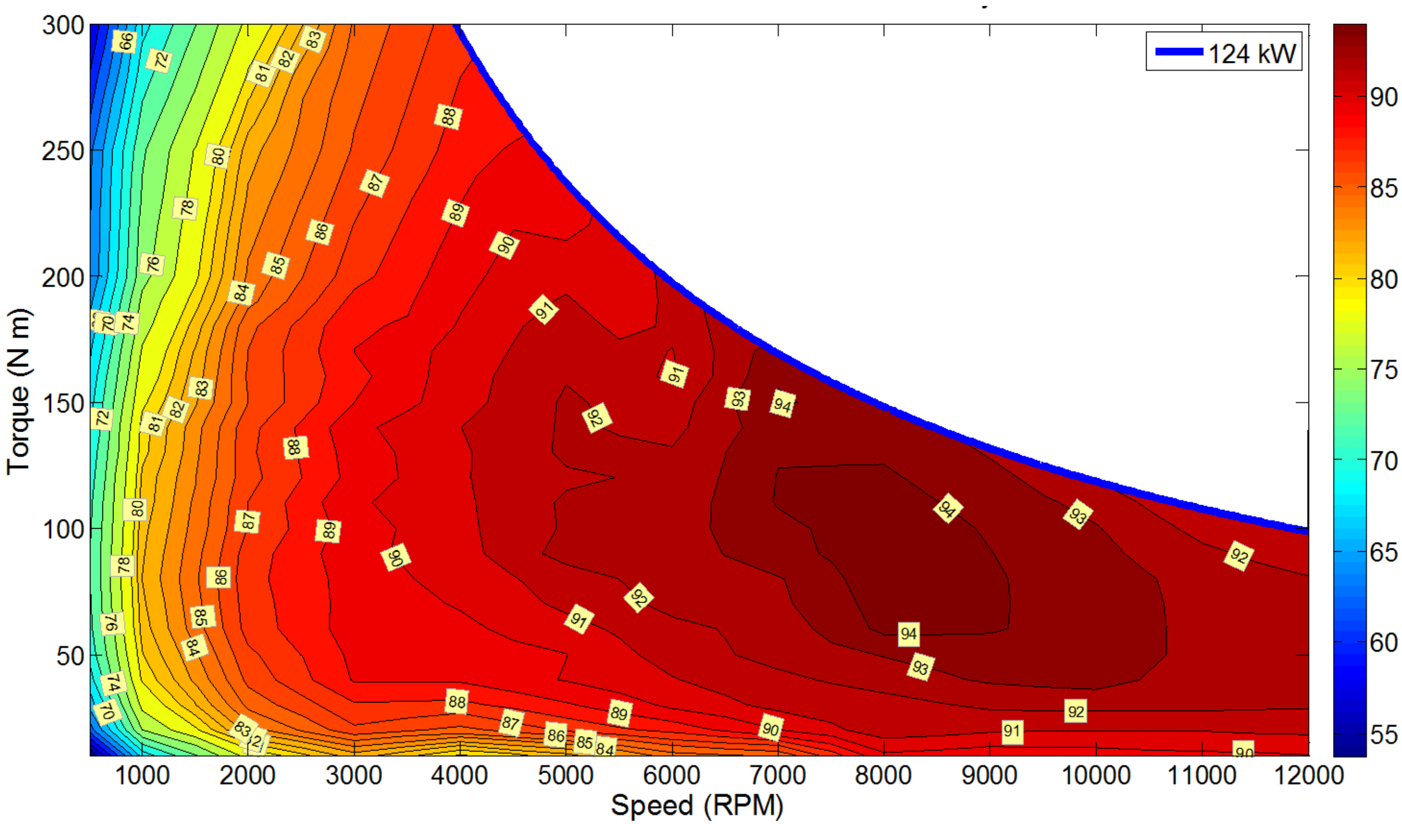
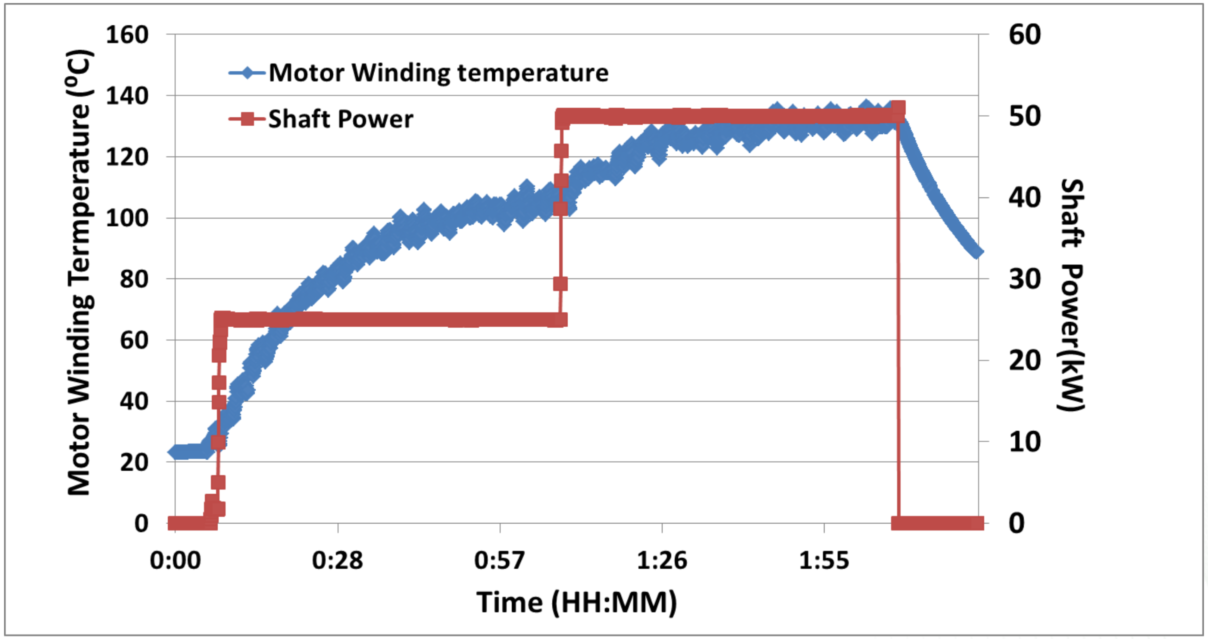
- Combined efficiency reaches above 94%



FY16 Accomplishments – 2014 Accord

Continuous tests of 2014 Honda Accord at 7000 rpm and 25 and 50 kW

- Temperature is roughly stable at 105C for 25 kW operation and 130C for 50 kW operation.



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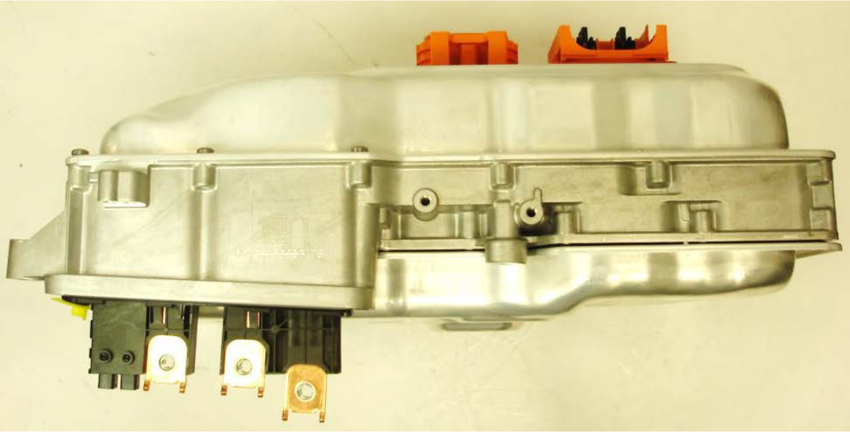
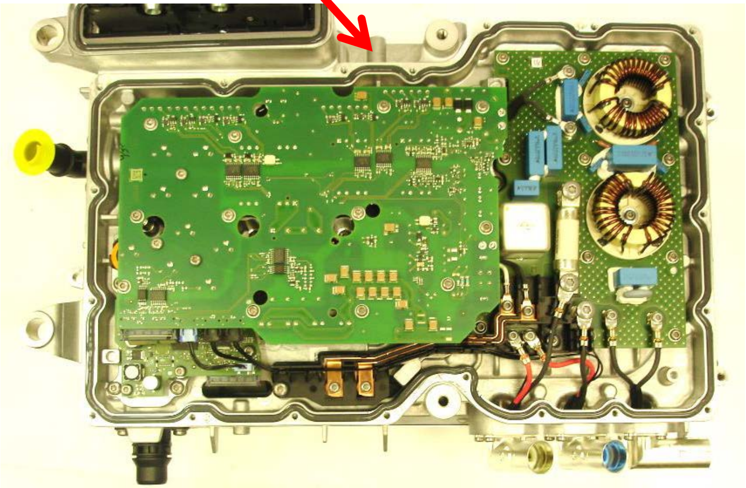
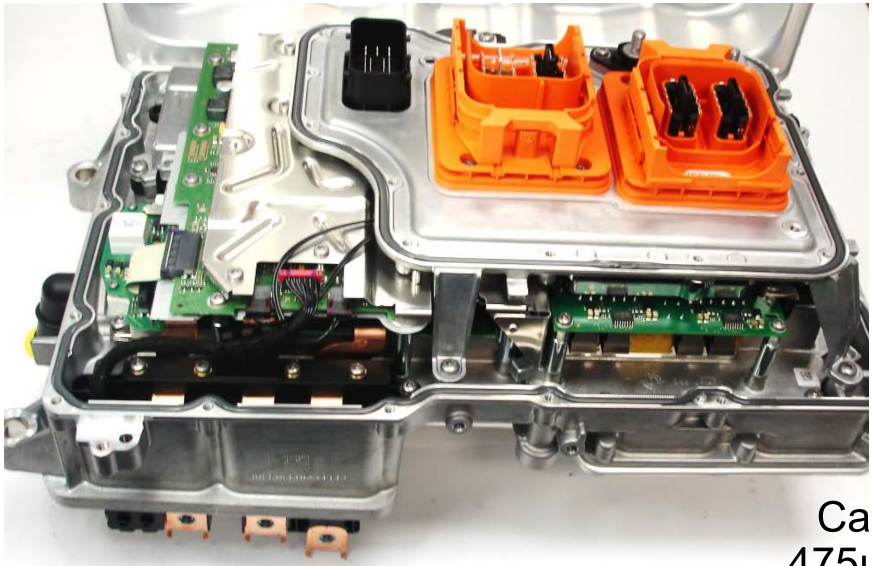
FY16 Accomplishments – 2016 BMW i3 PCU

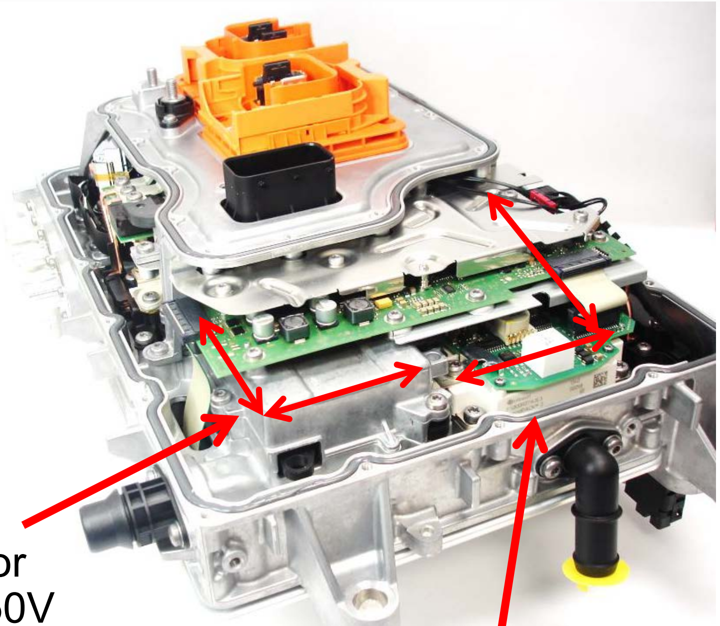
- PCU: 19 kg, as received
- Nominal battery specs:
  - 355.2 V
  - 18.1 kWh
- DC/DC converter
  - ~355VDC →~12 VDC
- 3.7 kW Charger



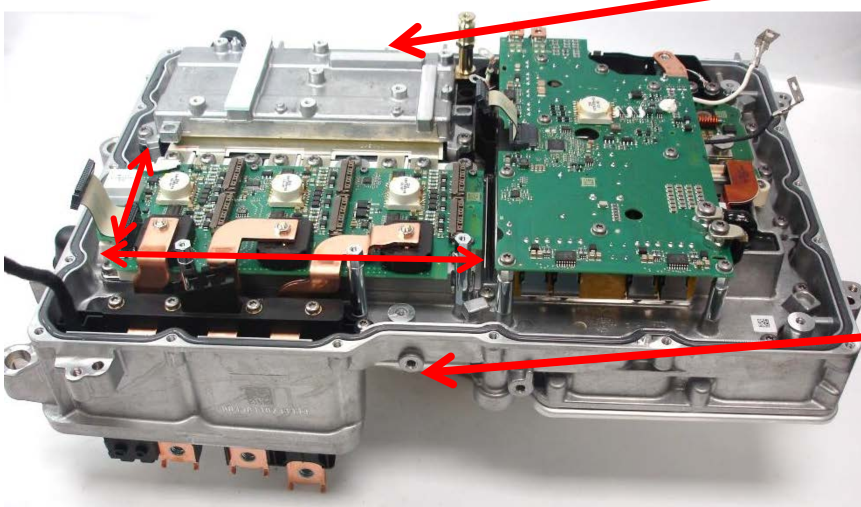


FY16 Accomplishments – 2016 BMW i3 PCU





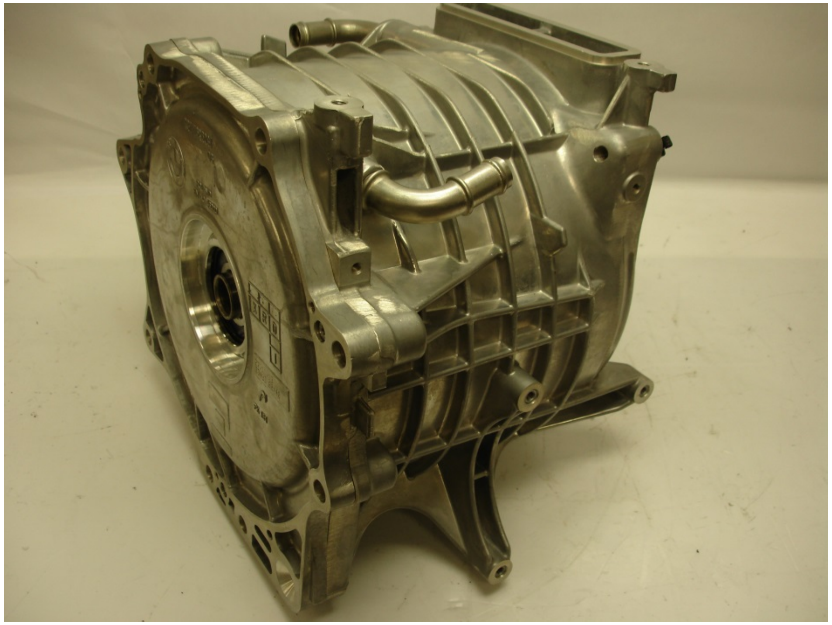
Capacitor
475µF, 450V

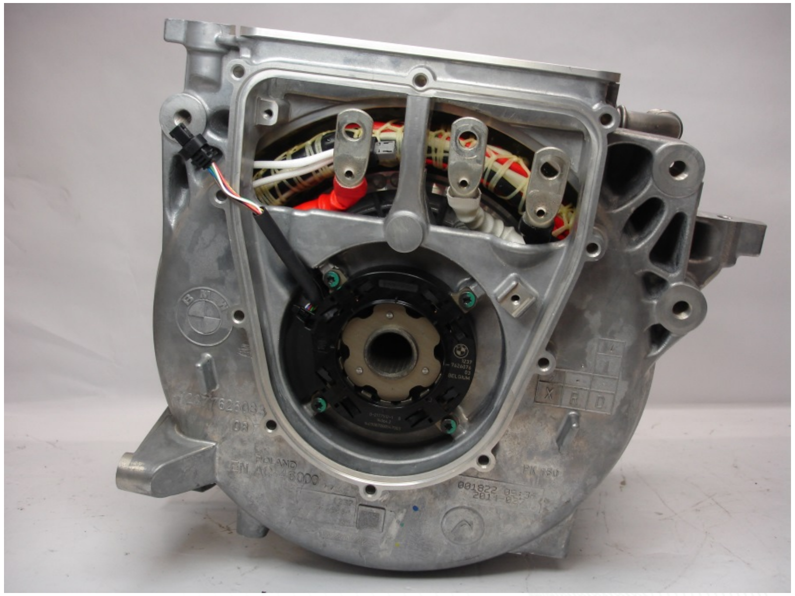


Power Module
Infineon FS800R07A2E3
650VDC, 800A/1600A peak

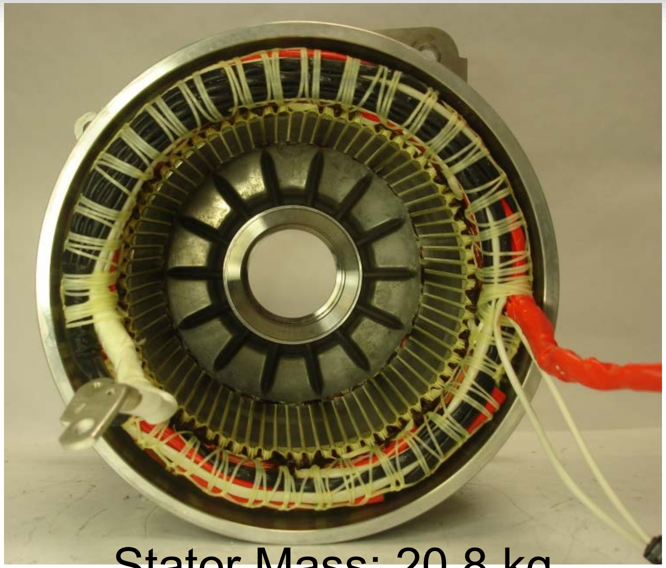
FY16 Accomplishments – 2016 BMW i3 Motor

- Stator assembly: 42kg, as received
- 125 kW, 250 Nm
- 2 temp sensors, 1 on coils, one at rotor bearing

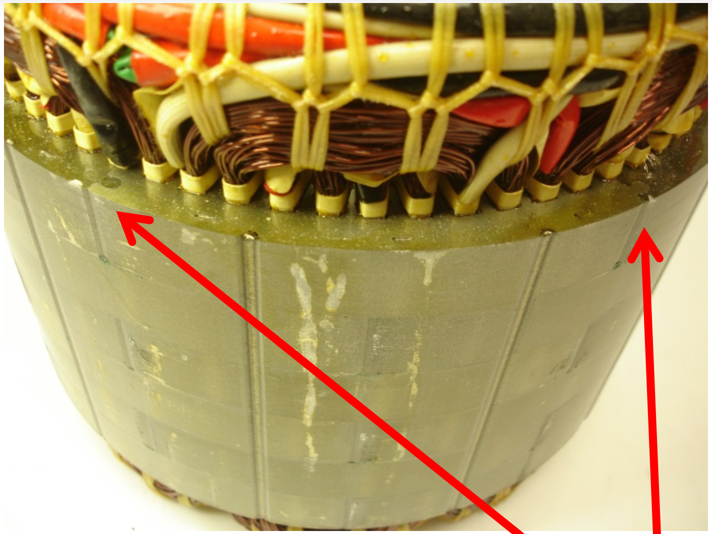


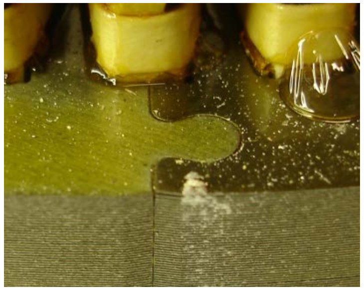


FY16 Accomplishments – 2016 BMW i3 Motor



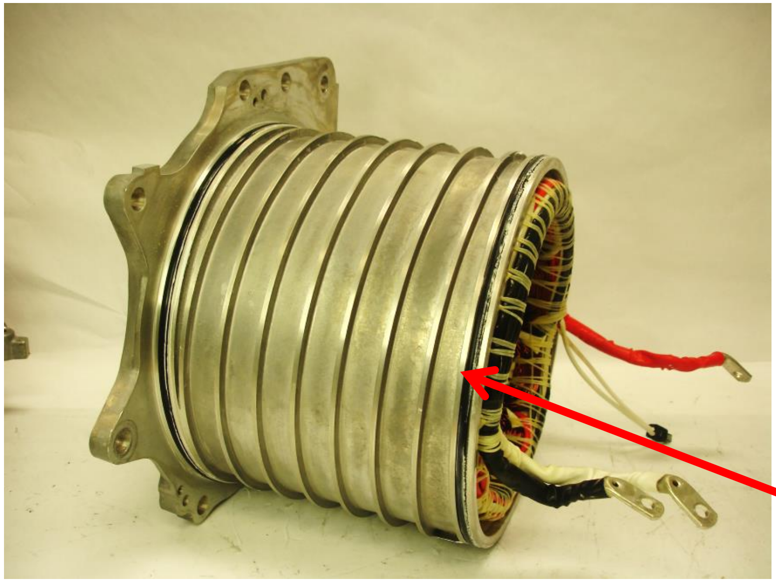
Stator Mass: 20.8 kg
72 Teeth, 12 poles





Stator laminations are made from separate pieces

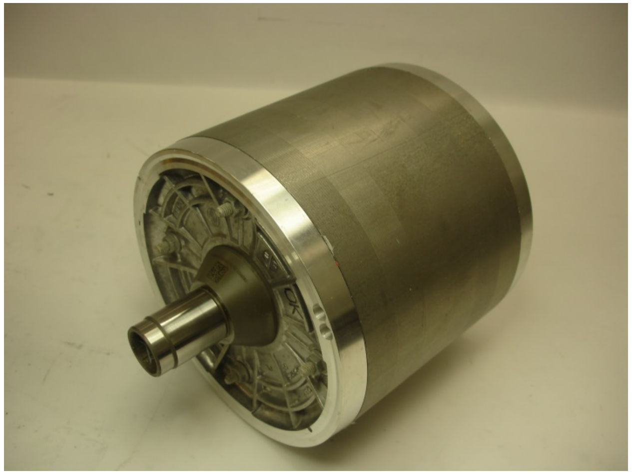
- Reduces manufacturing waste
- 6 sections around stator
- Staggered axially to avoid negative impacts at interface



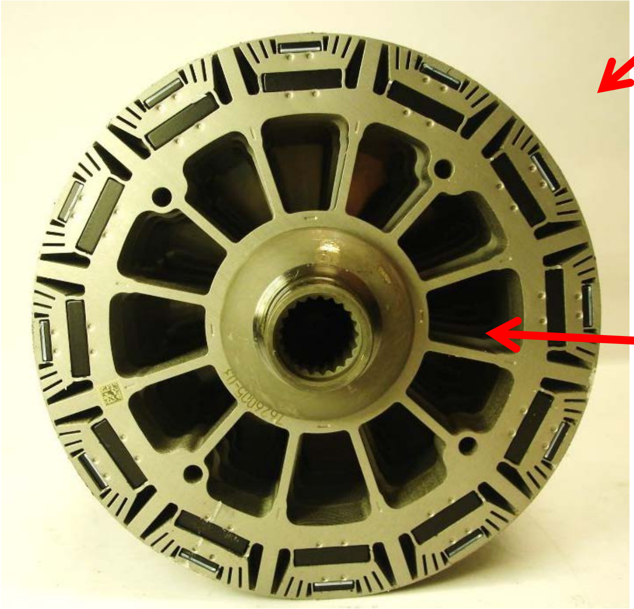
Spiral channel mates with outer housing for uniform cooling

FY16 Accomplishments – 2016 BMW i3 Motor

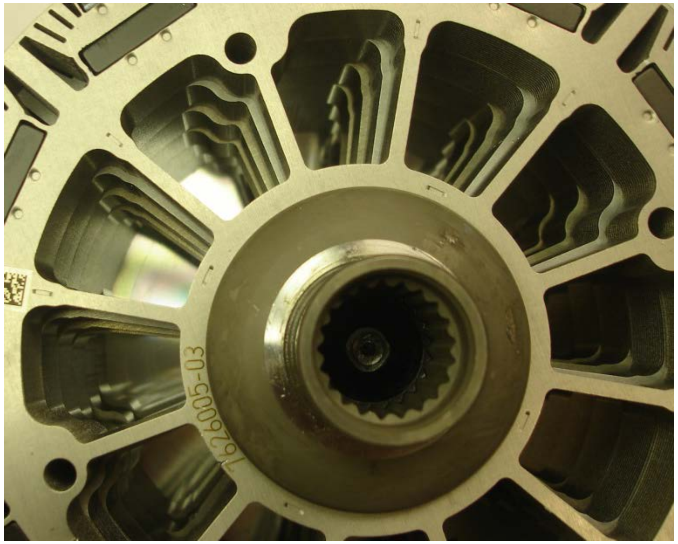
Rotor Mass: 14.2 kg



1 small magnet and 1 large magnet per pole



Magnet skewing



Responses to Previous Year Reviewers' Comments

- One reviewer noted a good report on Toyota vehicles. To another, the analysis is well done, although several questions were raised, i.e., how can the work be more widely distributed, is any effort being made to understand and document the control algorithms used, and if Argonne is doing this work, can a link or contact be provided to get access to the information?
  - Response: ORNL performs component level analysis, while Argonne performs analysis at the vehicle level, and collaborations with them have help established common operation conditions (e.g. speed, torque, etc) as well as maximum vehicle acceleration conditions.

- One reviewer said the results are not as fast as he would like, but considering the budget and resources, he is very satisfied. A different reviewer commented that a focus on quick turnaround will result in improved value.
  - Response: We are working on improving the turnaround on the work. Preliminary teardown information is available prior to the comprehensive benchmarking data, and we plan to present this information to EETT when available. Dynamometer test cell evaluations often require the design, fabrication, and assembly of complex interface hardware. Furthermore, the comprehensive data collected during the benchmarking efforts requires a significant amount of time for data processing, documentation, and formatting in the preparation of a final report.

Partners/Collaborators

Logo	Organization	Role
Argonne NATIONAL LABORATORY	ANL	• Provides system parameters to ORNL from on-the-road tests – Includes extreme hot/cold temperature tests • Examples: – Coolant temperature range and common operation conditions – Battery voltage range and common operation conditions • ORNL provides component efficiency and operational characteristics for AUTONOMIE – Also provides to EPA, automotive manufacturers, and public
NREL NATIONAL RENEWABLE ENERGY LABORATORY	NREL	ORNL provides component efficiency and operational characteristics to NREL for thermal studies.

Proposed Future Work

- **Remainder of FY16**
  - Finalize comprehensive benchmarking of BMW i3.
  - Complete destructive analysis of BMW i3.
  - Complete teardown assessments of BMW i3.
  - Design interfaces for and instrument i3 for testing.
  - Initiate benchmarking of 2nd generation LEAF charger, depending on availability.
- **FY17 and FY18**
  - Select commercially available EV/HEV systems relevant to DOE's VTO mission.
  - Perform standard benchmarking of selected system.

Summary

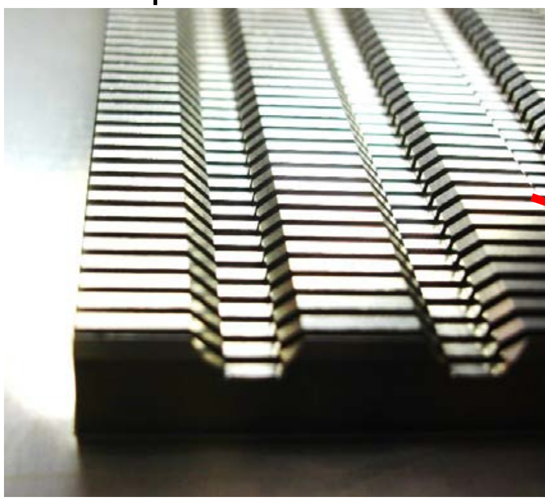
- **Relevance:** The core function of this project is to confirm power electronics and electric motor technology status and identify barriers and gaps to prioritize/identify R&D opportunities.
- **Approach:** The approach is to select leading EV/HEV technologies, disassemble them for design/packaging assessments, and test them over entire operation region.
- **Collaborations:** Interactions are ongoing with other national laboratories, industry, and other government agencies.
- **Technical Accomplishments:** Tested and reported on more than eight EV/HEV systems including recent efforts on the 2014 Honda Accord inverter and motor.
- **Future work:** Complete Accord HEV dynamometer testing and continue benchmarking BMW i3.

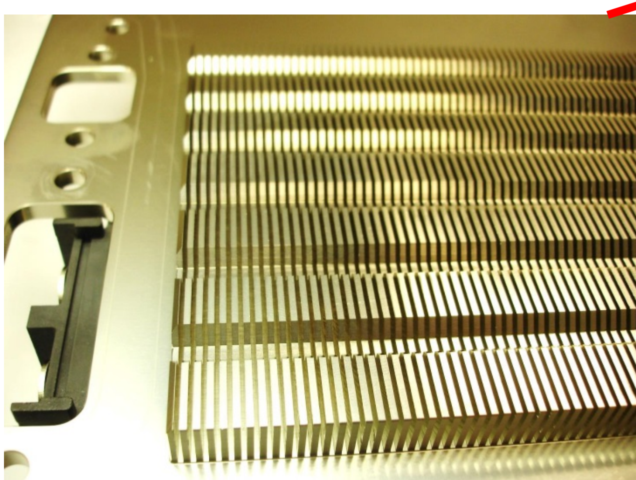
Back-up Slides

2014 Accord Power Converter Heat Exchanger

Accord Power Converter Unit Heat Exchanger

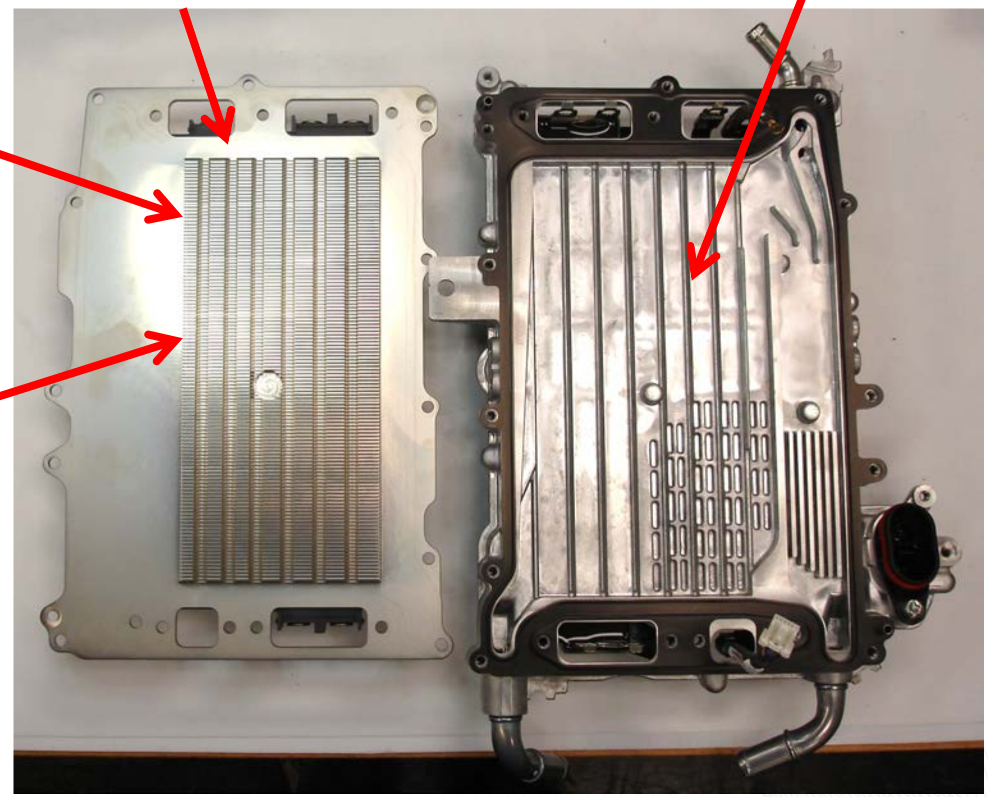
Close-up of fins on bottom of power module





Power Module

Boost inductor and bulk capacitor housing



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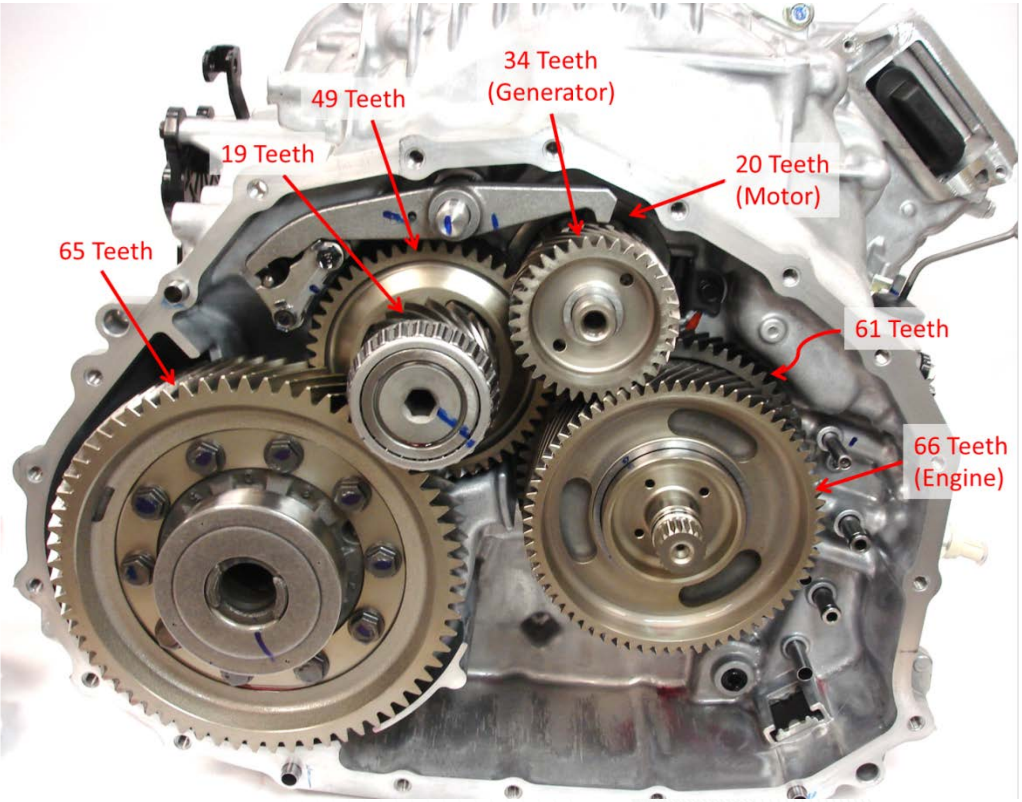
2014 Accord Transaxle

- Essentially series hybrid until engine locks in with a clutch, where the gear ratio from engine to drive-axles is: 65/19x49/61 = 2.748
  - The axle rpm is about 13 times the vehicle speed.
  - For engine speed of 4,000 rpm, this gives 112 mph.
  - 2,000 rpm correlates to 66 mph
- Fixed gear ratio from electric motor to drive-axles
  - 65/19x49/20 = 8.38
  - 14000 rpm → 128 mph
  - 6536 rpm → 60 mph
- Generator speed is 66/34 = 1.94 faster than engine speed



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Accord Motor and Generator Cooling System