Power Electronics and Electrical Power Systems Research Center

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Organization

Power Electronics and Electrical Power Systems Research Center
Director: Mitch Olszewski

Power Electronics and Electric Machinery Group
Burak Ozpineci

Power and Energy Systems Group
Aleks Dimitrowski
Power and Energy Systems Group

• A staff of 18 researchers
• World class facilities
  - Distributed Energy Communications and Control Facility (DECC)
  - Visualizing Energy Resources Dynamically on Earth (VERDE)
  - Powerline Conductor Accelerated Testing Facility (PCAT)
• Focus on integrating Distributed Generation into grid, SmartGrid, vehicle charging, and grid control issues
• The group is actively involved in partnerships with several universities, private and public companies, other federal agencies, and consortiums.
• Projects supported by various offices of DOE, DHS, and industry.
Power and Energy Systems Group

- Interface with distributed energy resources such as microturbines, fuel cells, and solar cells
- Multilevel converters for utility applications such as static var compensation, voltage sag support, HVDC intertie, large variable speed drives
- Aggregation of multiple fuel cells to form a high power generator
- Application of DC distribution to existing AC infrastructure
- Smart plug-in hybrid electric vehicle chargers with grid support
Power Electronics & Electric Machinery Group

- A staff of 35 researchers
- 700 m² laboratories
- Only DOE national laboratory with an all-encompassing PEEM program.
- The Center’s world-wide reputation is supported by awards, patents, publications, and recognition by professional societies, academia, industry and DOE.

100 kW, installed (Chattanooga Bus)
Soft switching and sensorless

- The Center is actively involved in partnerships with several universities, private and public companies, other federal agencies, and consortiums.
- Projects supported by various offices of DOE, DOD, and industry.
- Plurality of funding is for hybrid-electric vehicles, and other areas include heavy hybrid vehicles, and transmission, and motors and drives for special applications.
- Projects directly funded by industrial partners allow proprietary work.
Research Capabilities

- Advanced power converters and adjustable speed drives
- Novel and conventional electric machines
- Power quality, efficiency, and power measurements
- Prototype development and evaluation

**Major equipment available:**
- 600 Volt, 600 ampere bi-directional dc power supply
- 100 HP, 10,000 rpm 4-quadrant dynamometer test cell
- 400 HP, 18,000 rpm eddy current brake dynamometer
- Automated wide bandgap device testing facility
- Power device packaging laboratory
- Environmental chamber (-50° C to 700° C)
- Rapid prototype machine shop
Power Electronics Research Areas (PEEM)

- Hybrid electric vehicle (HEV) applications such as motor drives or dc-dc converters
- Soft-switching inverters and dc-dc converters
- Application of wide-band gap power electronics
- Simulation, modeling and analysis of power electronics for transportation applications
- High temperature packaging of power devices
- Reliability assessment of present power semiconductor module packages
Electric Machine Technology Research Areas

- Novel electric machine technology
  - Permanent magnet (axial and radial gap)
  - Topologies that do not use PMs (e.g., switched reluctance, novel flux coupled)
  - Induction (novel designs and rotor bar technology)
  - DC machines (advanced brush technology, soft-commutated, homopolar)
  - Superconducting generator

- Motor control – sensorless motor drive techniques, circuits and control for extended constant power range for high speeds

- Design, thermal, efficiency, and performance models for AC machines

- Prognostics and failure diagnostic techniques
Thermal Management

- Investigated various kinds of coolants and cooling systems of power electronics and electric machines.

Sample Projects

- Refrigerant-Cooled Inverter (direct cooled power devices; actively cooled capacitors)
- Thermal Buffer
- Direct-Cooled Power Electronics Substrate
- Benchmarking of Competitive Technologies
Completed Technology Development
16,000 RPM IPM Rotor

- Concept provides stationary field excitation at both ends of the rotor
- Enables the elimination of the boost converter and the decrease of core losses at high speeds
- At low speed, the field can be enhanced
- Produces high starting and accelerating torque and better performance over the entire speed range
The Technology

The machine contains an uncluttered rotor and a PM rotor. The two rotors and the engine are coupled to a planetary gear set.

The PM rotor and the armature form one machine while the uncluttered rotor with the PM rotor forms a second machine.

As the armature drives the PM rotor to produce torque to drive the wheel, the uncluttered rotor can also drive the PM rotor for a higher wheel torque. The uncluttered rotor sees a reaction torque that further increases the wheel torque via the gears.
Triple Voltage DC/DC Converter

- Employ a 3-phase configuration
  - Reduce dc bus capacitor requirements ($i_{MCL}, i_{MCH} \rightarrow 0$)
  - Increase dynamic response
  - Increase power density by spreading heat sources
Integrated Inverters for HEVs and FCVs

- **Background**
  - Electrical motor driven compressors for HVAC are favored in HEVs because of their superior performances over the conventional engine driven counterparts
    - efficient variable speed operation
    - flexible packaging
    - low refrigerant emissions
  - FCVs require an electrical motor driven compressor
  - Existing HEVs employ two separate inverters
  - Purpose of the project is to reduce the system cost
Direct-Contact, Two-Phase Cooled Inverter
FY10 Completions
FY10 Project Closeout

Direct Water-Cooled Power Electronics Substrate

Research Focus Area: Power Electronics ➔ packaging

Objectives
• Develop a power electronics substrate that is directly cooled with water/ethylene glycol (WEG) coolant to reduce inverter size and weight by eliminating the base plate, thermal interface material, and cold plate.

Projected Benefits
• Volume, Weight, and Cost Reduction - ORNL structure allows for the maximum cooling surface area to be utilized within the smallest geometrical volume.
  – Weight reduction of approximately 17% as compared to the Camry.
  – Volume reduction of ~40% compared to Camry.
  – Achieving a reliable design using silicon devices with 105°C Water-Ethylene Glycol (WEG) coolant.
  – Cost reductions of ~15% by eliminating base plate, TIM, and cold plate.

Accomplishments
• Techniques for metallization and plating of the substrates to allow chip sintering defined.
• FEA results were validated by comparing to experimental results. Agreement between 10-15% was achieved.
• Maximum junction temperature maintained below 165°C using 105°C coolant at 30kW continuous power.
• All major components have been fabricated and assembled.
• Patent published

Reason for Ending in FY10
• Feasibility and benefits of concept using Si devices with WEG cooled substrate proven through both simulations and experimental tests

Potential Next Steps
• Incorporate concept into future packaging work with alternate geometries
FY10 Project Closeout

High-Temperature, High-Voltage Fully Integrated Gate Driver Circuit

Research Focus Area: Power Electronics ➞ temperature-tolerant devices

Objectives
- Develop a “universal” silicon-on-insulator (SOI)-based high-temperature, high-voltage gate driver
  - Function from -40°C to 200°C ambient without heat sinks or cooling mechanisms.
  - Driver designed as a “universal gate drive” to meet various field-effect transistor (FET) specifications. Capable of driving various types of wide bandgap (WBG) silicon carbide or gallium nitride switches such as MOSFETs and normally-on or normally-off JFETs.

Projected Benefits
- Combined with commercially available WBG-based power switches, this SOI gate drive will help to realize high-temperature DC-DC converters and traction drive systems for HEVs and PHEVs
- An enabling technology to reduce the cooling requirements of power electronics

Potential Next Steps
- Work with industry to transition technology for specific applications
- Utilize devices in packaging and high temperature research at laboratory (ex. Integrated IMMD project)

Accomplishments
A highly integrated SOI chip has been designed, fabricated, and packaged for testing at ambient temperatures of at 200°C. The device has several features:
- On-chip voltage regulator
- Under-voltage lockout, short circuit, de-saturation, and thermal shutdown protection
- Gate current monitoring
- Low-voltage differential signaling (LVDS) circuit
- Drive current capability of >5 A at 200°C
- Switching frequency >100 kHz
- 100% high-side duty cycle with charge pump

Reason for Ending in FY10
- Significant industrial interest generated
- Deemed time to proceed to commercialization
FY10 Project Closeout

Novel Packaging to Reduce Stray Inductance in Power Electronics

Research Focus Area: Power Electronics ➔ packaging

Objectives
• Develop innovative packaging concept for devices in large power modules that significantly reduces the stray inductance

Projected Benefits
• Decreased device stress
• Increased inverter reliability
• Increase device capability
• Reduction in inverter costs

Accomplishments
• A new packaging method based on P and N-cells has been developed to reduce the stray inductance between the active switch (IGBT) and diode.
• Electromagnetic and circuit simulation shows reduction of parasitic inductance (20% reduction) and resistance, and corresponding improvement in overshoot voltage in the proposed package module (15% reduction).
• A 10 kW phase leg power module has been developed that incorporates the novel circuit layout.

Reason for Ending in FY10
• Industry performing similar research

Potential Next Steps
• Continuing in FY11 with carryover funding to explore potential for paralleling devices
• Utilize concept in future projects and packaging work at Laboratory, where appropriate
High Temperature Air Cooled Traction Drive Inverter Packaging

Research Focus Area: Power Electronics
Temperature tolerant devices

Objectives
• To demonstrate the feasibility of air cooling for power electronics while achieving DOE Vehicle Technologies Program 2020 inverter targets.

Projected Benefits
• System cost reduction through the elimination of the auxiliary liquid cooling system.

Reason for Ending in FY10
• On hold pending air heat transfer enhancement and air cooling system balance of plant assessments being performed at NREL in FY11.

Accomplishments
• Completed a parametric study to determine the feasibility and boundary conditions required for an air-cooled 55 kW peak/30 kW continuous power rated inverter.
• Two designs were assessed
• Parameters were varied for steady state and under drive cycles to determine design and junction temperature effects.

<table>
<thead>
<tr>
<th></th>
<th>Design A</th>
<th>Design B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Density (kW/l)</td>
<td>12.4</td>
<td>12.01</td>
</tr>
<tr>
<td>Pressure Drop (in.H2O) @ 30 CFM</td>
<td>1.3</td>
<td>0.436</td>
</tr>
<tr>
<td>Pressure Drop (in.H2O) @ 60 CFM</td>
<td>5.0</td>
<td>1.64</td>
</tr>
<tr>
<td>Ideal Blower Power (W) @ 30 CFM</td>
<td>40.3</td>
<td>13.9</td>
</tr>
<tr>
<td>Ideal Blower Power (W) @ 60 CFM</td>
<td>312</td>
<td>104.5</td>
</tr>
</tbody>
</table>

Comparison of the performance of the two inverter design packages

Potential Next Steps
• Utilize designs, simulation models, and knowledge generated in future work on air cooling.

Plot of device junction temperature over the US06 drive cycle
FY11 Portfolio
Wide Bandgap Materials

Research Focus Area: Power Electronics

→ temperature-tolerant devices

Objectives

• Acquire, test, and characterize new wide bandgap (WBG) technology power devices.

• Assess the system level impact of WBG semiconductor devices on hybrid electric vehicles.

• Engage potential suppliers and prepare for use of technology as it matures to that needed for automotive applications.

Projected Benefits

• Evaluation of device performance provides insight into the development of maturing high temperature device technologies.

• Potential for smaller automotive power converters that can operate at higher temperatures and efficiencies.

Status

• Acquired, tested, and characterized silicon carbide (SiC) JFETs, MOSFETs, BJTs, and diodes.

• Developed SPICE model for a 1,200 V, 10 A SiC JFET.

• Developed a traction drive model to simulate the performance of the WBG devices over different drive cycles.

<table>
<thead>
<tr>
<th></th>
<th>10 kHz</th>
<th>20 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inverter Efficiency [%]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70°C</td>
<td>97.43</td>
<td>97.39</td>
</tr>
<tr>
<td>105°C</td>
<td>95.41</td>
<td>95.34</td>
</tr>
<tr>
<td><strong>Inverter Energy Loss [kJ]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70°C</td>
<td>338.9</td>
<td>617.6</td>
</tr>
<tr>
<td>105°C</td>
<td>344.3</td>
<td>626.7</td>
</tr>
</tbody>
</table>
Inverter Using Current Source Topology

Research Focus Area: Power Electronics
- innovative topology
- packaging

Objectives
- Develop new ZCSI topologies that combine the benefits of ORNL's Current Source Inverter (CSI) efforts and MSU's work on Z-Source Inverters (ZSI) to significantly reduce cost and volume through the integration of voltage boost, inverter, regen and EV/PHEV charging functions

Projected Benefits
- Reduce dc link bus capacitor size and cost by 75% (caps about 20% of cost and 30% of volume of VSI)
- Eliminate external boost converter by incorporating 3X voltage boost in inverter
- Eliminate the uncontrolled PM regeneration failure mode
- Increase motor reliability and efficiency by providing sinusoidal voltages & currents to the motor
- Enhance inverter reliability by tolerating phase-leg shoot-through and open-circuit conditions
- Can operate as a charger in EVs and PHEVs

Status
- Two new ZCSIs with a reduced component count, have been simulated. Both have a higher boost ratio of 3 vs. 2 for the previous ZCSI.
- A design for a 55 kW ZCSI has been completed using first generation RB-IGBT technology. The design yields a specific power of 4.89 kW/kg and a power density of 15.5 kW/L.
- Simulation results confirmed the feasibility of using the ORNL V-I converter-based CSI topology in series and power-split series/parallel HEV configurations. The CSI dual-motor-drive PE using RB-IGBTs provides:
  - specific power 6.4 kW/kg,
  - power density 9.9 kW/kg,
  - cost $15.4/kW
A Segmented Drive System with a Small DC Bus Capacitor

Research Focus Area: Power Electronics
→ innovative topology
→ packaging

Objectives
• Develop a 55 kW inverter prototype capable of:
  – 60% reduction in the dc bus capacitor ripple current
  – Significant reduction in cost and volume of dc bus capacitor

Projected Benefits
• Reduce weight and volume by 25% compared to standard voltage source inverter (VSI)
• Reduce dc link bus capacitor size and cost by 60% (caps about 20% of cost and 30% of volume of VSI)
• Reduce battery losses and improve battery operating conditions by reducing battery ripple current
• Significantly reduce the motor torque ripples and switching losses by 50%
• Increase inverter reliability
• Enable high temperature operation

Status
• A 55 kW segmented inverter prototype with a 60% reduction of dc bus capacitor has been designed, built, and successfully tested with an inductor-resistor load and an induction motor. Test results show significant reductions of
  – 55~75% in capacitor ripple current
  – 70~90% in battery ripple current
  – 60~80% in motor ripple current

Comparison of dc bus capacitor ripple current vs. speed at various percentages of rated torque. (Motor ratings: torque, 91 Nm; current, 37.5 Arms)
Power Device Packaging

Research Focus Area: Power Electronics

Objectives
- Identify the limitations and shortcomings with existing device packaging approaches.
- Develop new packaging concepts to overcome the issues for improved power density, thermal management, cost, and reliability.
- Complement other packaging and thermal management research efforts within DOE Vehicle Technologies Program.

Projected Benefits
- Enhanced cooling
- Inverter size reduction
- Reliability improvements
- Improved power density

Status
- Multiple state-of-the-art commercial packaging technologies have been benchmarked
- Advanced packaging approaches are being assessed with the objective to develop new packaging
- Packaging Laboratory has been designed and outfitted

Module benchmarking activity

Test setup for parasitic parameter extraction
Converter Topologies for Wired and Wireless Battery Chargers

Research Focus Area: Power Electronics ➔ vehicle charging

Project Objectives
• Develop an isolated, integrated 5kW converter and battery charger for power management and battery recharging in PHEVs.
• Develop converter topologies suitable for wireless charging systems.

Projected Benefits/Impacts
• Integrated charger
  • 70% reduction in cost and volume compared to on board stand alone chargers
  • Achieve bidirectional power flow for V2G support
• Wireless charger
  • Eliminates user intervention
  • Maximizes electric range of PHEVs

Status
• A project completed in FY09 has demonstrated an integrated charger (no galvanic isolation) with: 1) 90% cost reduction compared to a standalone charger, 2) high efficiencies of 93%~97%, and 3) charging, mobile power generation, and vehicle-to-grid operations.
• A project funded internally through LDRD has demonstrated wireless power transfers of up to 4 kW across a 10” airgap of two antennas at efficiencies of 90%~95% depending on the operating frequency, power level and relative position of the antennas.

ORNL Wireless Charging Prototype
A New Class of Switched Reluctance (SR) Motors Without Permanent Magnets

Research Focus Area: Electric Machines
→ high performance non-PM motors

Objectives
• Design and develop a motor of at least 55 kW peak power that incorporates a non-conventional flux path design that utilizes a torque-ripple reduction control method
• Develop a high power density motor without permanent magnets (PMs) or the limitations of conventional SR motors
  – Overcome torque and acoustic noise issues

Projected Benefits
• Eliminate PMs in motor
  – Reduce dependency on China for PMs
• Reduce motor costs through elimination of expensive rare earth materials

Status
• Verified through simulations that the design meets 2015 performance targets and 2020 cost targets with less than 5% torque ripple
• Developed custom software to interface to FEA software and enable faster design turn around time
• Designed entire assembly, prepared drawings for fabrication, received all parts, and began assembling model verification prototype
Novel Flux Coupling Motor Without Permanent Magnets

Research Focus Area: Electric Machines ➔ high performance non-PM motors

Objectives
- Develop a traction motor without rare earth permanent magnets (PMs) achieving specific power and power density similar to PM machines but at lower cost and with higher efficiency.

Projected Benefits
- Concept achieves the benefits of PM machines without rare earth magnets
  - Reducing dependency on China for rare earth materials
  - 20% cost reduction, based on present material costs
  - 3% overall efficiency increase due to adjustable field
  - Free from temperature restrictions of PM materials

Status
- Significant advances have been accomplished in the simulation and design proving the feasibility of meeting DOE’s 2020 motor power density target.
- Work is ongoing to reduce costs and volume to achieve 2020 targets.
- A breakthrough on the mechanical design was achieved allowing the rotor to safely operate at 14,000 RPM.
- The prototype motor is at the fabrication stage.

<table>
<thead>
<tr>
<th>Camry</th>
<th>Novel Machine</th>
<th>2020 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. power output</td>
<td>70 kW (tested)</td>
<td>115 kW (computed)</td>
</tr>
<tr>
<td>Weight</td>
<td>36.3 kg</td>
<td>55.7 kg</td>
</tr>
<tr>
<td>Volume</td>
<td>13.9 Liters</td>
<td>13.6 Liters*</td>
</tr>
<tr>
<td>kW/kg</td>
<td>1.9 kW/kg</td>
<td>2.1 kW/kg</td>
</tr>
<tr>
<td>kW/l</td>
<td>5.0 kW/l</td>
<td>8.5 kW/l</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.61 – 1.00</td>
<td>0.75 – 1.00</td>
</tr>
<tr>
<td>Cost</td>
<td>**10.7 $/kW</td>
<td>***6.1 $/kW</td>
</tr>
<tr>
<td></td>
<td>($749 for 70 kW)</td>
<td>($702 for 115 kW)</td>
</tr>
</tbody>
</table>

* Volume calculation of new machine based on maximum height, width, and depth of motor components only (i.e. stator core, winding extensions, and rotor excitation cores).

** Requires 1kg of high grade PMs at $90/kg

*** Includes additional cost of 11kg steel and 3kg copper wire (+40.00) but eliminates 1kg magnet (-$90.00)
Motor Packaging with Consideration of Electromagnetic and Material Characteristics

Research Focus Area: Electric Machines
⇒ high performance non-PM motors

Project Objectives
• To investigate design and packaging approaches that improve power capabilities without increasing motor volume or effecting electromagnetic performance.

Projected Benefits/Impacts
• Increase continuous power rating of a motor for a specific motor volume.
  • Targeting a continuous power output increase of 30% for a given maximum stator temperature and specified running conditions.
• Decrease motor volume for a specific continuous power rating.
• Increase efficiency of the motor since lower operational temperatures yield lower $I^2R$ losses, which results in lower running temperatures.
• Allow higher coolant temperatures.

Status
• No accomplishments to date because this is a new start
• Data and information available from benchmarking
• Vehicle simulator developed in previous project provides power demand requirements
Benchmarking of Competitive Technologies

Research Focus Area: Integrated Traction Drive System ➔ benchmarking technologies

Objectives
• Benchmark leading hybrid electric vehicle (HEV) traction drive subsystems via:
  – Design, packaging, and fabrication assessments
  – Comprehensive efficiency and performance mapping

Projected Benefits
• Assess current state-of-the-art for components and systems, performance parameters, and technology gaps so that research efforts leading to target attainment can be identified
• Establish the technology baseline for the DOE APEEM Program
• Ensure that the DOE program will not duplicate technical innovations that are part of commercially available technology

Status
• Completed evaluation of the 2010 Prius
  – Performed efficiency mapping
  – Completed packaging and manufacturing analysis as well as component performance assessment
• Results indicate
  – Motor has large 96% efficiency region
  – Inverter efficiency reaches 99%
  – System efficiency between 5,000–7,000 rpm and 40–75 Nm reaches 95%

2010 Prius Power Control Unit

- Main Capacitor Module
- Driver/control boards and power terminals
- 12V accessory converter
- Inductor/small caps
- Cooling infrastructure

Managed by UT-Battelle
for the Department of Energy
High Power Density Integrated Traction Machine Drive

Research Focus Area: Integrated Traction Drive System
→ innovative systems designs

Objectives
• Develop a reliable, fault-tolerant, integrated modular motor drive (IMMD) that is capable of achieving;
  – Reliable operation with 105°C cooling and 200°C junction temperatures
• Extend Si device operation to higher temperatures utilizing advanced packaging approaches

Projected Benefits
• Increased power density and reduce costs by modularizing both the machine and power electronics and then integrating them into a single combined machine-plus-drive structure
• Extend Si device operation to higher temperatures utilizing advanced packaging approaches

Status
• A 6-phase, 10-pole PM machine has been simulated and identified as the most promising motor configuration.
• A heterarchical control architecture has been developed and simulated for achieving fault-tolerant operation.
• High temperature static and switching behaviors of candidate Si devices have been tested and their performance characterized.
• A baseline 10 kW phase-leg power module with 105°C cooling has been designed and simulated.

6-phase Machine

Heterarchical Control Architecture

Test Setup for Characterizing Devices at High Temperature

Thermal Simulation of the Phase-leg Package
Integration of Novel Flux Coupling Motor and Current Source Inverter

Research Focus Area: Integrated Traction Drive System

→ innovative systems designs

Project Objectives
• Develop an integrated motor/inverter meeting the DOE 2020 targets
  • Reduces capacitor requirements through the use of the CSI
  • Eliminate the inductor of the CSI by sharing the field coil inductor of the Novel Flux Coupling Motor

Projected Benefits/Impacts
• Significant reductions in the cost, size, weight, and performance of the traction drive system by eliminating the permanent magnets and the heavy inductor of the current source inverter.
• Achievement of the FreedomCAR 2020 system targets of 1.4 kW/kg and 4 kW/l.

Status
• New Start