U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Benchmarking of Competitive Technologies

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Oak Ridge National Laboratory

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Project ID: APE006

2012 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting
Washington, D.C.

Overview

Timeline

- Start: FY04
- Finish: Ongoing

Barriers

- Obtaining parts for newly released vehicles
- Integrating ORNL developed controller with OEM components
- Adapting non-standard motor assembly to test cell

Budget

- Total project funding
  - DOE: 100%
- Funding received in FY11: $465K
- Funding received in FY12: $550K

Partners

- Argonne National Laboratory
- Electric Transportation Applications
- Idaho National Laboratory
- National Renewable Energy Laboratory
- ORNL Team Members
  - Steve Campbell, Chester Coomer
  - Andy Wereszczak, Materials Science and Technology Division

Objectives

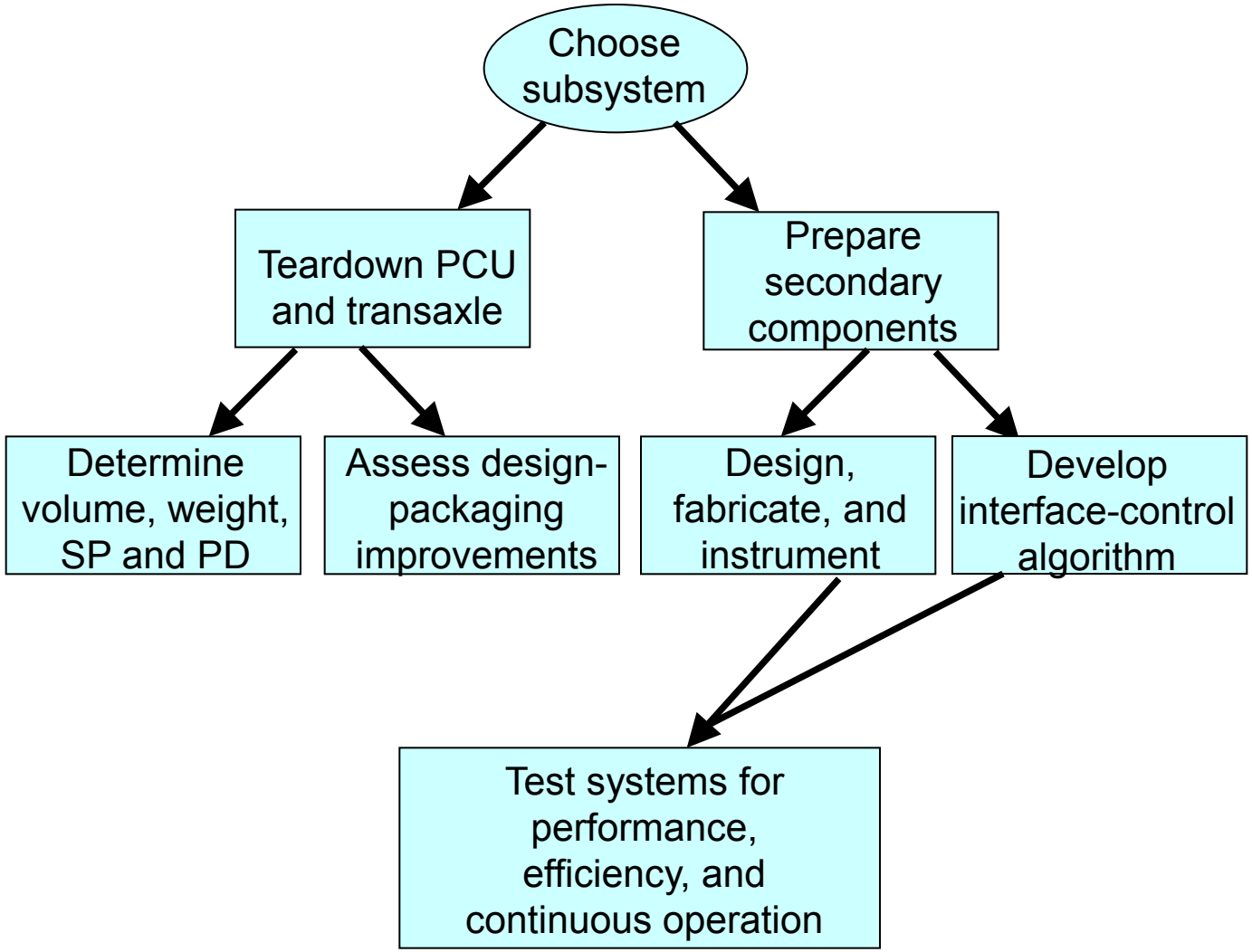
- **Benchmark on-the-road HEV or PEV vehicle technologies**
  - Assess design, packaging, and fabrication characteristics from intensive disassembly of subsystems
    - Determine techniques used to improve specific power and/or power density
    - Reveal compositions and characteristics of key components
      - Trade-offs (e.g. magnet strength vs coercivity)
      - General cost analysis
  - Examine performance and operational characteristics during comprehensive test-cell evaluations
    - Establish realistic peak power rating (18 seconds)
    - Provide detailed information regarding time-dependent and condition-dependent operation
  - Develop conclusions from evaluations and assessments
    - Compare results with other HEV technologies
    - Identify new areas of interest
    - Evaluate advantages and disadvantages of design changes
      - Example: Complexity of LS 600h double sided cooling system

- **FY12 objectives**
  - Complete 2011 Hyundai Sonata hybrid benchmarking studies
  - Complete 2012 Nissan Leaf hybrid benchmarking studies

Milestones

Month/Year	Milestone or Go/No-Go Decision
September 2011	**Milestone: Completed 2011 Hyundai Sonata inverter/motor testing (completed in November due to driver board issues)**
September 2011	**Go/No-Go decision: Determined which on-the-road HEV or PEV system is available and desirable to benchmark**
September 2012	**Milestone: Complete 2011 Hyundai Sonata inverter/generator testing**
September 2012	**Go/No-Go decision: Determine which on-the-road HEV or PEV system is available and desirable to benchmark**

Approach



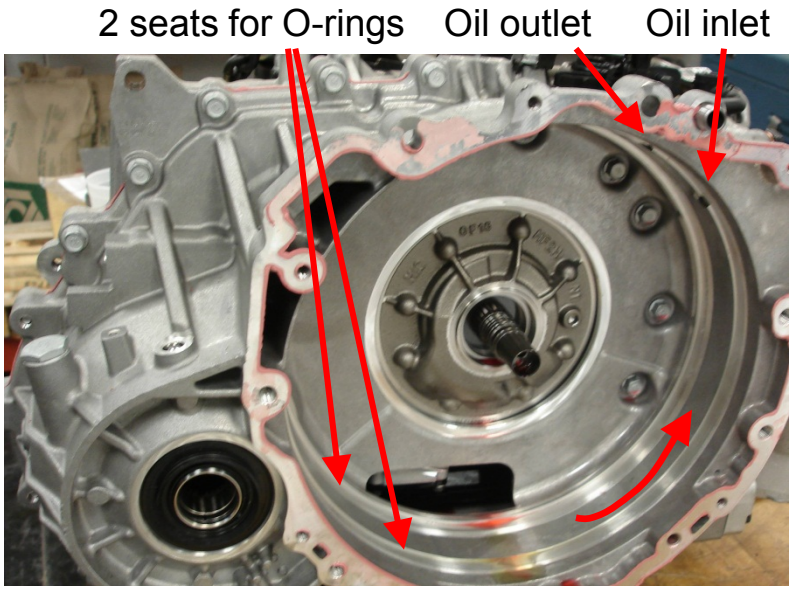
Overall Technical Accomplishments

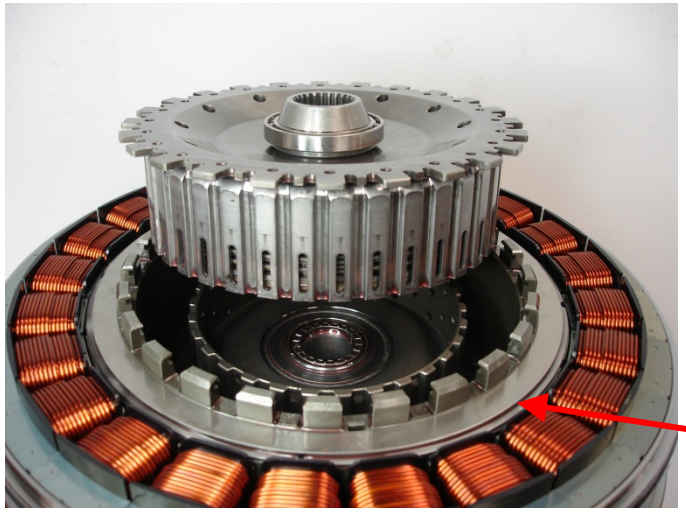
- **Detailed comparisons of progressing technologies**
  - 2004 Prius, 2006 Accord, 2007 Camry, 2008 LS 600h, 2010 Prius, and 2011 Hyundai Sonata
  - 2011 Sonata motor improves over similarly benchmarked system
    - PD and SP nearly 2x 2006 Accord and comparable to 2004 Prius,
    - Falls short of 2010 Prius, 2008 LS 600h, and 2007 Camry
      - Note: Sonata has 270V DC bus versus 650V and has lower speed rating
  - 2011 Sonata PEM improves over similarly benchmarked system
    - PD and SP similar to 2010 Prius/2007 Toyota when including boost converter mass/volume
    - PD and SP similar to 2004 Prius when neglecting boost converter mass/volume

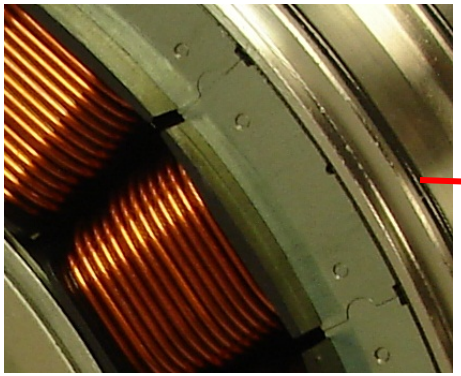
Component & Parameter	2011 Sonata (30 kW)	2010 Prius (60 kW)	2008 LS600h Lexus (110 kW)	2007 Camry (70 kW)	2006 Honda Accord (12 kW)	2004 Prius (50 kW)
Motor						
Peak power density, kW/L	**3.0**	**4.8**	**6.6**	**5.9**	**1.5**	**3.3**
Peak specific power, kW/kg	**1.1**	**1.6**	**2.5**	**1.7**	**0.5**	**1.1**
Inverter Excludes generator inverter (parenthetical values exclude boost converter mass/volume)						
Peak power density, kW/L	**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	**6.9**	**6.9** (16.7)	**7.7** (14.9)	**5.0** (9.3)	**2.4**	**3.8** (6.2)

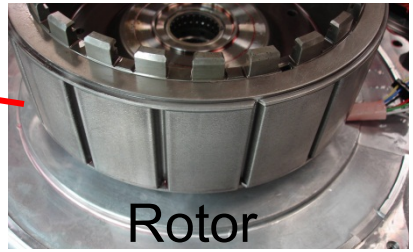
Technical Accomplishments (1)

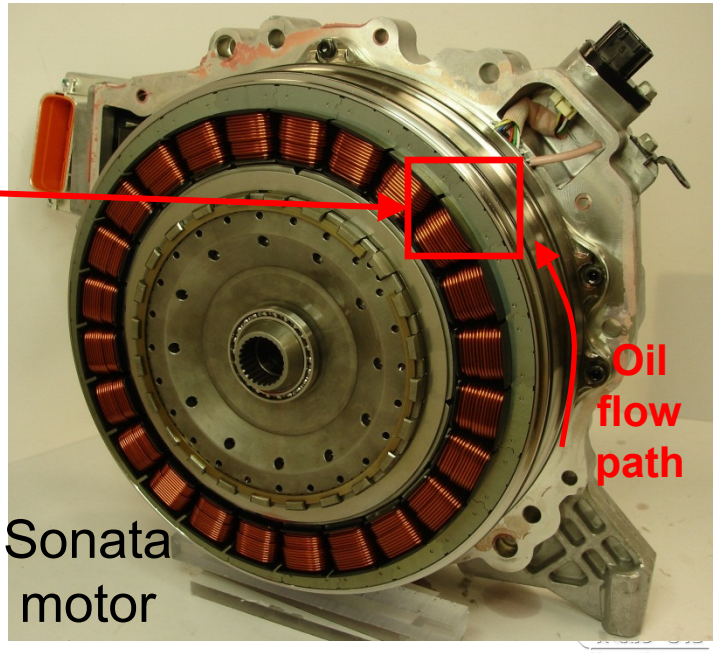
- **Sonata transaxle/transmission**
  - Conventional 6 speed transmission
  - Motor replaces torque converter
    - But not simply interchanged
  - Primary motor: 205 Nm and 30 kW ratings
    - Approximate corner speed: 1400 rpm
    - Motor very similar to Honda hybrids
    - 24 stator teeth and 16 rotor poles
  - Resolver similar to Toyota/Honda
  - 3-phase oil pump
  - Clutch integrated into motor rotor
  - Oil cooling path around stator







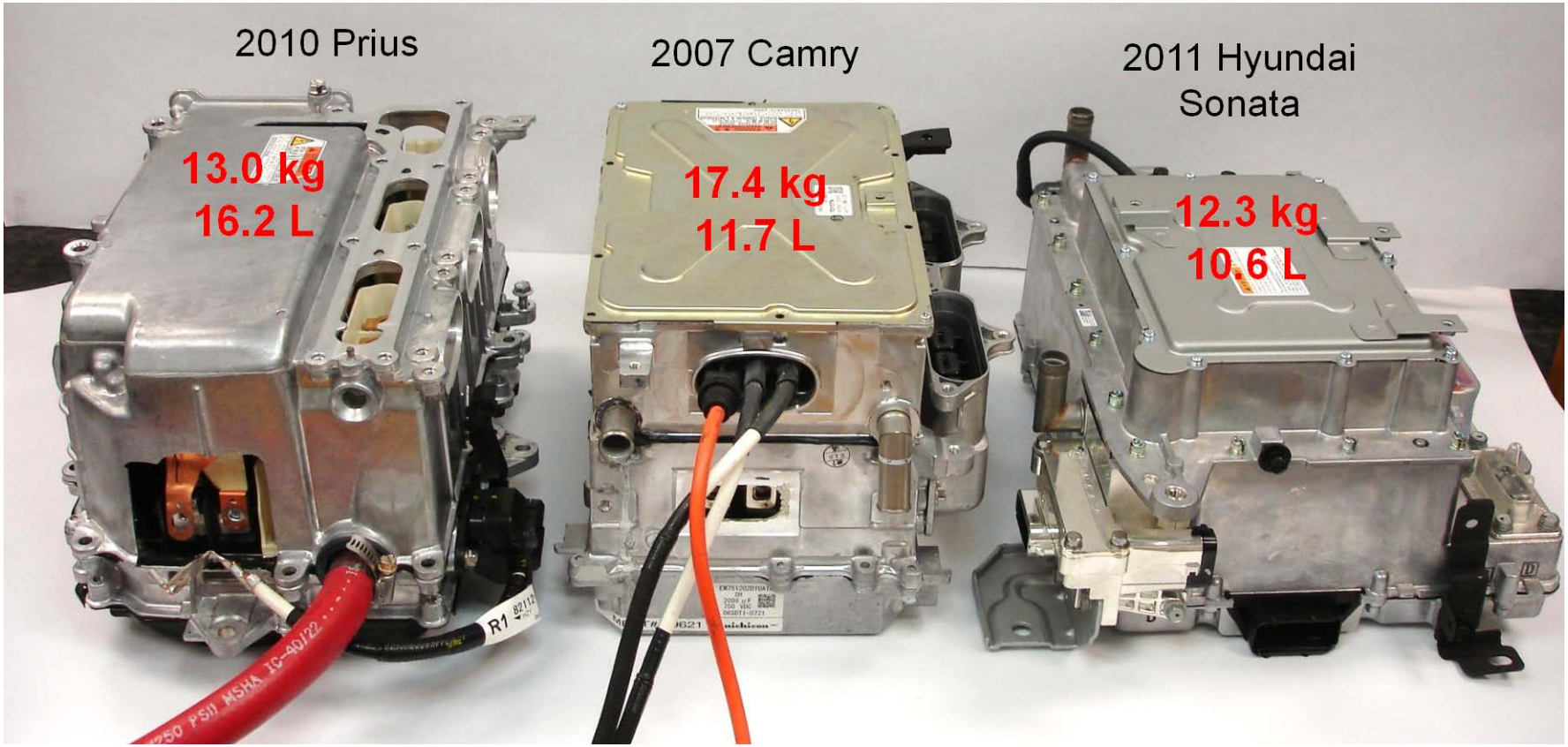




Technical Accomplishments (2)

- **Comparison of hybrid PCUs**
  - Comparable volume despite much lower power capabilities

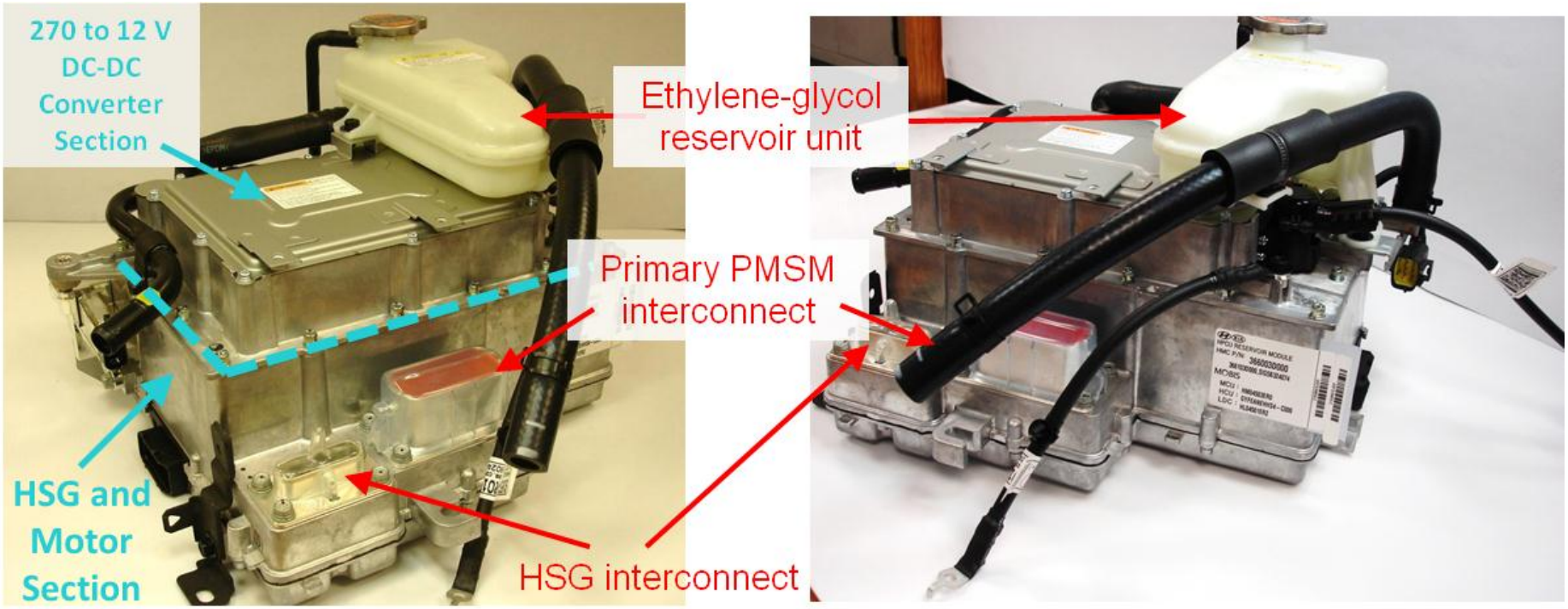
(Updated labels)



Technical Accomplishments (3)

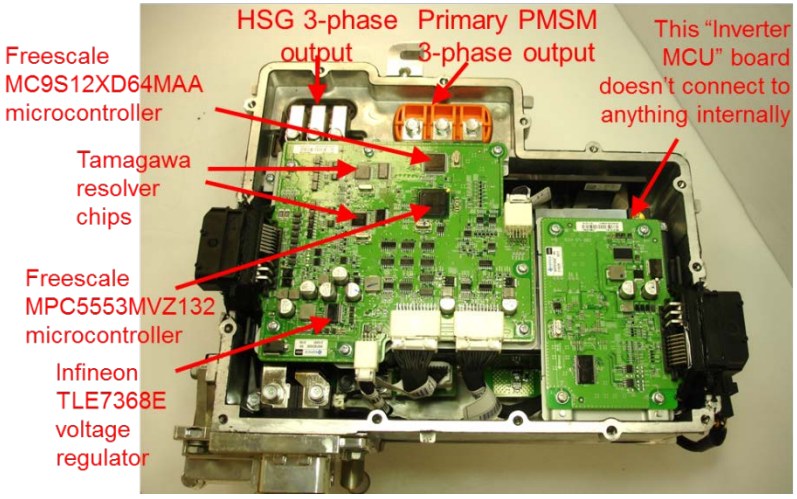
- **Hyundai Sonata PCU compartments**
  - Includes inverters for HSG and primary PMSM
  - 270V to 12V accessory converter
    - Note alternator efficiency
  - Cooling system reservoir with pressure bleed cap (HSG and PCU)

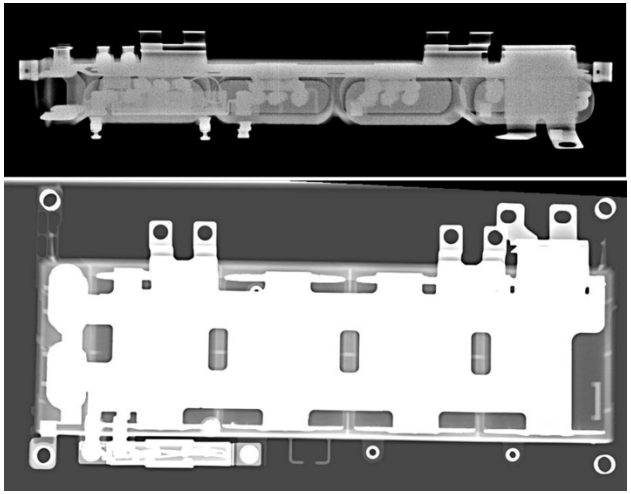
(Updated images/labels)

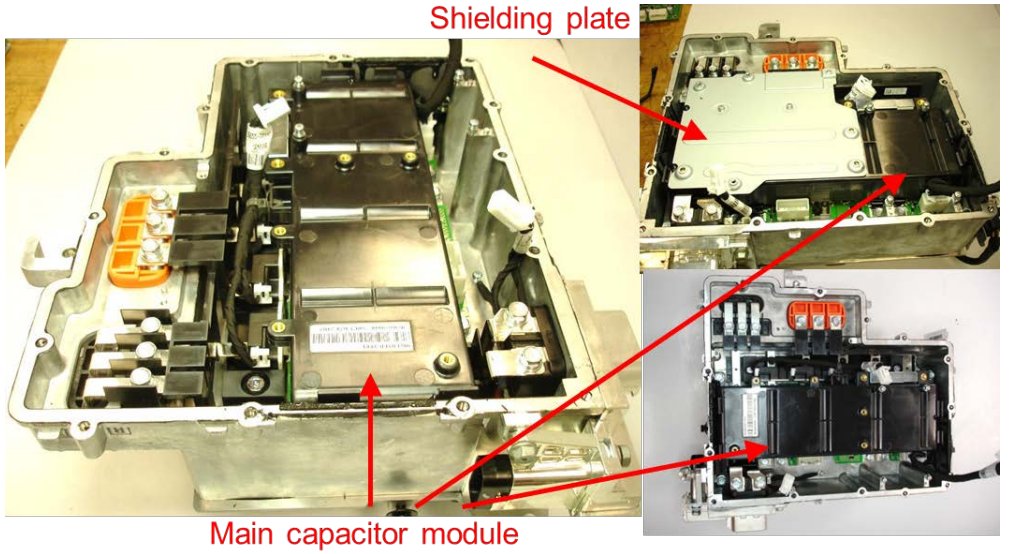


Technical Accomplishments (4)

- **PCU in series with HSG on ethylene glycol coolant loop**
- **Cast aluminum heat exchanger**
- **Many recognizable components on control board**
- **SH Film Capacitor by Nuintek**
  - 600V, 680 µF and two 0.28 µF capacitors
  - Integrated bus bars
- **LEM HAH1DR-500S and 300S current transducers (two each)**

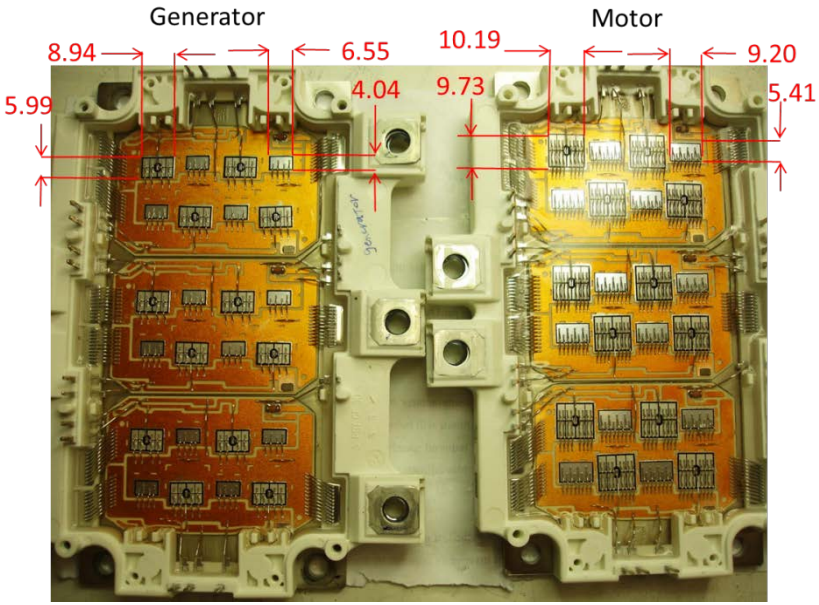


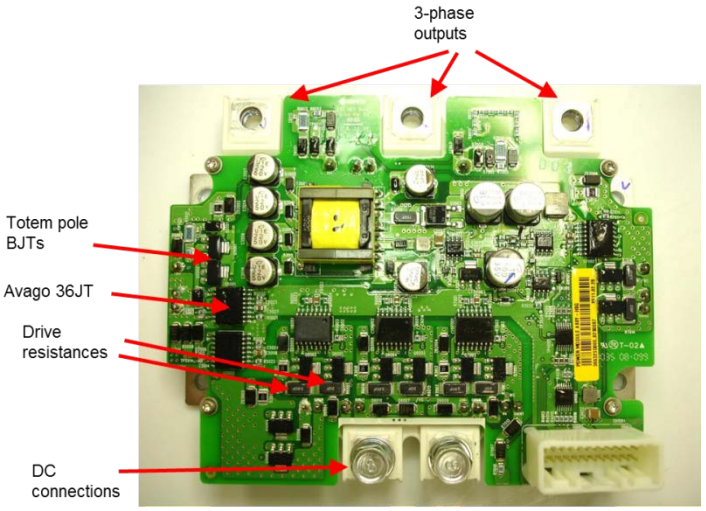


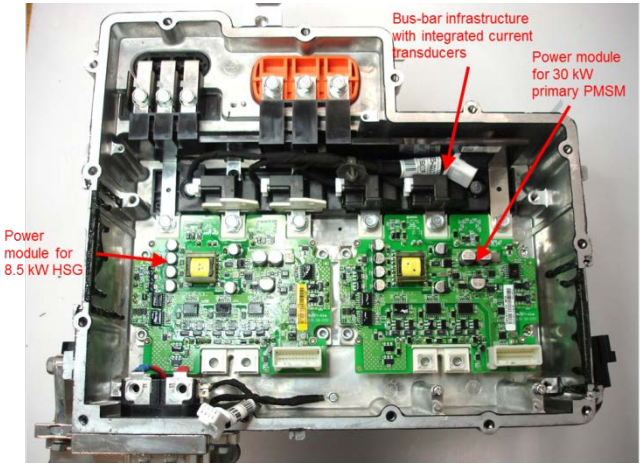


Technical Accomplishments (5)

- **Standard gate drive circuitry**
  - Avago driver
  - Totem pole BJT output
- **30 kW and 8.5 kW Infineon PEMs**
  - Appears to be HybridPack1
  - Same package size for both power levels
- **Motor IGBT and diode cross-sectional area about 1.9 times that of HSG**
  - 30/8.5 = 3.53
- **Total cross-sectional silicon area: 2155 mm^2**
  - Motor: 1195 mm^2
  - HSG: 960 mm^2

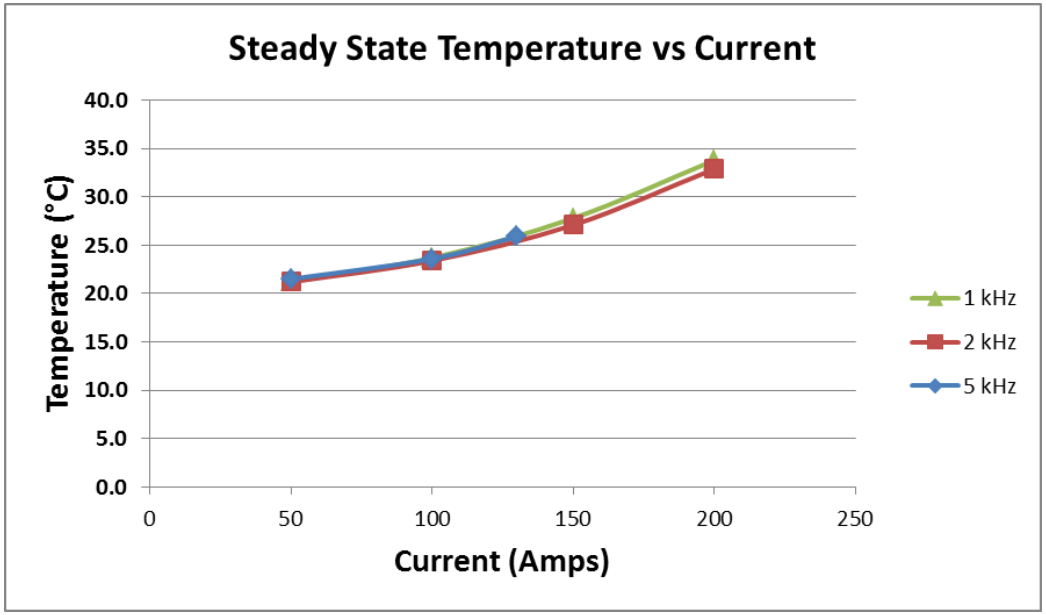


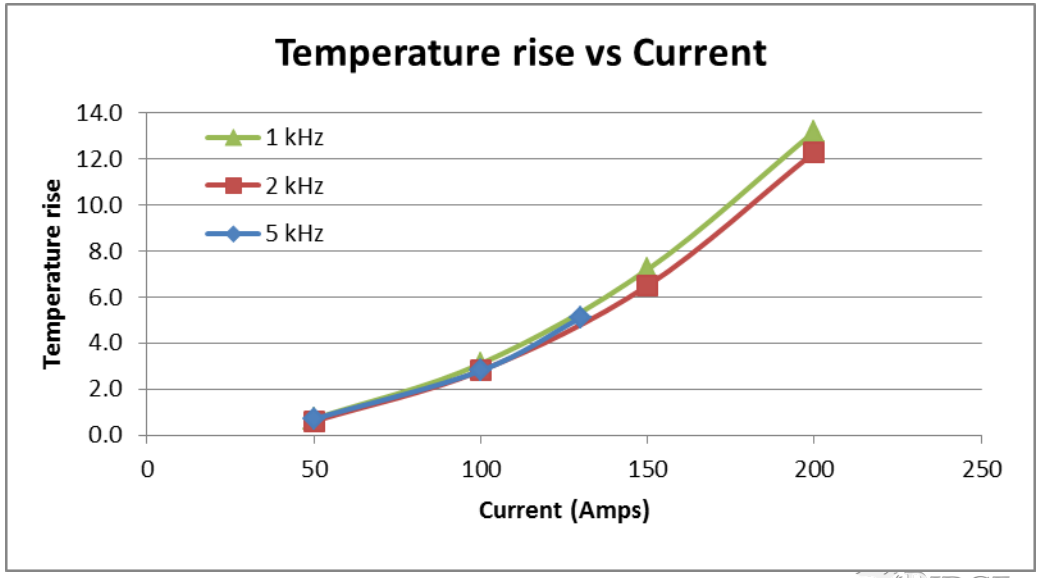




Technical Accomplishments (6)

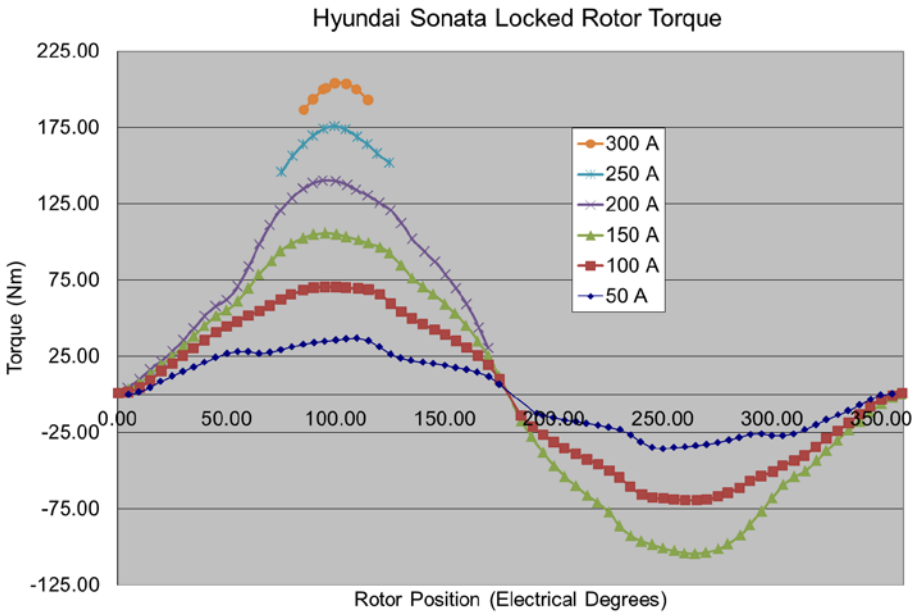
- **Hyundai Sonata 888 µF capacitor tests**
  - Ripple current tests conducted in environmental chamber with steady ambient temperature of 21C
  - Temperature measurement observed after steady-state conditions observed (nearly constant temperature)
  - Usually 30-60 minutes to reach steady state
  - Delta-T relatively unaffected by frequency between 2 and 5 kHz

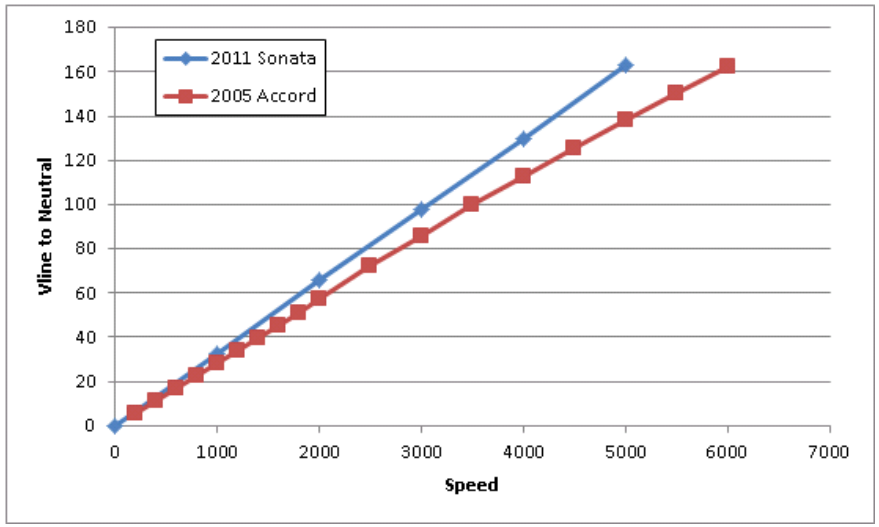


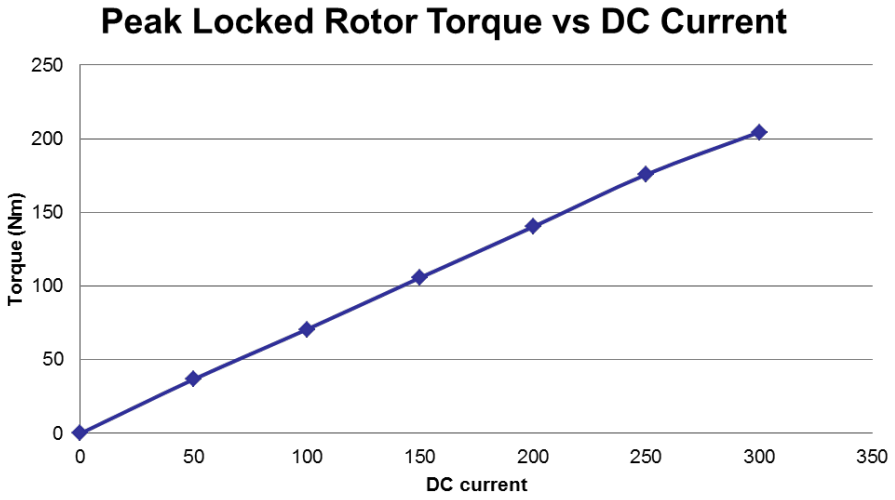


Technical Accomplishments (7)

- **Sonata motor back-EMF reaches 120 V_{ln} at about 3,750 rpm**
  - 120 is approximate maximum output from 270V DC link inverter
- **About 300 A_{DC} required to produce published peak torque of 205 Nm**
- **Torque-per-current is nearly linear up to 250 A_{DC}**
- **Slight indication of saturation at 300 A_{DC}**
  - Toyota machines operate in saturation at much lower current levels
- **Additional results available**

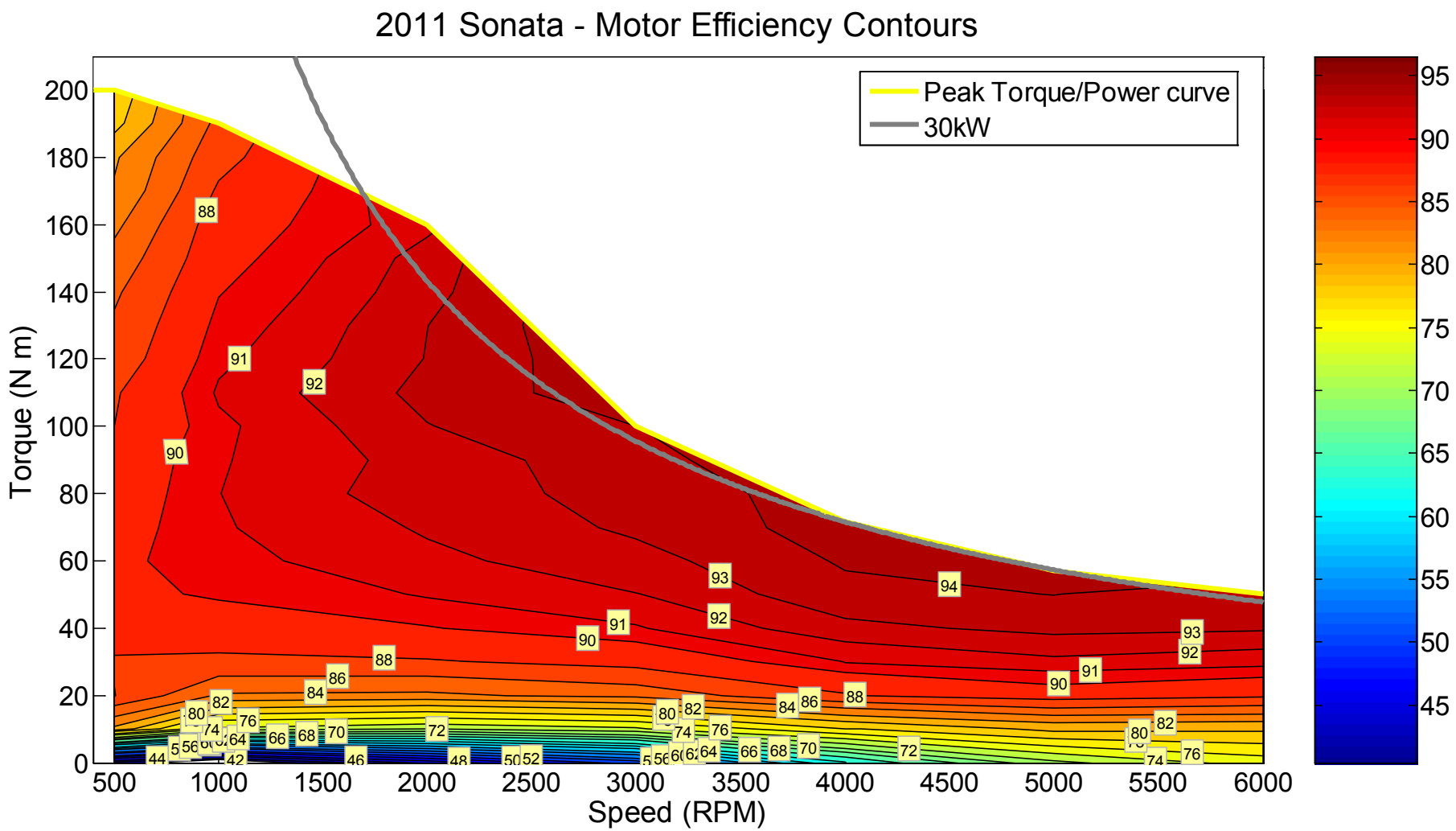






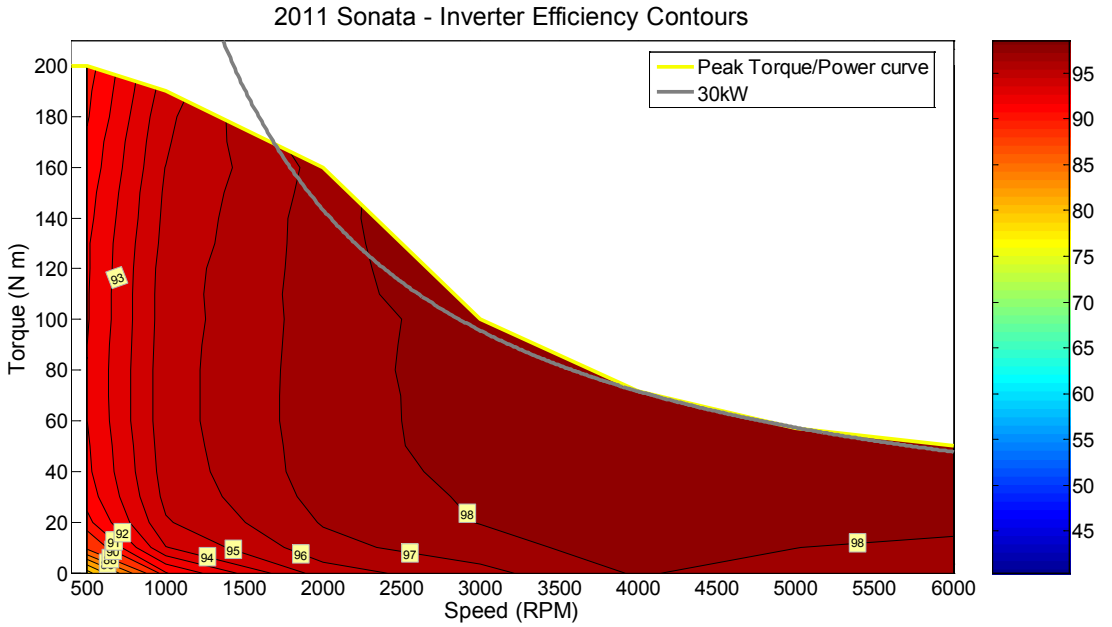
Technical Accomplishments (8)

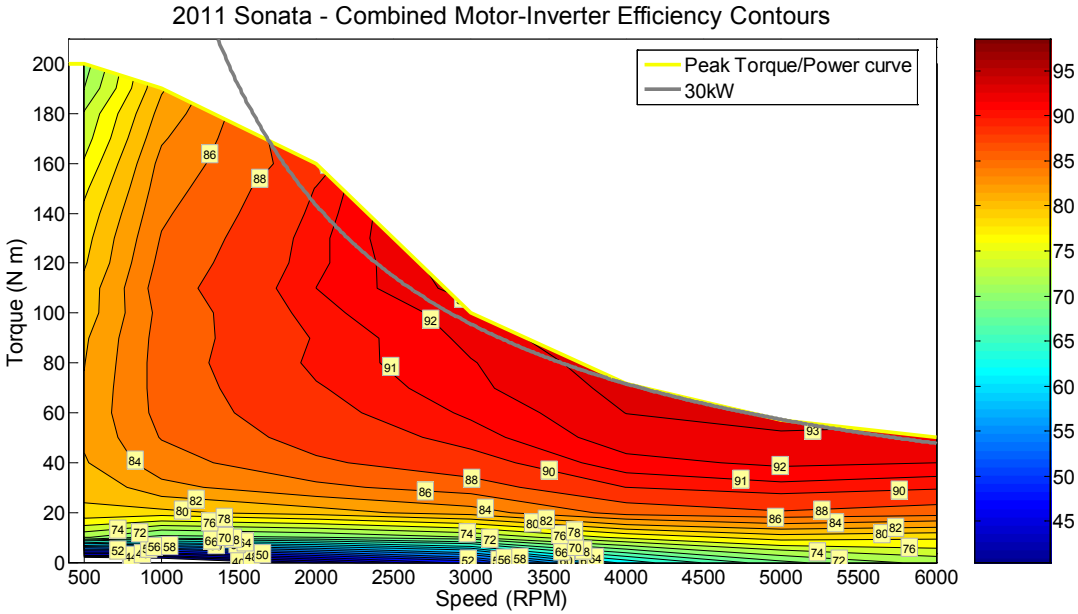
- **Sonata motor reached more than 30 kW**
- **Considerable operation range above 90%**
- **Maximum efficiency above 94%**
- **30 kW reached at rated speed (6,000 rpm)**
  - Either mechanical speed rating or 30 kW desired at speeds for EV operation



Technical Accomplishments (9)

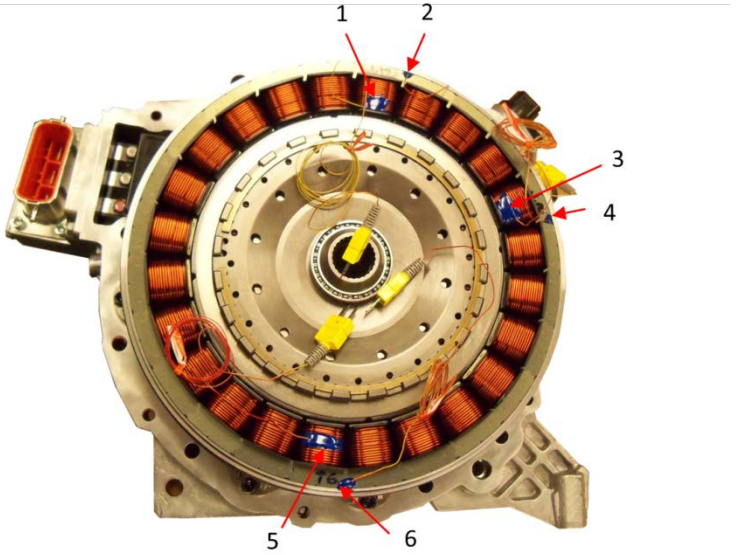
- **Maximum Sonata inverter efficiency of over 98%**
- **Maximum combined motor-inverter efficiency is about 93%**

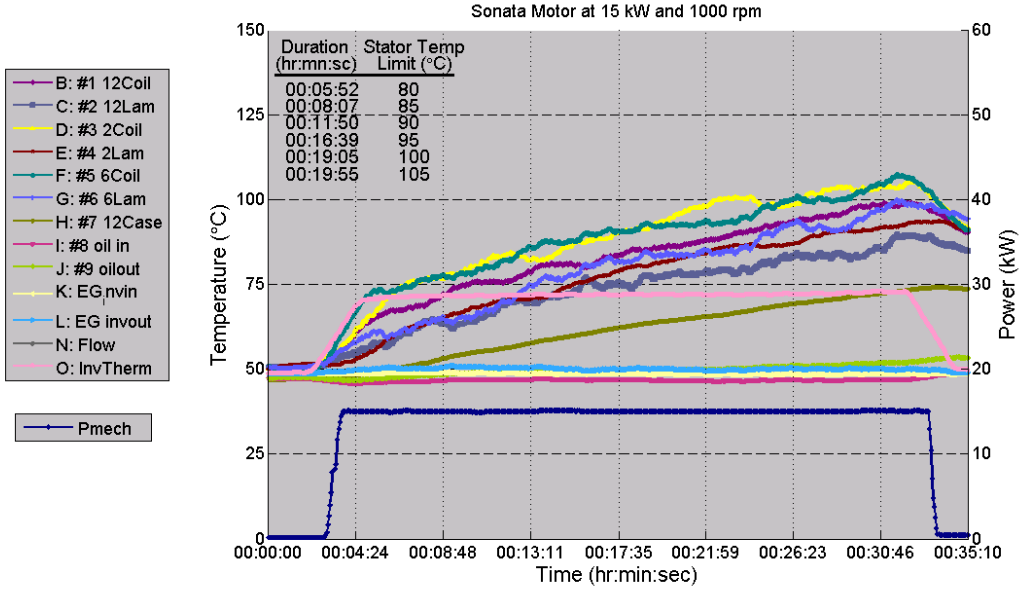




Technical Accomplishments (10)

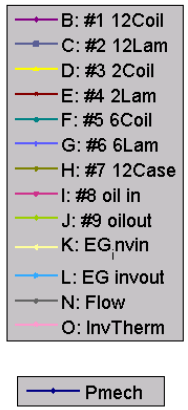
- **Sonata motor continuous tests conducted with 50C coolant**
  - 1,000 rpm and 15 kW
  - 3,000 rpm at 15 and 25 kW
  - 5,000 rpm at 15 and 25 kW
- **Inverter most stressed at 1,000 rpm (pink trace corresponds with inverter thermistor)**
- **Thermocouple locations:**
  - Thermocouples 2, 4, & 6 are located in the center of the cooling channel
  - Thermocouple 7 is located on the exterior of the housing at the 12 o'clock position similar to the placement of thermocouple 2
  - Thermocouples 8 & 9 are located in the inlet and outlet of the oil cooling lines, respectively

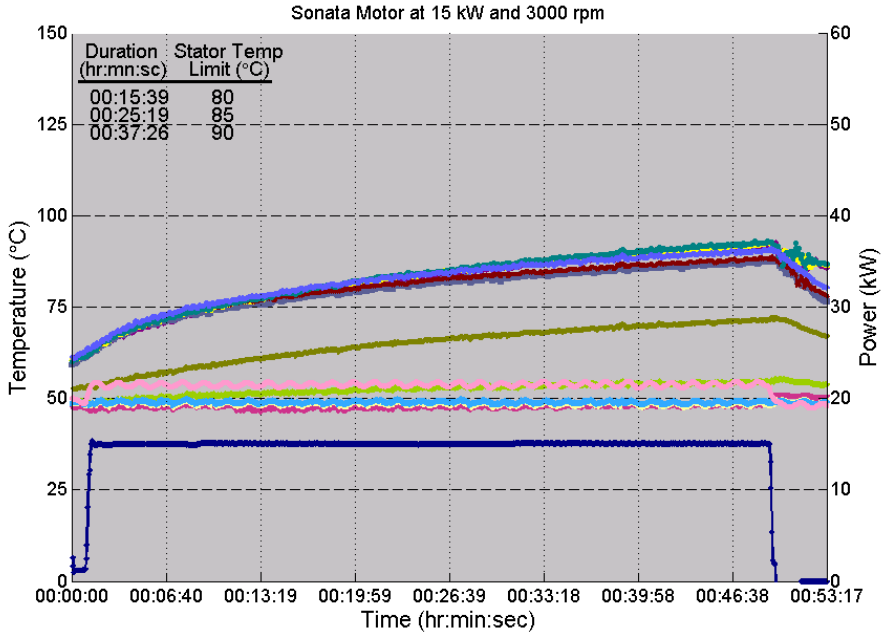


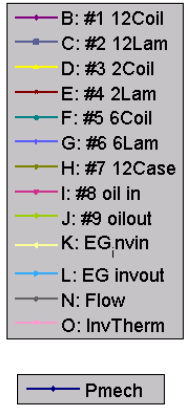


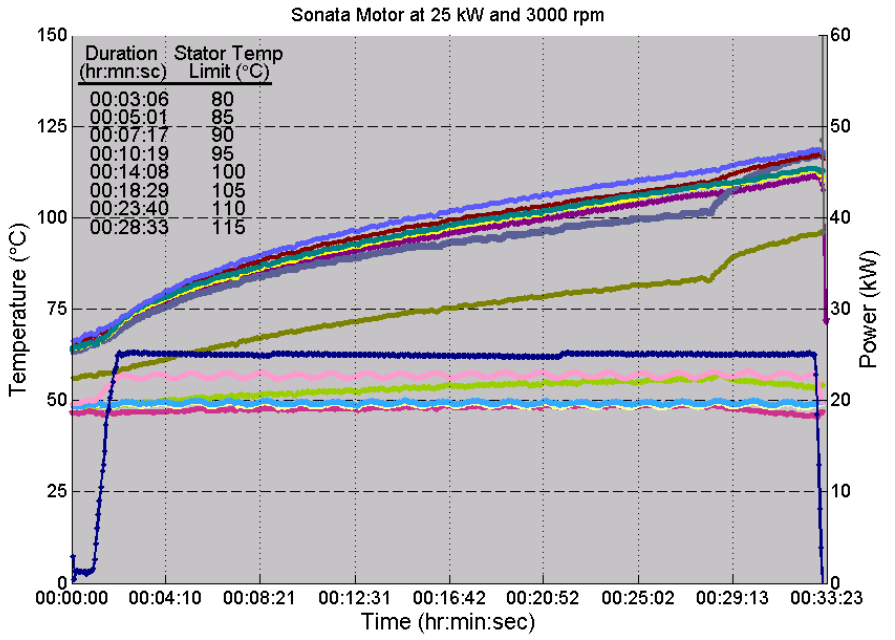
Technical Accomplishments (11)

- Sonata motor operates at 15kW and 3000 rpm for about an hour without reaching 100C
- Operates at 25kW and 3000 rpm for about 30 minutes and hottest temperature reaches about 115C
- Note low inverter temperature



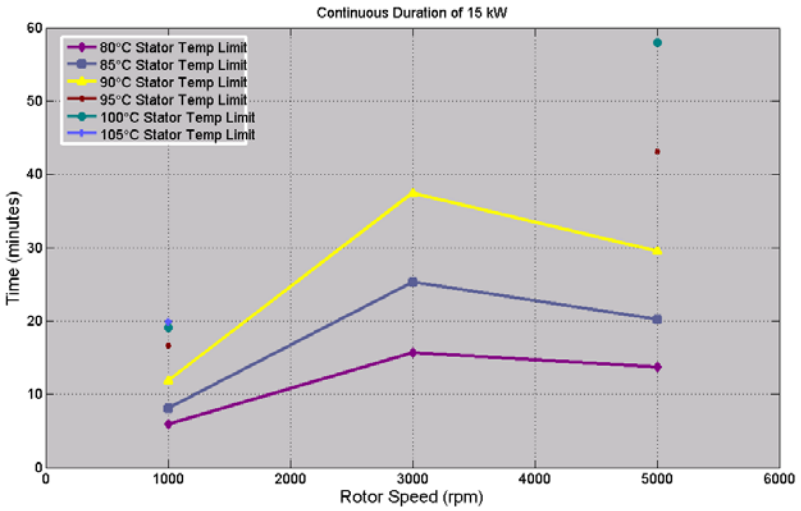


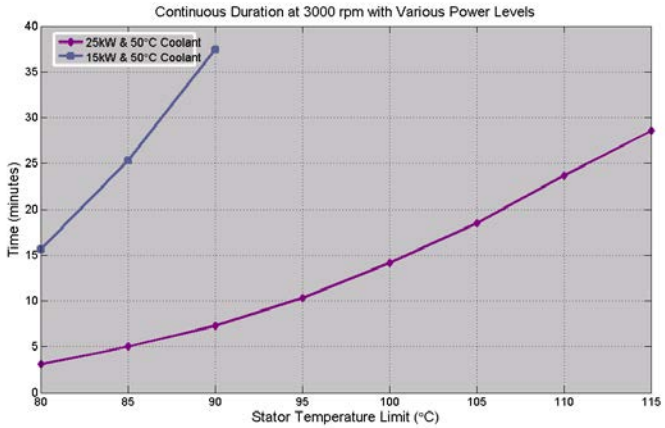


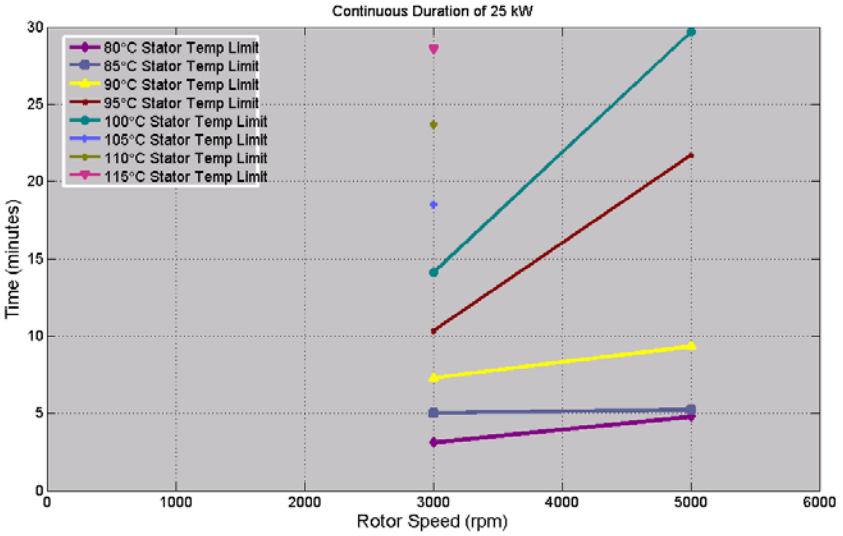


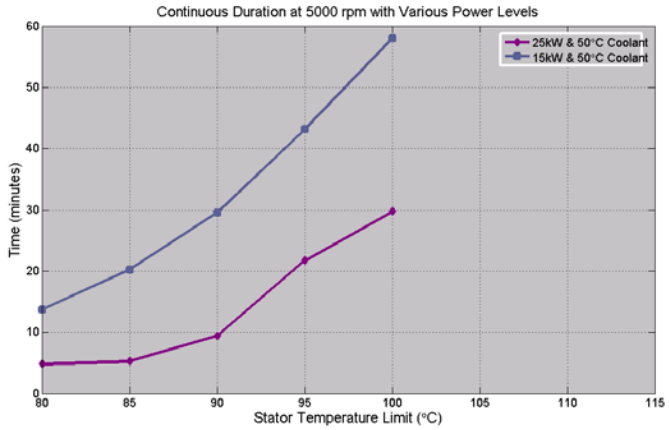
Technical Accomplishments (12)

- **Sonata motor duration versus speed:**
  - 1000 rpm / 15kW operation begins slow thermal runaway after 15 minutes
  - Note difference between 25 kW duration at 3000 and 5000 rpm
  - 15 KW operation is slightly better at 3000 rpm than for 5000 rpm
  - 25 kW operation much better for 5000 rpm tests



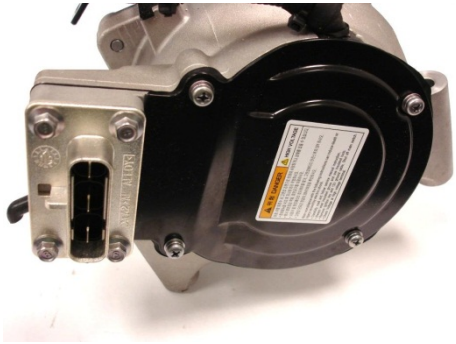


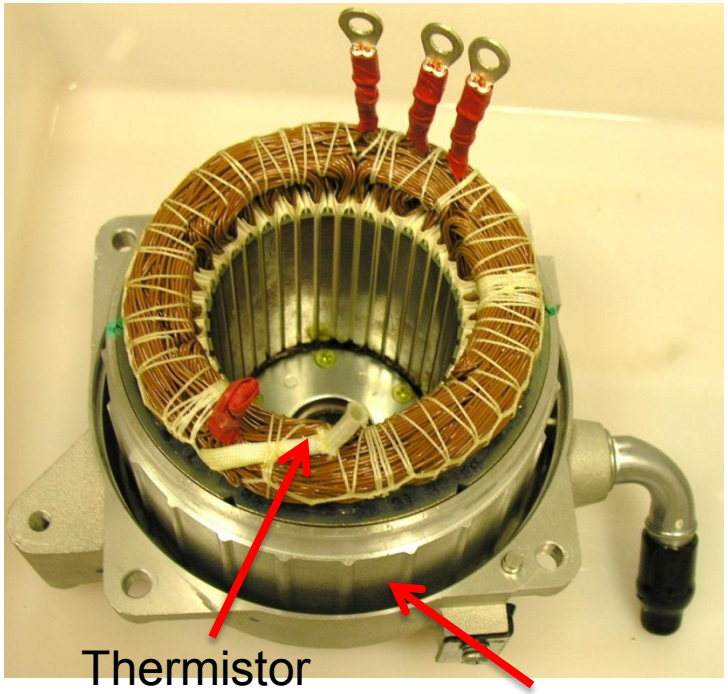




Technical Accomplishments (13)

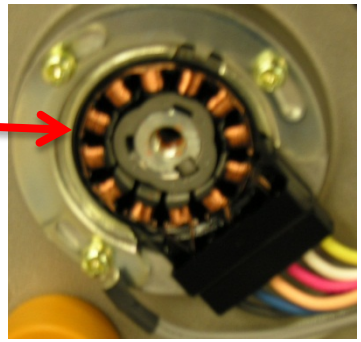
- **Sonata Hybrid Starter Generator (HSG)**
  - 43 Nm, 8.5 kW
  - 3-phase IPM machine
  - Cold start, restart, and generates when low SOC
  - Separate low-temperature coolant loop for HSG and HPCU
  - Drives and is driven by engine belt (crankshaft)
  - Roughly same size as alternator
  - 36 stator slots, 8 pole rotor
  - Ethylene glycol cooling jacket

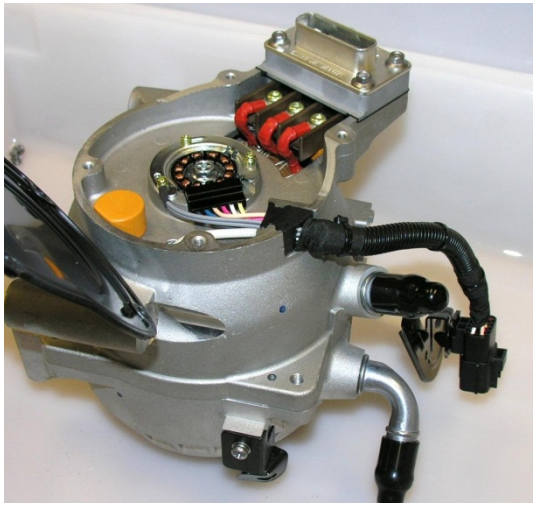


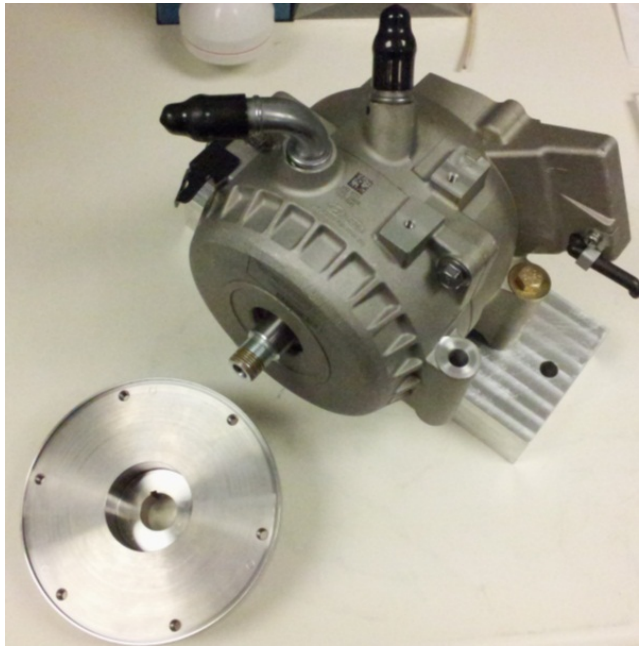


Technical Accomplishments (14)

- **Position resolver**
  - 12 pole stator
  - 3 lobes on resolver rotor
- **Sonata HSG Shaft adapter and mounting plate designed and fabricated**

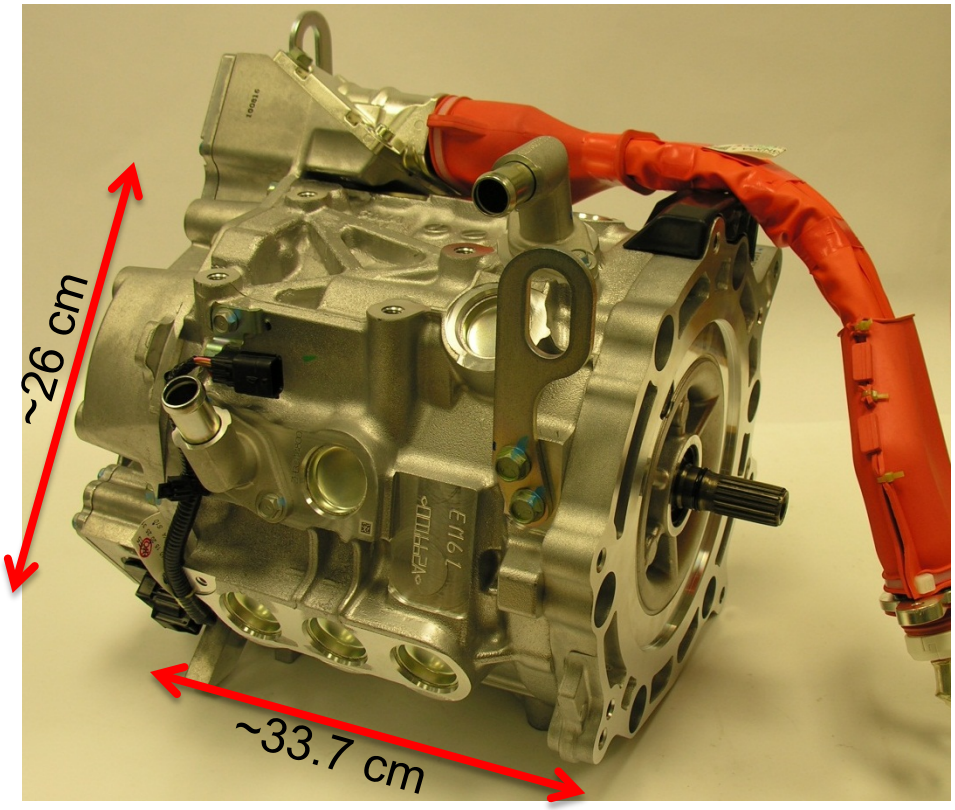


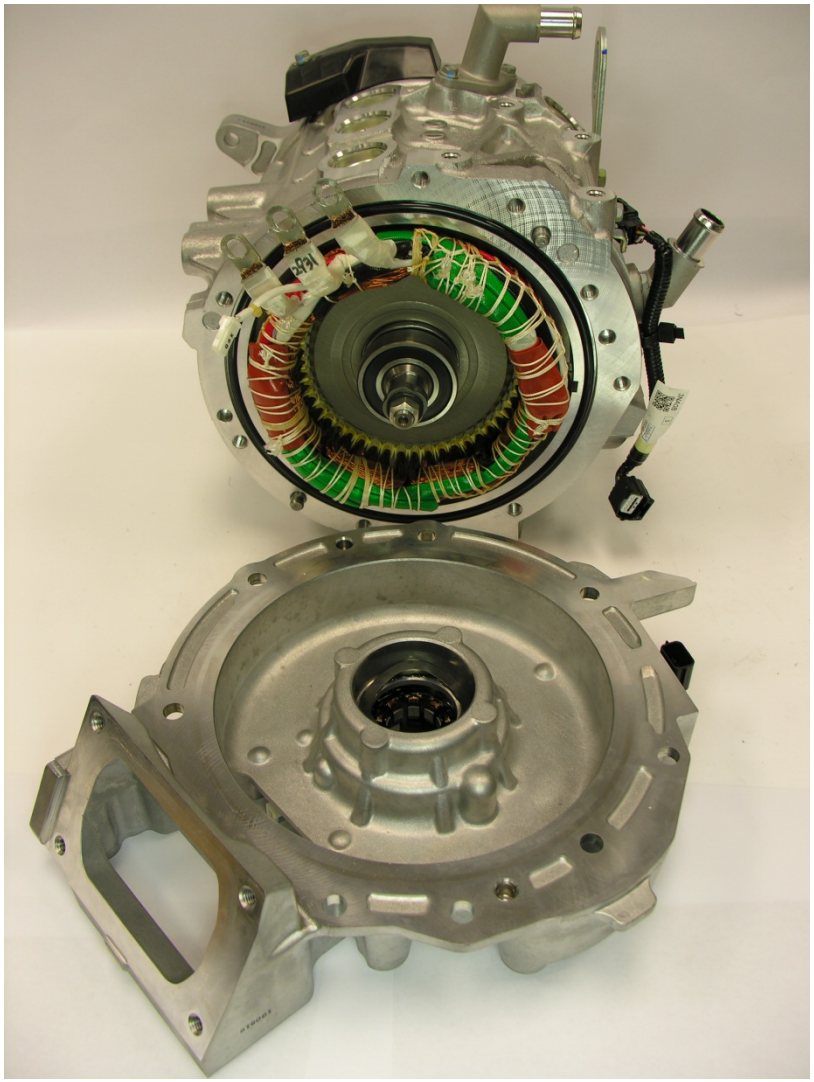




Technical Accomplishments (15)

- **2012 Nissan Leaf motor assembly**
  - Exterior water jacket surrounds motor
  - Shaft and support plate design underway for adaption to ORNL test equipment



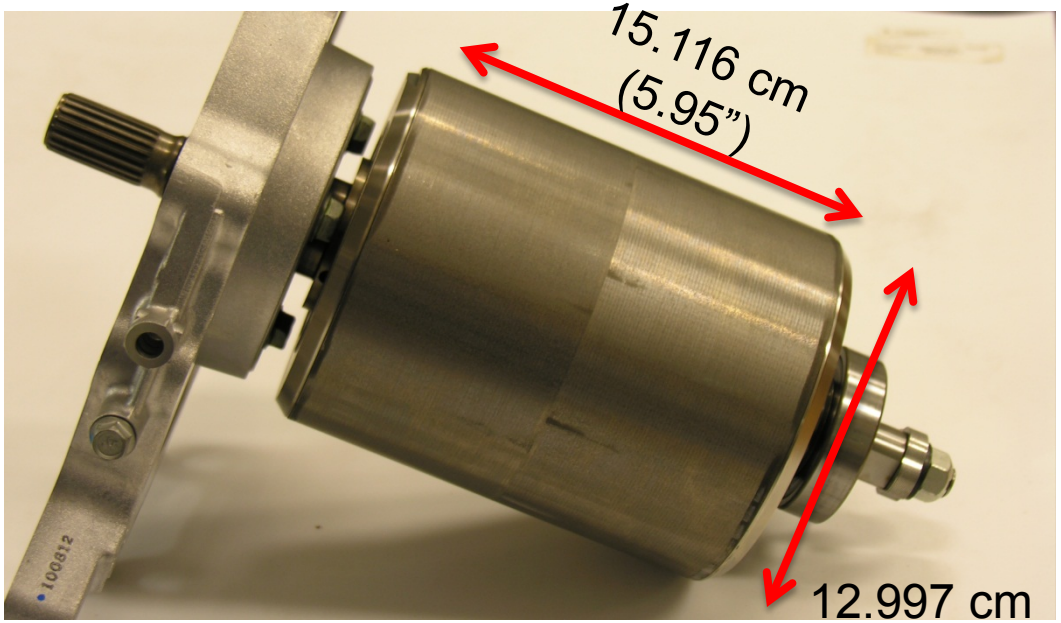


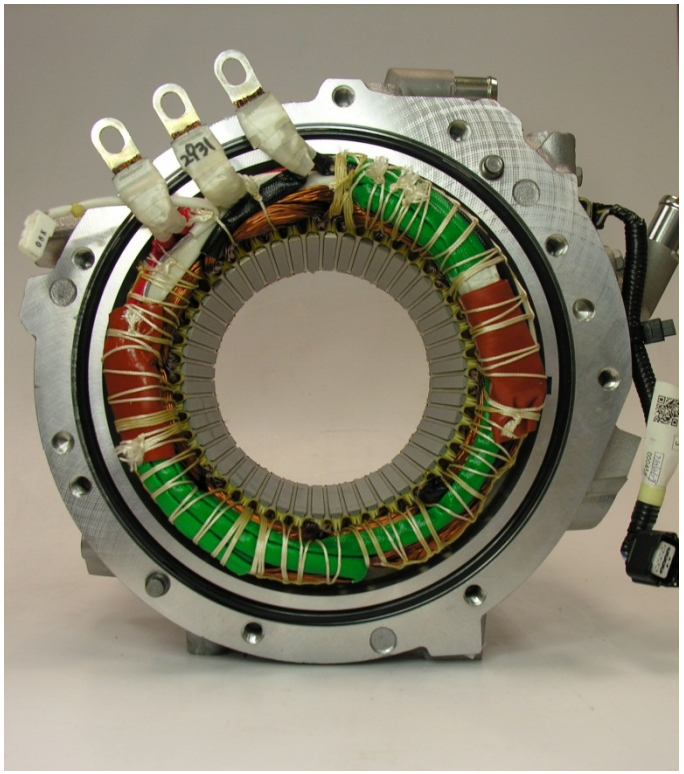
Total mass, as received:
~56kg, ~123 lb)

Technical Accomplishments (16)

- **2012 Nissan Leaf motor**
  - 48 stator slots with 8 poles
  - Similar to Lexus LS 600h design
  - Published ratings:
    - ❑ 80 kW
    - ❑ 280 Nm
    - ❑ 10,390 rpm
      - 9,655 rpm needed for 90 mph

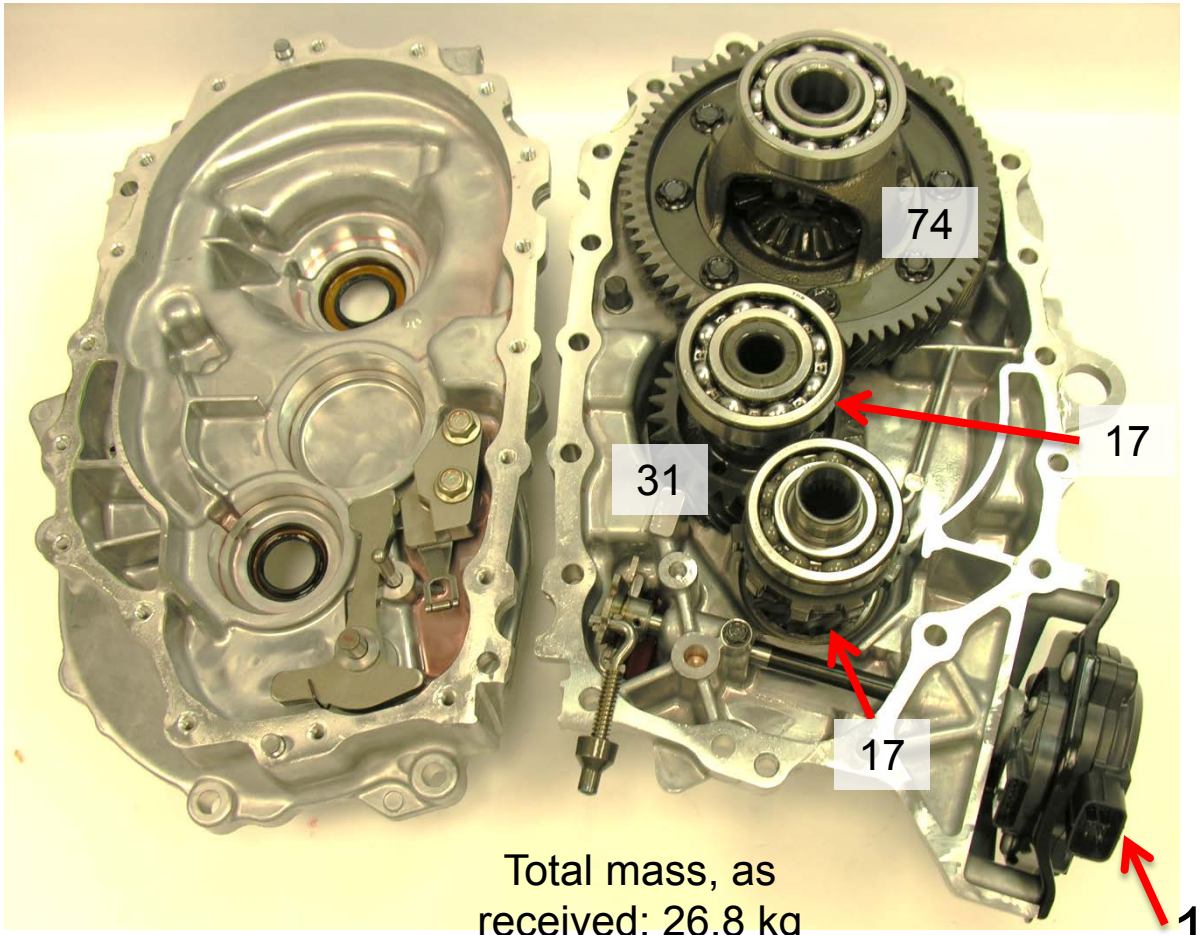
Stator O.D.: ~ 19.812 cm (7.8”)



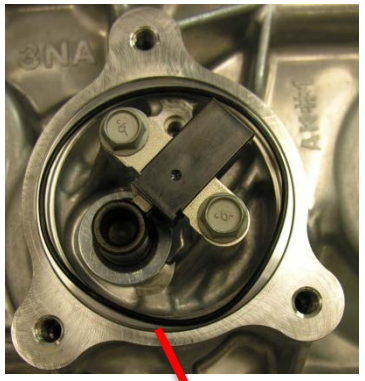


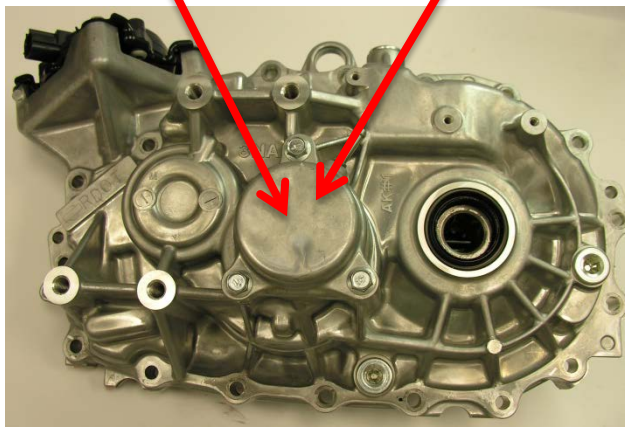
Technical Accomplishments (17)

- **Total drive ratio: 31/17 * 74/17 ~= 7.94**
- **Brush contacts used to ground shaft of drive gear**
- **12-8 switched reluctance motor and elliptical gear used to engage parking gear**



Total mass, as received: 26.8 kg 59 lb)

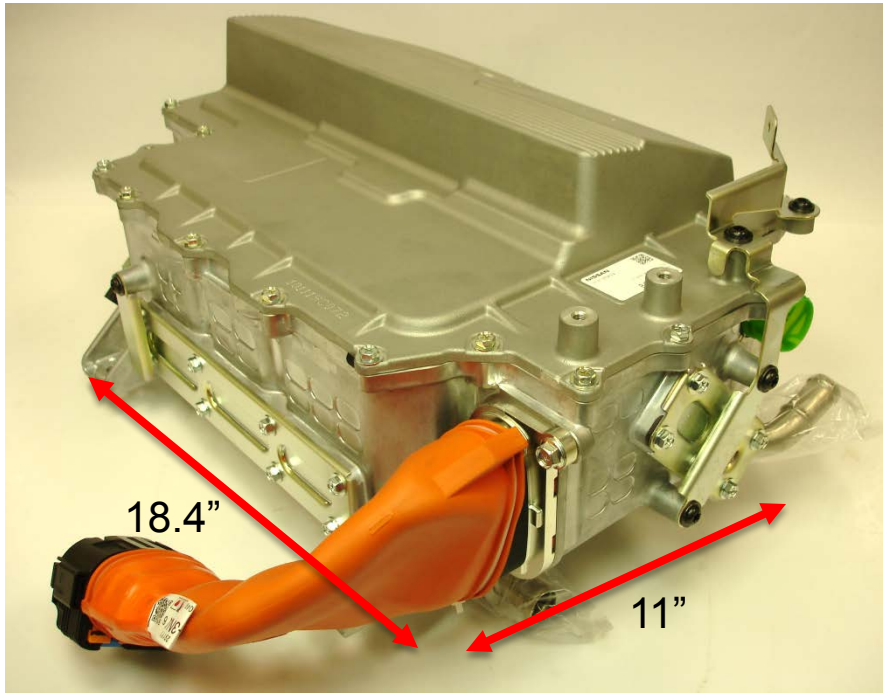


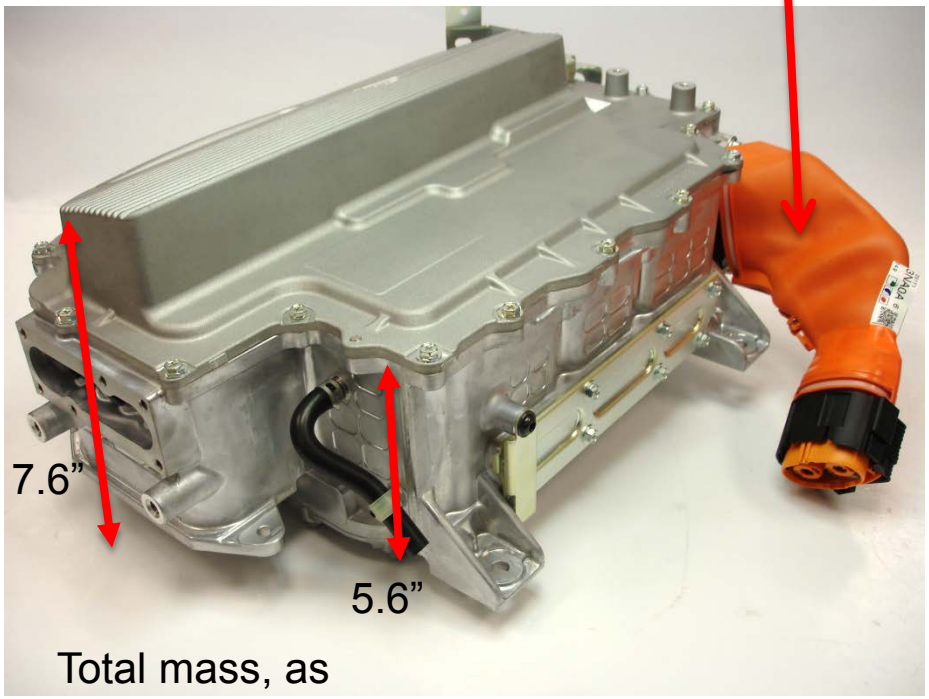


12-8 SR motor

Technical Accomplishments (18)

- **Nissan Leaf inverter assembly contains**
  - One 3-phase inverter
  - Control board with resolver position and current transducer feedback
  - IGBT driver board
  - Main capacitor
  - Bleed-resistor
- **Approximate dimensions shown below**



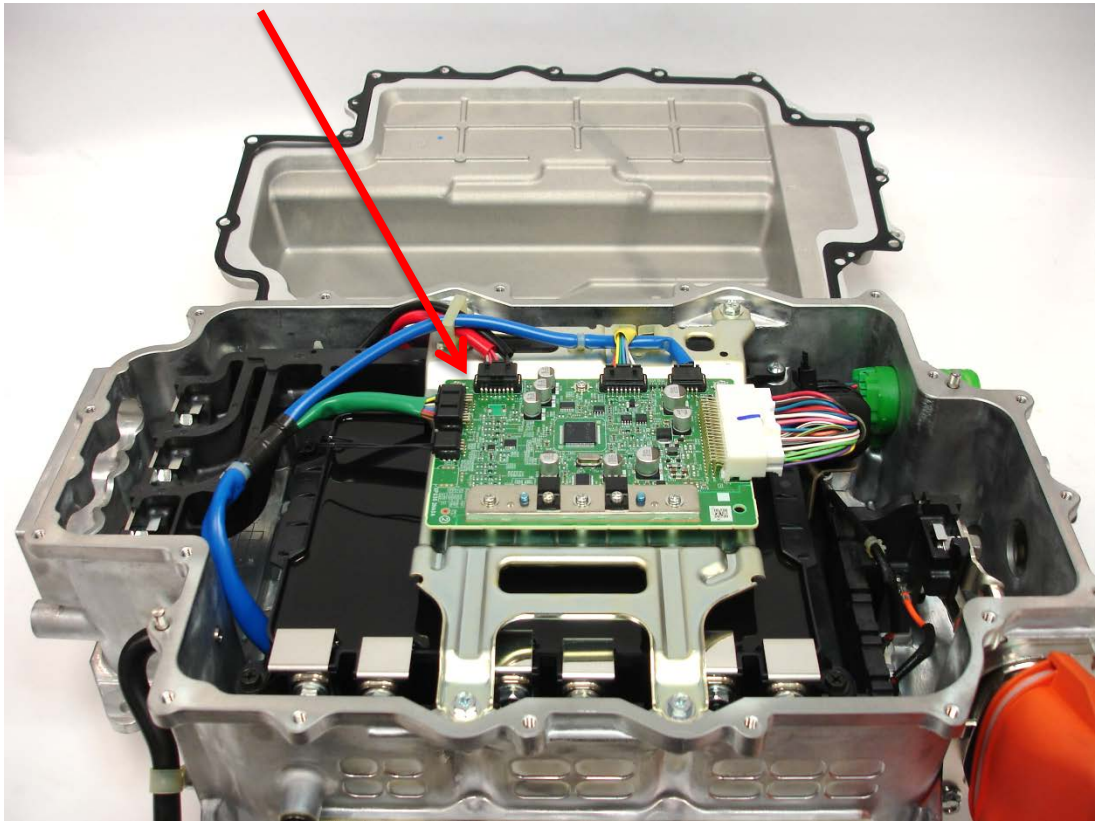


Total mass, as received: 16.2 kg (35.7 lb)

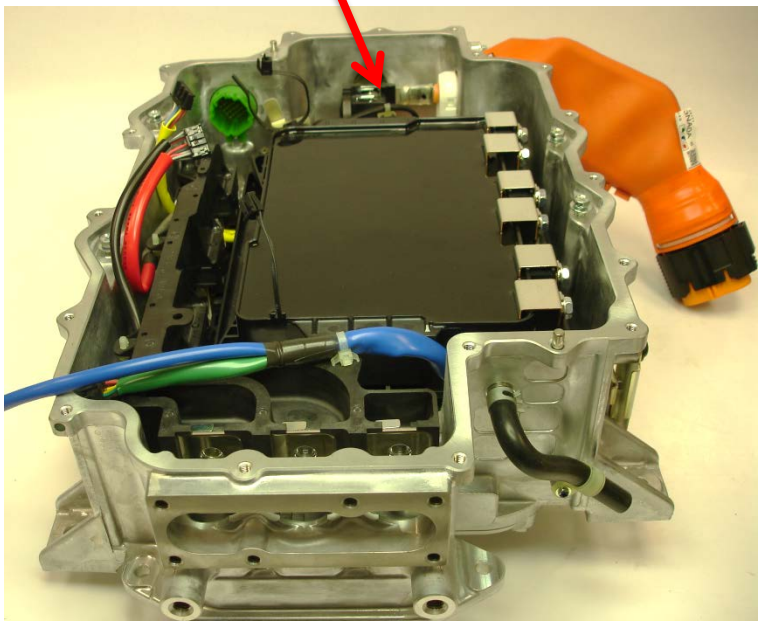
Technical Accomplishments (19)

- **Nissan Leaf inverter assembly**
  - Tamagawa position resolver chip
  - DC conductors (two) ~ 1/0 AWG
  - AC conductors (three) ~ 3/0 AWG

Control/interface board

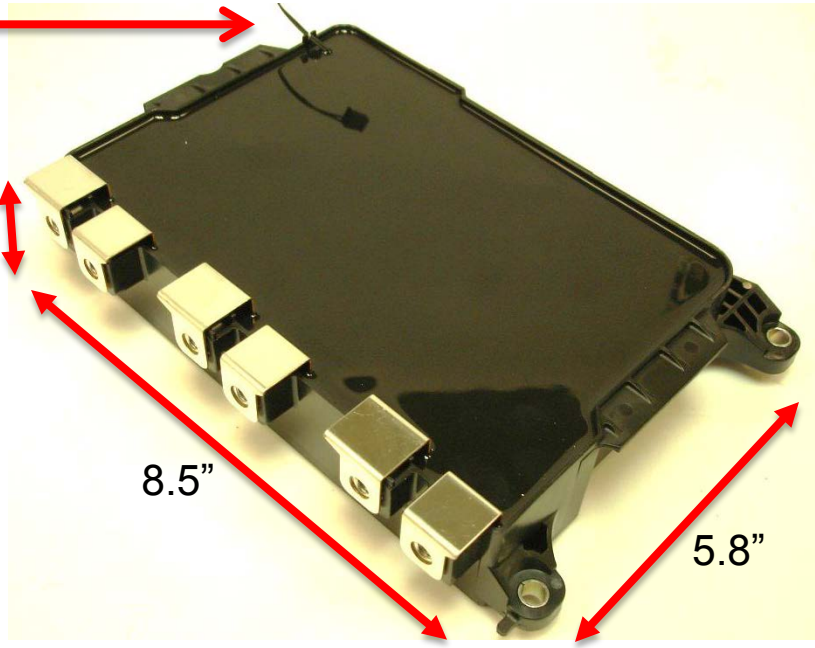


Substantial DC conductors

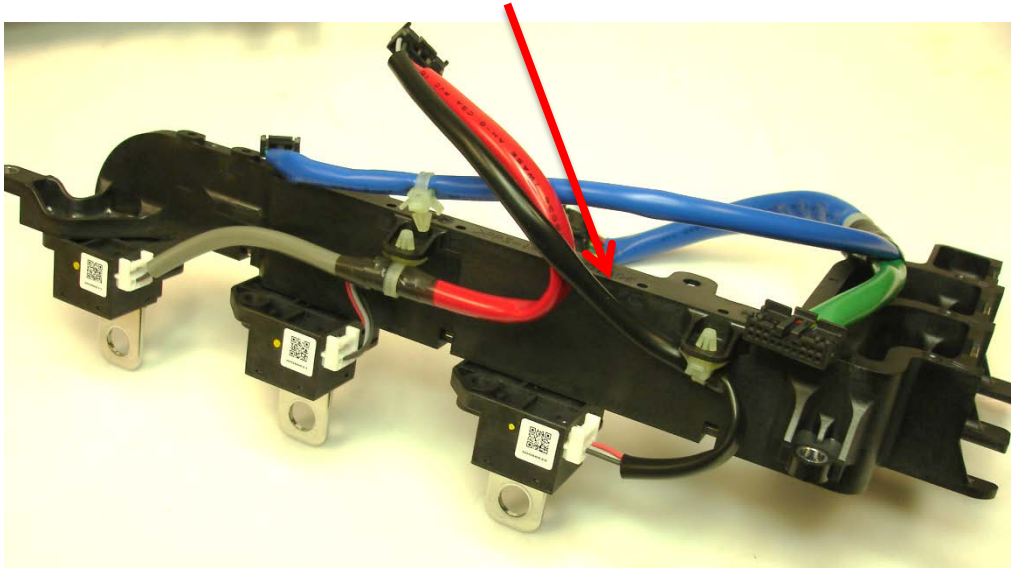


Technical Accomplishments (20)

- **Nissan Leaf inverter**
  - Capacitor module
    - 600V ,1186.5 μF
    - 600V , 1.13 μF
    - Integrated bus bars with two DC terminals for each IGBT power module
    - Integrated thermistor
    - Approximate dimensions shown below

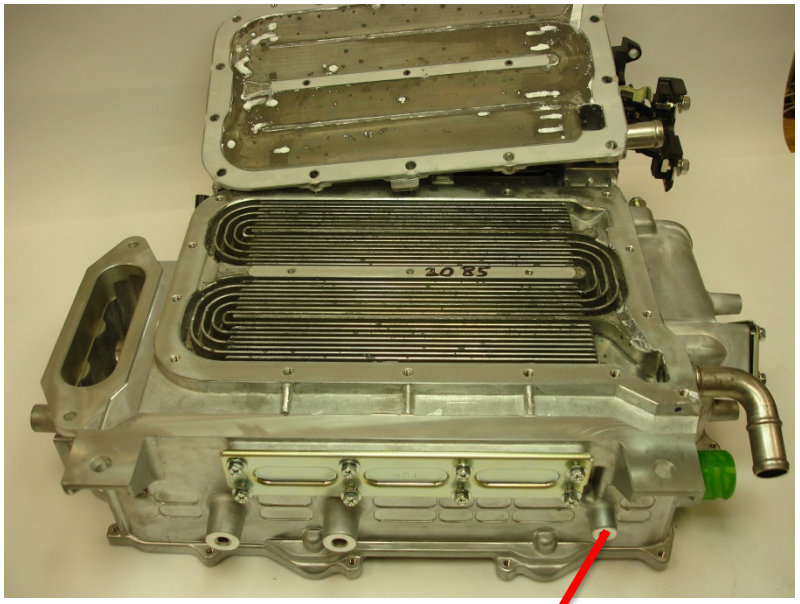


Three current transducers with integrated 3-phase bus bars

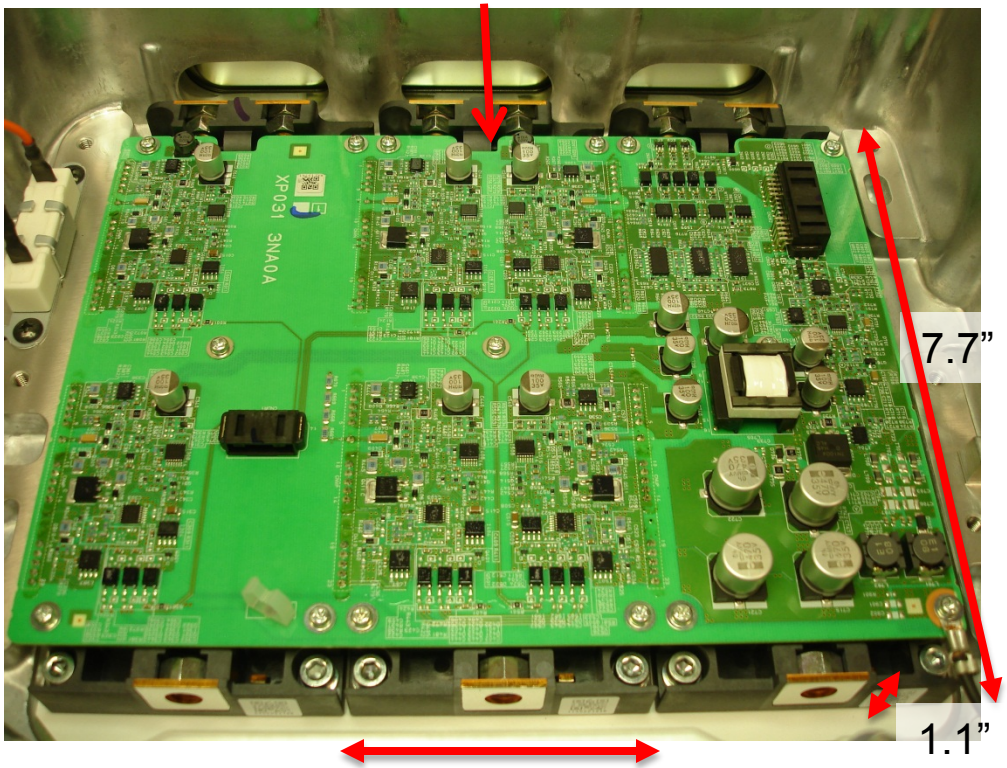


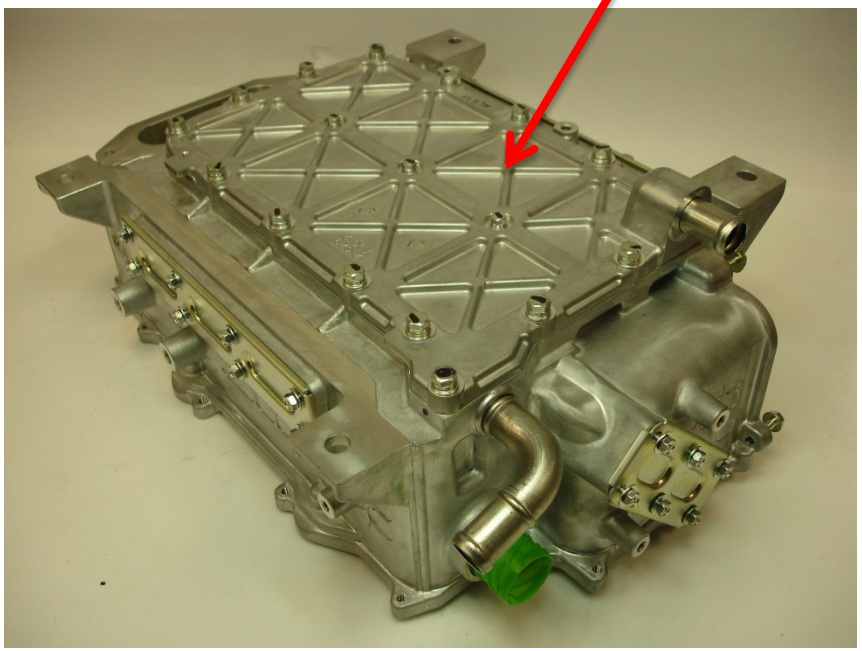
Technical Accomplishments (21)

- **Nissan Leaf inverter**
  - 3 IGBTs and 3 diodes per switch
  - 18 IGBTs and 18 diodes total
  - Serpentine water-ethylene glycol coolant loop
  - 3 separate IGBT modules



IGBT driver board





Collaborations

- **Argonne National Laboratory**
  - ANL provides vehicle level data obtained during extensive drive cycle testing which enables the observation of common operation conditions and trends observed on a system-wide basis
  - Converter, inverter, and motor characteristics such as efficiency and performance are supplied to ANL for use in system-wide vehicle modeling
- **Electric Transportation Applications and Idaho National Laboratory**
  - ETA and INL collaborate on a fleet vehicle testing program in which fleet vehicles undergo normal driving and maintenance schedules. The study of components from these vehicles provides information related to the reliability and operation long-term susceptibility of the designs.
- **National Renewable Energy Laboratory**
  - NREL utilizes temperature measurements observed during performance and efficiency tests to assess the characteristics of the thermal management system
  - NREL provides feedback and suggestions in regards to the measurements (such as thermocouple placement) useful to thermal management system assessments
- **Oak Ridge National Laboratory, Materials Science & Technology Division**
  - Provides detailed material analysis of components such as magnets and power electronics packages

Future Work

- **Benchmarking efforts will focus on technologies of interest to DOE, the Electrical and Electronics Technical Team, and Vehicle Systems Analysis Technical Team**

Summary

- Various drive systems sub-assemblies fully assessed (Prius, Accord, Camry, LS 600h, Sonata motor)
  - Power density and specific power determined
  - Design specifications validated
  - Red highlight indicates 2020 targets reached

Component & Parameter	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	**3.0**	**4.8**	**6.6**	**5.9**	**1.5**	**3.3**
Peak specific power, kW/kg	**1.1**	**1.6**	**2.5**	**1.7**	**0.5**	**1.1**
Inverter Excludes generator inverter (parenthetical values exclude boost converter mass/volume)						
Peak power density, kW/L	**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	**6.9**	**6.9** (16.7)	**7.7** (14.9)	**5.0** (9.3)	**2.4**	**3.8** (6.2)

Design Feature	2012 Leaf*	2011 Sonata	2010 Prius	2008 LS 600h	2007 Camry	2006 Accord	2004 Prius
Motor-related Technology							
Motor peak power rating	80 kW	30 kW	60 kW	110 kW	70kW	12.4 kW	50 kW
Motor peak torque rating	280 Newton meters (Nm)	205 Nm	207 Nm	300 Nm	270 Nm	136 Nm	400 Nm
Rotational speed rating	10,400 rpm	6,000 rpm	13,500 rpm	10,230 rpm	14,000 rpm	6,000 rpm	6,000 rpm
Power electronics-related Technology							
IPM Cooling	Heat sink with water/glycol loop	Heat sink with water/glycol loop	Direct cooled, single side water/glycol loop	Double-sided infrastructure, water/glycol loop	Heat sink with water/glycol loop	Air-cooled heat sink	Same as Camry
Bi-directional DC-DC converter output voltage	N/A	N/A	200-650 Vdc	288-650 Vdc	250–650 Vdc	N/A	200–500 Vdc
High-voltage (HV) Ni-MH battery	403.2 V, 59.5 Ah	270 V, 5.3 Ah	201.6 V, 6.5 Ah	288 V, 6.5 Ah,	244.8 V, 6.5 Ah,	144V, 6.5 Ah	201.6 V, 6.5 Ah,
	90 kW	34 kW	27 kW	36.5 kW	30 kW	13.8 kW	20 kW