Benchmarking EV and HEV Technologies

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Oak Ridge National Laboratory

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Project ID: APE006

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Overview

Timeline

• Start – FY04
• Finish – Ongoing

Budget

• Total project funding
  – DOE share – 100%
• Received in FY13:
  – $450 K
• Funding for FY14:
  – $500 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
  – Lixin Tang
  – Curt Ayers
  – Randy Wiles
  – Steven Campbell
  – Zhenxian Liang
  – Andy Wereszczak
• John Deere
• ANL
• NREL
• Ames Lab
Project Objectives/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 2013 through March 2014):**
- Complete 2013 Nissan LEAF charger teardown assessments and testing.
- Complete 2013 Toyota Camry PCU teardown assessments.
<table>
<thead>
<tr>
<th>Date</th>
<th>Milestones and Go/No-Go Decisions</th>
<th>Status</th>
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<td>December 2013</td>
<td><strong>Go/No-Go decision:</strong> Identify and procure EV/HEV components.</td>
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Approach/Strategy

Select subsystem(s)

Disassemble components

- Determine volume, weight, SP and PD

Assess design-packaging improvements

Prepare components

- Design, fabricate, and instrument

Develop interface & control algorithm

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


<table>
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<tr>
<th>Component &amp; Parameter</th>
<th>2020 DOE Targets</th>
<th>2012 Leaf (80 kW)</th>
<th>2012 Sonata HSG (23 kW)</th>
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<td>6.6</td>
<td>5.9</td>
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<td>Peak specific power, kW/kg</td>
<td>1.6</td>
<td>1.4</td>
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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)
Technical Accomplishments (1)

2013 Nissan LEAF On-board Charger Assessments Completed – same mass as inverter

Mass, as received: 16.3 kg (~36 lbs)
Approximate volume: 11L

9.875” = ~ 25.0 cm
15.875” = ~ 40.3 cm

Varies:
3.09” to 4.3”
7.8 cm to 10.9 cm

Cast aluminum ethylene-glycol coolant channels

Mass, as received: 3.2 kg

Nichicon Capacitor
Inductor/Choke
Controls/communication
Isolation
2013 Nissan LEAF On-board Charger

- Several power stages
- 124-240 VAC input
- 380 V nominal output
- Why so large?
  - Power quality concerns for both grid and battery
  - Need for isolation
Technical Accomplishments (3)

- Typical charger circuitry except for
  - Dual secondary isolation transformer
  - Two secondary side full bridge diode rectifiers in series
  - Combination of control and power driver isolation
Technical Accomplishments (4)

- Team was able to overtake OEM controls and operate the system at will.

- PFC test results
  - Zero crossing looks great (often a troublesome area)
  - 92.4% efficient for 120V operation at about 3 kW
  - 96.4% efficient for 240V operation at about 6 kW
Technical Accomplishments (5)

- **PFC test results**
  - Use Unitrode PFC regulator
  - Chopper frequency: 30 kHz
  - Limits AC input current at about 24 Arms

- **DC-DC converter efficiency** was about 94% at 3.3 kW and 120V
  - Total Efficiency: ~87%
  - Approximate total efficiency for 240V operation: 91-92%
Technical Accomplishments (6)

2008 LS 600h PCU studies from FY08-FY09

- LS 600h power module much more advanced than previous designs
  - Double sided power module and cooling infrastructure
  - Glimpse into the future

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2013 Toyota Camry PCU

- Similar to 2008 LS 600h
  - Total mass: 15.3 kg
  - Total volume: 12.3 L
  - Includes several converters
    - Motor inverter
    - Generator inverter
    - Bi-directional boost converter
    - 12V ancillary converter
Technical Accomplishments (8)

2013 Toyota Camry PCU

- Toyota System Architecture
  - 420V, 320 uF capacitor at battery input
  - 750V, 1600 uF capacitor on boost output/inverter DC link
  - Both contained within one module made by Panasonic
2013 Toyota Camry PCU

- Reduced size/complexity of driver circuitry
- 12 V DC-DC
  - ~3.1 kg
  - ~1.45 L
Technical Accomplishments (10)

2013 Toyota Camry PCU
• 12 Phase legs (24 IGBTs/Diodes)
  – 3 for the generator
  – 6 for the motor
    • Two in parallel for each phase
  – 3 for the boost
Technical Accomplishments (11)

2013 Toyota Camry IGBT Characterization

- At 200A, forward voltage drop is about 400 Watts
- Two devices in parallel (400A) → ~800 Watts
- This is close to the current required to produce peak torque
Comments on Power Density and Specific Power

- 2013 Camry PCU power density and specific power are the highest observed thus far
  - 105 kW power rating not empirically verified

- 2012 Sonata HSG has considerably high power density and specific power given the small size
  - Uniform cooling enables this boost in performance
  - Peak efficiency is relatively low, especially with belt losses considered

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<td>John Deere</td>
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| 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. |
Collaborations and Coordination (2)

Component Analysis (ORNL)
- Design and packaging analysis
  - Mass, volume, etc.
- Sub-component characterization
  - Magnets, capacitors, power electronics (PE), etc.
  - Material compositional analysis
- Comprehensive dynamometer evaluation
  - Motor and inverter efficiency, performance, and operational characterization
- Benchtop Evaluations
  - Converter efficiency and performance characterization
  - Boost converter, battery charger, 12 V converter, etc.

Component in the Loop Analysis (ORNL)
- Drive cycle component behavior analysis
- Hardware in the loop evaluations
  - Vehicle emulation
  - Battery emulation
  - Component emulation (various)

Vehicle Level Analysis (ANL)
- Level I vehicle system studies
  - Chassis dynamometer drive cycle analysis
  - Environmental emulation (temperature)
  - On-the-road data collection
  - Basic instrumentation and CAN parameter recording
- Level II vehicle system studies
  - Comprehensive instrumentation and data collection

Vehicle Modeling (ANL)
- Utilizes feedback from ANL vehicle analysis
- ORNL component analysis

Conditions for emulating component operation in a vehicle
- Coolant temperature
- Switching frequency
- Operation regions and conditions

Information needed for component modeling
- Efficiency mapping
- Component characteristics
Future Work

• **Remainder of FY14**
  – Finalize teardown assessments.
  – Conduct component analysis.
  – Instrument and prepare for testing.
  – Conduct comprehensive benchmarking.

• **FY15**
  – Select commercially available EV/HEV system relevant to DOE’s VTO mission. Candidates include:
    • BMW i3.
  – 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 2012 Nissan LEAF inverter, motor, and 2013 charger.

• **Future work:** FY14 efforts are delayed due to component availability, but alternative plans are in place, and FY15 plans are being discussed with DOE and EETT.