Benchmarking of Competitive Technologies

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Oak Ridge National Laboratory
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Project ID: APE006

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

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Milestone or Go/No-Go Decision</th>
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<tbody>
<tr>
<td>September 2011</td>
<td><strong>Milestone</strong>: Completed 2011 Hyundai Sonata inverter/motor testing (completed in November due to driver board issues)</td>
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Approach

Choose subsystem

Teardown PCU and transaxle

Determine volume, weight, SP and PD

Assess design-packaging improvements

Design, fabricate, and instrument

Prepare secondary components

Develop interface-control algorithm

Test systems for performance, efficiency, and continuous operation
Overall Technical Accomplishments

- Detailed comparisons of progressing technologies
  - 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

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<tr>
<th>Component &amp; Parameter</th>
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<td>3.0</td>
<td>4.8</td>
<td>6.6</td>
<td>5.9</td>
<td>1.5</td>
<td>3.3</td>
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<td>1.7</td>
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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)

2010 Prius: 13.0 kg, 16.2 L
2007 Camry: 17.4 kg, 11.7 L
2011 Hyundai Sonata: 12.3 kg, 10.6 L
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)
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
  - \( \frac{30}{8.5} = 3.53 \)

- **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 21°C
  - 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 $V_{in}$ 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

2011 Sonata - Motor Efficiency Contours
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 100°C
- Operates at 25kW and 3000 rpm for about 30 minutes and hottest temperature reaches about 115°C
- 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

  ![Motor Image]

  Stator O.D.: ~ 19.812 cm (7.8”)

  ![Stator Image]

  15.116 cm (5.95”)

  12.997 cm (5.12”)

  Managed by UT-Battelle
  for the U.S. Department of Energy
Technical Accomplishments (17)

- Total drive ratio: $31/17 \times 74/17 \approx 7.94$
- 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)
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**

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**DC input from battery**

- 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

![Dimensions](image_url)
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
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

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<td>Motor peak power rating</td>
<td>80 kW</td>
<td>30 kW</td>
<td>60 kW</td>
<td>110 kW</td>
<td>70 kW</td>
<td>12.4 kW</td>
<td>50 kW</td>
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<td>Motor peak torque rating</td>
<td>280 Newton meters (Nm)</td>
<td>205 Nm</td>
<td>207 Nm</td>
<td>300 Nm</td>
<td>270 Nm</td>
<td>136 Nm</td>
<td>400 Nm</td>
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<td>Rotational speed rating</td>
<td>10,400 rpm</td>
<td>6,000 rpm</td>
<td>13,500 rpm</td>
<td>10,230 rpm</td>
<td>14,000 rpm</td>
<td>6,000 rpm</td>
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<td>IPM Cooling</td>
<td>Heat sink with water/glycol loop</td>
<td>Heat sink with water/glycol loop</td>
<td>Direct cooled, single side water/glycol loop</td>
<td>Double-sided infrastructure, water/glycol loop</td>
<td>Heat sink with water/glycol loop</td>
<td>Air-cooled heat sink</td>
<td>Same as Camry</td>
</tr>
<tr>
<td>Bi-directional DC-DC converter output voltage</td>
<td>N/A</td>
<td>N/A</td>
<td>200-650 Vdc</td>
<td>288-650 Vdc</td>
<td>250-650 Vdc</td>
<td>N/A</td>
<td>200–500 Vdc</td>
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<tr>
<td>High-voltage (HV) Ni-MH battery</td>
<td>403.2 V, 59.5 Ah</td>
<td>270 V, 5.3 Ah</td>
<td>201.6 V, 6.5 Ah</td>
<td>288 V, 6.5 Ah</td>
<td>244.8 V, 6.5 Ah,</td>
<td>144V, 6.5 Ah,</td>
<td>201.6 V, 6.5 Ah,</td>
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