U.S. Department of Energy
Office of Advanced Automotive Technologies
1000 Independence Avenue S.W.
Washington, D.C. 20585-0121

FY 1999

Progress Report for the Power Electronics and Electric Machines Program

Energy Efficiency and Renewable Energy
Office of Transportation Technologies
Office of Advanced Automotive Technologies
Energy Management Team

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March 2000

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1. INTRODUCTION

Power Electronics and Electric Machines Program

On behalf of the Department of Energy's Office of Advanced Automotive Technologies (OAAT), I am pleased to introduce the Fiscal Year (FY) 1999 Annual Progress Report for the Power Electronics and Electric Machines Program. Together with DOE laboratories and in partnership with private industry and universities, OAAT engages in high-risk research and development that provides enabling technology for fuel-efficient and environmentally-friendly light and heavy duty vehicles.

The Power Electronics and Electric Machines Program supports the Partnership for a New Generation of Vehicles (PNGV), a government-industry partnership striving to develop by 2004 a mid-sized passenger vehicle capable of achieving up to 80 miles per gallon while adhering to future emissions standards and maintaining such attributes as affordability, performance, safety, and comfort. Power electronics and electric machines research is key to PNGV program success as it focuses on improving traction motors and their advanced control devices used in hybrid and fully-electric propulsion systems. Hybrid vehicles have demonstrated promise in achieving PNGV goals of high fuel economy and low emissions.

The goal of the Power Electronics and Electric Machines Program is to develop power electronics and electric machinery technologies that enable dramatic increases in component integration and flexibility while improving reliability and ruggedness and achieving significant reductions in cost, volume, and weight. National laboratories and universities are conducting high-risk, enabling technology R&D focused on overcoming the critical technical barriers that impede the development of advanced power electronics and electric machines. The lead laboratory in the Power Electronics and Electric Machines Program is Oak Ridge National Laboratory (ORNL). This program requires the close coordination of research and diagnostic efforts at a number of national laboratories and universities, including Argonne National Laboratory (ANL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratory (SNL), and Pennsylvania State University.

The Power Electronics and Electric Machines Program is also partnering with automotive suppliers and other federal government agencies to develop technologies that will be compatible with automotive-scale manufacturing and other attributes conducive to wide-scale deployment in allied applications to ensure lowest possible cost. This approach ensures that the resulting technologies reside with companies that not only have the capability to supply derived products, but also have a return-on-investment incentive to do so.

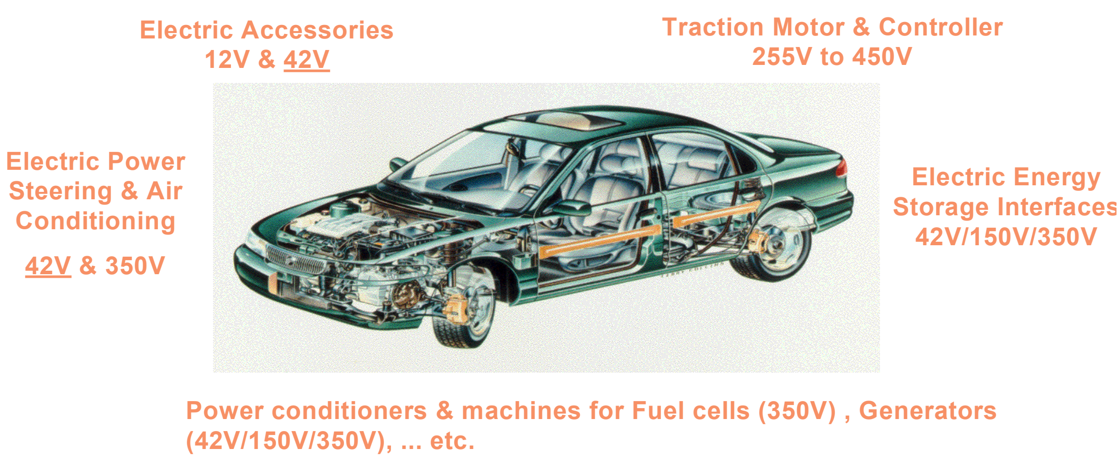
Within OAAT, the Power Electronics and Electric Machines Program works in cooperation with the Automotive Propulsion Materials, Advanced Combustion and Emissions Control, and the Fuel Cells for Transportation research and development programs. Projects within the Power Electronics and Electric Machines Program address integrated power controls, integrated chassis system controls, and navigational and communication systems that are needed to enable the success of these other OAAT programs.

Addressing Technical Challenges

During the past 10 years, significant progress has been made in the development of more efficient electric machinery such as permanent magnet AC traction motors and high-power electronic controls. These technologies demonstrate the feasibility of designing and delivering hybrid and electric vehicles that can achieve the performance levels of current light-duty automobiles. However, major barriers must still be overcome in power electronics and electric machines development, including high cost, volume and thermal management, weight, integration issues, and reliability and ruggedness.

Materials, processing, and fabrication technologies for both power electronics and electric machinery are currently too expensive for automotive applications. Existing power electronics and electric machinery are bulky, heavy and difficult to package in automotive applications. The challenge of simultaneously achieving low cost and high performance is exacerbated by the need to effectively package and cool the components.

The components necessary for the high fuel economy, low emission PNGV vehicles require power electronics components to be smaller and lighter in weight. Integration of the power electronics and motors into one package would promote greater packaging density and use fewer connectors, hoses and cables while reducing weight, volume and cost and offering greater reliability. One of the important technical barriers being addressed is the prevention of overheating and failure of vehicle electronics' thermal management. Both materials and advanced controller topologies are under investigation.



Automotive Applications of Power Electronics Technology

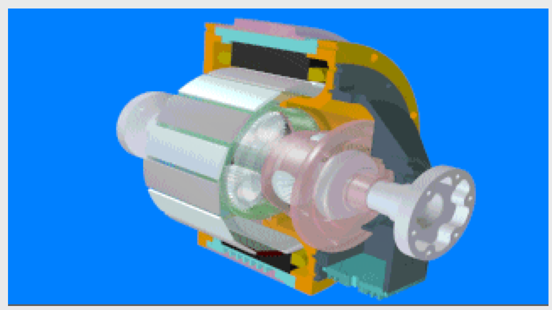
For automotive applications, power electronics and electric machinery need to be very rugged and reliable for 150,000 mile vehicle lifetime. In particular, the electrolytic capacitors, a key component of power electronics, generally have an operating and shelf life of only five years. Achieving a target of 10-15 years and 5,000 to 10,000 hours of operation in the harsh automotive environment remains a major challenge.

FY 1999 Accomplishments

In addition to the numerous technical accomplishments reported in the project briefs that follow, several accomplishments relating to improved program planning and the integration of commercial development projects deserve mention, including:

- **Peer Review Meeting**: In May 1999 DOE's Office of Transportation Technologies (OTT) held the first Power Electronics peer review meeting at Oak Ridge National Laboratory. The peer review provided an opportunity for industry program participants (automotive manufacturers, OEMs, etc.) to learn of laboratory capabilities/accomplishments in power electronics R&D and thereby facilitating technology transfer. It also fostered interactions among the National Laboratories, universities, and private companies conducting power electronics R&D.

- **AEMD Development**: In late FY 1999, DOE awarded two additional contracts to conduct research, development, and demonstration for an Automotive Electric Motor Drive (AEMD). The first of these contracts was issued for the design, fabrication, and testing of an axial gap DC brushless motor. The second was issued for the building of an AC induction machine for series and parallel configurations. The second contract also includes the development of a complete virtual reality based computer model of induction machines using an extension of the ADVISOR model, developed by the National Renewable Energy Laboratory.



Automotive Electric Motor Drive Concept

- **AIPM Development**: DOE awarded three cost-shared contracts under the Automotive Integrated Power Modules (AIPM) initiative to integrate power electronics and motors into a single propulsion unit that will offer an even greater impact on system cost and reliability.

- **Advanced Capacitors**: Research and development of advanced capacitors using polymer separators, originally developed at Sandia National Laboratory, was initiated in late 1999.

- **SBIR Contributions**: Advanced exploratory research in power electronics and electric machines is being supported through the Small Business Innovative Research (SBIR) Program. Two contracts were awarded in FY 1999 to develop thermo-electric devices, and an additional contract was awarded for the design of advanced automotive sensors. Three Phase 1 contracts were awarded for the development of DC axial gap, switched reluctance, and AC induction motors, respectively. Finally, two Phase 2 contracts were awarded; the first for the design and fabrication of AC induction machines (in collaboration with TACOM); and, the second for the design and fabrication of a DC brushless axial gap motor, which will be exhibited at the FY 2000 Future Truck competition.

Future Directions

The Power Electronics and Electric Machines Program is planning to increase its emphasis on advanced capacitor research and development, including advanced materials. This is in response to the growing recognition that the capacitor industry has been slow to keep pace with the requirements of modern electronic devices.

In FY 2000, ANL is expected to begin a new project to test and evaluate a variable-axial gap DC brushless motor capable of 10 to 90 kW of power.

With the initiation of the contract for the development a virtual-reality based model of induction machines, we hope to develop a new approach to commercial R&D that can lead to significant reductions in the cost of the down-selection process by which industry decides on which technologies and approaches to evaluate through limited production and bench testing.

The remainder of this report presents project abstracts that highlight progress achieved during FY 1999 under the Power Electronics and Electric Machines Program. The abstracts summarize national laboratory projects and provide an overview of the work being conducted to overcome the technical barriers associated with the development of advanced power electronics and electric machines. *Section 3. Advanced Materials for Power Electronics* is a reprint of project briefs reported under the FY 1999 Progress Report for Propulsion Materials. The briefs have been included in this volume due to their direct relevance and importance to the successful development of power electronics and electric machines. In addition, we have included brief project descriptions of work that is to be conducted by our industry partners in FY 2000 covering the development of Automotive Integrated Power Modules (AIPM) and Automotive Electric Motor Drives (AEMD).

David Hamilton, Program Manager
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Office of Transportation Technologies

2. ENABLING TECHNOLOGIES FOR AIPM AND MOTOR DEVELOPMENT

A. Inverter/Converter Topology and Packaging R&D

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Objectives

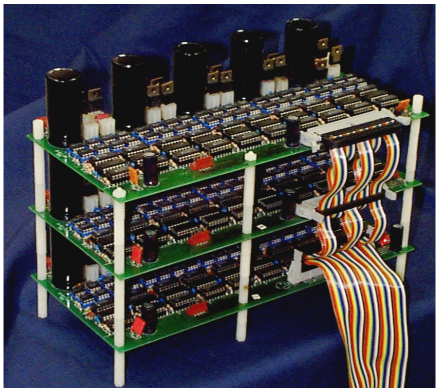
- Investigate and develop inverter/converter topologies & packaging techniques for hybrid electric vehicle applications to increase efficiency and reliability and reduce costs to meet the PNGV goals.

Approach

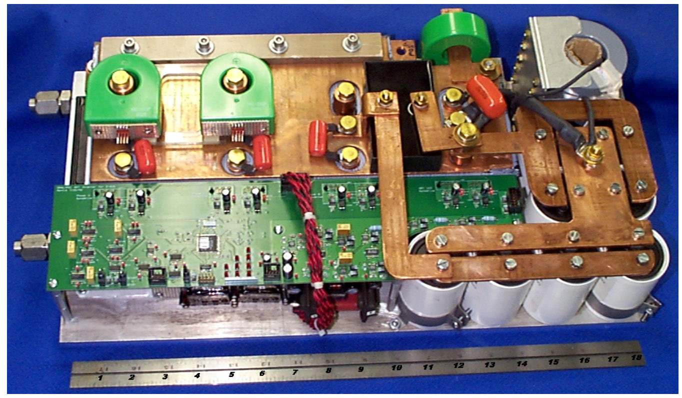
- Advance and complete the 10 kW auxiliary resonant tank (ART) inverter prototype. Put this new soft-switching technology developed and patented at ORNL into a practical use in an electric bus traction drive.
- Develop new soft-switching topologies to minimize component count and costs (passive soft-switching snubber inverter, [SSSI]).
- Simulation and prototyping of the newly devised isolated bi-directional dc/dc converter to prove the concept.
- Investigate and develop multilevel inverter topologies and controls to resolve the voltage unbalance problem, and demonstrate cost reduction and feasibility for low-voltage hybrid electric vehicles and dc/dc conversion of dual-battery systems.

Accomplishments

- A 100 kW ART inverter was fabricated and fully tested in an electric bus traction drive. Very high efficiency (>97% for 10~100% load) and reliable operation have been demonstrated.
- The new bi-directional dc/dc converter has been fully simulated and designed. A 5kW prototype is underway. Initial results show that the new converter using half the number of devices can achieve 40% volume and 30% cost reduction.
- A new gate drive technique was developed for multilevel inverters, which eliminated the need for isolated power supplies and reduced the cost to 1/3. A breadboard has demonstrated the feasibility. Printed circuit board layout and fabrication of a multilevel inverter prototype are underway. The study showed that a low-voltage MOSFET-based multilevel inverter is well suited for low-voltage traction drives and dc/dc conversion of dual battery (12V and 42V) systems.



10 kW Multilevel inverter prototype



100 kW ART inverter

Figure 1. Inverter prototype hardware.

Future Directions

- Prototyping to demonstrate a 200kW SSS inverter.
- Prototyping of the new DC/DC converter.
- Investigation of multilevel inverters and development of controls to solve the problems of voltage unbalance, cost, and packaging

Publications

F. Z. Peng and D. J. Adams, "An Auxiliary Quasi-Resonant Tank Soft-Switching Inverter," IEEE IAS Annual Meeting, Rome, Italy, 2000.

F. Z. Peng, "A Generalized Multilevel Inverter Topology with Self Voltage Balancing," IEEE IAS Annual Meeting, Rome, Italy, 2000.

F. Z. Peng, "Large Motor Drives," *Encyclopedia of Electrical and Electronics Engineering*, John Wiley & Sons, 2000.

F. Z. Peng, "Compensation of Non-Periodic Reactive and Harmonic Current," IEEE Power Engineering Summer Meeting, Seattle, Washington, July 16–20, 2000

F. Z. Peng, "An Electric Bus Traction Drive System with Soft-Switching Inverter and Speed Sensorless Induction Motor Control," IEEE The 3rd International Power Electronics and Motion Control Conference, Beijing China, August 15–18, 2000.

F. Z. Peng, "Speed and Flux Sensorless Field Oriented Control of Induction Motors for Electric Vehicles," pp. 133–139 in *IEEE/APEC*, New Orleans, Louisiana, 2000.

F. Z. Peng, "Harmonic Sources and Filtering Approaches, -Series/Parallel, Active/Passive, and Their Combined Systems-," pp.448–455 in *IEEE IAS Annual Meeting*, Phoenix, Arizona, 1999.

L. M. Tolbert, F. Z. Peng, and T. G. Habetler "Dynamic Performance and Control of a Multilevel Universal Power Conditioner," pp.440–447 *IEEE IAS Annual Meeting*, Phoenix, Arizona, 1999.

F. Z. Peng et al, "A Series LC Filter for Harmonic Compensation of ac Drives," IEEE/PESC, Charleston South Carolina, 1999.

J. Chang, J. Hu, and F. Z. Peng, "Modular, Pinched DC-Link and Soft Commutated Three-Level Inverter," IEEE/PESC, Charleston South Carolina, 1999.

B. Electric Machinery R&D

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Objectives

- The five tasks of this project are focusing on meeting the DOE's hybrid electric vehicle (HEV) motor objectives to reduce size, weight, volume and cost, improve performance and reliability, and to simplify the drive system. In part, this project investigates alternative options such as the soft-commutated dc motor and the high-power-density homopolar motor that have a significant cost impact for HEV drive systems.

Approach

- This project consisted of five tasks that included the *Directly-Controlled-Air-Gap-Flux Permanent-Magnet (PM) Machine*, *Copper Rotor, Soft-Commutated DC Motor, Flux Guides,* and *Homopolar Motors*. Adjustments were made to focus on the selected tasks in line with the available budget. The progress of the four selected tasks is briefly reported as follows.

Future Directions

- Development and prototyping of a full-scale direct controlled field-weakening PM machine.

- Design, build, and test flux guides to achieve further improvement.

- Design and build a full-scale soft commutated dc machine.

- A small prototype high-power density homopolar motor will be designed and tested.

- Develop and test a full size copper rotor bar prototype motor.

<u>Directly-Controlled-Air-Gap-Flux Permanent-Magnet (PM) Machine</u>

The advantage of this new type of machine is that the air-gap fluxes are controlled directly by the stationary field-weakening control coils. No control of the direct- and quadrature-axis current components is necessary. Therefore, the inverter and control are greatly simplified and no position sensor is required. Under a normal control range, the demagnetization due to field weakening is not an issue with this new technology. Unlike the conventional inverter controlled field weakening, the PMs of this new machine are actually strengthened under a field-weakening situation. A 10:1 or higher field-weakening ratio can be obtained. This technology is particularly useful for, but not limited to, electric vehicle motor drives and generators. This new technology is robust due to its simple operation principle. The 1999 progress of this task is as follows.

(a) The prototype machine was modified with a smaller dc supply and a hand-held scope for a portable demonstration unit. Successful demonstrations were aimed for obtaining leveraged funding support.
(b) The effects of the stator core gap in the directly-controlled-air-gap-flux PM machines were investigated. With a stator core gap, a less negative control current is needed for a given line voltage, but more positive control current is required for a given field weakening. The core gap can be determined according to the desired field weakening range of the application.

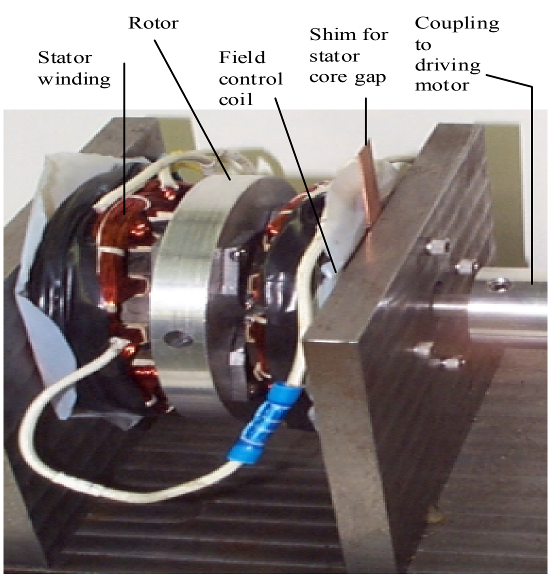


Figure 1. A prototype directly-controlled-air-gap-flux PM machine with core gap.

<u>Soft Commutated Direct-Current (DC) Motors</u>

The goal of the PNGV program is to bring the HEV into the market place. Consumers want a good vehicle at a reasonable cost. The soft commutated DC traction motor does not require an inverter to run the motor. Therefore, it has a significant potential to meet the cost objective. The efforts during 1999 are as follows:

(a) A brush test bed was constructed with the intent of investigating the contact properties of different brushes sliding on a copper ring at different linear velocities for various current densities with different lubrication options. The brush life expectancy can be greatly prolonged if there is a five-angstrom thick lubricant film between the brush and the base metal of ring or commutator. Samples were prepared for tests awaiting the completion of the test bed construction.

(b) A second-generation low-voltage soft commutated dc motor is being designed and fabricated considering novel designs that lower the cost for the motor.

<u>Copper Rotor Manufacturing Technology</u>

The squirrel-cage induction motor is a strong candidate for the traction motor of an electric vehicle. The efficiency of an induction motor can be increased significantly if the squirrel-cage is made of copper. Unfortunately, copper die cast manufacturing of the rotor is not cost effective because the die cannot last long under the very high temperature of the molten copper in processing. Our copper rotor task has the potential to solve this manufacturing problem.

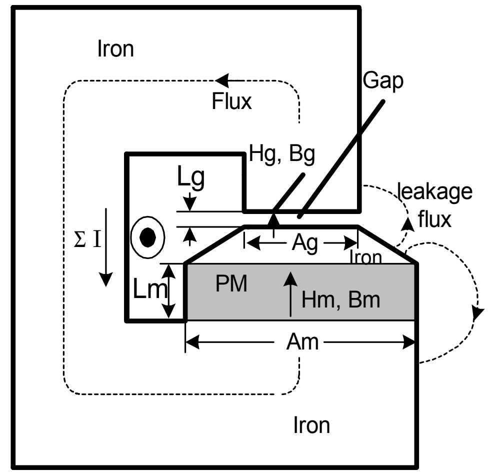
The 1999 work on this task was the development of small prototypes. They were produced to track the relationships between the joint quality and the manufacturing control parameters. The 1999 work focused on solving the problem of minor joint defects.

Flux Guides for PM Machines

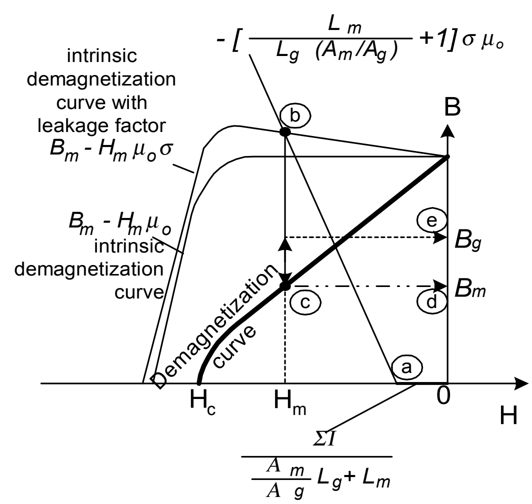
PM electric machines are known for having a high power density. The costs of PMs of different materials vary greatly. Research options are using a lower grade PM for cost reduction or increasing power density with a high grade PM. This project introduces a third option, which is the effective flux enhancement of PM machines through three-dimensional flux guides. On the basis of a higher effective flux the stator winding can be more compact; consequently, a lighter stator and a higher efficiency PM machine can be obtained. This technology can be used for both PM motors and generators.

The 1999 work was to look into this task through a theoretical analysis and to confirm the theory by conducting basic tests.

(a) In order to determine an effective flux guide design, an intrinsic demagnetization curve that considers the magnetic leakage was derived for a general flux path of Fig. 2a and shown in Fig. 2b.



(a)



(b)

Figure 2. (a) Flux path with air gap area, *Ag*, PM area, *Am,* and leakage flux.
(b) Intrinsic demagnetization curve considering leakage flux for obtaining flux densities *Bm* and *Bg.*

Figure 3 shows four experimental setups of the magnetic-path arrangements. Their measured air-gap flux densities given in Table 1 agree with the expectations derived from the intrinsic demagnetization curve with the consideration of leakage flux. This analytical tool can be used to design the flux guides.

(b) On the basis of the analysis, Figure 4 shows the flux guides that can increase the power density of various PM machines.

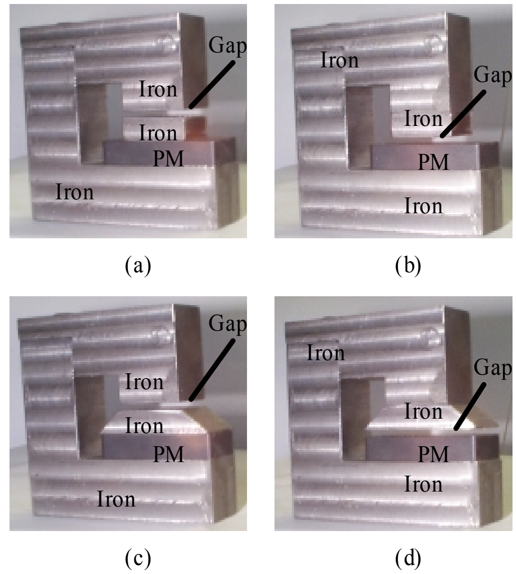


Figure 3. Four experimental setups

		(a)	(b)	(c)	(d)
Bg	Ceramic #5 0.105" gap 0.387" PM	2.5 kgauss	2.8 kgauss	2.5 kgauss	2.8 kgauss
	Nd+B 0.098" gap 0.394" PM	4.0 kgauss	4.7 kgauss	5.7 kgauss	4.6 kgauss
	Nd+B 0.295" gap 0.197" PM	1.6 kgauss	2.1 kgauss	1.9 kgauss	2.1 kgauss

Table 1. Measured air-gap flux densities of four experimental setups with different air gaps and PM thicknesses.

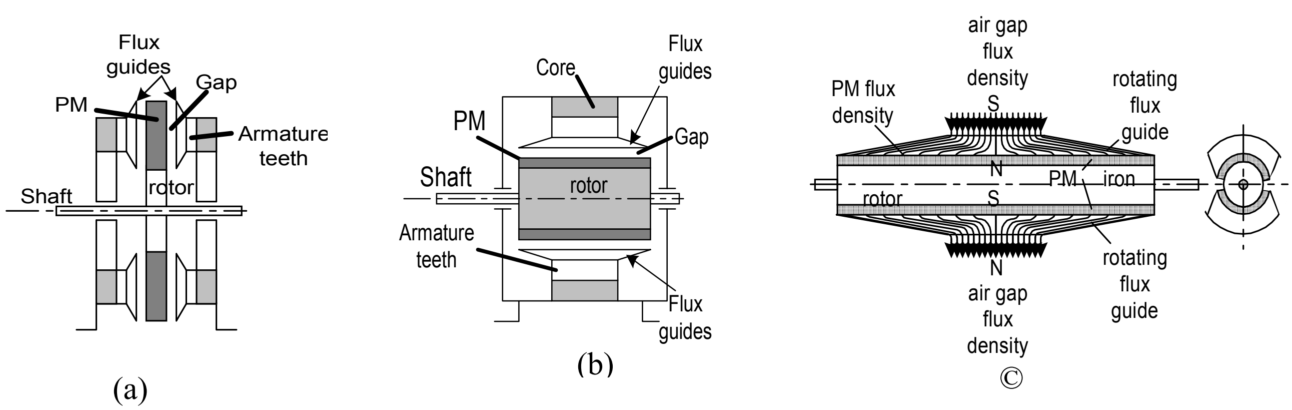


Figure 4. (a) An axial-gap PM machine with stationary flux guides extended in the radial directions. (b) A radial-gap PM machine with stationary flux guides extended in the axial directions. (c) A radial-gap PM machine with rotating flux guides.

Publications

John S. Hsu, "A Machine Approach for Field Weakening of Permanent-Magnet Motors," 2000 Future Car Congress, Paper No. 2000-01-1549, Society of Automotive Engineers, April 2–6, 2000.

John S. Hsu, "Direct Control of Air Gap Flux in Permanent Magnet Machines," IEEE Transactions on Energy Conversions, Paper No. TR7001, 2000.

John S. Hsu, "Soft Commutated Direct-Current Motors," 1998 IEEE Workshop on Power Electronics in Transportation, IEEE Power Electronics Society, Dearborn, Michigan, October 22–23, 1998.

John S. Hsu, "Induction Motor Field Efficiency Evaluation Using Instantaneous Phasor Method," 1998 IEEE/IAS Annual Meeting, St. Louis, Missouri, October 12–16, 1998.

C. Field Weakening and Magnet Retention for PM Machines

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Objectives

- To analyze known field-weakening methods for electronically switched PM motors and to determine if these techniques can be generalized and applied to the PNGV HEV application.

- To study methods for retaining the magnets at speeds from 2,000 to 12,000 RPM.

- The final objective is to compare attributes of all PM type motors that are PNGV HEV candidates and recommend one as the PM traction motor system of choice.

Approach

- As the first part of the field-weakening study and generalization, PM motors suitable for PNGV application were classified by the shape of their back-emf, which is sinusoidal for PM Synchronous Machines (PMSMs) and trapezoidal for Brushless dc Machines (BDCMs). PNGV specifications call for operation at speeds five times higher than base speed, which is the speed at which the back-emf equals the bus voltage. The general method of controlling direct and quadrature currents for operation above base speed does not work well for trapezoidal back-emfs. To solve this problem, a dual mode inverter control (DMIC) was developed which is able to drive motors with sinusoidal and trapezoidal back-emf voltage waveforms. The advantage of the DMIC is that typical PMSM and BDCM designs with very low motor inductance can be operated at rated power for speeds above 5X base speed as either a motor or generator without exceeding the rated base speed current.

Accomplishments

- Candidate traction motors for the HEV are the induction motor, the PM brushless dc motor (PMBDCM), and the switched reluctance motor. Induction motors, whose use is widespread in industrial processes and commercial and residential heating, ventilating, and air conditioning (HVAC), provide the type of torque-speed curves needed for typical automotive drive schedules. For example, they deliver relatively constant torque to achieve acceptable acceleration from rest to some intermediate or base speed and constant horsepower for highway driving. PMBDCMs, whose technology is being rapidly advanced at ORNL (Figure 1), are of interest because they are more efficient than induction motors and may be designed to have higher specific power (kW/kg) and power density (kW/L). The switched reluctance motor (SRM), whose operation is similar to that of a stepper motor, is the most robust and potentially the cheapest candidate; however, it has not been characterized yet at the power levels required for HEVs. ORNL is evaluating and testing how effectively the PMBDCMs and the SRMs may be used as HEV traction drives.

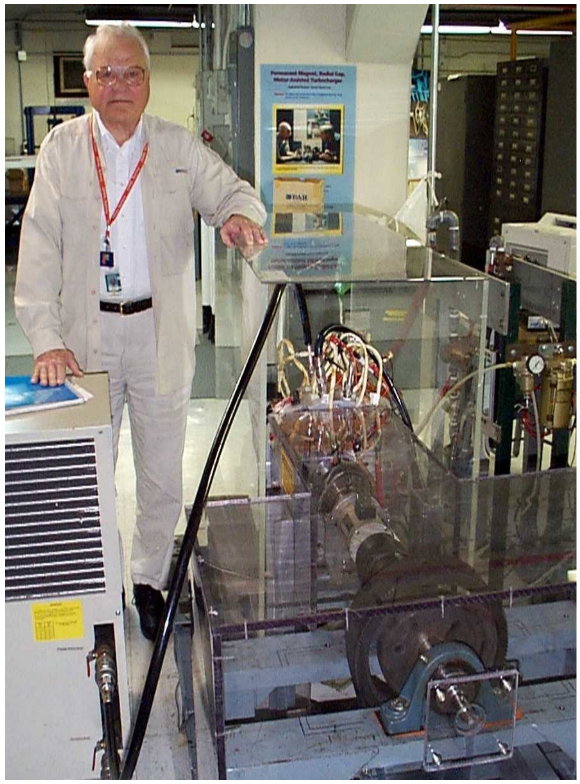

Figure 1. PMBDCM.

- PM motors are readily driven to a base speed, which is determined by the voltage at which the back-emf equals the input driving voltage. Until recently, PMBDCMs were designed so that base speed was top speed, resulting in a costly over-design in traction applications. More recently, phase advance has been used to drive commercial PMBDCMs above base speed, but for PM motors with typical inductances of 0.07 mH, peak current at 5X base speed was already 4 times larger than peak current at rated base speed power. Obviously, special control is necessary to drive a PMBCM beyond base speed. One possible control is to reduce the field of the PMs. ORNL has developed and patented an elegant way to accomplish field weakening by using flux control. Another possible control is to selectively inject current into the motor when the back-emf is below the drive voltage. ORNL has recently developed and demonstrated technology that enables a PMBDCM to be driven over six times base speed without exceeding the current rating at base speed. The motor is driven using pulse-width modulation (PWM) below base speed and changed to the new control mode above base speed. ORNL is pursuing plans to integrate the new control system with a PWM inverter and demonstrate power delivery of 15 kW by a PM axial gap BDCM designed to meet traction motor requirements of a parallel HEV configuration.

Future Directions

- Complete design of DMIC and gearless HEV PM motor.
- Report documenting testing of DMIC and gearless HEV PM traction motor.
- Assessment of known PM HEV drive system candidates.

Publications

J. M. Bailey et al., *Field-Weakening Schemes and Magnet-Retention Techniques for Permanent Magnet Machines,* ORNL/TM-1999/74 (draft), Oak Ridge National Laboratory, Lockheed Martin Energy Research Corporation, 1999.

J. M. Bailey and J. S. Lawler, "Constant Power Speed Range Extension of Surface Mounted Permanent Magnet Motors," Disclosure ERID 0716 : Patent Application Submitted, 2000.

D. Fiberoptic Microsensors for Automotive Power Electronics

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Objectives

- To establish feasibility of an approach for measuring currents and voltages using microcantilevers in conjunction with optical fibers. The goal is to:

  1) fabricate a microcantilever unit, which will respond by flexing in the presence of an electric field or current-induced magnetic field; and
  2) sense the motion of the cantilever by use of a single optical fiber.

- An inductively coupled light-emitting diode (LED) approach will also be evaluated. The intent is to use this alternative technology to develop sufficiently accurate voltage and current sensors with greatly (>> 10:1) reduced size and cost.

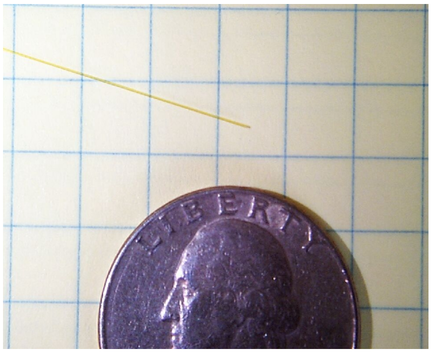
Approach

- The goal of this project is to develop an effective means for measuring current and voltages of the power electronics inverter drive package. The approach is to combine fiberoptics with Micro-Electromechanical Machines (MEMs) technology. This will lead to sensors which are:

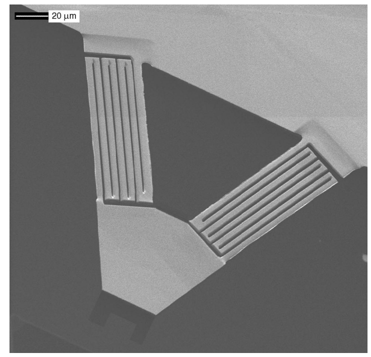
  1. Lightweight,
  2. Small,
  3. Energy efficient,
  4. Inexpensive,
  5. Accurate, and
  6. Responsive.

- These sensor characteristics will improve the performance of inverters by enabling precise switching. In addition, such sensors will aid development and test engineers in optimizing designs. Present sensor technology uses significant drive current, takes up space, is heavy, and is too expensive in consumer drive packages.

- The high currents and voltages involved with inverter operation in conjunction with the extremely fast switching speeds provide a challenging diagnostic environment. Sensors are required which are immune to electromagnetic interference (EMI) as well as accurate. Our approach is to combine two technologies, fiberoptics and MEMs. For current measurement, microcantilevers are coated with a magnetic material. When placed close to a current source, the cantilever will flex in proportion to the induced magnetic field that accompanies the current. The cantilever motion is sensed optically with an optical fiber in close proximity to the microcantilever. The target range for current sensing is 1 to 600 amps. Voltage measurement will be pursued in the coming year by depositing other material types on a cantilever.



Typical Optical Fiber



An ORNL cantilever

Figure 1. Optical fiber and cantilever.

Accomplishments

- This new program is steadily approaching its goals. The major accomplishments are as follows:

    1. Two effective methods for coating magnetic material onto commercial atomic-force microcantilevers are demonstrated:
        - RF sputtering, and
        - pulsed laser deposition.
    2. Modeling indicates time responses approaching 1 MHz for physically realistic cantilevers – typical dimensions are 150 by 50 by 10 microns.
    3. Magnetic fields as low as six gauss are detected in the lab using a microcantilever coated with phosphor. The significance of this is that six gauss is the field that would by experienced by a cantilever placed 5 mm from a conductor carrying one amp. Since the cantilevers will be mounted much closer, the potential sensitivity of the technique is thus demonstrated.
    4. Testing in the relatively uniform field of a Helmholtz coil has verified that cantilever deflections are proportional to current, as seen below.

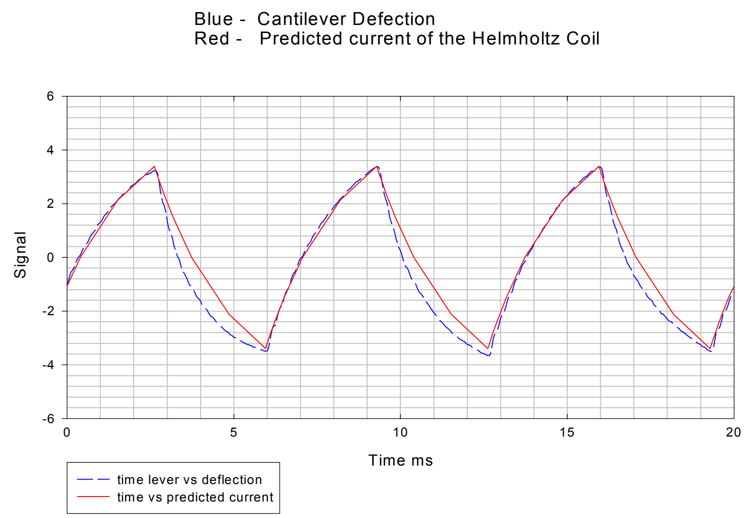


Figure 2. Cantilever deflection and current.

Future Directions

- The effort in FY 2000 will be improving the cantilever fabrication process with subsequent demonstration of fast response current sensing. Different coating materials will be selected in order to fabricate voltage and temperature sensors. For the voltage sensor, the cantilever will function as one plate of a capacitor. For temperature sensing, an appropriate bimaterial cantilever will flex as a function of temperature. We have observed this temperature-dependent flexure under certain conditions in the past and can engineer it for this application. In addition, effort will be expended in miniaturizing the method for reading out the microcantilever flexure. All these efforts are aimed at achieving the technical performance of the sensors using methods and components that will, with the expected economy of scale, result in inexpensive yet high performance devices.

Publications

R. L. Hardy, "Optical Methods of Electric Current Measurement," ORNL-TM-2000/81, Oak Ridge National Laboratory Report, Lockheed Martin Energy Research Corporation, August 1999.

J. W. Lim, "MEMS Detectors for Calorimetric Spectroscopy and Magnetic Field Detection," informal report for the ERULF (Energy Research Undergraduate Laboratory Fellowship) Program, December 1999.

E. Automotive Integrated Power Module Validation Testing and Contract Support

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Objectives

- The goal is to provide technical support to the Automotive Integrated Power Module (AIPM) Contracts Manager, to develop test procedures, design, acquire and prepare the test equipment, and to perform the validation testing of the AIPMs supplied by DOE's AIPM contractors.

- To provide electrical and environmental test support to AIPM developers/suppliers of preliminary and production design AIPM test articles leading to the refinement of the deliverable units. The conformance to established specifications will be assessed and the results will be utilized to determine the suitability of the AIPM technology for automotive applications.

Approach

- The AIPM validation and test support effort will be accomplished through the development of validation criteria taken from test data requirements set forth in IEEE P1461. Necessary test documents and standards will be acquired and studied in order to develop comprehensive testing protocols. Pass/fail criteria will evolve into electrical and environmental test procedures for qualifying the units. Drafts of the procedures will be reviewed by in Electrical and Electronics Technical Team (EE/TT) members and in-house testing staff. Acquisition and/or fabrication of equipment necessary to accomplish the testing tasks will be performed and scheduling of the tests, test facilities, and necessary personnel will be coordinated. Efforts will be made to minimize expenses and provide the most expedient results in the validation process through the utilization of ORNL in-house expertise and equipment.

Accomplishments

- ORNL is tasked with evaluation of three vendors' power modules designed for automobile traction motor drives. These evaluations will include basic electrical/electronic functionality testing followed by load and control testing driving a standard motor. Environmental tests will follow the functional and load tests. This segment of evaluations includes thermal cycling and soak, salt spray, dust infiltration, vibration shaker, and shock tests. Electromagnetic emissions will be measured when the units are at various load conditions on the test stand

- All referenced test standards and pertinent documents were acquired and studied. The selection of valid tests and testing sequencing of the modules was finalized. Questions concerning the AIPM specification and solicitation involving current and power levels as well as specific environmental tests were resolved. The effected documents were amended and submitted to DOE.

- All of the environmental test procedures were completed and reviewed by the management of the ORNL Environmental Effects Laboratory (EEL). The development of the functional test and electrical characterization tests are underway. The report template, which will accompany the test unit throughout its testing cycle, is being written. Upon completion of the electrical tests, a testing flowchart will be created which will be included in the test documentation package. The flow chart will contain test decision points and branches. This will be available to the test operator throughout testing to insure consistent, adequate and thorough evaluation of the modules.

- The purchase or design of equipment necessary for the testing of the AIPMs is underway. Some of the test equipment was received during FY99. Computers and data acquisition equipment, to allow for monitoring of testing via the Internet, have arrived as well as meters, current sensors, power supplies, and motors for load simulation. Some upgrades of the environmental test equipment have been made.

- A design for a relatively small, inexpensive cooling system for the AIPMs has been completed and parts are being procured. Parts for the second power supply have been obtained and the build of this unit is nearly complete.

- Arrangements and plans to provide for all testing to be conducted ORNL have been finalized. Economical means have been devised to enable the performance of the salt spray and dust tests to be done on site rather than going to a commercial test laboratory. Designs for these alternative test facilities have been reviewed and approved by the EEL manager. All support equipment necessary for the tests has been identified.

- The PEEMRC is relocating soon, and the dynamometer is to be assembled there with data acquisition hardware and software specifically for testing AIPMs. The software will be developed to allow automatic and possibly remote control of the testing and data acquisition. The dynamometer will be controlled by computer allowing long term tests with automatic data acquisition, as well as variable load cycles (such as the Federal Urban Driving Schedule [FUDS]) to simulate real world loads on the motor/AIPM.

Figure 1. New PEEMRC Laboratory Located at the National Transportation Research Center.

Future Directions

- In FY 2000, development of the detailed test plans for the individual segments of the evaluation was initiated. The project is waiting for the signing of contracts with vendors for the development of the AIPM prototypes. The prototypes are expected at ORNL in the 2nd to 3rd quarter of FY 2001, with ORNL evaluations completed by the end of FY 2001. PEEMRC has also begun developing the dynamometer control concepts and data acquisition methods that will be required for evaluating the AIPMs.

F. HEV Motor/Inverter Modeling

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Objectives

- To provide a methodology to evaluate HEV traction drive systems which consist of an electric induction, PM, or switched reluctance motor, an inverter, and a controller proposed as PNGV candidates.

Approach

- This will be done by developing motor and inverter performance and thermal models and performing system testing for model affirmation. An important activity will be interfacing these models with detailed DOE HEV simulation codes such as ADVISOR and PNGVSAT. An additional activity will be to estimate and compare economic benefits.

Accomplishments

- ORNL is developing interactive LabView based models of HEV traction motor/inverter drive systems. A stand-alone interactive design code for radial gap PM motors (RGPMM) has been verified against independent PM motor design implementation of PM equations. Modules within the design code may be used for motor design, dynamic performance estimates, performance map generation, road test simulation, nameplate generation, and drawing generation. This model includes temperature feedback effects on stator wire resistance and magnet performance. Models of the inverter, battery, bearing friction, and windage have been integrated with the RGPMM motor model.

- Based on nameplate data generated by the model, the road test simulation module responds to speed and power demand inputs and to ambient temperature changes, to provide temperature feedback and to estimate temperature distributions inside the motor as well as voltage, current, frequency, efficiency, and losses.

- An induction motor model based on an enhanced stator-referred equivalent circuit representation is also available. It too consists of several interactive modules including a model finder, which generates the parameters of the equivalent circuit from nameplate data, a road performance simulator, a temperature estimator, and a voltage estimator. The road test simulator shows time-dependent performance and temperatures for varying speed, power, or torque output demands, terminal voltage, frequency, and ambient temperature. Figures 1 and 1 show the model outputs for the road performance simulator.

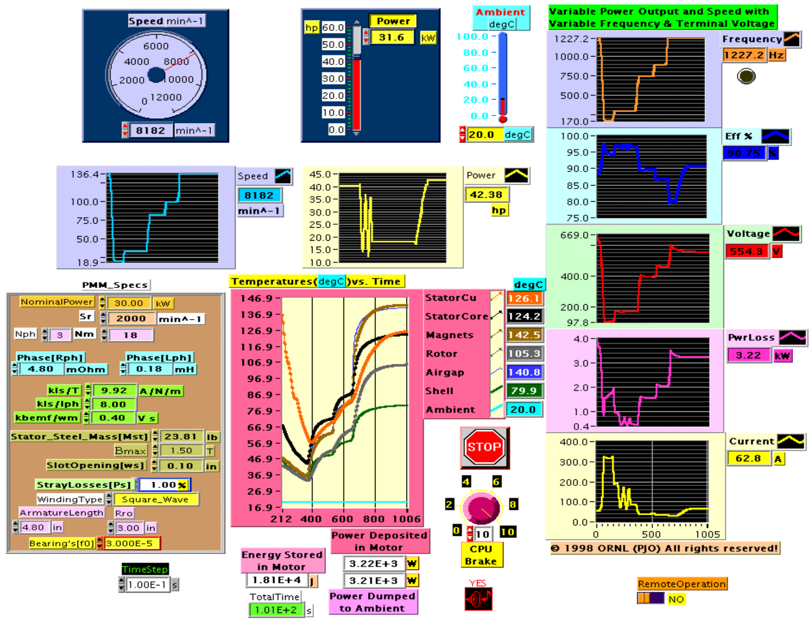

Figure 1. Road Test Simulator for Radial Gap PM Motor Model.

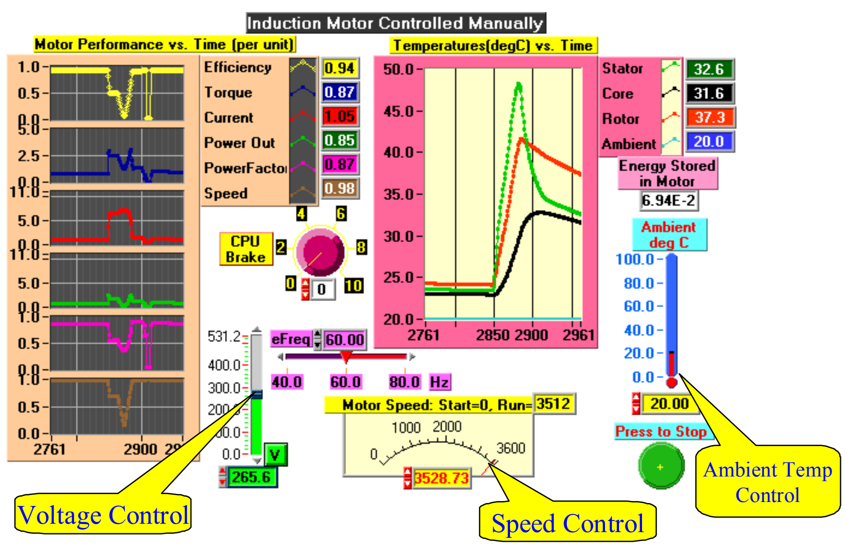

Figure 2. Road Test Simulator for Induction Motor Model.

Future Directions

- During the next year, ORNL will be completing a model of the axial-gap PM motor which will be used to design the 15 kW PMBDCM used to demonstrate ORNL's new technology for driving a compact, gearless, 15 kW HEV PM motor with high specific power and high power density, at 4.7 times base speed without exceeding its current or power specifications at base speed. ORNL will also be developing a model of a SRM. The objective is to apply that model to the prototype SRM that is being tested for affirmation of the model and then to apply it for evaluation of commercial follow-on SRM drive systems.

Publications

P. J. Otaduy, J. W. McKeever, and J. M. Bailey, “Model-based Generation of Scaling Laws for Radial-Gap Permanent Magnet Motors,” Paper 00FCC-36, Future Car 2000, April 2000.

J. W. McKeever, “HEV Voltage Sensitivity Life-Cycle Cost Sensitivity to Battery-Pack Voltage of an HEV,” Paper 00FCC-17, Future Car 2000, April 2000.

J. W. McKeever, S. Das, L. M. Tolbert, L. D. Marlino, and A. Nedungadi, *Effects of Battery-Pack Voltage on Hybrid Electric Vehicles*, ORNL/TM-2000/24, (draft in progress), 2000.

G. HEV Switched Reluctance Machines

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Objectives

- The SRM is a cheaper, more robust traction drive, but commercially available units do not meet PNGV traction drive requirements. Furthermore, commercially available SRMs have certain undesirable inherent characteristics such as harsh waveforms, high torque ripple causing torsional vibration and noise, and torque/speed curves different from those of an induction motor. If these can be moderated or eliminated, the simplicity of this robust motor makes it an excellent candidate to meet cost, volume, weight, and reliability goals. To promote development of a viable commercial SRM, ORNL will provide independent evaluation of machines provided by industry. Additionally, ORNL will develop innovations on SRM technology.

Approach

- Although the SRM will be robust and cheap, it requires a different type of drive inverter. SRMs with single digit powers have been commercially preferred for use in washing machines and dish washers; none have been commercially available at HEV power levels. Recently, ORNL procured a prototype SRM that was designed to deliver HEV level power. One unknown is whether or not the noise generated by an HEV SRM will be acceptable for HEV use. ORNL will collaborate with the vendor to characterize the prototype SRM.

Accomplishments

- ORNL has set up the test apparatus for accurately measuring torque pulsations and acoustic and vibration behavior which will be used to quantify the noise generated by the SRM and inverter drive system. This type of motor testing is somewhat different from traditional motor evaluations since the parameters being studied are different. The test apparatus is ready for installation in a transportable cabinet so that it may be moved among the various motor test sites at ORNL. Baseline data will be determined from other machine types (such as induction motors) before testing of SRMs begin. In this way, the sound generated may be compared with the sound generated by a baseline motor.

- Two vendors have been located to provide SRMs and drives to evaluate. Testing is expected to begin in FY 2000.

Future Directions

- During FY 2000, research activities will center on comparative performance and sound generation evaluations of these SRMs with the baseline motor/inverter system.

H. Advanced Inverter Technology Demonstration

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Objectives

- This project was intended to promote transfer of a new ORNL soft-switching power inverter technology quickly into the automotive traction drive commercial marketplace by proving its capabilities. This technology advances the state-of-the-art in traction drives by reducing volume, weight, and life-cycle costs while increasing reliability and performance by improving components and systems.

Approach

- ORNL has been developing power inverters for automotive and other applications for several years. One area of this development has been in soft-switching inverters, where the power electronics switches are caused to switch at low voltage and current (low stress) conditions. One of these technologies, named Auxiliary Resonant Tank (ART), was built and proven using a 10 kW prototype built and tested in the laboratory.

- This project included scaling-up of the inverter from its first prototype, developing a field-hardened inverter, installation and testing on the actual vehicle, with data acquired from field and laboratory testing for performance evaluation.

Accomplishments

- The ORNL 10 kW prototype was successfully scaled up to 100 kW in a laboratory evaluation unit and subsequently in a field-hardened unit. Along with the help of Cooperative Research and Development Agreement (CRADA) partners in Chattanooga, TN, the field-hardened unit was installed and tested on an electric shuttle bus that normally operates in the Chattanooga downtown area. This vehicle is all-electric and driven by a single commercial 75 kW oil-cooled induction motor.

- Laboratory data for the 100 kW unit showed inverter efficiency above 95% for the entire load range of the inverter. Soft switching allows an inverter to operate more efficiently in the low load region than conventional hard-switching inverters. Field tests showed the inverter to successfully power the electric bus through several hours of steady state and driving-cycle test track evaluations.

- In addition to the soft-switching inverter development and on-vehicle testing, a control method for the induction motor known as self-sensing was incorporated into the project and tested successfully in the laboratory and in the field. This technique allows the inverter to power and control the motor without the use of speed or flux sensors that are normally used in this and most other automotive applications.

Future Directions

- This project was completed with successful laboratory and field testing of the hardened 100 kW inverter in the last quarter of FY 99. The ART technology was successfully demonstrated during this project. One important future direction for this research would be to continue the development of the self-sensing algorithms to provide more robust control of the vehicle in the field. Sensitivity to vehicle accelerations should be studied to provide the best control of the vehicle.

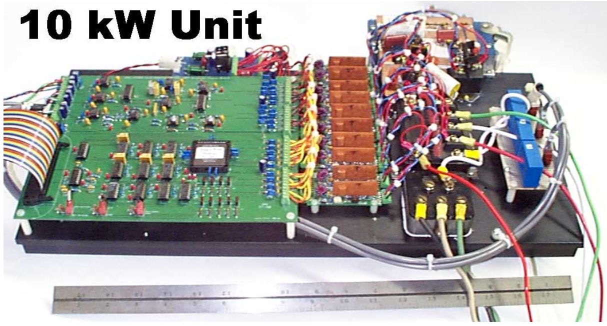

Figure 1. 10 kW ART Prototype.

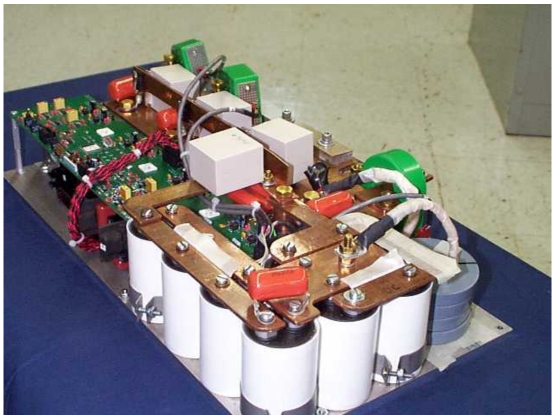

Figure 2. ORNL's first 100 kW prototype ART.

Figure 3. Installation of ORNL 100 kW inverter in CARTA Electric Shuttle Bus.

Publications

A final report covering the scaled-up inverter design and the CRADA work involving installation and testing of the field unit is written and is presently being reviewed prior to publication.

I. Independent Motor, Inverter, and Component Validation

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Objectives

- To receive power electronics and electric machinery components, inverters, or motors for independent evaluation, establish the evaluation test plan, configure for testing, execute the test plan, and report the evaluation results to the source organization and to OAAT.

Approach

- Receive components, inverters, or motors for independent evaluation, establish the evaluation test plan, configure for testing, execute the test plan, and report the evaluation results to the developer and to OAAT.

Accomplishments

- During FY 1999, ORNL characterized four Nano-structure multi-layer capacitors from Lawrence Livermore National Laboratory and evaluated the linearity of a ceramic capacitor from TRS Ceramics and Argonne National Laboratory. Because they operate at temperatures much lower than standard capacitors, ceramic capacitors from Pennsylvania State University were incorporated as part of ORNL inverters to test their behavior as snubbers. This work was leveraged by a summer intern who built a device for measuring the dielectric absorption of capacitors. Dielectric absorption is the tendency of the dielectric to recharge after discharging and can have a serious effect on circuits that depend on the stability of a capacitor's charge.

- These evaluations provide a channel for ORNL to work with researchers and suppliers to help guide research toward commercial products that fill HEV needs. They also serve as a practical progress check along the research path and highlight those components which have superior potential to meet OAAT research and development goals and for which further development is warranted.

Future Directions

- Components that might be evaluated are capacitors with new ceramic materials to reduce their size and make them more reliable. Another material for evaluation is better insulation or more efficient heat transfer material such as carbon foam, which may improve reliability and increase volumetric power. For FY 2000, ORNL will continue as an evaluation and guidance resource, especially for the associated OAAT programs that develop improved capacitors and materials for inverters and motors. Cost depends upon the number of items selected for evaluation.

Publications

J. W. McKeever et al., "Independent Motor, Inverter Evaluation of Ultracapacitors and Component Evalutaion," (ORNL/TM report draft to be prepared).

J. Micro Heat Pipe Development

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Objective:

- Develop improved approaches for thermal management in electronic systems.

Approach:

- Develop techniques for designing, fabricating, and characterizing micro heat pipe substrates.

Accomplishments:

- Fabricated and characterized several wick geometries for micro heat pipe structures.
- Developed assembly processes and techniques for micro heat pipes based on Kovar substrates.
- Developed thermal characterization techniques for micro heat pipes.
- Carried out thermal characterization of Kovar micro heat pipes demonstrating significantly improved performance.
- Developed a thermal simulation model of micro heat pipe to allow estimates of thermal performance in different applications.

Introduction

Sandia has developed techniques for fabricating thin, flat plate substrates which closely match the coefficient of thermal expansion (CTE) of semiconductors but which also have high effective thermal conductivity. The basic micro heat pipe (MHP) geometry is shown in Figure 1. The substrate is two plates of material with an edge seal. Between the two plates is a vapor chamber and textured micro capillary wick. Once the substrate is charged with a

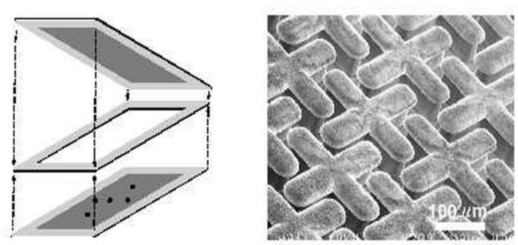

Figure 1 (left) Basic design of the heat pipe substrate: two plates with wick features on their inner surface are separated by spacers and sealed along the edges. (right) Enlargement of heat pipe wick showing micromachined features on wall surfaces.

working fluid, a heat-producing die on the surface drives vaporization of the fluid which transports to cooler regions of the substrate where it then condenses. The capillary forces in the wick structure drive fluid towards the heated region to replenish that lost through vaporization. The structure forms a closed passive system that can possess high effective thermal conductivity.

For this work we selected Kovar metal as the substrate wall material because its coefficient of thermal expansion (CTE) matches that of very-large-scale-integrated-circuits (VLSI) and GaAs semiconductor die materials. Integrating the micro heat pipes with Kovar significantly increases the effective thermal conductivity over that of Kovar alone.

Photolithography was used to make the heat pipe wick features thereby allowing us to design the shape and spacing of the wick patterns to optimize performance. Efforts were also directed towards the development of assembly techniques and processes for the MHP. The operations include: (1) laser drilling of the fill port hole in one wick plate; (2) resistance welding of the internal supports to one wick plate; (3) assembly and laser tack welding of wick plates to the spacer frame; (4) laser seam welding of the assembly edges; (5) resistance welding of internal supports to the opposite wick plate; (6) leak testing; (7) bead blasting and Ni/Au plating; and (8) solder attachment of the fill tube. Process schedules were developed allowing reliable fabrication of the heat pipe structures.

A thermal testing system was developed to evaluate the performance of the MHP. Temperatures were measured as a known heat input was applied to the surface of the heat pipe, while the temperature at the edge of the heat pipe was constrained to a fixed value. An assembly test die mounted near the center of the heat pipe was used as a heater. A temperature map of the full surface was measured using an infrared imaging system as illustrated in Figure 2. An example of measurements made on an

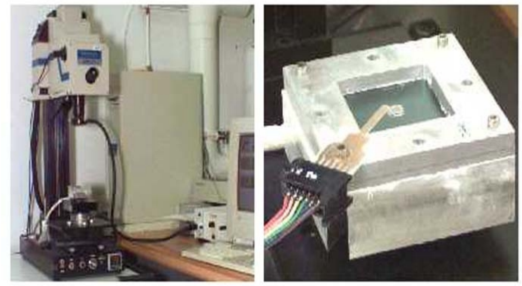

Figure 2. (left) Infrared imaging system and heat pipe mounting fixtures. (right) Detailed view of test fixture seen at the left on the thermal stage below the lens.

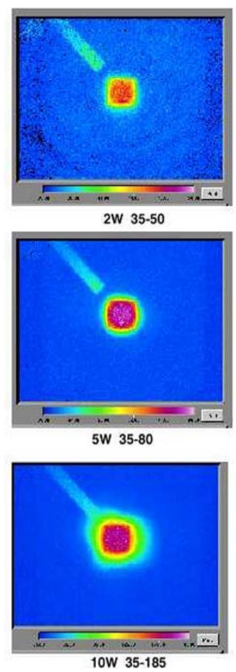

Figure 3. Temperature maps for 2, 5 and 10 watts power to the test die mounted on an MHP. The base temperature was 35°C for these tests on the CD5CD6 prototype.

MHP is shown in Figure 3. The color maps show the temperature distributions across the surface of the MHP in each case.

Temperature profiles across the front side of the heat pipe are plotted in Figure 4 for the full distance in the field of view. Since the die at the center is not coated with a high emissivity surface, the temperature resolution is lower leading to the variations near the peak.

To help characterize the heat pipe performance we developed a simple thermal model. The model is based on experimentally determined heat transfer coefficients rather than first principles describing the fluid drag, pumping pressures, vaporization kinetics, and boiling in the heat pipe. A 3D simulation of the test conditions using the known material properties and geometry was used to extract a value for the heat transfer coefficient of the interface layer between the heat pipe wall and fluid. This heat transfer coefficient summarizes the effects of the myriad physical processes in the heat pipe.

A value for the heat transfer coefficient was derived from experimental measurements by adjusting the coefficient value until the model matched the experimental temperature profiles. We found that a single heat transfer coefficient value allowed us to estimate temperatures over the range of conditions occurring in these experiments.

Figure 5 shows the results of this simulation using the geometry of the CD5CD6 heat pipe and a power of 5 watts.

The results of the simulation are compared with the measurement in Figure 6. The calculated profile gives a reasonable comparison to the measured results. This model can be used to estimate temperatures

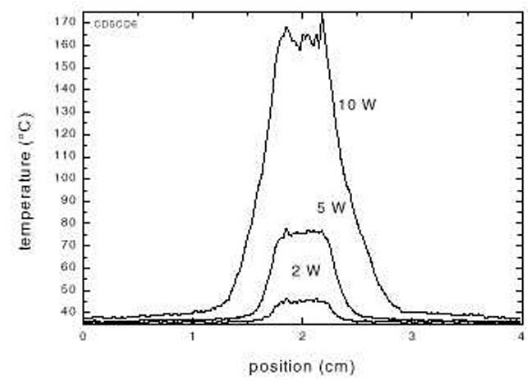

Figure 4. Plots of temperature profiles across CD5CD6 prototype heat pipe for the cases shown in Figure 3.

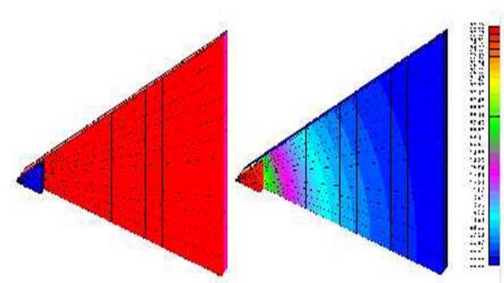

Figure 5. Simulation of a one-eighth section of the CD5CD6 heat pipe geometry, including a die mounted at the center dissipating 5 watts and the edge constrained to a fixed temperature. The colors on the mesh at the left indicate the type of material; the mesh at the right shows a color-coded temperature map of the die and substrate surfaces.

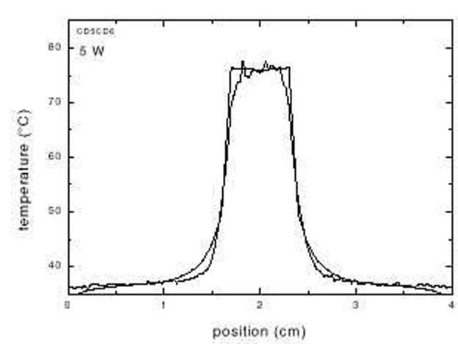

Figure 6. Comparison of profiles from the model and from test results. The model is based on a constant interface heat transfer coefficient.

for other power and die placement conditions.

This report has described the first steps in the development of a new technology for cooling microelectronics by embedding micro scale heat pipes in a flat plate substrate. Thermal test results from prototype designs that integrate micro heat pipes within substrate walls of Kovar metal show that the addition of micro heat pipes enhances thermal conductivity by a factor of 2.5 over that of Kovar alone. These new substrates are made with relatively low-cost processes and materials.