Benchmarking EV and HEV Technologies

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Oak Ridge National Laboratory

U.S. DOE Vehicle Technologies Office
2015 Annual Merit Review and Peer Evaluation Meeting

June 9, 2015 **Project ID: EDT006**

ORNL is managed by UT-Battelle for the US Department of Energy

Overview

Timeline

- Start – FY04
- End – Ongoing

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY14: $ 500K
- Funding for FY15: $ 540K

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 2020 targets.

Partners

- ORNL Team members
  - Lixin Tang
  - Curt Ayers
  - Randy Wiles
  - Steven Campbell
  - Zhenxian Liang
  - Andy Wereszczak
- John Deere
- 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
- **Objectives** (March 2014 through March 2015):
  - Complete 2014 Honda Accord HEV teardown assessments.
  - Conduct 2014 Honda Accord HEV dynamometer testing.
  - Initiate teardown of BMW i3 inverter assembly and electric motor.

Milestones

Date	Milestones and Go/No-Go Decisions	Status
December 2014	Go/No-Go decision: Identify and procure EV/HEV components.	Go.
March 2015	Milestone: Determine core functionality and general design approach of HEV/EV subsystems.	Complete.
June 2015	Milestone: Perform initial testing on HEV/EV subsystems.	On Track.
August 2015	Milestone: Complete benchmarking tests of selected subsystem and assess design characteristics and operation with respect to 2020 DOE targets.	On Track.

Problem to be Addressed

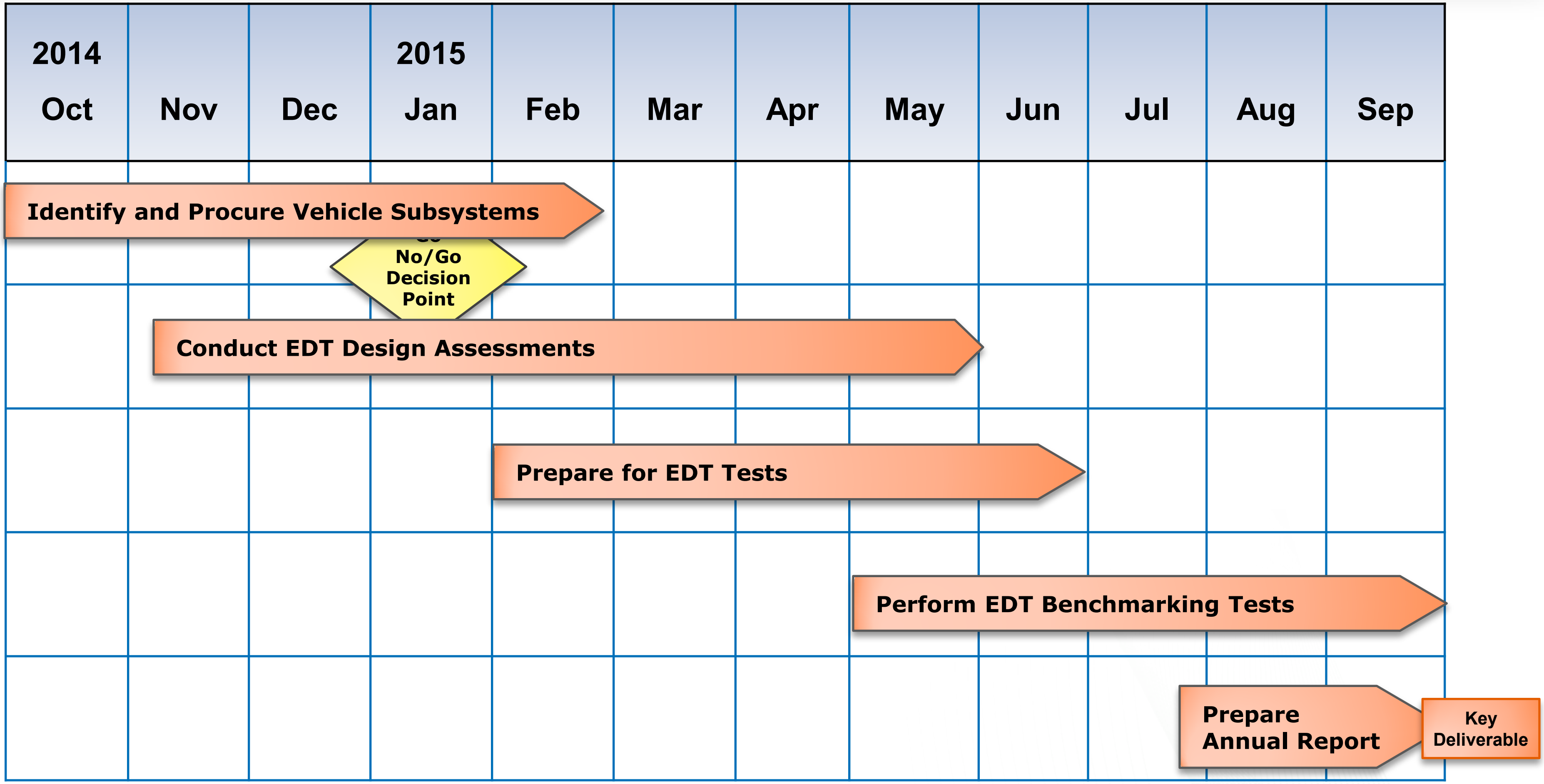
- Without detailed knowledge of state-of-the-art technologies and their progression, vital feedback is lacking in many areas, including:
  - Design and functional assessments
    - Magnet and capacitor characteristics
    - Power control unit and electric motor design and packaging
    - Converter (e.g. 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?

Benchmarking Defines State-of-the-Art

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

FY15 Tasks to Achieve Key Deliverable



Go No/Go Decision Point: Determine if EDT components of interest are available.

Key Deliverable: Annual report with findings from benchmarking assessments.

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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, and 2014 Accord.

Component & Parameter	2020 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)

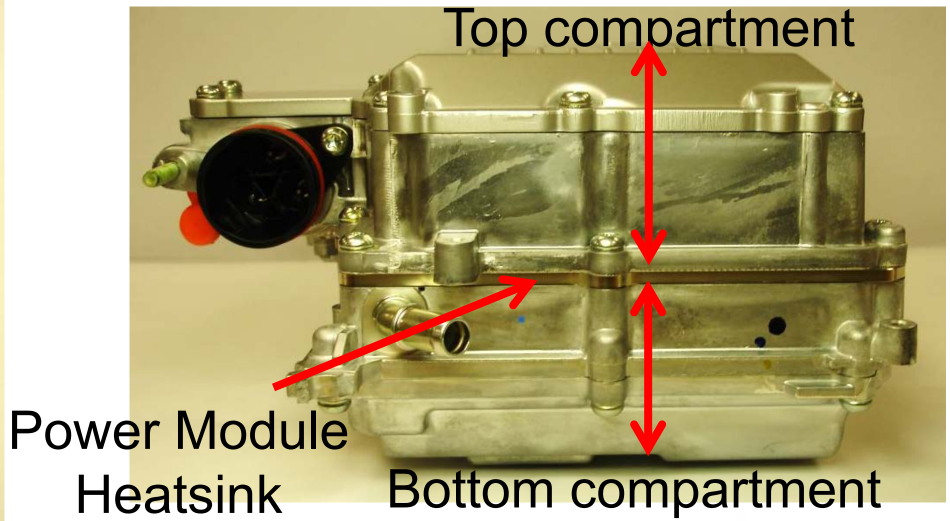
Note: All power density and specific power levels in table are not apples-to-apples. (e.g. LEAF and Sonata have continuous capability near their published rated power)

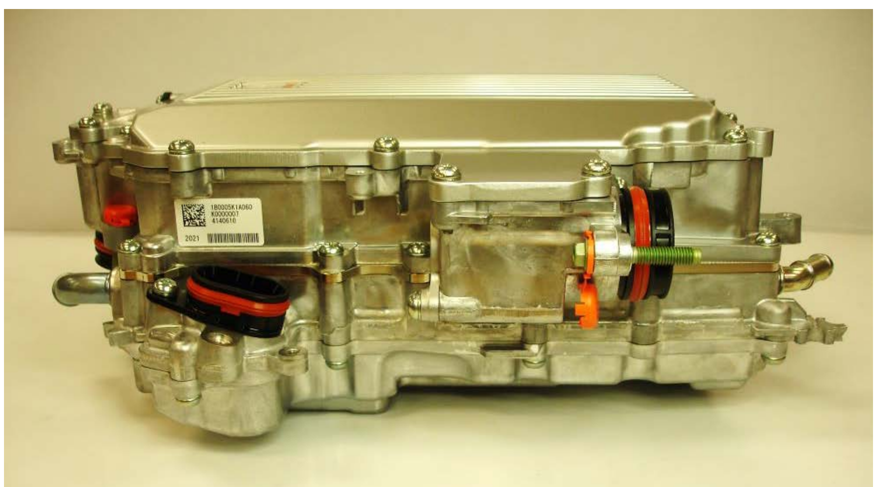
FY15 Accomplishments – 2014 Accord

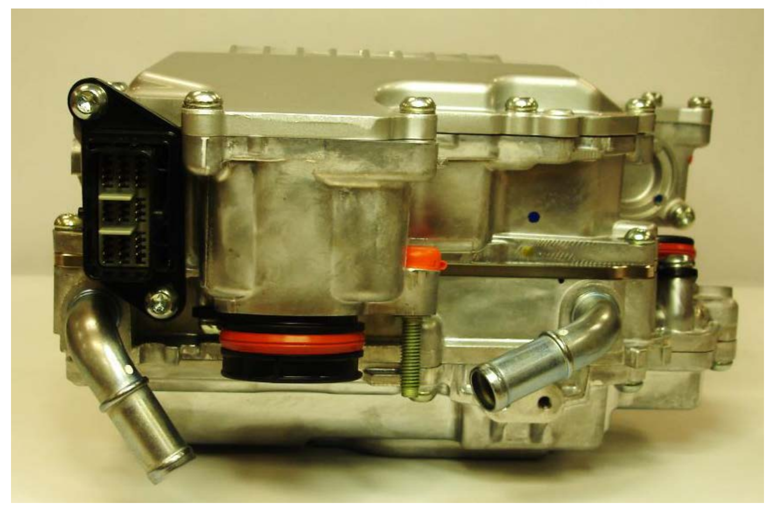
- 2014 Accord is first mass produced 'full' hybrid by Honda offered in U.S.
- Power Converter Unit manufactured by Fuji Electric

FY15 Accomplishments – 2014 Accord

Various views of 2014 Accord Power Converter Unit



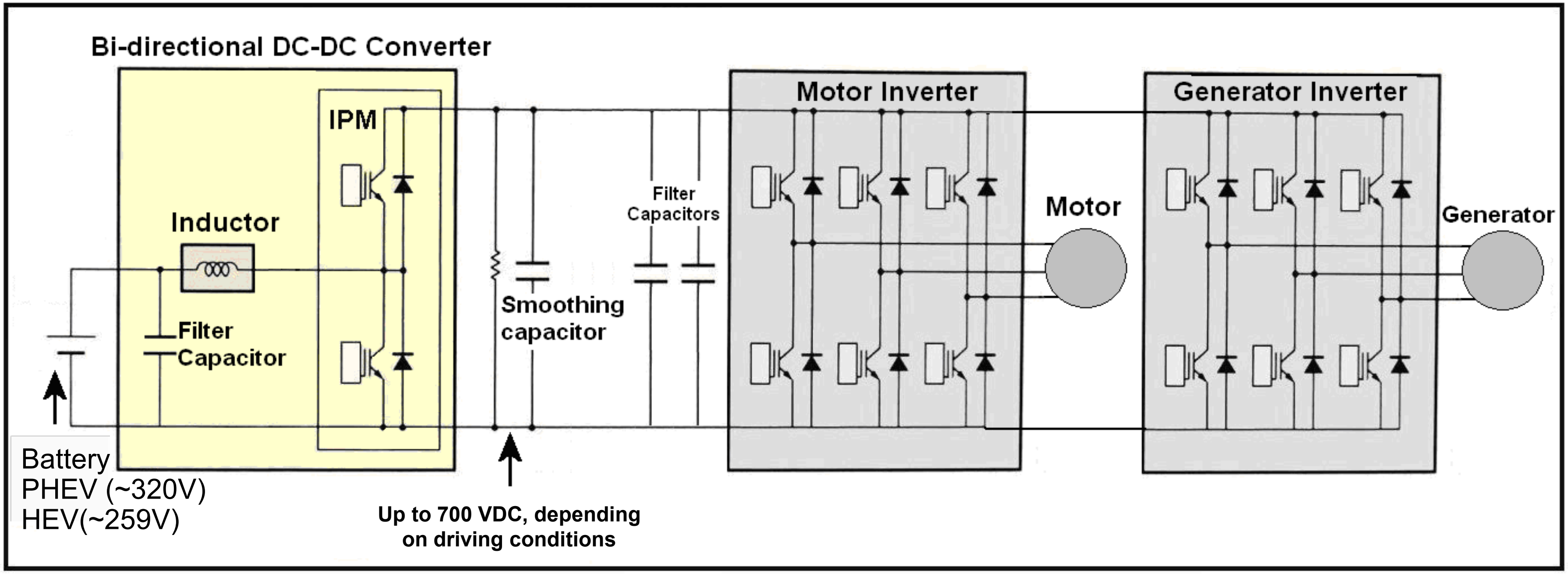




FY15 Accomplishments – 2014 Accord

Electrical schematic of Accord hybrid system

Converter/Inverter system similar to Toyota system



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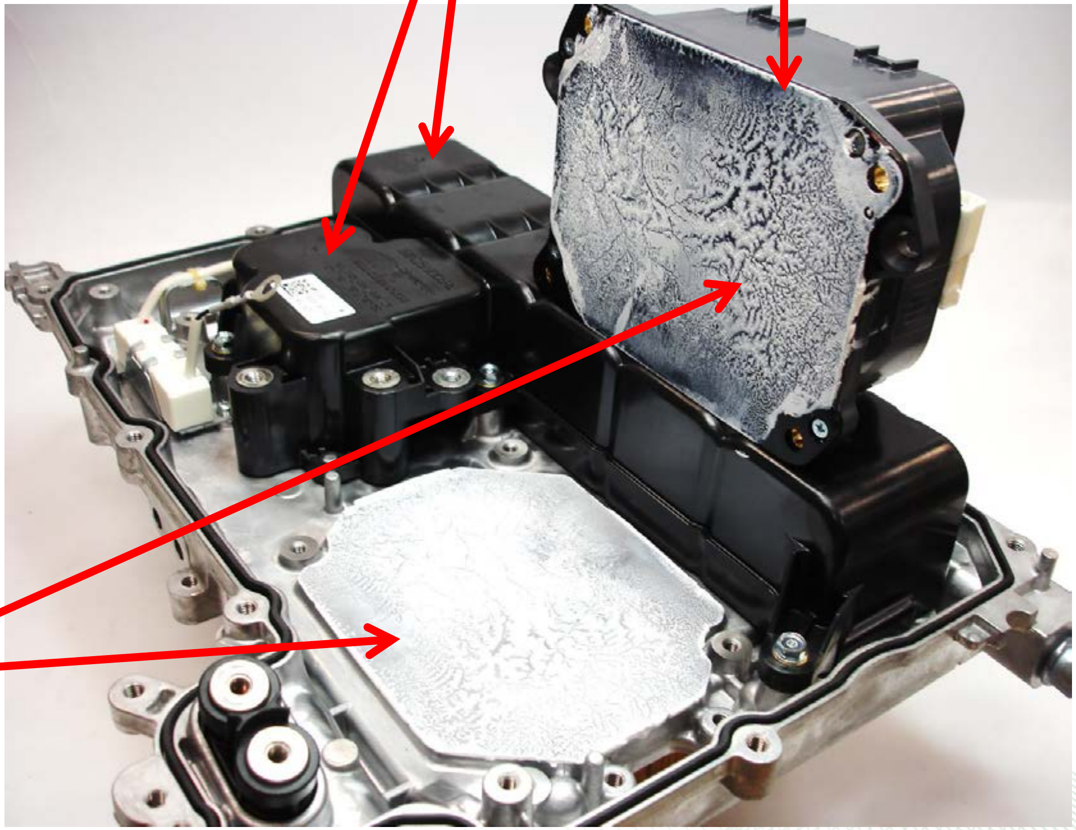
FY15 Accomplishments – 2014 Accord

Bottom Compartment of Accord Power Converter Unit

- Capacitor assembly:
- 411 uF, 370Vdc (battery input)
- 1,125 uF, 700 Vdc (boosted DC link)
- Two small 0.047uF,700 Vdc

Boost inductor

Bulk capacitors



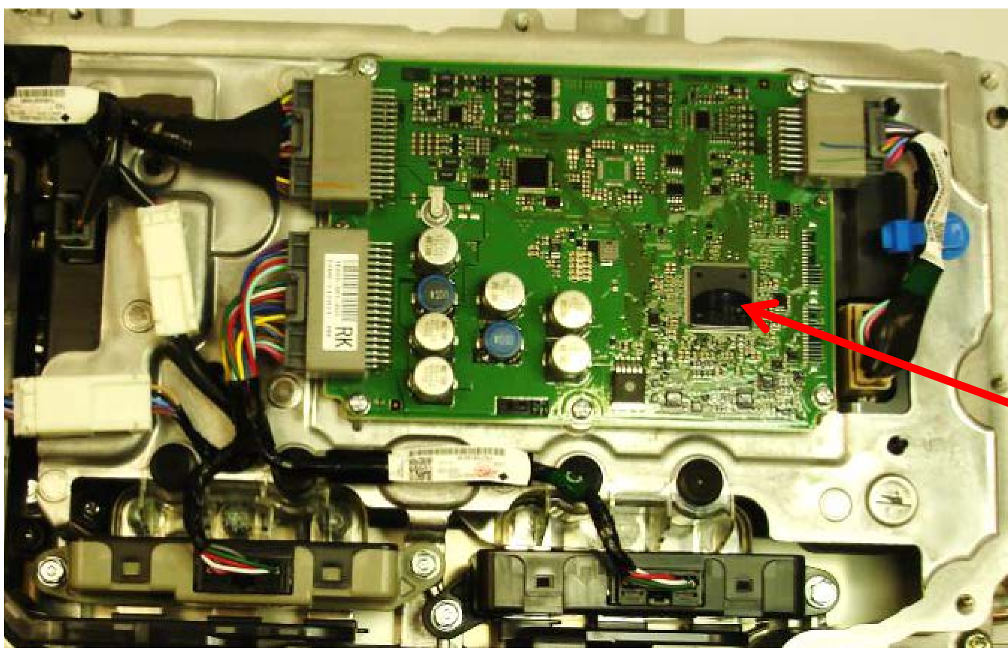
Thermal paste to mate inductor with heat exchanger

FY15 Accomplishments – 2014 Accord

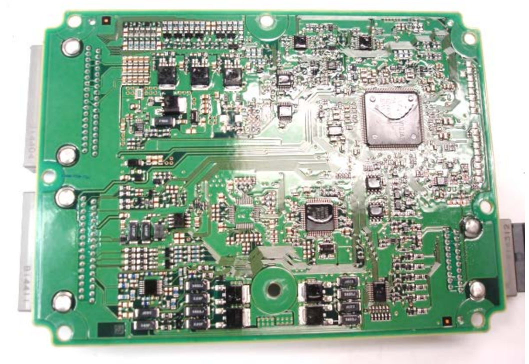
2014 Accord Power Converter Unit – Top Compartment

- Same microcontroller used for motor and generator
  - D70F3507M1GJA2 – by Renesas,
  - V850 Family → V850E2/Px4
  - 32 bit, 512 kB Flash, 40 kB RAM, 32 kB data flash, 32 MHz, 100 pins, 22 ch x 12bit A/D, 8 channel DMA, 112 channel DTC, 11 external interrupts, 73 I/Os, 32 PWM outputs, 3-phase output function, 2 CAN channels, -40 to 125C

Control board



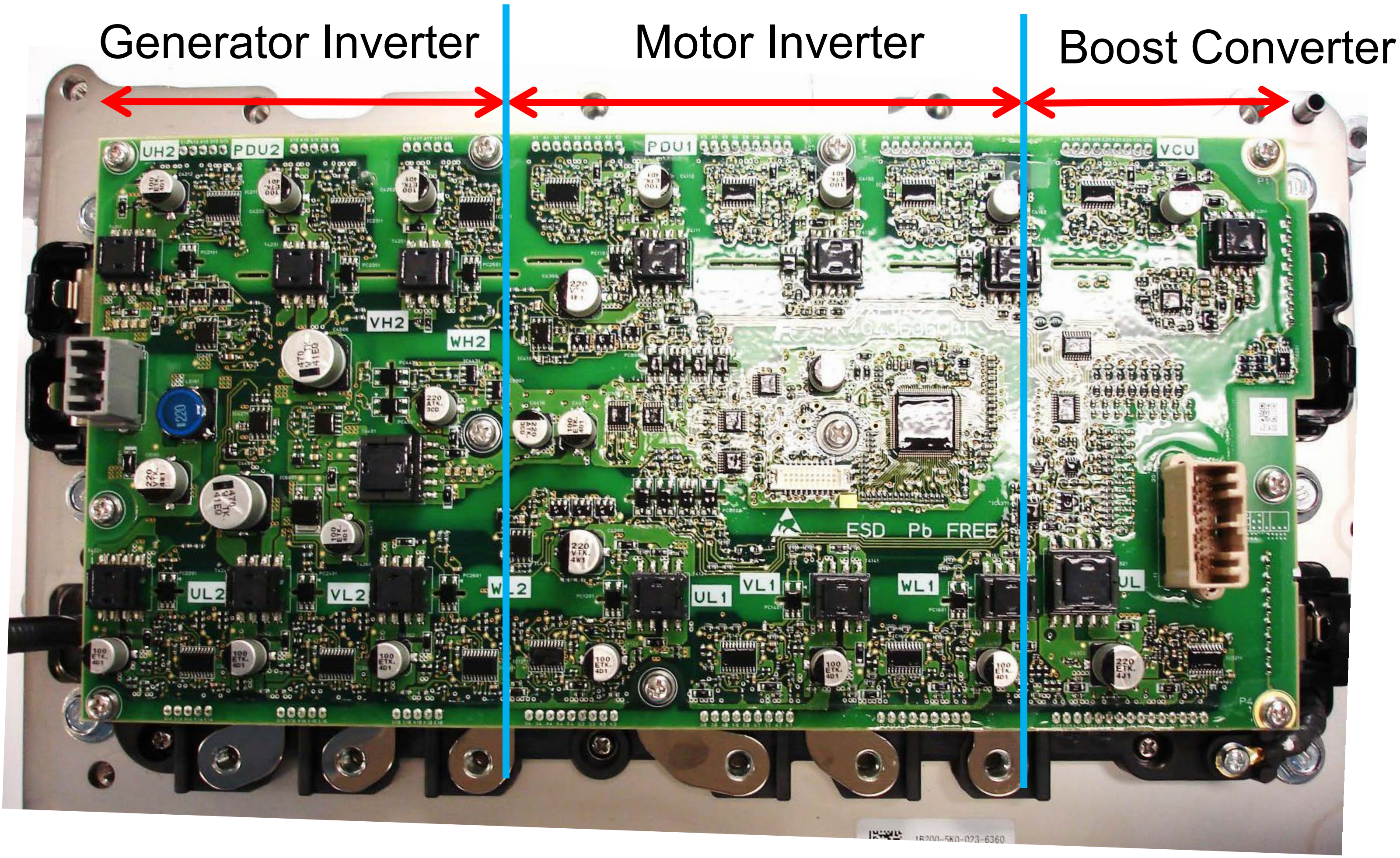
Bottom of control board



FY15 Accomplishments – 2014 Accord

- Motor inverter: 2 IGBTs per switch
- Generator inverter: 1 IGBT per switch
- Boost converter: 3 IGBTs lower switch, 2 IGBTs upper switch

2014 Accord Power Converter Unit
Power Module



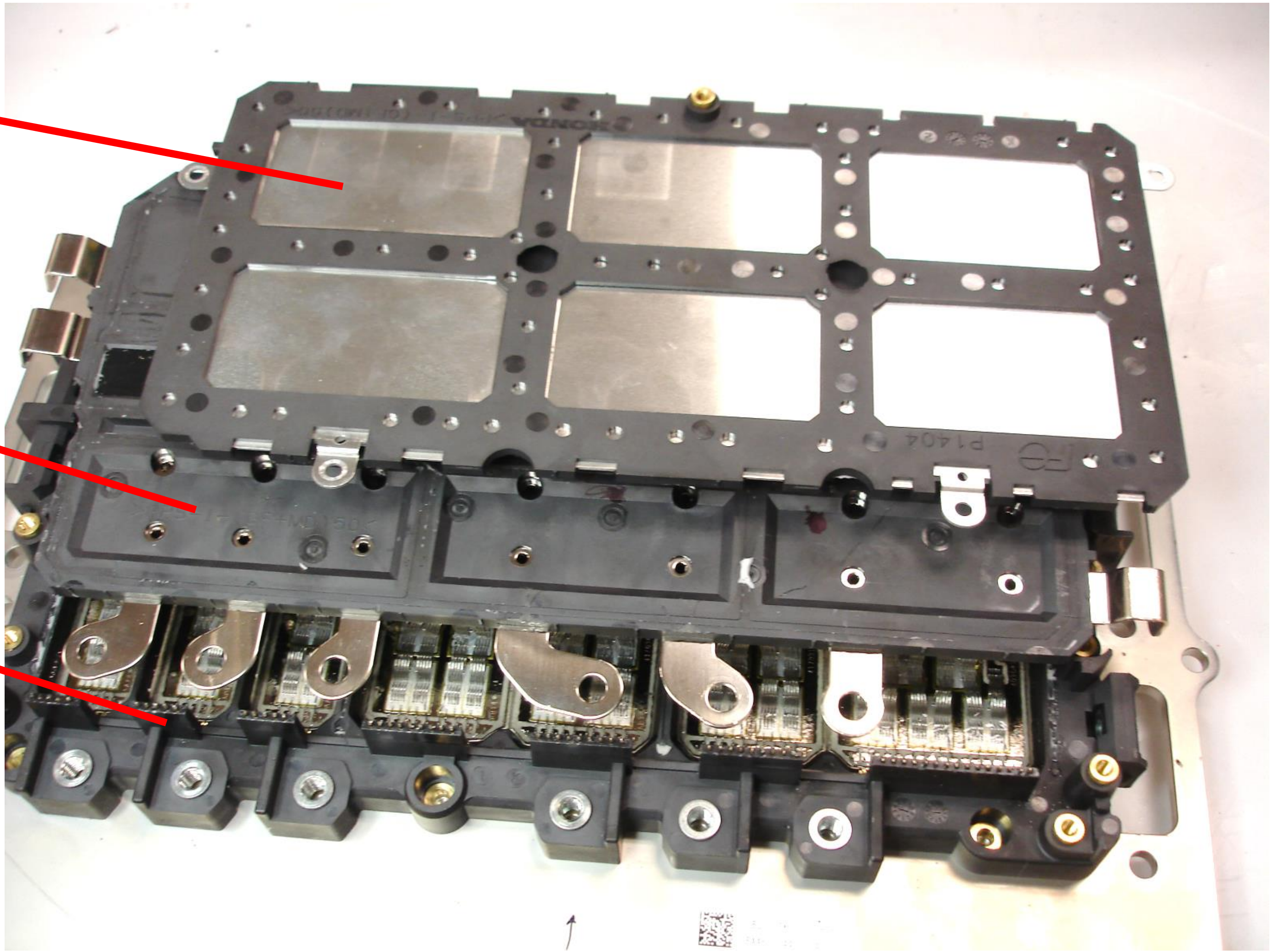
FY15 Accomplishments – 2014 Accord

2014 Accord Power Converter Unit – Power Module

EMI shield

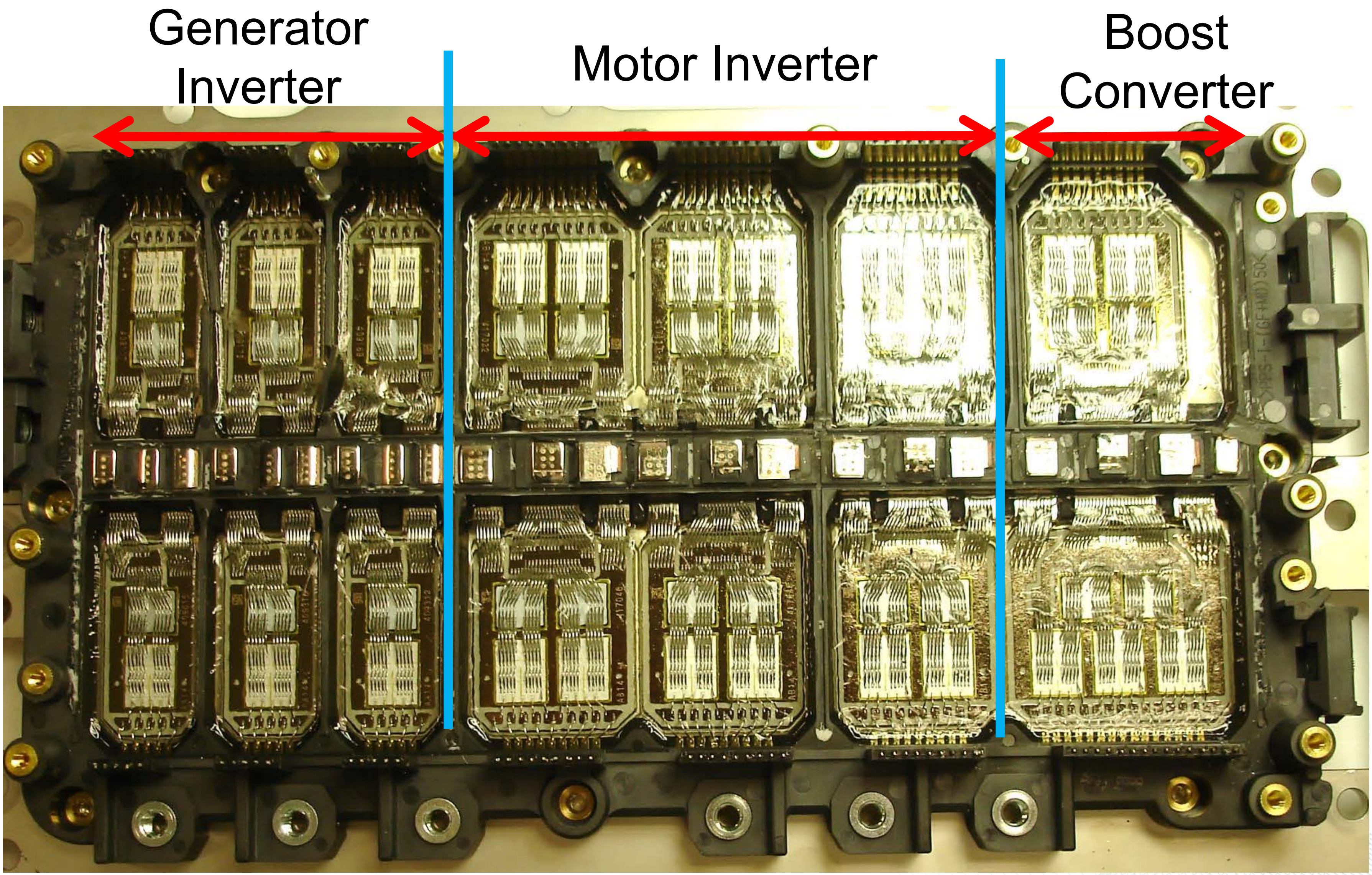
Bus bar infrastructure

Power electronics devices and integrated cooling



FY15 Accomplishments – 2014 Accord

2014 Accord Power Converter Unit – Power Module



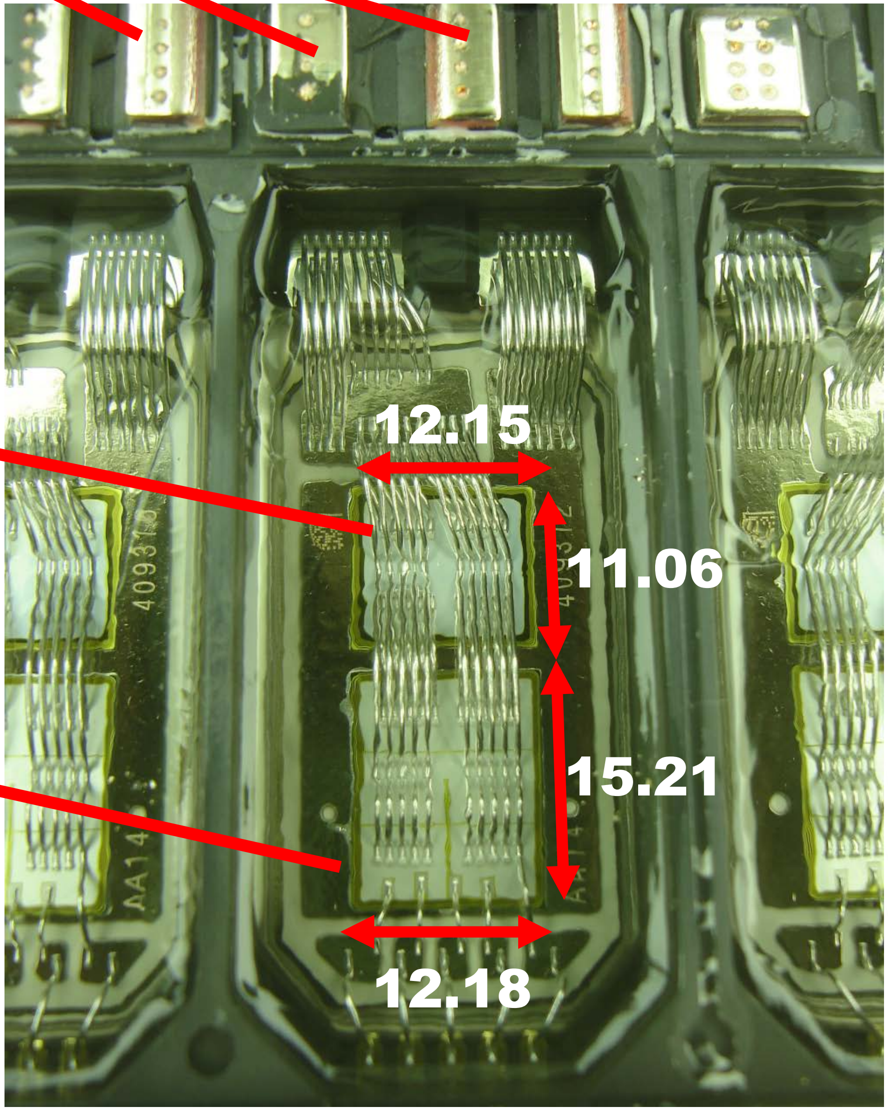
FY15 Accomplishments – 2014 Accord

Accord Generator Inverter Power Electronics

Bus bar interfaces

Diode

IGBT



Motor, generator, and boost converter IGBTs and diodes have the same dimensions:

- Diode:
  - 12.15mm x 11.06 mm
  - 134.38 mm^2
- IGBT
  - 12.18mm x 15.21 mm
  - 185.26 mm^2

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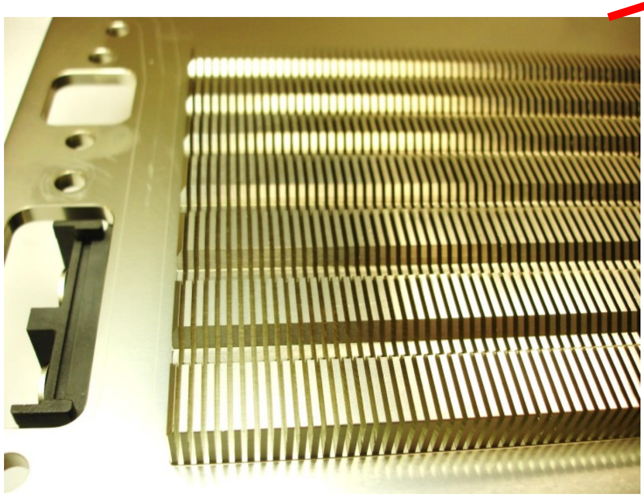
FY15 Accomplishments – 2014 Accord

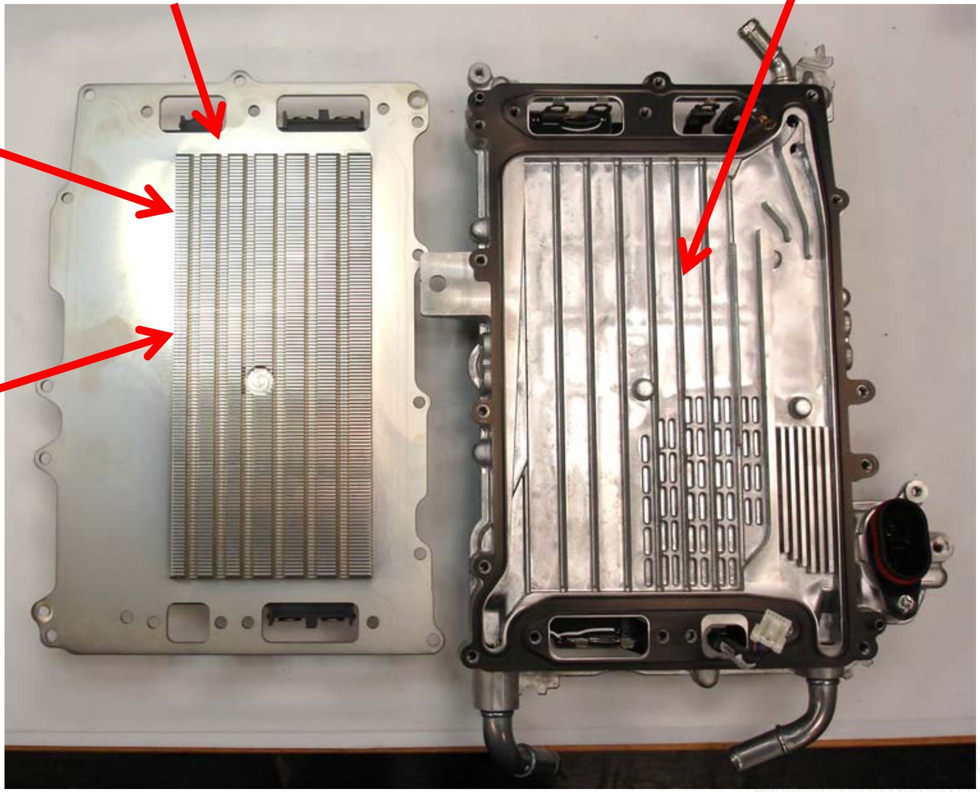
Accord Power Converter Unit Heat Exchanger

Close-up of fins on bottom of power module



Power Module

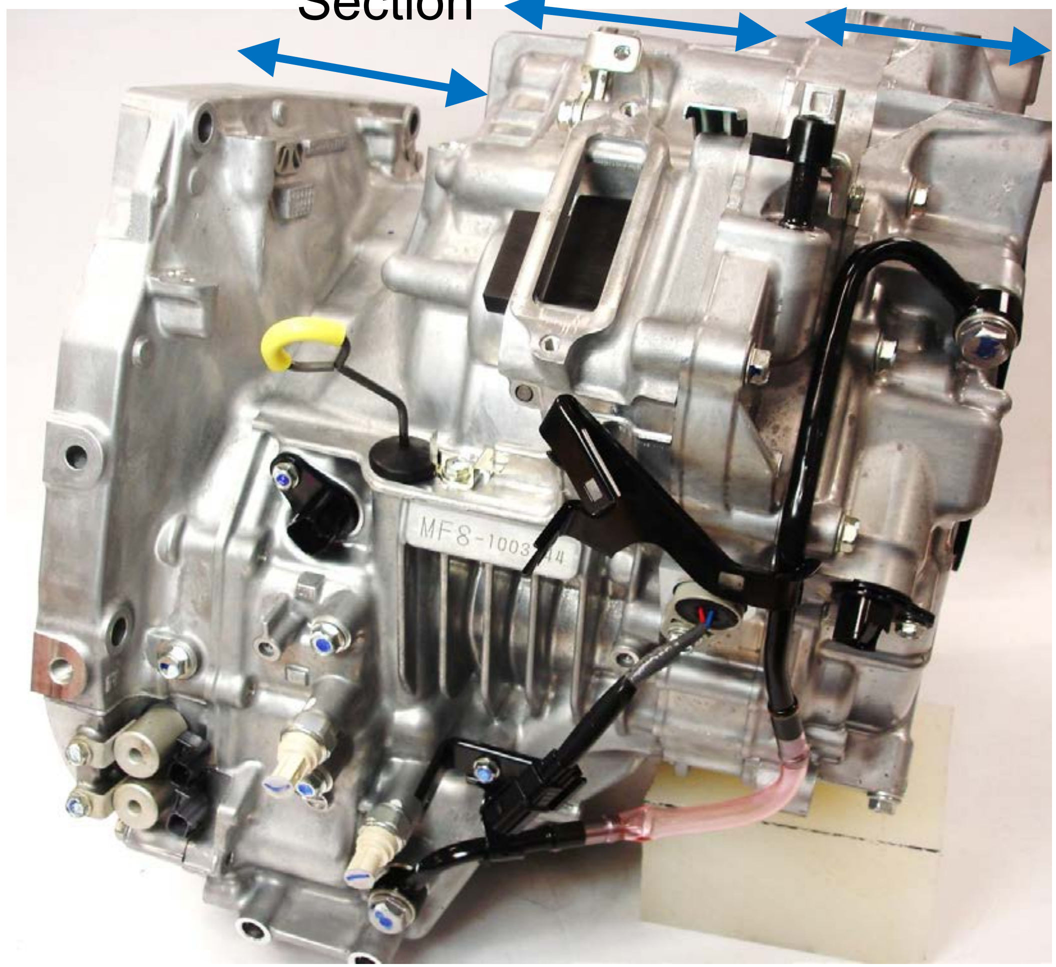
Boost inductor and bulk capacitor housing



FY15 Accomplishments – 2014 Accord

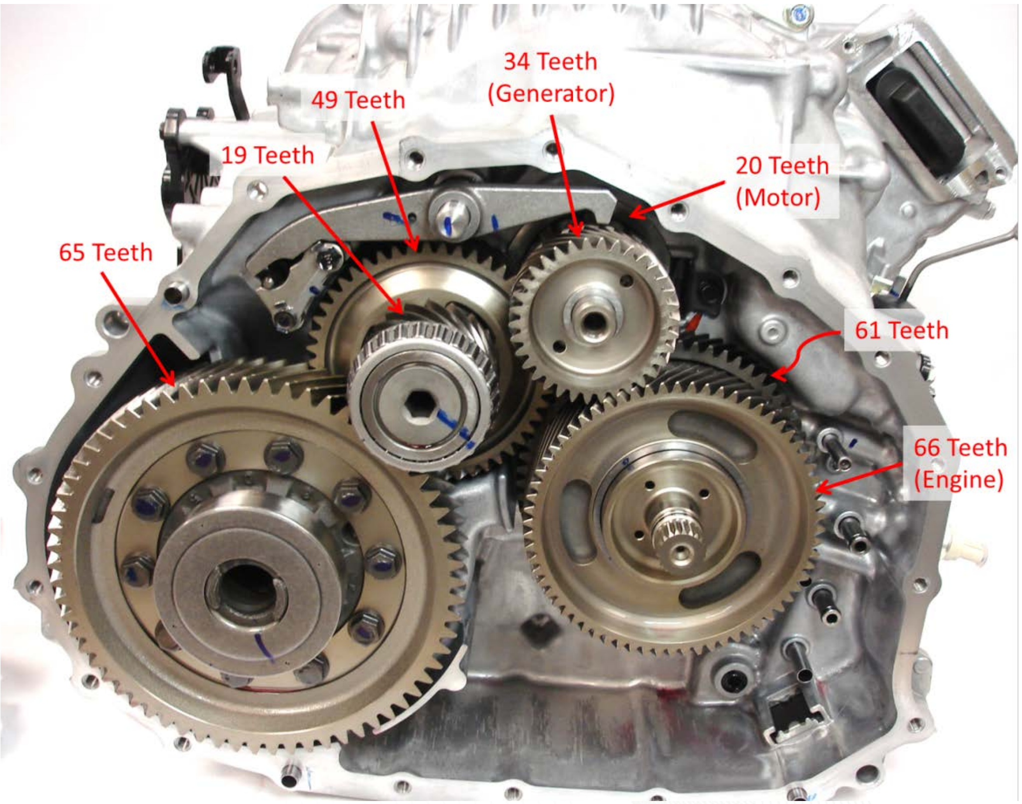
Accord Transmission Sections and External Components

- Transmission mates to engine with flywheel on splined shaft
- No torque converter
- Total Mass: 113.5 kg (249.5 lbs) - Camry hybrid transmission mass is 108 kg



FY15 Accomplishments – 2014 Accord

- 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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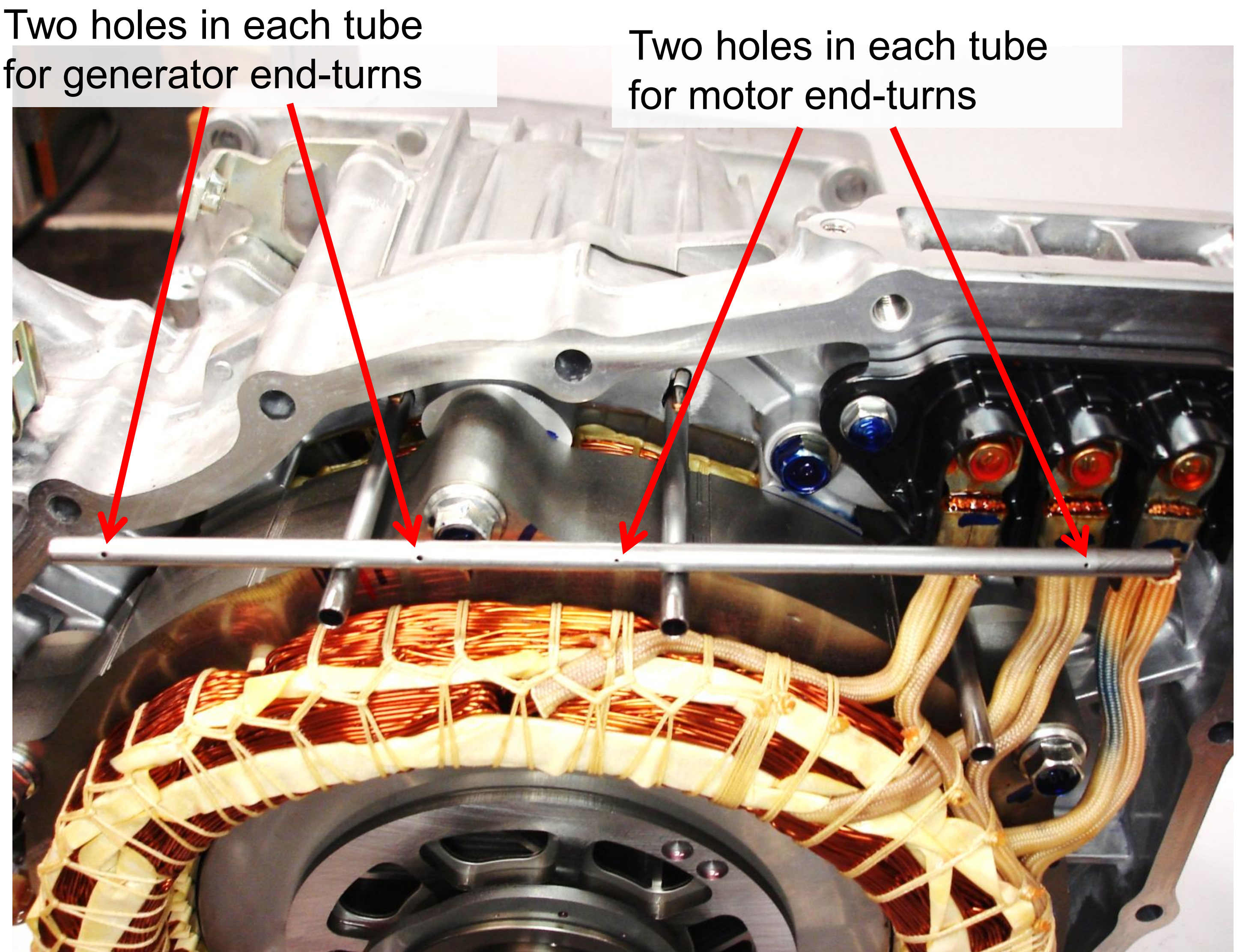
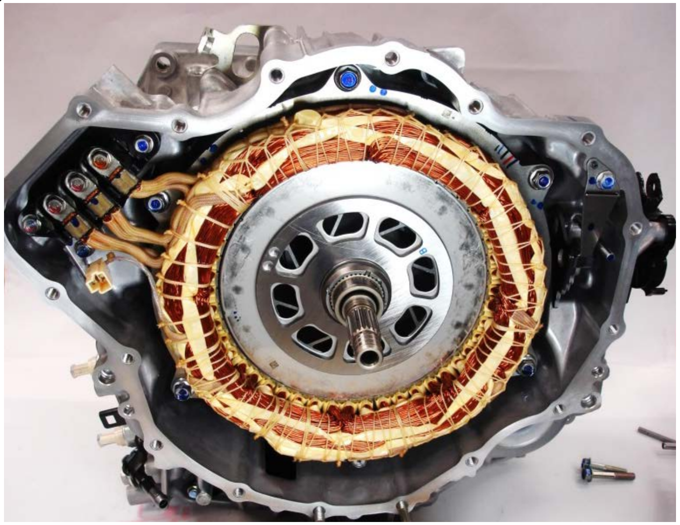
FY15 Accomplishments – 2014 Accord

Accord Motor and Generator Cooling System



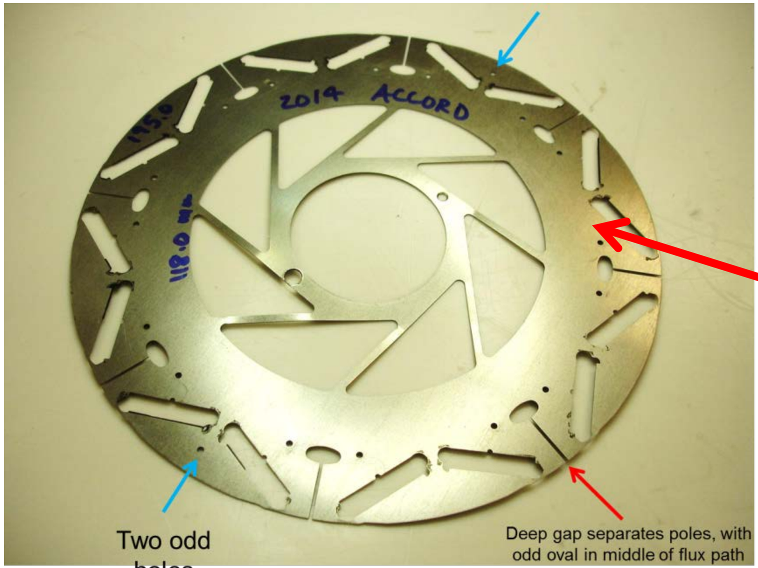
FY15 Accomplishments – 2014 Accord

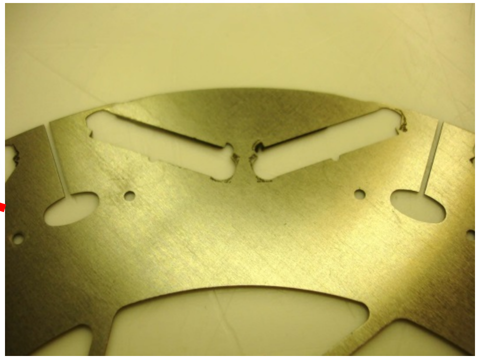
- Generator and Motor stator and rotor laminations appear to be identical
  - Stator OD: 29.13 cm
  - Rotor OD: 19.5 cm
- Motor specifications
  - Stack length: 6.17 cm (1.64 times generator: 3.762cm)
  - Rotor mass: 11.8 kg
  - Stator mass: 20.8 kg
  - Total magnet mass: 1.24 kg



2010 Prius rotor lamination

2014 Accord rotor lamination





FY15 Accomplishments – 2014 Accord

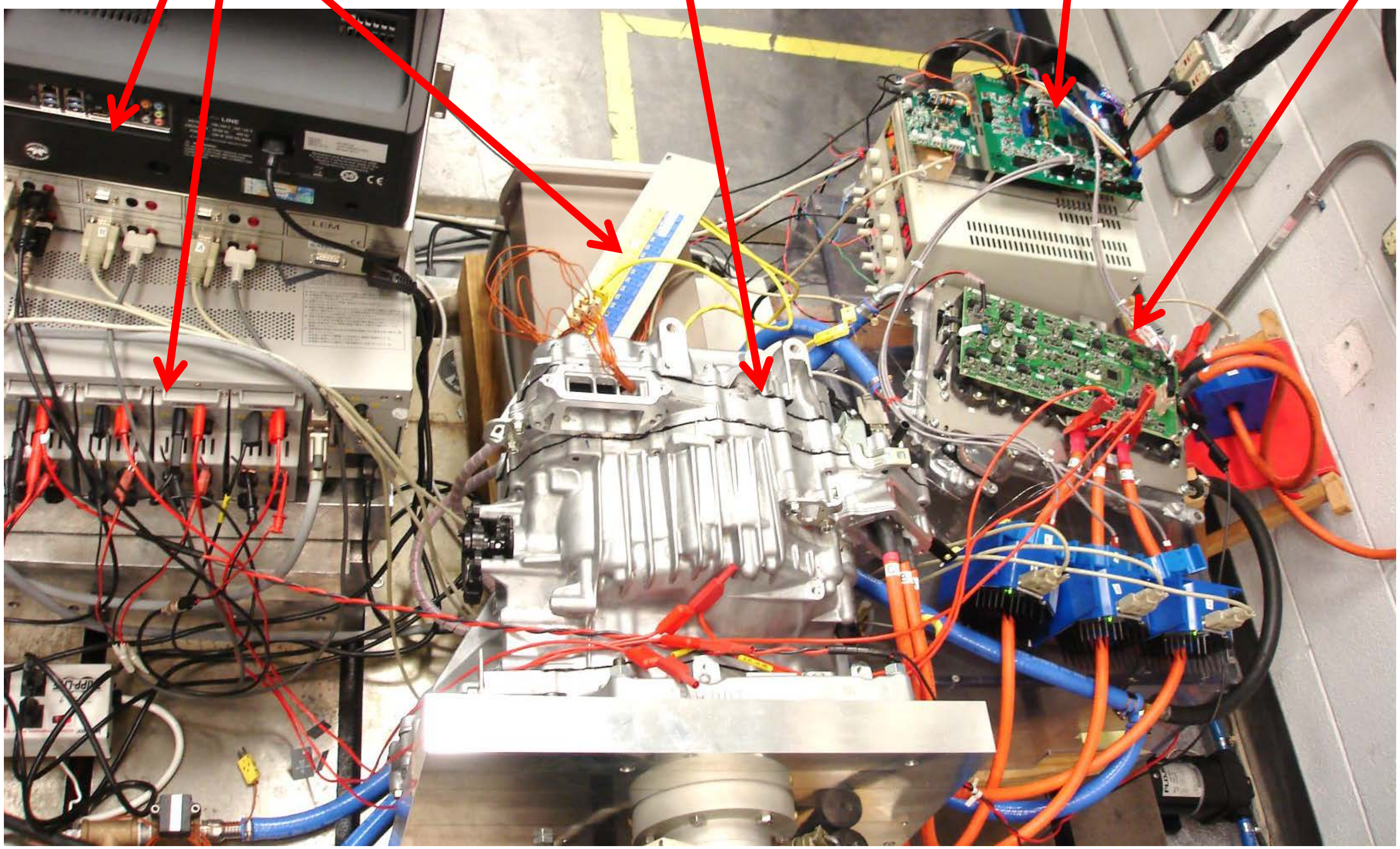
Accord Hybrid Inverter and Motor on Dyno

Power analyzers and other data acquisition equipment

Accord Motor/Transmission

ORNL Controller

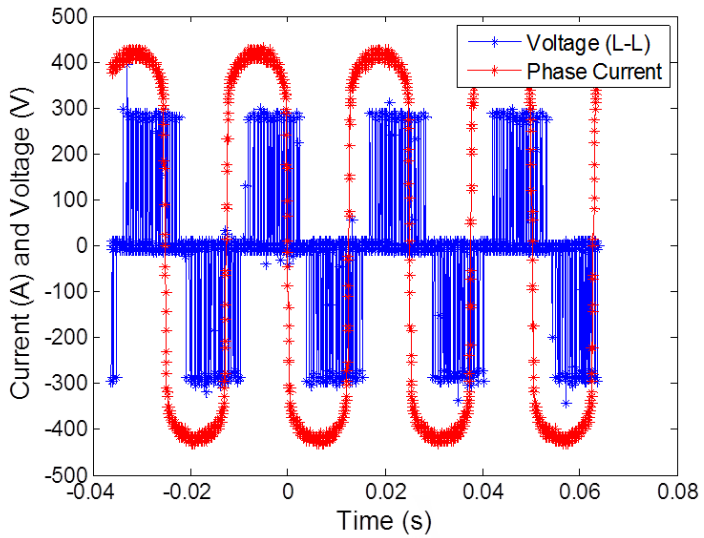
Accord Inverter

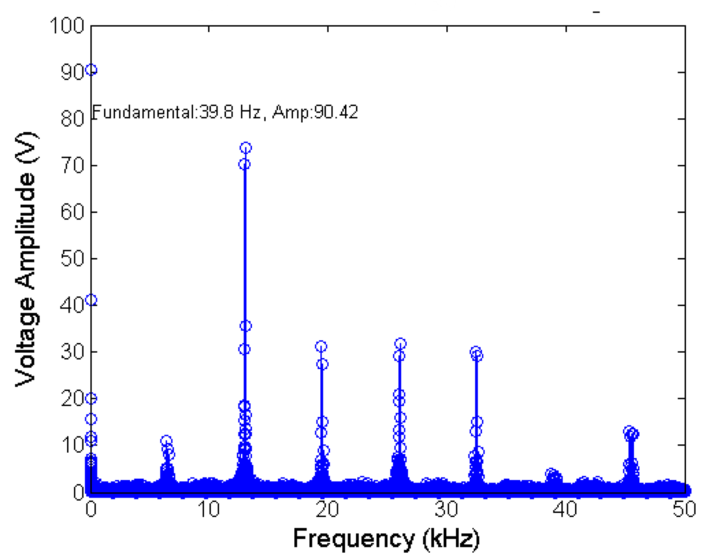


FY15 Accomplishments – 2014 Accord

ORNL/ANL Collaboration (Vehicle testing)

- Obtained three-phase voltage and phase current at the following points at ANL:
  - 5 MPH, ~545 rpm
    - Coast, 100 Nm, 200 Nm, 264.8 Nm →5.7 kW, 11.4 kW, 15.1 kW
  - 10 MPH, ~1089 rpm,
    - Coast, 100 Nm, 200 Nm, 252 Nm → 11.4 kW, 22.7 kW, 28.8 KW
  - 20 MPH, ~2179 rpm,
    - Coast, 100 Nm, 200 Nm, 254 Nm → 22.81 kW, 45.6 kW, 68.0 KW
  - 30 MPH, ~3268 rpm,
    - Coast, 100 Nm, 200 Nm, 254 Nm → 34.2 kW, 68.5 kW, 86.9KW
  - 40 MPH, ~4358 rpm,
    - Coast, 100 Nm, 200 Nm, 254 Nm→ 45.6 kW, 91.3 kW, 115.9 KW
  - 50 MPH, ~5447 rpm,
    - Coast, 100 Nm, 200 Nm → 57.0 kW, 114.1 kW (floored)
  - 60 MPH, ~6536 rpm,
    - Coast, 100 Nm, 172 Nm → 68.4 kW, 117.7 kW (floored)
  - 70 MPH, ~7626 rpm,
    - Coast, 100 Nm, 148 Nm → 79.9 kW, 118.2 kW (floored)
  - 80 MPH, ~8715 rpm,
    - Coast, 100 Nm, 126 Nm → 91.3 kW, 115.0 kW (floored)

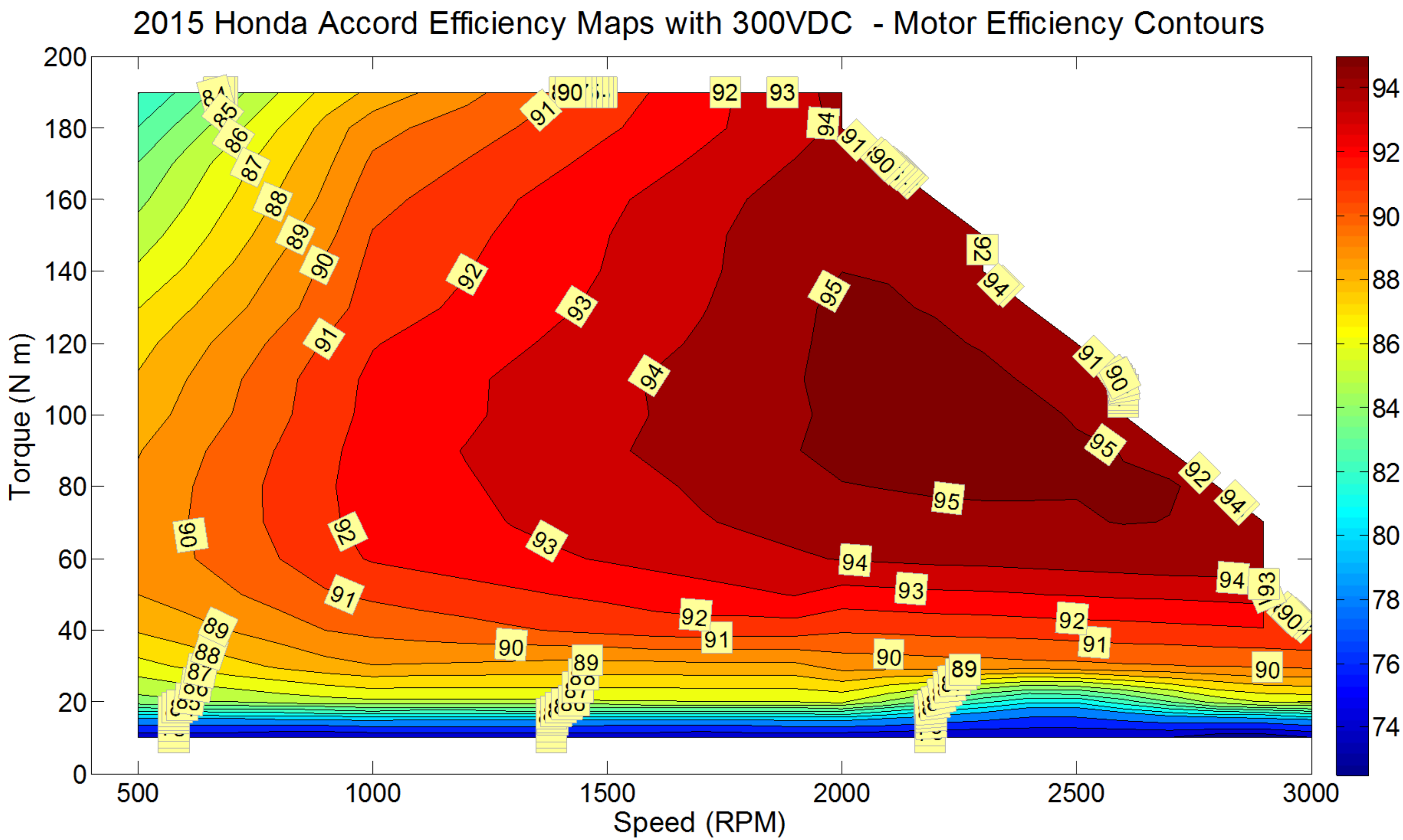




FY15 Accomplishments – 2014 Accord

Preliminary Results: Motor Efficiencies at 300VDC

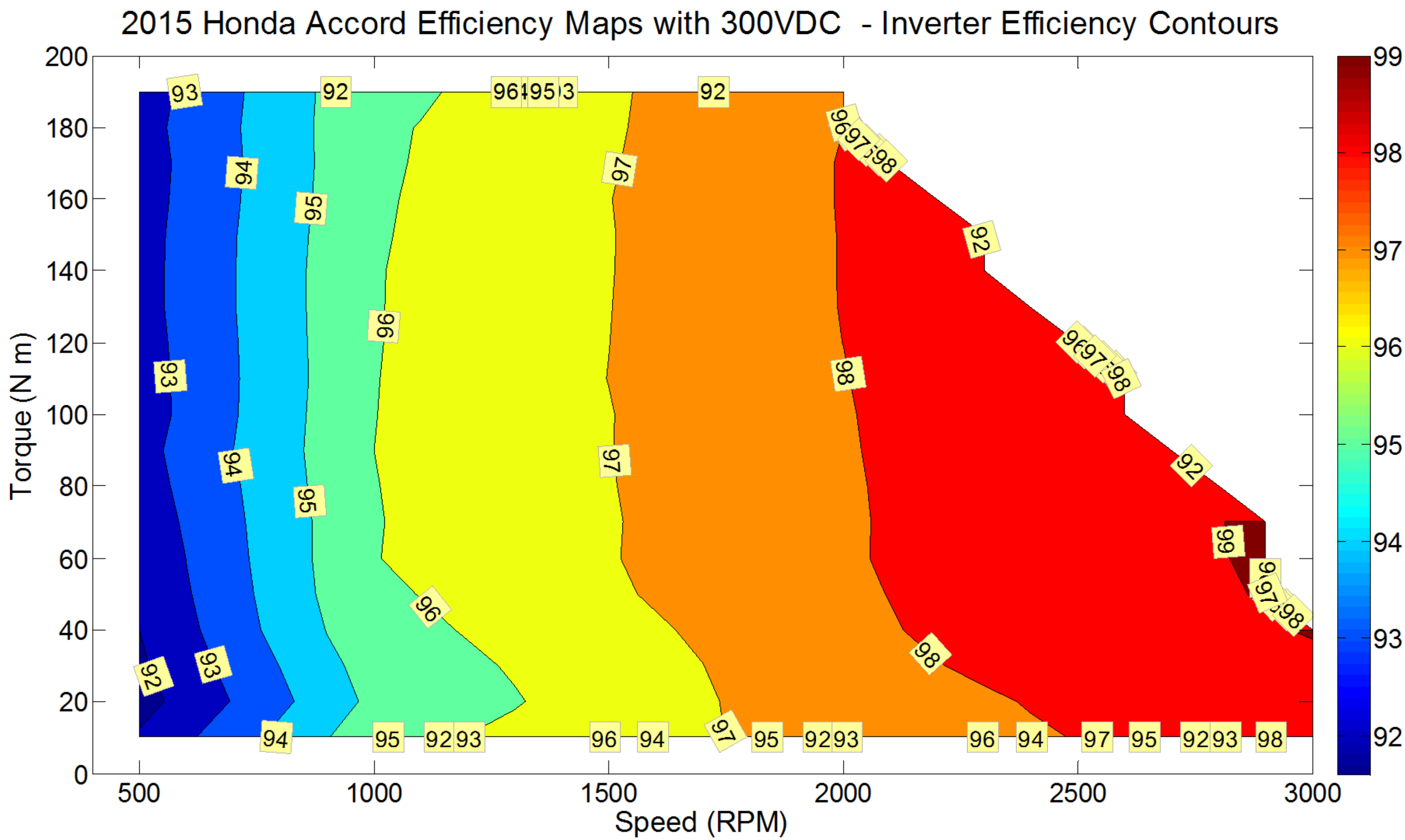
- Motor efficiency reaches above 95%



FY15 Accomplishments – 2014 Accord

Preliminary Results: Inverter Efficiencies at 300VDC

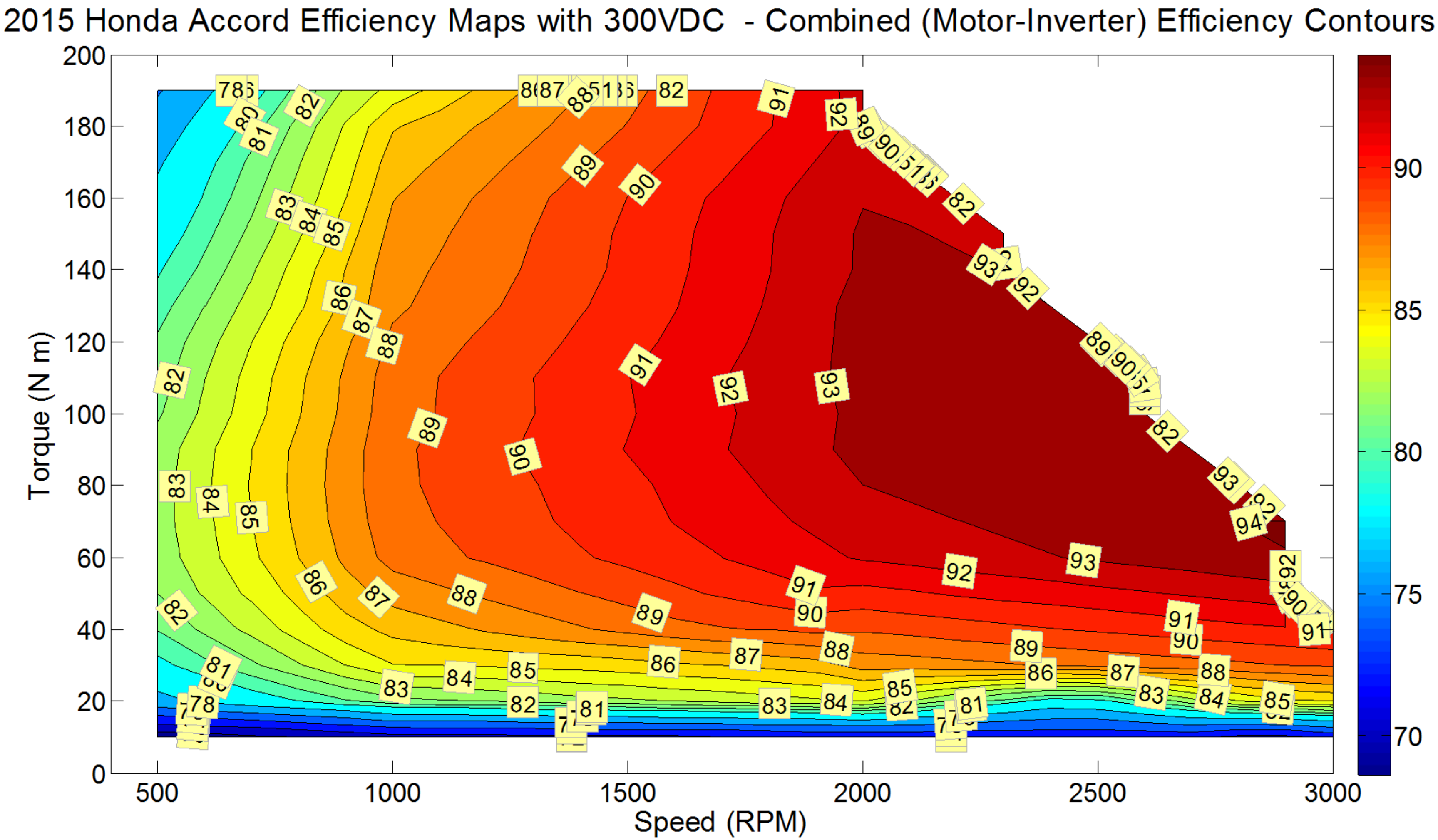
- Inverter efficiency reaches 99%



FY15 Accomplishments – 2014 Accord

Preliminary Results: Combined Efficiencies at 300VDC

- Combined (motor and inverter) efficiency reaches above 93%



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: 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.
  - A webpage dedicated to the benchmarking project will be developed for better dissemination of information.

- 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, and thus, there are uncontrollable delays in the process of preparation. 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
	John Deere	Provides input and general collaboration in the area of benchmarking.
	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	ORNL provides component efficiency and operational characteristics to NREL for thermal studies.
	Ames Lab	Ames provides insight into magnet characterization and conducts quantitative analysis on samples from ORNL.

Proposed Future Work

- **Remainder of FY15**
  - Finalize comprehensive benchmarking of Accord.
  - Complete destructive analysis of Accord.
  - Complete teardown assessments of BMW i3.
  - Design interfaces for and instrument i3 for testing.
  - Initiate benchmarking of 2^{nd} generation LEAF charger, depending on availability.
- **FY16**
  - 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.