Introduction

The U.S. Department of Energy (DOE) and the U.S. Council for Automotive Research (composed of automakers Ford, General Motors, and DaimlerChrysler) announced in January 2002 a new cooperative research effort. Known as FreedomCAR (derived from "Freedom" and "Cooperative Automotive Research"), it represents DOE's commitment to developing public/private partnerships to fund high-risk, high-payoff research into advanced automotive technologies. Efficient fuel cell technology, which uses hydrogen to power automobiles without air pollution, is a very promising pathway to achieve the ultimate vision. The new partnership replaces and builds upon the Partnership for a New Generation of Vehicles initiative that ran from 1993 through 2001.

The Vehicle Systems subprogram within the FreedomCAR and Vehicle Technologies Program provides support and guidance for many cutting-edge automotive and heavy truck technologies now under development. Research is focused on understanding and improving the way the various new components of tomorrow's automobiles and heavy trucks will function as a unified system to improve fuel efficiency. This work also supports the development of advanced automotive accessories and the reduction of parasitic losses (e.g., aerodynamic drag, thermal management, friction and wear, and rolling resistance).

In supporting the development of hybrid propulsion systems, the Vehicle Systems subprogram has enabled the development of technologies that will significantly improve fuel economy, comply with projected emissions and safety regulations, and use fuels produced domestically.

The Vehicle Systems subprogram supports the efforts of the FreedomCAR and Fuel Partnership and the 21st Century Truck Partnership through a three-phase approach intended to

- Identify overall propulsion and vehicle-related needs by analyzing programmatic goals and reviewing industry's recommendations and requirements and then develop the appropriate technical targets for systems, subsystems, and component research and development activities;
- Develop and validate individual subsystems and components, including electric motors, emission control devices, battery systems, power electronics, accessories, and devices to reduce parasitic losses; and
- Determine how well the components and subsystems work together in a vehicle environment or as a complete propulsion system and whether the efficiency and performance targets at the vehicle level have been achieved.

The research performed under the Vehicle Systems subprogram will help remove technical and cost barriers to enable the development of technology for use in such advanced vehicles as hybrid and fuel-cell-powered automobiles that meet the goals of the FreedomCAR Program.

A key element in making hybrid electric vehicles practical is providing an affordable electric traction drive system. This will require attaining weight, volume, and cost targets for the power electronics and electrical machines subsystems of the traction drive system. Areas of development include these:

- Novel traction motor designs that result in increased power density and lower cost;
- Inverter technologies involving new topologies to achieve higher efficiency and the ability to accommodate higher-temperature environments;
- Converter concepts that employ means of reducing the component count and integrating functionality to decrease size, weight, and cost;
- More effective thermal control and packaging technologies; and
- Integrated motor/inverter concepts.

This report highlights the activites and progress achieved in the Advanced Power Electronics Research and Development Effort during FY 2006. We are pleased with the progress made during the year and look forward to continued work with our industrial, government, and scientific partners to overcome the challenges that remain to delivering advanced power electronics and electric machines for vehicle applications.

Below are summaries of major accomplishments for each technical project.

Thermal Control for Inverters and Motors

- An oil spray cooling system for a 6000-rpm drive motor was designed, fabricated, and tested. The cooling was significantly improved from similar motors that incorporate oil-sling cooling systems.
- ORNL has designed, built, and tested an inverter half the size of a commercially available module of the same power rating. The dc test reached 600-A capability (200 A per leg) and the ac switching test achieved 250 Arms for a 3-phase output.

Identifying the Barriers and Approaches to Achieving High-Temperature Coolants

- The study was performed to identify practical approaches, technical barriers, and cost impacts for achieving high-temperature coolant operation for certain traction drive subassemblies and components of hybrid electric vehicles (HEVs). The results of the study showed it to be evident that a few formidable technical and cost barriers exist, and no effective approach for mitigating the barriers was evident in the near term.
- All significant barriers that pertain to the inverter, dc link capacitor, and motor were identified.
- Approaches for resolving many of the barriers were discussed in the study.
- Component-level issues were addressed in the study for operation at a significantly higher coolant temperature. These issues generally pertained to the cost and reliability of existing or near-term components that would be suitable for use with 105°C coolant. The assessed components included power electronic devices/modules such as diodes and insulated gate bipolar transistors (IGBTs), inverter-grade high-temperature capacitors, permanent magnets (PMs), and motor-grade wire insulation. The need for potentially modifying/resizing subassemblies such as inverters, motors, and heat exchangers was also addressed in the study.

Advance Thermal Interface Materials to Reduce Thermal Resistance

- Several CNT growth processes have been investigated and initial thermal resistance measurements on two-sided carbon nanotube TIM were conducted

Modeling Two-Phase Spray and Jet Impingement Cooling

- Completed and published results on 2 phase jet model
- Transferred results from single phase jet impingement modeling to low R IGBT structure
- CRADA with Bowles Fluidics to evaluate self-oscillating jets

Direct Cooling Options: An Assessment of Air Cooling for Use with Automotive Power Electronics Applications

- Developed thermal subsystem model for forced air and compressed air cooling
- Performed investigations of air cooling potential and system requirements

Thermal subsystem simulations

- Thermal resistance model developed to evaluate cooling potential of thermal control technologies
- Performed initial investigations into the impact of PHEVs on component thermal loads

Uncluttered CVT Machine

- The design of the proof-of-concept uncluttered rotor without windings and a half stator wound core to couple to the uncluttered rotor was completed. The uncluttered rotor and its half stator were fabricated, and the uncluttered rotor teeth were machined out of solid steel instead of laminations in order to lower costs for the proof-of-concept prototype. The uncluttered rotor concept for the brushless rotating stator (or armature) was proved through tests conducted on the prototype.

Interior Permanent Magnet Reluctance Machines with Brushless Field Excitation—16,000 rpm

- The 16,000-rpm motor design was completed and the prototype fabricated. Initial testing was performed and a dimensional and cost analysis was made based upon the Toyota Prius motor. This motor design enables better motor performance with system cost savings. Also, if used in a vehicle architecture requiring a boost converter, this motor can produce 250-kW output at 16,000 rpm. This significantly widens the possible applications for this type of motor.

High-Power-Density Reluctance Interior Permanent Magnet Machines—6000 rpm

- The new technology derived from this project shows that the air-gap flux density produced by the new PM arrangement can be doubled compared with that of the Toyota/Prius motor. The PM torque component is proportional to the product of the PM fundamental air-gap flux density and the current of the motor. Therefore, the higher PM fundamental air-gap flux density produces higher toque at a given current of the motor and hence a higher power density of the motor.

Control of Fractional-slot Surface-mounted PM Motors with Concentrated Windings

- Two 55-kW surface permanent magnets (SPMs) with fractional slot concentrated windings (FSCW) incorporating FreedomCAR targets were designed and studied. SPM1 was selected for developing an analytical model to accurately predict the stator tooth and yoke iron losses in FSCW-SPM machines. SPM2 was selected for an analytical model comparison study.
- The SPM2 motor was modeled with SPEED software, and ORNL collaborated with the University of Wisconsin at Madison (UWM) to compare design parameters calculated using SPEED's PC-BDC module with those calculated by UWM.
- A closed-form analytical model was successfully developed that can accurately predict the stator tooth and yoke iron losses in FSCW-SPM machines during open-circuit operation.
- A detailed point-by-point finite-element analysis (FEA) of FSCW-SPM machines was completed and is proving very useful in identifying the relative contributions of hysteresis and eddy-current losses in different parts of the machine as a function of rotor speed.
- Three control schemes were developed.
  - The UWM scheme controls to ensure maximum motor efficiency and shows how motor losses under load may be sufficiently reduced by field weakening, which increases total current, to offset the additional I2R losses and thereby improve motor efficiency.
  - The first ORNL scheme is a low-cost scheme because it eliminates current sensors. The ORNL simulator assumes losses that increase with the square of the speed.
  - The second ORNL scheme uses a set of antiparallel silicon controlled rectifiers in each phase to ensure that any load is accommodated with minimum current, which ensures that it is a maximum overall efficiency scheme.

- ORNL evaluated its first control scheme with the simulator for two constraints, first so that rated current is not exceeded and second so that rated power is not exceeded. The limiting current constraint allows considerably more power to be delivered over a large part of the power speed curve.

Extending the CPSR of Synchronous Reluctance Motors

- FLUX2D software was applied to a model of a PM motor that was created by ORNL to determine the phase advance, which is the angle between the center of a rotor pole and the stator current orientation that will produce maximum torque. The model of the PM motor was created with inset magnets, and the magnets were turned off to simulate a synchronous reluctance motor with doubly salient poles. The torque produced was then calculated for a fixed rotor as the current in the stator was varied over one pole, and for current fixed in the stator with the rotor turned through one pole angle. Definite maxima were found with only rough agreement between the two approaches. A similar exercise with COMSOL demonstrated good agreement between the two approaches for estimating the phase advance for maximum torque.

- Using SPEED as a design tool, two synchronous reluctance motors were modeled to attempt to meet FreedomCAR targets. The first model with four turns per pole could not deliver maximum power at 2000 rpm. Adequate power at 2000 rpm required eight turns per pole, which doubled the amount of copper to increase both cost and weight. The motor was too heavy and too expensive to meet FreedomCAR goals.
- A per-phase model was designed by applying a winding function to a synchronous reluctance motor with salient rotor and stator poles to determine the inductance that should be used. This approach yielded direct and quadrature inductances, which had to be added for use in the model. Unfortunately, flux fringing, verified by a COMSOL analysis, indicated that use of the winding function was clearly an approximation. Later work showed that a reliable model should include not only flux fringing but also saturation.

Advanced Traction Motor Development

- The technical report entitled *FreedomCAR Advanced Traction Drive Motor Development Phase 1* was issued in September 2006. The report documents the design effort and conclusions reached by UQM Technologies, Inc. during the Phase 1 task. A 6 pole-pair machine with 36 slots in a 3-slot-per-pole configuration was determined to be the final design choice. The final design met or exceeded most of the 2010 FreedomCAR goals and traction motor technical targets.

Wide Bandgap Materials

- Several silicon carbide (SiC) Schottky diodes, junction field effect transistors (JFETs) and gallium nitride (GaN) Schottky diodes were acquired.
- SiC Schottky diodes, JFETs, and GaN Schottky diodes were tested, characterized, and modeled.
- A 55-kW all-SiC inverter was modeled and its performance was compared with that of similarly rated all-Si and Si-SiC hybrid inverters.
- High-temperature packages were built for SiC power devices to operate at 200°C.
- All-Si and Si-SiC (Si IGBTs and SiC Schottky diodes) hybrid inverters were built and tested and the results compared.

Integrated dc/dc Converter for Multi-Voltage Bus Systems

- Topology development
  - A half-bridge–based dc/dc converter was developed that can interconnect the 14-V, 42-V and high-voltage buses and can reduce the component count by 50% over the conventional full-bridge–based technologies. Further refinements have eliminated the inductor capacitor (LC) filter for the 14-V bus.
  - Interleaved modular configurations using the half-bridge as building blocks share the capacitor legs and provide a greater degree of component count reduction as the number of modules increases when scaling up the power level.
  - The capacitor leg current in the interleaved configurations can be significantly reduced, thus decreasing the capacitance.
  - A novel control scheme was also devised that can control the power flow among the three buses and reduce the flux density of the transformers.

- Prototype demonstration
  - A 4-kW prototype was designed and built using two 2-kW modules.
  - The prototype was successfully tested at load power levels of up to 4.6 kW.
  - Efficiencies were measured between 93.0 and 95.8% over a wide power range of 0.5 to 4.6 kW.
  - Evaluation of the prototype indicates that it exceeds the 2015 FreedomCAR targets for specific power and power density and the 2010 cost target.

Cascaded Multilevel Inverter

- A control algorithm was developed to keep the capacitors charged.
- The inverter/converter was simulated in PSpice and Simulink.
- A design simulation of an electrical drive system with the inverter/converter was developed.
- A 1.2-kW prototype was designed.

Advanced Converter Systems for High-Temperature HEV Environments

- Michigan State University designed and fabricated a 10-kW dc/dc converter module based on one of its earlier topologies.
- The University of Tennessee (UT) and ORNL devised an alternative dc/dc converter topology and fabricated a low-power proof-of-concept circuit to demonstrate its feasibility.
- UT and ORNL designed a high-temperature gate drive using a new silicon-on-insulator process by Atmel.
- Pennsylvania State University evaluated capacitors for high-temperature applications.

dc/dc Converter for Fuel Cell and Hybrid Vehicle

- Ballard focused on the production beta design to address differences between the DOE goals and the Alpha design results. The major achievement in FY 2006 was the design and verification of the final beta unit to meet the targets. Tasks included
  - Electrical improvements over the Alpha design
  - Cost reduction
  - Volume reduction
  - Weight reduction
  - Thermal design improvement
  - Manufacturing process improvements

Fully Integrated HEV Traction Motor Drive Development Using Thermoelectrics and Film Capacitor Innovations

- The thermoelectrics (TE) research that was performed was used to produce a comparison chart of commercially available TE devices. Many manufacturers' products were evaluated, and the data have been pulled together for comparison of costs and capabilities. Informative results were obtained that provide good insight into how the available TEs perform, and how some emerging TE technologies are improving performance in some helpful areas.
- A motor type was chosen in order to provide a tangible basis for design concepts and packaging innovations. The design chosen was a commercially available General Electric 5-kW induction motor.

Benchmarking of Competitive Technologies

- The efficiency mapping tests of the Prius PM synchronous motor (PMSM) and inverter were completed in a specially prepared test cell using an ORNL controller system developed for this project.
- The benchmarking design and packaging evaluation was completed for the Accord subsystems.

- The Accord motor was prepared with a new rotor shaft design and motor end plates, and the inverter was prepared through analysis of the circuit and the construction of auxiliary circuitry.
- Tests were completed on the Accord subsystems that included back–electromotive force, locked rotor, and efficiency mapping.
- Prius and Accord technical evaluations and test results were documented, and technical reports were issued for both during the year.

Component Characterization

- Commercial film and ceramic capacitor benchmarks were defined and characterized.
- Capacitor test samples were tested in two modes, statically and dynamically. Capacitor testing in the static mode requires a thermal cycling process that must continue uninterrupted for extended periods of time. Capacitor testing in the dynamic mode requires testing at thermal extremes and requires ripple current and bias voltage input from the operator.
- Magnet benchmarks for bonded and sintered magnets were defined and characterized.
- Magnet test samples were tested over a temperature range from 20 to 235°C.
- The development of a data acquisition system using LABView was completed to control the environmental chamber and to log data from the measuring instruments for capacitor evaluations.

High Temperature Film Capacitors

- Invented chemical synthesis procedures for three different polymer film families: (1) low cost polyphenylated polyethylene dielectrics, (2) polyaryl ether dielectrics, and (3) Norbornene based purified product.
- Developed a chemical synthesis route that resulted in lower cost polyphenylated polyphenylene product that should reduce cost of these polymer films by more than a factor of ten compared to previous synthesis routes.
- Demonstrated excellent high temperature electrical performance for low cost polyphenylated polyphenylene polymer dielectrics spin deposited on Al Coated Si wafers (dissipation factor less than 0.01 at 150^{o}C).

Embedded Capacitors for (P)HEV Power Electronic Systems

- Refined $LaNiO_3$ (LNO) buffer layers to avoid deleterious effects of a parasitic low capacitance interfacial oxide layer.
- Developed a core technology of PLZT/ LNO/ Ni capacitor foils with dielectric constants > 1150 (1.5 $\mu F/cm^2$) and loss ≤ 0.06.
- Developed PLZT/LNO/Ni capacitor foils reaching 580 V with breakdown fields ≥ 1.2 MV/cm.

Glass Ceramic Dielectrics for DC Bus Capacitors

- In FY2006 we evaluated flat panel display glass from Schott North America. The dielectric constant of 7 is triple that of conventional polymers, which will decrease the capacitor size by over 60%. In addition the permittivity is constant up to 400°C which far exceeds the DOE FreedomCAR goal of 140°C.

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