

Benchmarking State-of-the-Art Technologies

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Oak Ridge National Laboratory

2013 U.S. DOE Hydrogen and Fuel Cells Program and
Vehicle Technologies Program Annual Merit Review
and Peer Evaluation Meeting

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Project ID: APE006

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Overview

Timeline

- Start – FY04
- Finish – Ongoing

Budget

- Total project funding
 - DOE share – 100%
- Funding for FY12:
 - \$550 K
- Funding for FY13:
 - \$450 K

Barriers & Targets

- 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
 - Steven Campbell
 - Chester Coomer
 - Zhenxian Liang
 - Andy Wereszczak
 - Materials Science and Technology Division
- Remy
- ANL
- NREL

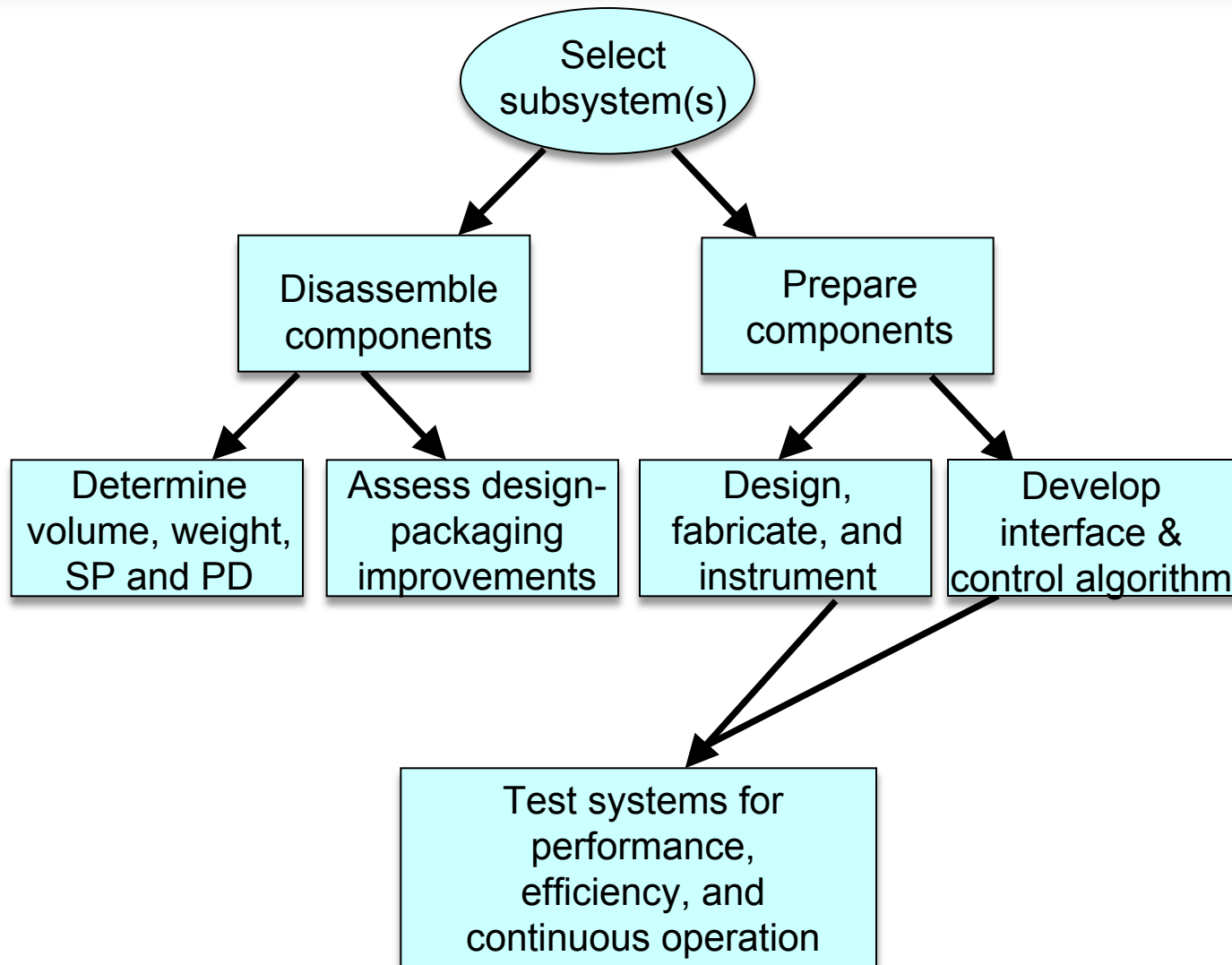
Project Objectives/Relevance

- **Overall Objective:** The core function of this project is to observe and define the current state-of-the-art of EV/HEV technologies.
 - 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 2012 through March 2013):**
 - Complete design/packaging assessments and operational characteristics/performance evaluations of 2012 Nissan LEAF® inverter/motor and 2012 Hyundai Sonata inverter/hybrid starter-generator (HSG)

Milestones

Date	Milestones and Go/No-Go Decisions	Status
September 2012	<u>Milestone:</u> Complete 2012 Hyundai Sonata inverter/HSG testing.	Complete.
September 2012	<u>Go/No-Go decision:</u> Determine if commercially available EV/HEV system is available and relevant to DOE's VTO mission.	Go.
September 2013	<u>Milestone:</u> Complete 2012 Nissan LEAF on-board-charger (OBC) design and packaging assessments.	On Track.
September 2013	<u>Go/No-Go decision:</u> Determine if commercially available EV/HEV system is available and relevant to DOE's VTO mission.	

Approach/Strategy



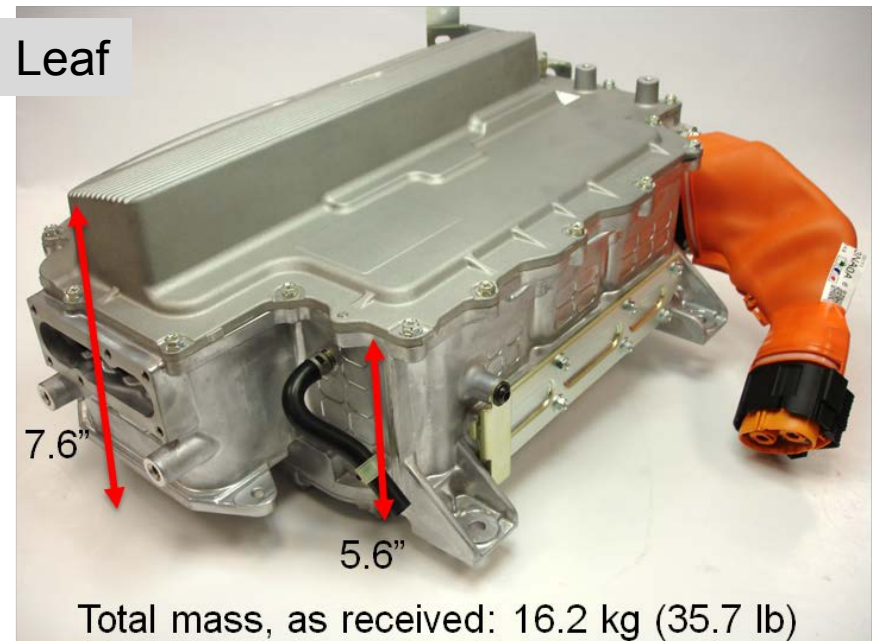
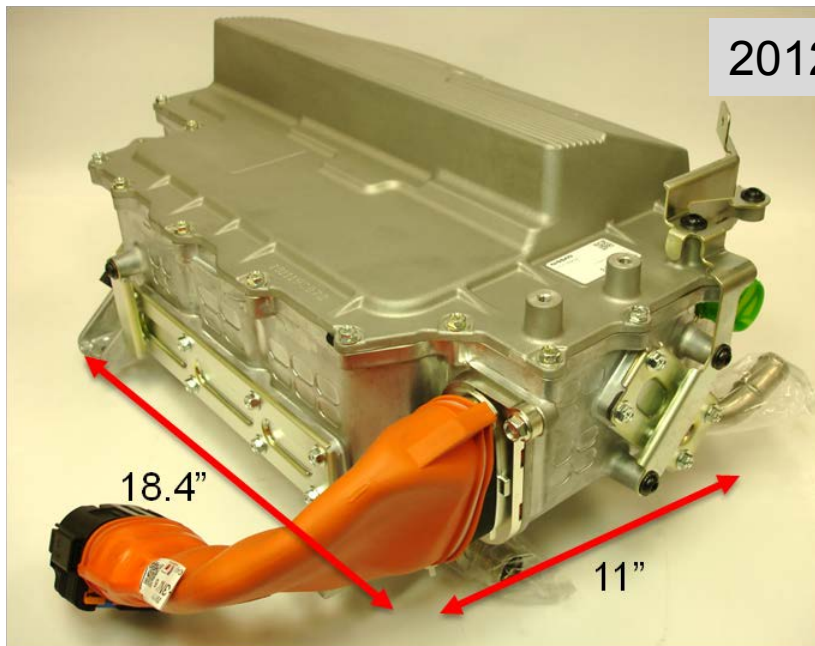
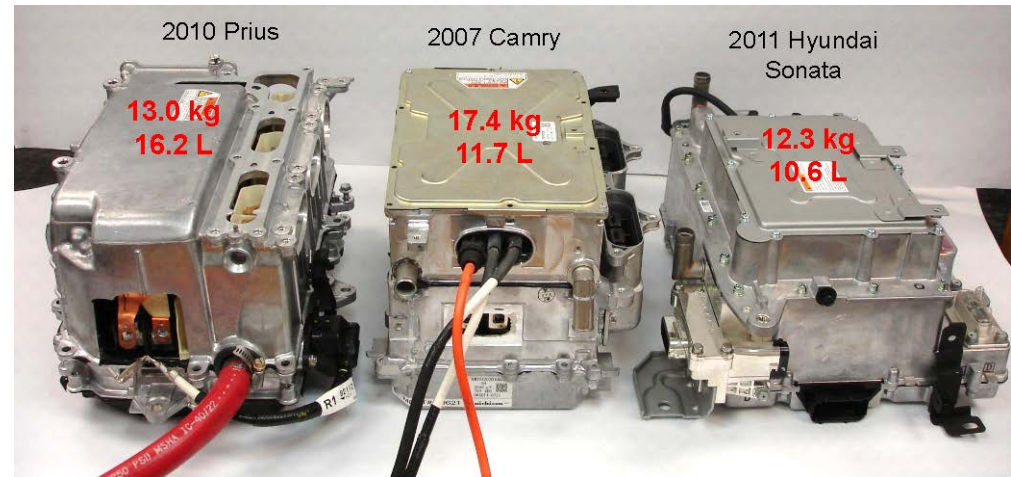
Overall Technical Accomplishments

- Prepared detailed comparisons of progressing technologies
 - 2004 Prius, 2006 Accord, 2007 Camry, 2008 Lexus LS 600h, 2010 Prius, 2011 Hyundai Sonata motor, 2012 Nissan LEAF, 2012 Hyundai Sonata HSG
 - Note: Power density and specific power levels in table are not apples-to-apples since LEAF and Sonata have continuous capability near their published rated power

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)	2006 Honda Accord (12 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	1.5	3.3
Peak specific power, kW/kg	1.6	1.4	1.9 (0.7)	1.1	1.6	2.5	1.7	0.5	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)	2.9	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)	2.4	3.8 (6.2)

Technical Accomplishments (1)

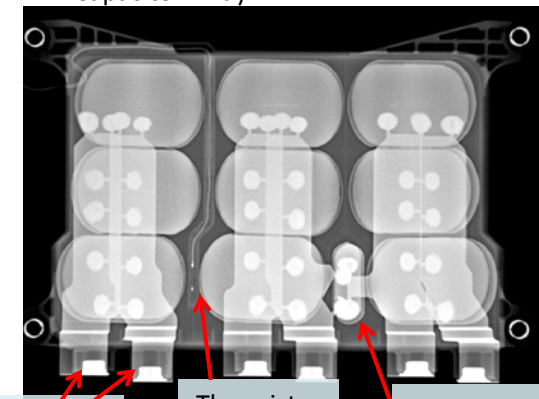
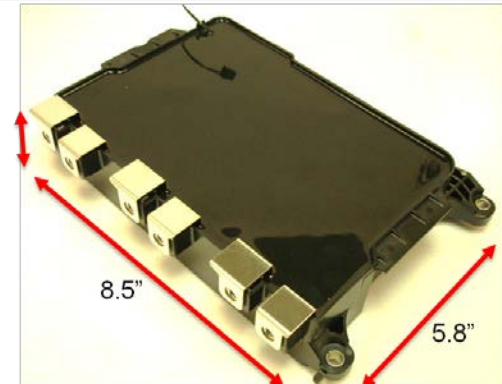
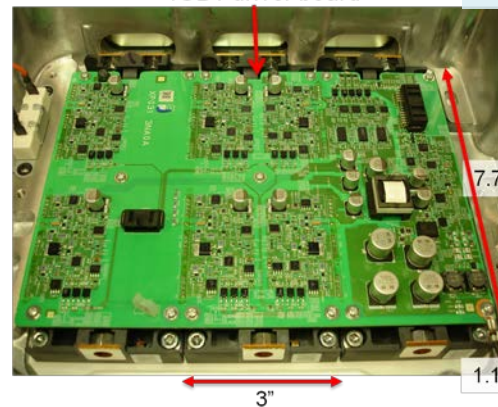
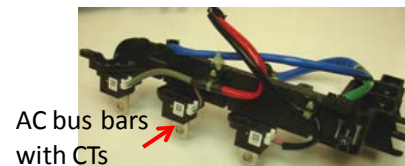
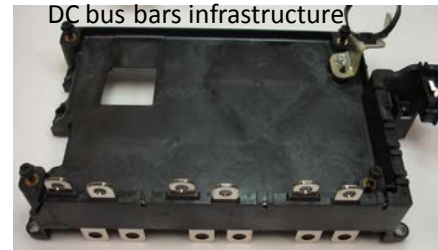
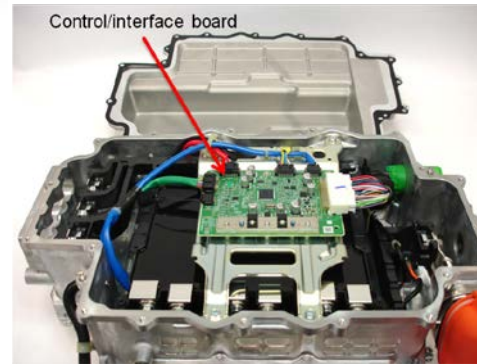
- Comparison of power converter unit (PCU) and inverter assemblies
 - Note: LEAF inverter assembly has only 1 inverter (no generator inverter, boost, or 12 V accessory converter)
 - LEAF sized for EV/continuous duty



~15.6 L, ~14.0 L without void space below lid

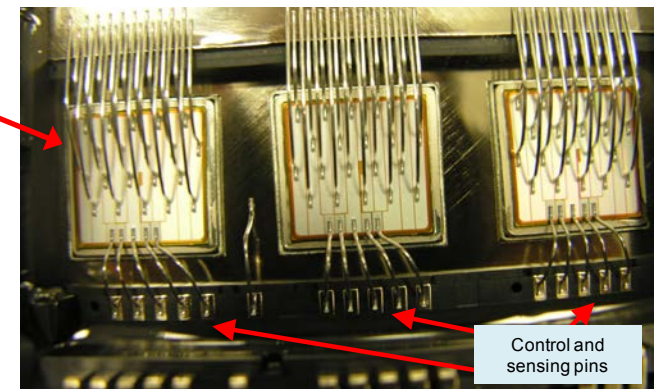
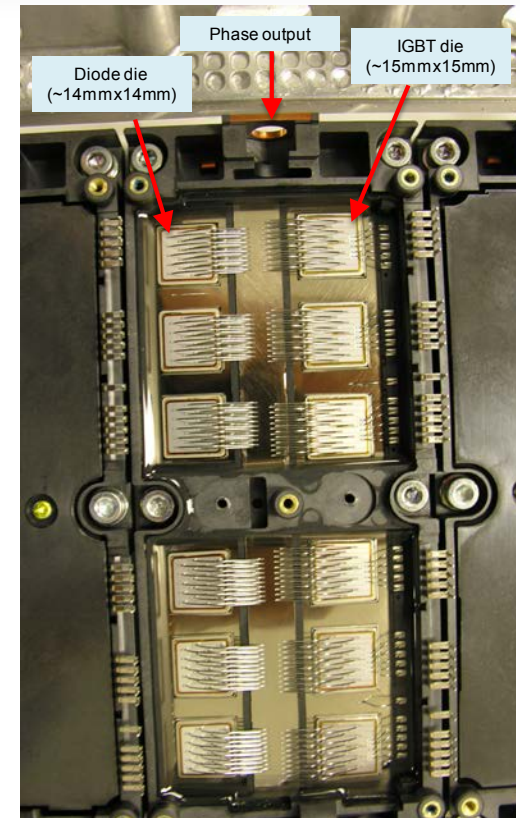
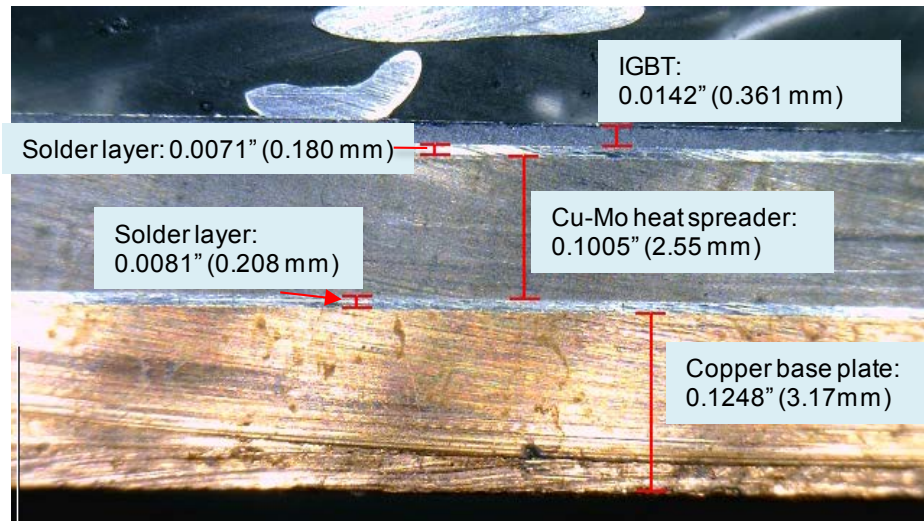
Technical Accomplishments (2)

- LEAF Control board includes
 - Voltage regulation for control and driver circuitry
 - Tamagawa AU6803 resolver chip
 - Renesas R5F71476FPV 32-bit microcomputer
 - 512 kB ROM, 16 kB RAM
- DC link parasitics
 - 600V, 1186.5 μF capacitor ($\sim 1.45\text{L}$)
 - SH Film capacitor by Panasonic
 - Integrated thermistor
 - Small 600V, 1.13 μF capacitor
 - 15 Watt, 61 k Ω bleed resistor
- Large conductors
 - DC: $\sim 1/0$ AWG
 - AC: $\sim 3/0$ AWG
- Three current transducers integrated with AC bus bars
- Driver board
 - On-chip diode for crude temperature sensing
 - Lower switches powered with same supply



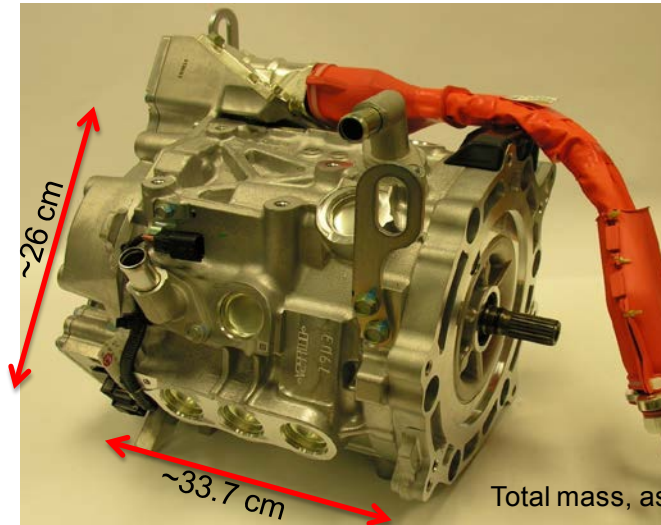
Technical Accomplishments (3)

- 3 IGBTs and 3 diodes per switch (18 IGBTs and 18 diodes total) in LEAF power electronics module (PEM)
- Separate module for each phase
 - 2 DC link terminals each (also on main capacitor)
- Zhenxian Liang (ORNL) conducted PEM analysis
 - 0.361 mm thick IGBT
 - Estimated ~1000V breakdown and 300A IGBT rating
 - IGBT soldered to 2.55 mm thick Co-Mo spacer for CTE matching
 - Spacer soldered to 3.17 mm thick copper base plate
 - Base plate is not electrically isolated – thin silicone based insulator is used
 - Thermal grease between base plate and insulator
 - Another thermal grease layer between insulator and chassis
 - IGBT: 15mm x 15mm, Diode: 14mm x 14mm

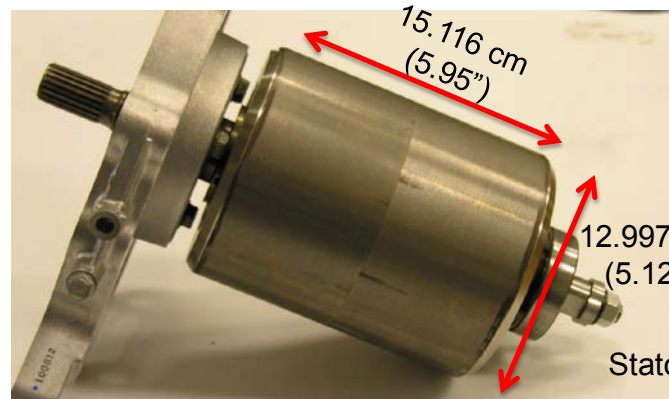
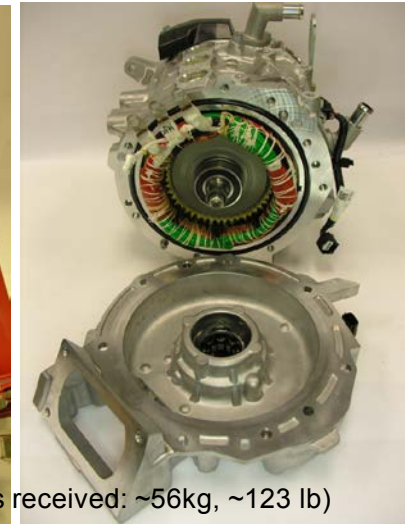


Technical Accomplishments (4)

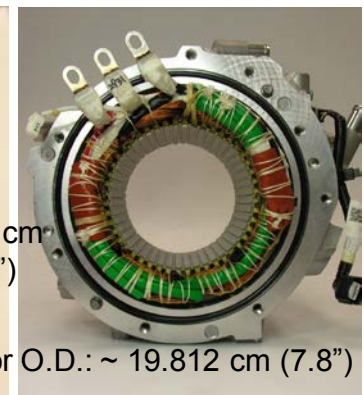
- LEAF Transaxle final drive ratio: 7.94
 - 64 mph → 7,000 rpm
 - 94.1 mph → 10,300 rpm
 - Small 12-8 SR motor used to engage parking brake
 - Spring loaded “brush” contacts on 2nd axis
- Motor design
 - Peak torque rating: 280 Nm
 - Speed rating: 10,390 rpm
 - Mass: ~56 kg (123 lb)
 - Volume: ~19 L
 - Stator O.D. : 19.8 cm (7.8")
 - Rotor O.D.: 13.0 cm (5.12")
 - Stack length: 15.1 cm (5.95")
 - Similar to LS 600h
 - 8 pole IPM with 48 stator slots
 - 3 cooling channels around stator perimeter for uniform cooling
 - Resolver with 10 stator teeth and 4 rotor poles (salient lobes)



Total mass, as received: ~56kg, ~123 lb)

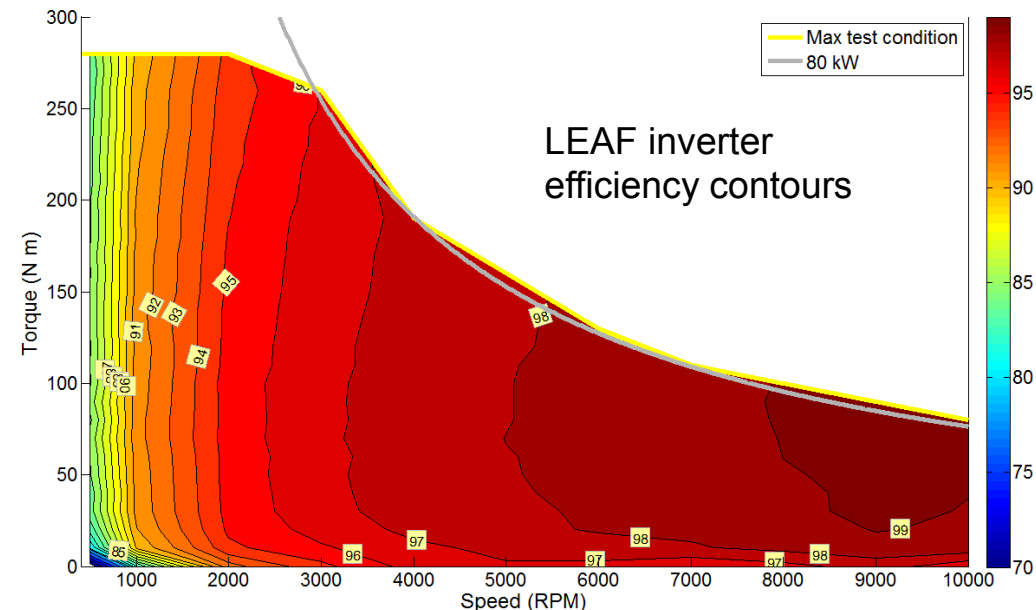
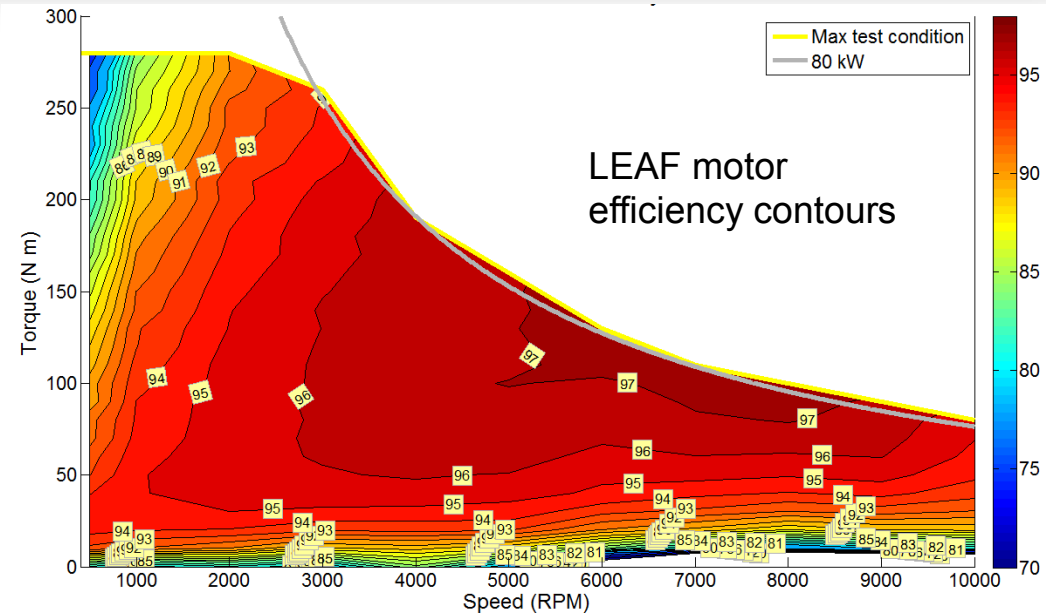


Stator O.D.: ~ 19.812 cm (7.8")



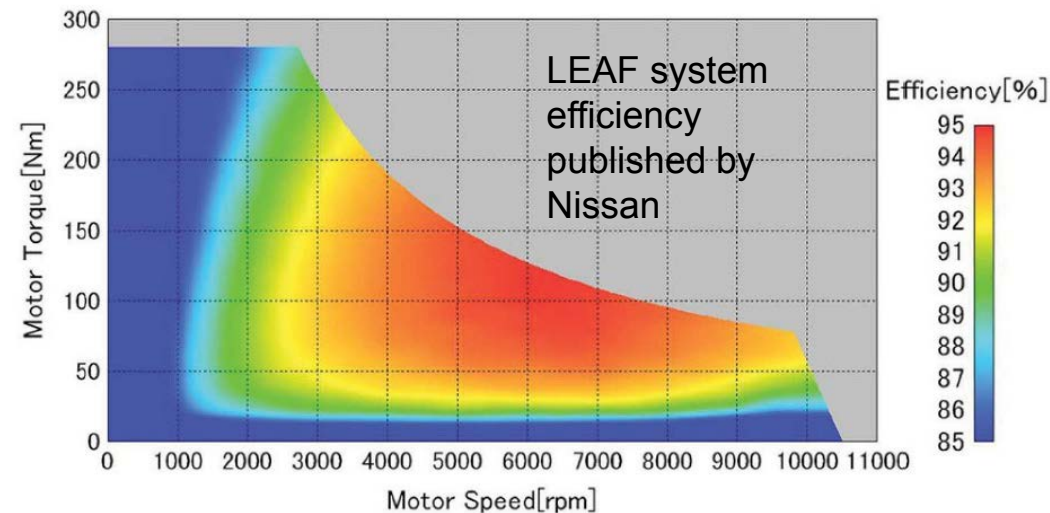
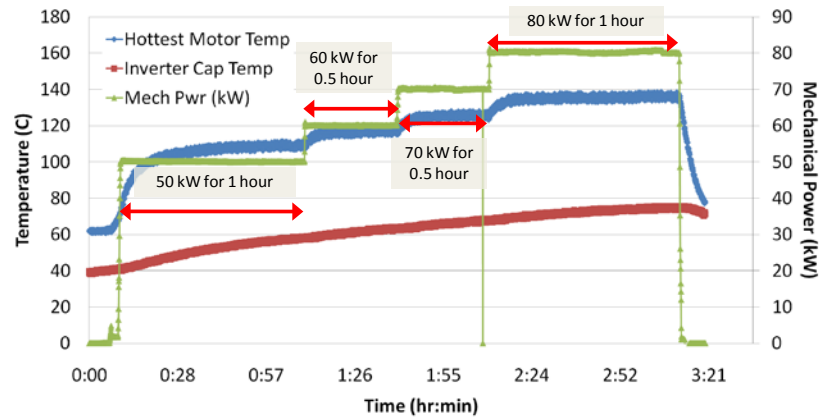
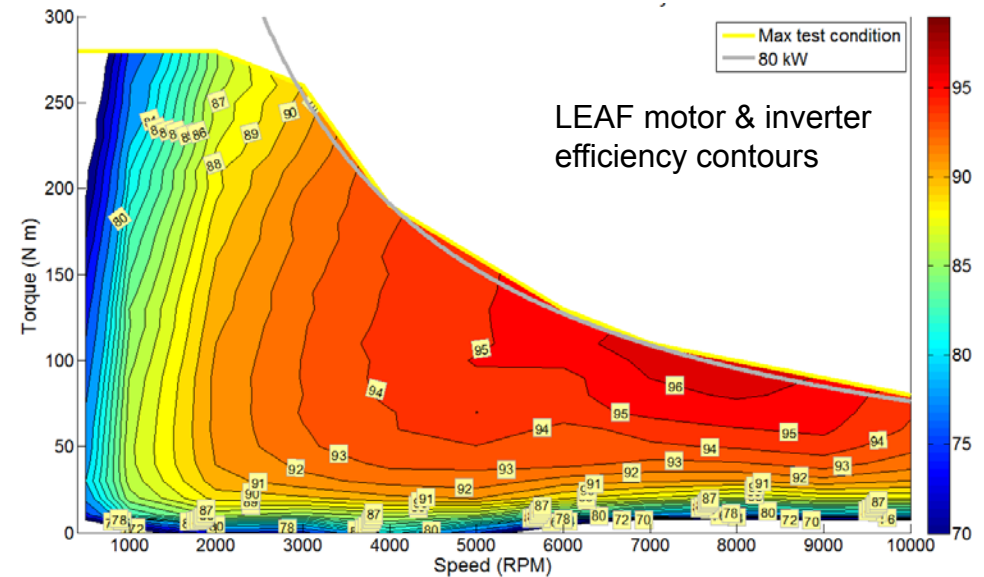
Technical Accomplishments (5)

- Published LEAF ratings verified (280 Nm and 80 kW)
 - Actually operated above 80 kW
- Tests conditions
 - DC-link voltage of 375 V
 - $f_{sw} = 5$ kHz
 - Water-Ethylene Glycol temperature: 65C
- Peak motor efficiency above 97% between 5,000 rpm and 9,000 rpm
 - Significant region above 90%
- Inverter efficiency above 99% for high speeds
- Stator laminations:
 - 0.3 mm (0.012") thick



Technical Accomplishments (6)

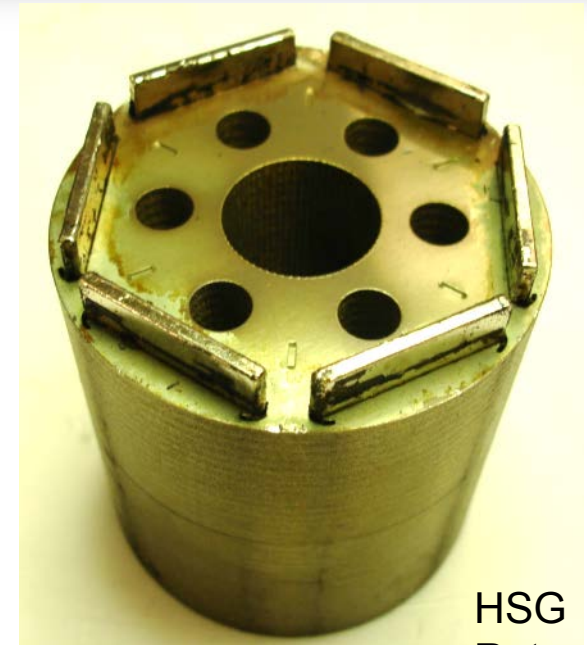
- Combined LEAF inverter/motor efficiency reached above 96%
 - General agreement with published efficiencies
 - ORNL measurements slightly higher
- Wide operation range above 90%
- Capable of operating at 80 kW continuously at 7,000 rpm with stator temperatures leveling out at about 135 C



"Power from Within", Nissan LEAF Special Edition of SAE Vehicle Electrification, p. 17, Feb. 23, 2011.

Technical Accomplishments (7)

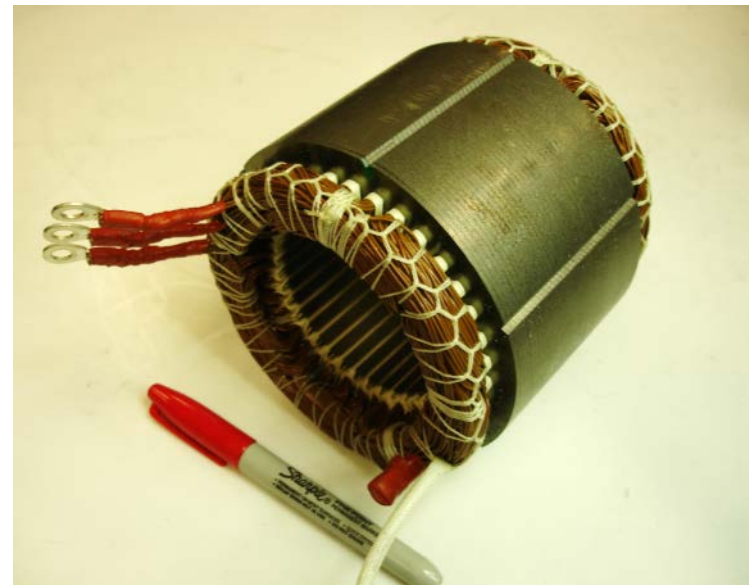
- Hybrid Starter Generator (HSG)
 - Published specifications: 43 Nm, 8.5 kW, 15,750 rpm
 - 3-phase, 36 slot, 6-pole IPM machine
 - Cold start, restart, and generates when low SOC
 - Separate low-temperature coolant loop for HSG and HPCU
 - Drives and is driven by engine belt (crankshaft)
 - Roughly same size as alternator



HSG
Rotor:
2.0 kg



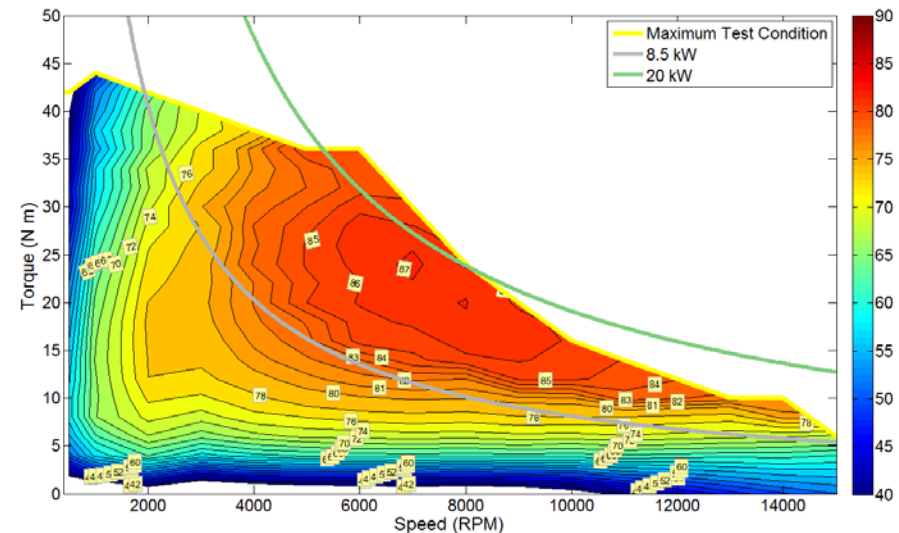
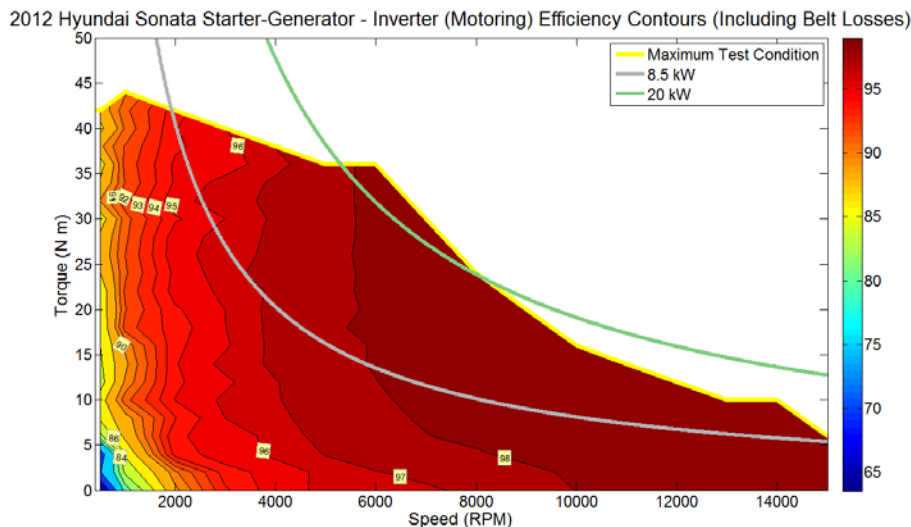
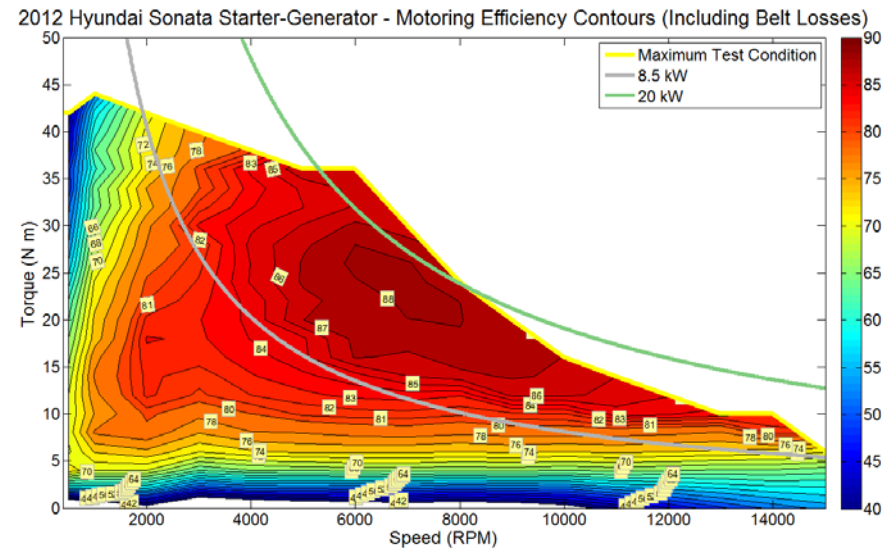
~12 kg, 3.1 L



HSG
Stator:
5.1 kg

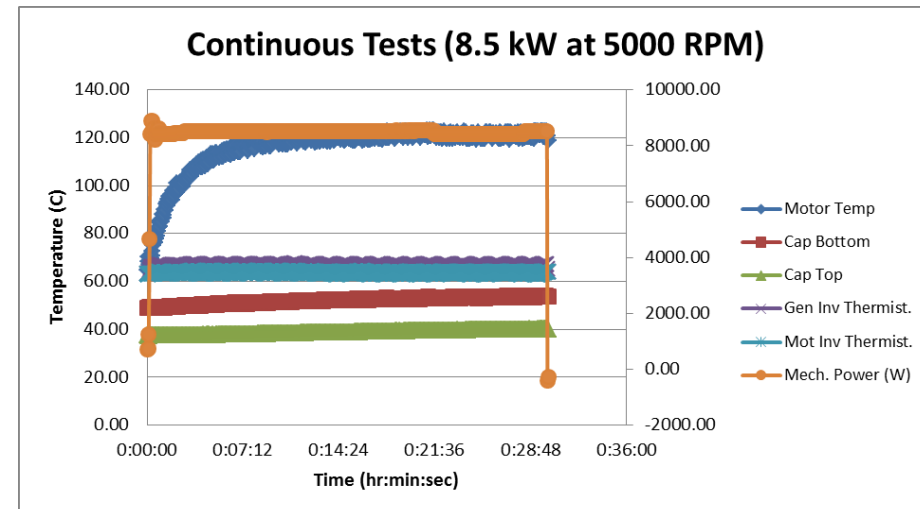
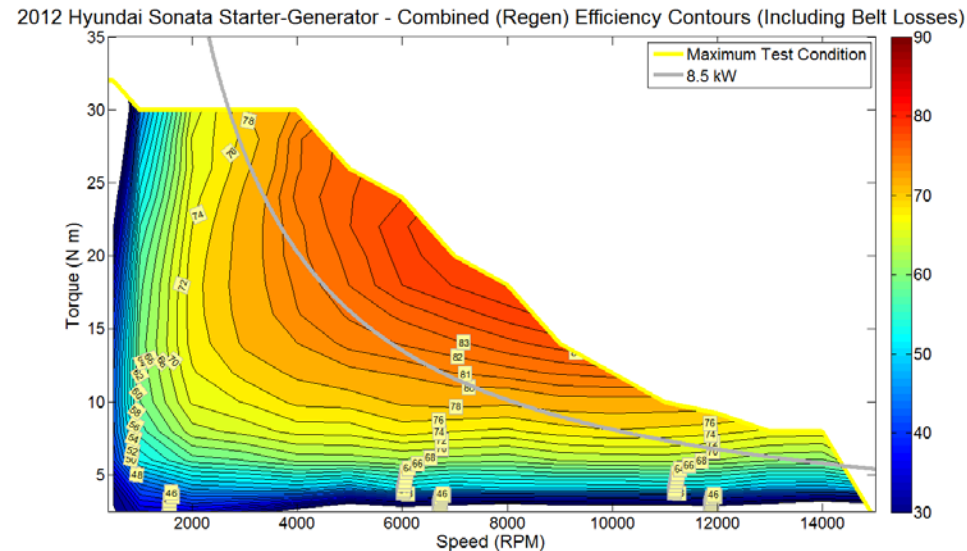
Technical Accomplishments (8)

- Reached above 20 kW operation
- HSG efficiency (including belt losses)
 - Peak: 88%, 84% with 8.5 kW operation limit
 - Belt losses
- HSG Inverter efficiency
 - Peak: 98%
- System (HSG & inverter) efficiency
 - Peak: 87%, 82% with 8.5 kW operation limit



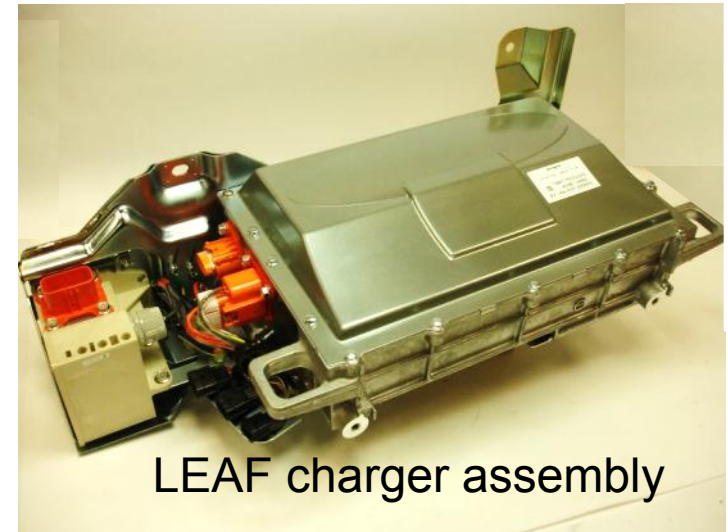
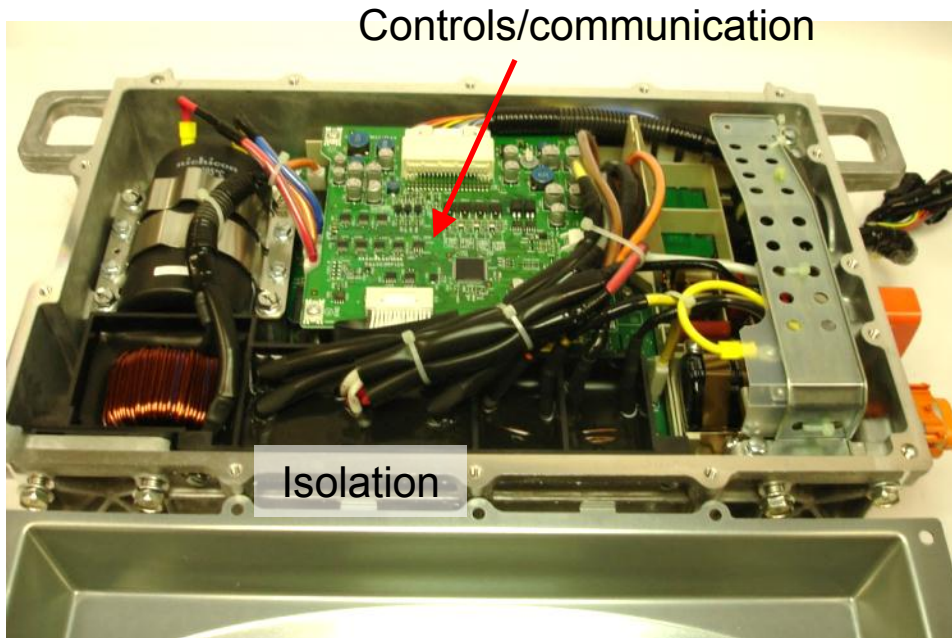
Technical Accomplishments (9)

- HSG regenerative efficiency
 - Peak: 87%, 83% with 8.5 kW operation limit
- HSG inverter efficiency
 - Peak 98%
- System regenerative efficiency
 - Peak 86%, 82% with 8.5 kW operation limit
- Belt losses
 - 1-2% at high power levels
 - 3-6% for moderate loads and low speeds
- Continuous tests at 8.5 kW, motor temperature:
 - Reached 160C after 3 minutes at 3,000 rpm
 - Stabilized at ~120C at 5,000 rpm
 - Stabilized at ~100C at 7,000 and 11,000 rpm
 - Stabilized at ~95C at 9,000 rpm



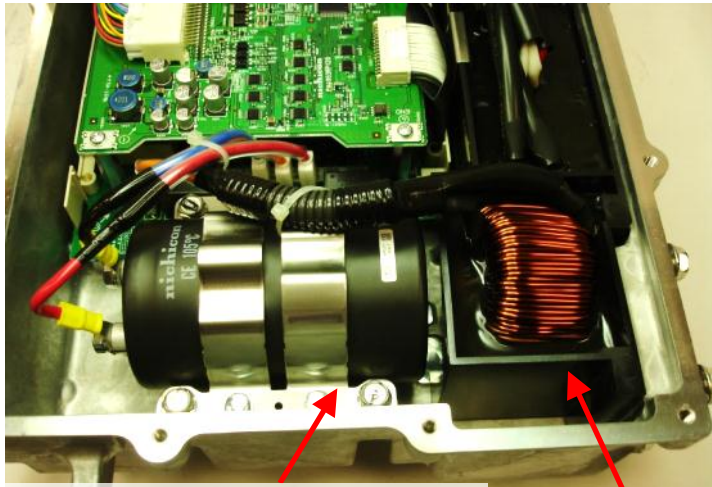
Technical Accomplishments (10)

- 2013 LEAF On-board charger assessments underway
 - Up to 6.6 kW (Separate DC-DC junction box for quick ~50 kW charging)
 - 120 VAC or 240VAC input



Technical Accomplishments (11)

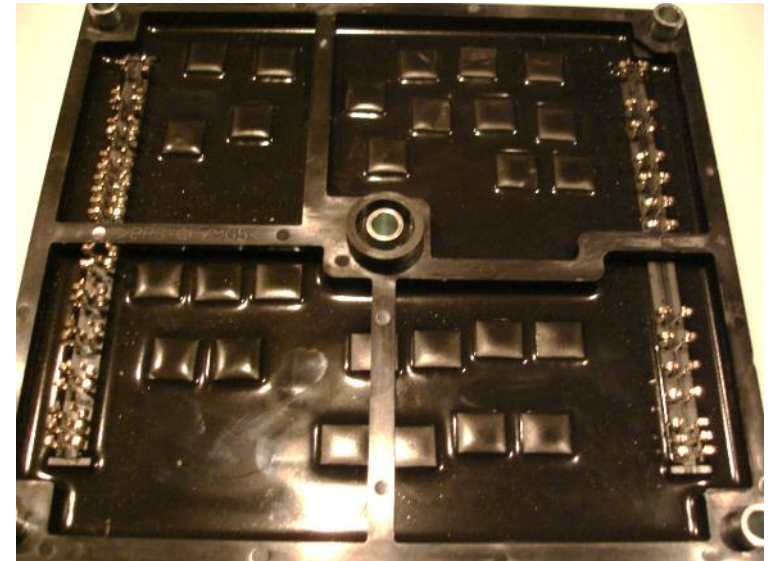
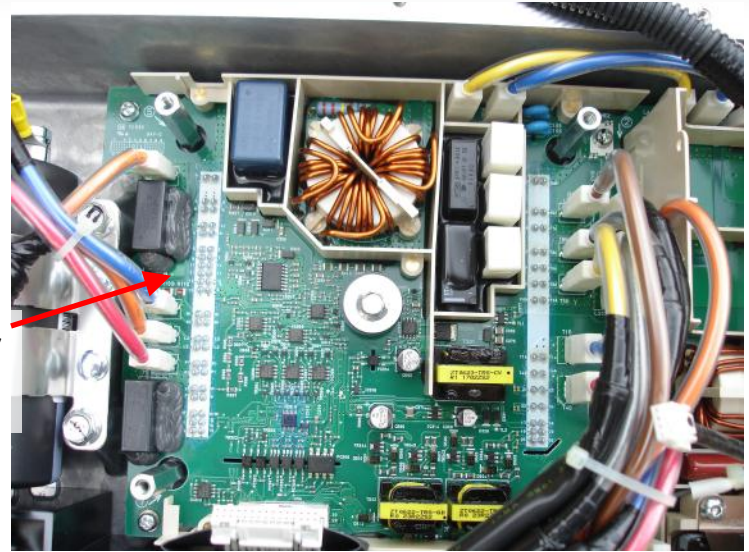
- 2013 LEAF On-board charger
 - Control board, driver/power board, and capacitor by Nichicon



Electrolytic Capacitor
(420 V, 2,700 μ F)

Filter
Inductors

Driver-Power
Board



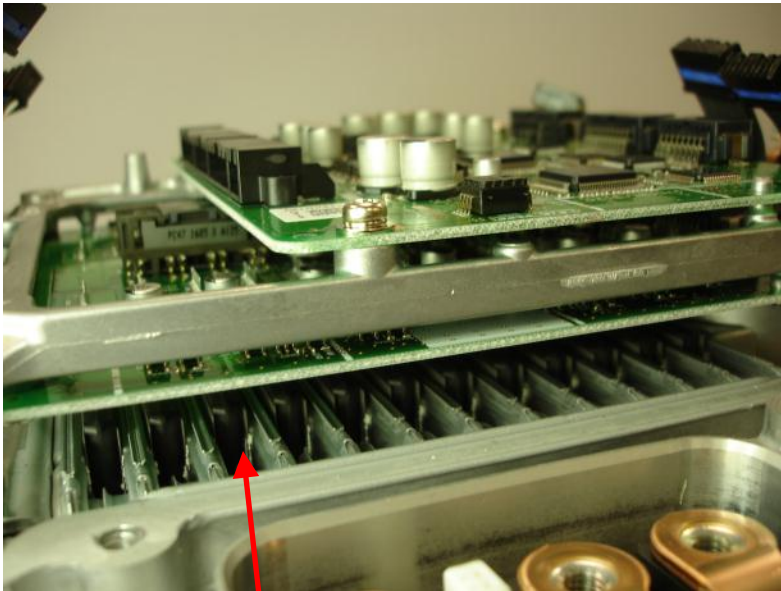
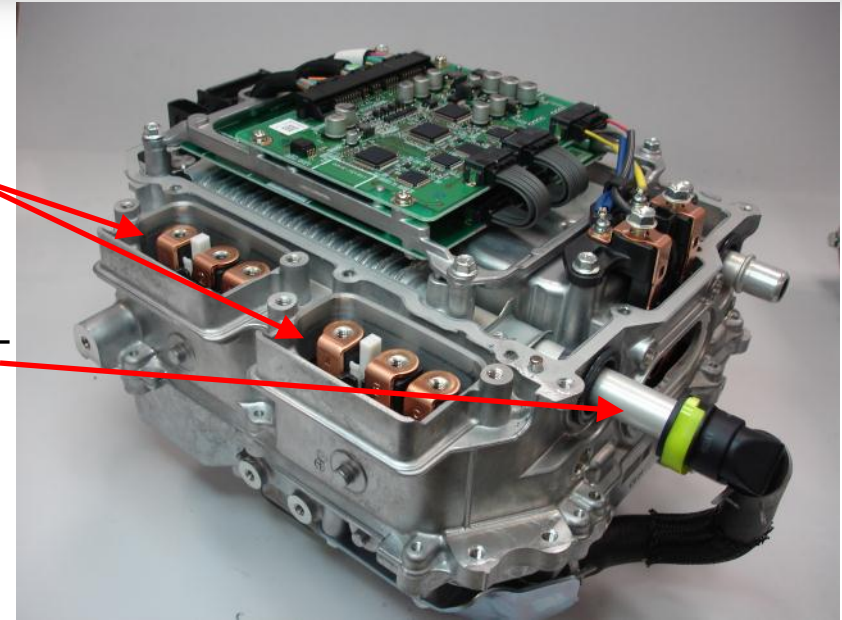
Electronics module (includes rectifiers, inverters)

Technical Accomplishments (12)

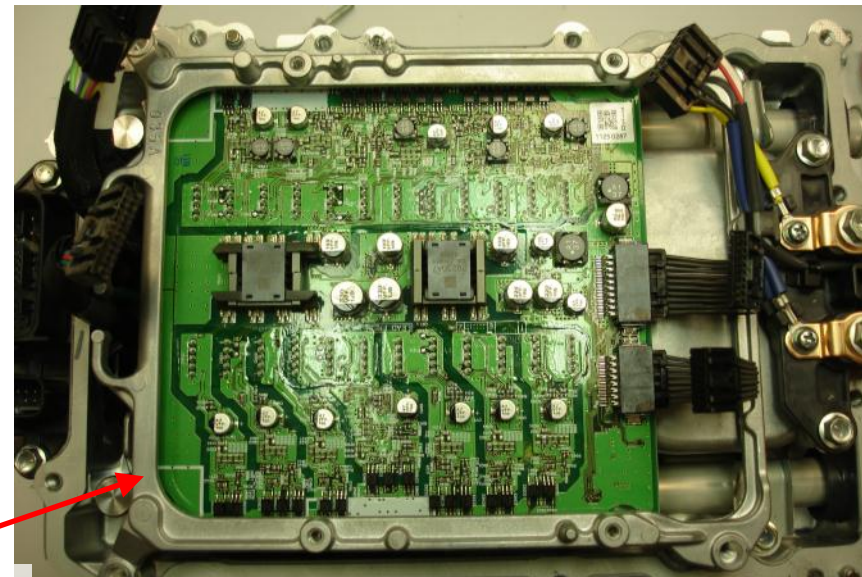
- 2013 Camry Inverter
 - Includes 12V buck converter
 - IGBT/diode packaging with two-sided cooling
 - Similar to Lexus LS 600h
 - Reduction of 6 IGBTs and diodes from previous Camry

Motor-generator outputs

Water ethylene-glycol






IGBT-diode packaging (24 total – 6 generator inverter, 12 motor inverter, 6 boost converter)



Compact driver board

Collaborations and Coordination

Organization	Type of Collaboration/Coordination
Remy 	<ul style="list-style-type: none">• Providing induction machines for comparisons (copper versus aluminum rotor bars).
ANL 	<ul style="list-style-type: none">• Provides system parameters to ORNL from on-the-road tests<ul style="list-style-type: none">– Includes extreme hot/cold temperature tests• Examples:<ul style="list-style-type: none">– Coolant temperature range and common operation conditions– Battery voltage range and common operation conditions• ORNL provides component efficiency and operational characteristics for AUTONOMIE<ul style="list-style-type: none">– Also provides to EPA, automotive manufacturers, and public
NREL 	<ul style="list-style-type: none">• ORNL provides component efficiency and operational characteristics to NREL for thermal studies.

Future Work

- **Remainder of FY13**

- Comparison tests on Remy induction motors: copper versus aluminum rotor bars.
- LEAF on-board charger tests and design/packaging assessments.
- Camry inverter packaging.
- Identify candidate commercially available EV/HEV systems available and relevant to DOE's VTO mission.

- **FY14**

- Select commercially available EV/HEV system relevant to DOE's VTO mission. Candidates include:
 - 2014 Camry inverter/motor.
 - 2014 Honda Insight.
 - Remy interior permanent magnet motor.
- Perform standard benchmarking of selected system.

Summary

- **Relevance:** The core function of this project is to observe and define the current state-of-the-art of EV/HEV technologies.
- **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 2012 Nissan LEAF inverter, motor, and 2013 charger.
- **Future work:** FY13 efforts are on track, and FY14 plans are in place.