4.4 ADVANCED POWER ELECTRONICS AND ELECTRIC MACHINES

Achieving FreedomCAR and Fuel Partnership goals will require the development of new technologies for power electronics and electric machinery. The new technologies must be compatible with high-volume manufacturing; must ensure high reliability, efficiency, and ruggedness; and must simultaneously reduce cost, weight, and volume. Key components for hybrid vehicles (with fuel cell and ICE prime movers) include motors, inverters/converters, sensors, control systems, and other interface electronics. Figure 18 shows the Power Electronics and Electric Machines activities with the resulting outputs and the collaboration between this sub-program and others.

This section discusses the needs and barriers specific to light vehicles. Heavy vehicle technologies are discussed in Section 4.2, Advanced Propulsion and Vehicle Efficiency Improvements.

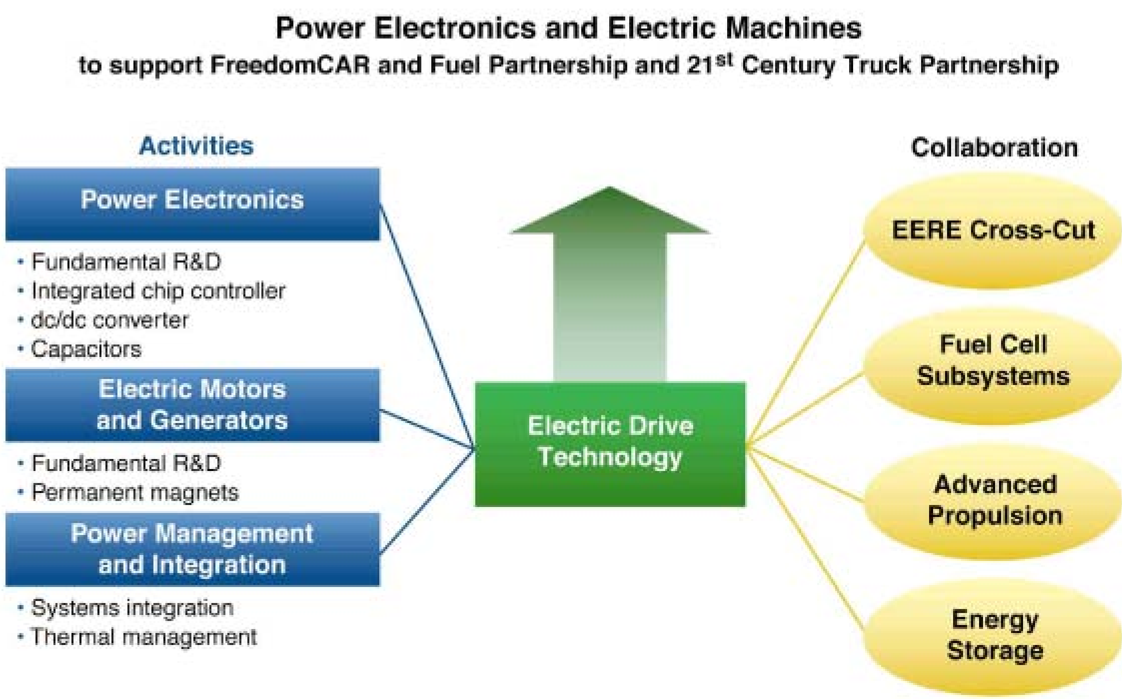


Figure 18. Power Electronics and Electric Machines activities with the resulting outputs and the collaboration between this sub-program and others.

Goals

Develop by 2010 an integrated electronics system that costs no more than $12/kW peak and can deliver at least 55 kW of power for 18 seconds and 30 kW of continuous power. Additionally, the propulsion system will have an operational lifetime of 15 years (a FreedomCAR and Fuel Partnership Goal).

Programmatic Status

The Advanced Power Electronics and Electric Machines sub-program is divided into three tasks: (1) power electronics, (2) electric motors/generators, and (3) power management and integration.

Power Electronics

The power electronics activity is focused on R&D for flexible, integrated, modular power inverters and electronics for power conditioning and control, including a power switch stage capable of running a variety of motors and loads.

An inverter is needed to convert dc power from a fuel cell or a battery to ac power for the motor. An automotive integrated power module (AIPM) has been developed that approaches the FreedomCAR and Fuel Partnership targets for weight and cost, but only if the coolant temperature is lower than desired. Further research will focus on the use of (1) silicon carbide (SiC) semiconductors, which can be operated at much higher temperatures than current silicon (Si) semiconductors; (2) improved thermal management technologies; and (3) innovative topologies that have the potential for reducing the weight, volume, and cost of the system.

Capacitors account for a major fraction of the weight, volume, and cost of an inverter. Currently, electrolytic aluminum capacitors are used for applications below 450 V; but, in addition to being bulky, they cannot tolerate high temperatures; tolerate very little ripple current; have short lifetimes; and, when they fail, sometimes do so catastrophically. Two promising alternatives to electrolytic aluminum are polymer-film capacitors and ceramic capacitors. Polymer-film capacitors are used for voltages above 450 V and are less bulky, but they also cannot tolerate sufficiently high temperatures. Research to date has identified several candidate polymers with higher-temperature capabilities, and that research will continue with an emphasis on scale-up and manufacturing technologies. Research also will continue on ceramic capacitors, which have the greatest potential for volume reduction and the ability to tolerate very high temperatures. The emphasis for ceramic capacitors will be on ensuring a benign failure mode and lowering the cost.

Current motor controller technology revolves around digital signal processors, but external circuitry is still required to accomplish all of the functions necessary for efficient motor control. A new R&D effort is being initiated to develop a system on a chip that will provide the opportunity for considerable cost reduction.

Hybrid fuel-cell-powered vehicles will require a bi-directional dc/dc converter to interconnect the fuel cell power high-voltage bus and the low-voltage bus for vehicle auxiliary loads. A new R&D effort is being initiated to develop innovative designs and demonstrate commercial viability in high-volume production. Technical issues to be addressed include choice of topology, filtering requirements, switches, switching frequency, radio-frequency interference (RFI) considerations, thermal management, and types of magnetic components. Cost, reliability, weight, and volume are critical factors.

Electric Motors and Generators

Emphasis in this activity is on advanced motor technologies, performance, low-cost materials, and thermal management systems that will yield higher power densities and cost-effective solutions.

Induction motors have the advantage of being the most widely manufactured and used, but they cannot meet the FreedomCAR and Fuel Partnership requirements of cost, weight, volume, and efficiency; and the likelihood of achieving additional improvements is low because the technology is mature. A permanent magnet motor has the highest power density; but it does not have a sufficient constant power speed range, and its costs are too high. Switched reluctance motors are potentially the lowest-cost candidate but have serious problems in terms of high torque ripple, high noise, and low power factor.

The Automotive Electric Motor Drive (AEMD) task has developed an external permanent magnet motor that met the power requirements but fell considerably short of cost, weight, and volume goals for the FreedomCAR and Fuel Partnership. Future research will focus on alternate designs for a permanent magnet motor and on field weakening to increase the constant power speed range.

The unacceptably high cost of permanent magnet motors is due to the high cost of magnet materials, magnet manufacturing, and rotor fabrication. Research is being conducted on polymer-bonded particulate magnets with the objectives of increasing the useful operating temperature from 150 to 200°C and decreasing the cost to about 25% of the current price of approximately $90/kg.

Power Management and Integration

This activity emphasizes system issues such as the integration of motor and power control technologies. A primary research focus is the thermal management of inverters and motors with two phase-cooling technologies. Advanced component modeling, fabrication, and manufacturing techniques are being investigated. Work is under way on integrating emerging power electronic technologies in order to manage and control high-power components, which will provide rapid, bidirectional energy flow to improve performance and lower costs.

Targets

Technical targets for inverters and motors for an HEV powertrain are presented in Table 18. The actual power rating (kW) and the cost ($) are highly dependent on a specific vehicle's electrical requirements. The greatest challenge is cost, which is intensified by the need to simultaneously increase performance and reduce size and weight. It is anticipated that efforts beyond 2006 will be focused on an integrated inverter/motor system. The trend toward an integrated system encompassing the motor, inverter, cooling system, and all interface connections is represented in the targets presented in Table 19.

Barriers

Barriers to achieving the technical targets include the following:

A. **Cost.** Materials, processing, and fabrication technologies for power electronics and electric machinery are too costly for automotive applications.

B. **Volume and thermal management.** Power electronics and electric machines are bulky and difficult to package for automotive applications. Current thermal management techniques are inadequate to dissipate heat in high-power-density systems. Achieving cost and goals is difficult because the components must be packaged and cooled effectively.

C. **Weight.** Current electric machinery and power electronics controllers are too heavy and require additional structural weight for support.

Table 18. Technical targets: inverter/motor powertrain		
	2003 status	2006
Power electronics (inverter)[a, b]		
Specific power at peak load	11 kW/kg	12 kW/kg
Volumetric power density	11 kW/L	12 kW/L
Cost[a]	$6/kW	$6/kW
Efficiency (10–100% speed FTP drive cycle)	97–98%	97–98%
Electric motors (traction)[a, b, c]		
Specific power at peak load[d]	1.0 kW/kg	1.2 kW/kg
Volumetric power density	3.5kW/L	5kW/L
Cost	$16/kW	$7/kW
Efficiency (10–100% speed, 20% rated torque)	93%	93%

[a] The targets are based on a series powertrain with 30 kW continuous power and 55 kW peak power. 2003 entries are taken from AIPM and AEMD specifications.

[b] Individual targets for inverters and motors are not listed for 2010 because future work will focus on the integrated system.

[c] Technical targets include the gearbox and connectors.

[d] 2006 target based upon accomplishments to date in AIPM and AEMD efforts. Targets have been altered for tradeoffs between integrated systems.

Table 19. Technical targets: integrated inverter/motor			
	2003 status	2010	2015
Integrated Motors and Inverter (traction)[a,b]			
Specific power at peak load	0.95 kW/kg	1.2 kW/kg	1.3 kW/kg
Volumetric power density	2.5 kW/L	3.4kW/L	3.5kW/L
Cost	$21/kW	$12/kW	$10/kW
Efficiency (10–100% speed, 20% rated torque)	90%	90%	95%
Lifetime	15 years	15 years	15 years

[a] The targets are based on a series hybrid fuel cell powertrain and reflect the transition from PNGV to the FreedomCAR and Fuel Partnership. The integrated system is composed of the motor, inverter, and gearbox in an integrated package.

[b] Numerical values may be modified based upon future input from the technical team.

D. **Reliability and ruggedness.** Power electronics modules and motors that meet the requirements for size and weight are not rugged or reliable enough to operate in harsh environments (e.g., extreme temperatures, humidity, dirt) for 150,000 miles or 15 years. Also, the operating and shelf life of energy storage (or buss) capacitors is only 5 years under moderate conditions.

These barriers must be considered together; one cannot be resolved at the expense of another. Performance must be improved, costs decreased, and size and weight reduced simultaneously.

Approach

The Power Electronics and Electric Machine effort focuses on R&D in key technologies that will enable achievement of the technical targets of the FreedomCAR and Fuels Partnership. The FCVT Program partners with automobile component suppliers to develop advanced technologies suitable for introduction into the marketplace. This cooperation ensures that the technical attributes, automotive-scale manufacturing, and cost sensitivities are addressed in a timely fashion and that the resulting technologies reside with companies that are willing and able to supply derived products to the automobile companies. National laboratories, universities, and small businesses will focus high-risk enabling technology R&D on overcoming the critical technology barriers. This research will be coordinated with the electrical and electronics FreedomCAR and Fuel Partnership technical team.

Current and Pending Elements

Current and pending elements of Advanced Power Electronics and Electric Machines R&D are listed in Table 20. Elements are being conducted by companies under cooperative agreements and by national laboratories and universities to support FCVT Program objectives. The Power Electronics elements related to a controller on a chip and a dc/dc converter are expected to start in FY 2004. Timing for the pending element on an integrated system will be determined in the near future.

Table 20. Current and pending elements (pending elements are printed in *italics*)

Elements	Objective/target	Benefit achieved
Power Electronics (Task 1)		
AIPM	5 kW/kg, 12 kW/L, $7/kW, >97% efficiency	Increased specific power and efficiency Reduced cost, volume, and weight
Controller on a chip	*Integrate functions and include necessary external circuitry in single semiconductor device*	*Performance targets achieved* *Reduced cost, volume, and weight*
dc/dc converter	*Achieve high-voltage (400-V) to 12-V output with 42V option*	*Increased specific power and efficiency* *Reduced cost, volume, and weight*
Z-source converter	*Combine dc/dc converter with dc/ac inverter into single-stage power conversion circuit*	*Reduced cost, volume, and weight and increased constant power speed ratio*
Higher-temperature inverter	*Increase useful operating temperature of inverter*	*Performance targets achieved* *Reduced cost, volume, and weight*
Capacitors	Produce a polymer-film dielectric that can operate continuously at 110°C Develop high-dielectric-constant, thin-film capacitors	Increased reliability and robustness Reduced cost and volume
Power Electronics R&D	Fundamental R&D	Increased specific power, efficiency, and thermal performance Reduced cost, volume, and weight
Electric Motors and Generators (Task 2)		
AEMD	1.6 kW/kg, 5 kW/L, $11/kW, >93% efficiency	Reduced cost, volume, and weight
New-configuration machine	*Develop interior permanent magnet motor that will meet FreedomCAR and Fuel Partnership targets for series system*	*Performance targets achieved* *Reduced cost, volume, and weight*
Permanent magnets	Reduce cost, increase maximum operating temperature to 200°C Increase energy product of NdFeB permanent magnets by 25%	Reduced cost, volume, and weight
Electric Machinery R&D	Fundamental R&D	Increased efficiency, improved thermal characteristics Reduced cost, volume, and weight
Power Management and Integration (Task 3)		
Integrated system	*15-year lifetime, capable of 55 kW for 18 s and 30 kW continuous*	*Increased specific power and efficiency* *Reduced cost, volume, and weight*
Thermal management	Improve thermal characteristics of power electronics and motors with combination of high-temperature materials and advanced cooling strategies	Increased power density and reliability, lower cost

Task Descriptions

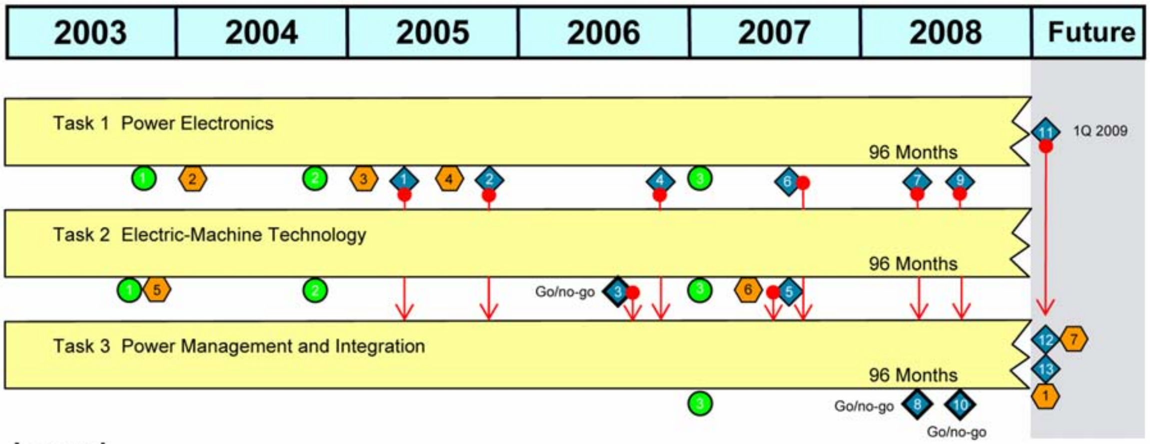
A description of each technical task, along with the estimated duration and the technical barriers associated with the task, is provided in Table 21.

Table 21. Tasks for Power Electronics and Electric Machines

Task	Title	Duration/ barriers
1	Power Electronics • Develop improved inverter/converter architectures and topologies, including special buss bar designs, and less expensive transistors to allow faster switching and enhanced performance • Develop improved packaging concepts, focusing on component integration with improved thermal management • Develop improved low-cost dielectric materials and improved capacitors with high-temperature, high-current capabilities, low equivalent-series resistance, and long operating lifetimes • Develop efficient control algorithms and sensorless control techniques • Develop a system-on-a-chip semiconductor controller suitable for automotive use • Develop a dc/dc converter suitable for automotive fuel cell applications	96 months Barriers A,B,C,D
2	Electric Motors and Generators • Develop advanced motor materials and manufacturing processes to reduce costs • Develop lower-cost magnet materials without sacrificing performance • Develop improved technologies for candidate motors	96 months Barriers A,B,C,D
3	Power Management and Integration • Develop and fabricate integrated motor/inverter drive systems with emphasis on cost, density, reliability, and efficiency • Develop advanced thermal management techniques for the inverter, motor, and other vehicle systems • Develop steady-state and dynamic electric-drive-system computer models, including the capability to determine performance/cost trade-offs for drive systems	96 months Barriers A,B,C,D

Milestones

The milestones for this sub-program are listed in the network chart.



Legend

Milestone

1. Build inverter using SiC components and evaluate thermal and performance improvements
2. Receive semiconductor motor controller deliverables
3. **Go/no-go.** Verify that developments in field-weakening techniques contribute to attaining technical targets for permanent magnet motors. If not, discontinue work on field-weakening techniques
4. Receive high-voltage to 42V/12V dc/dc converter deliverables for testing and evaluation
5. Validate contribution of developments in magnet materials to technical targets for motors
6. Validate improvements in inverter packaging methods
7. Receive improved capacitor for test and evaluation
8. **Go/no-go.** Evaluate progress toward development of integrated motor-controller and decide whether to continue, downselect, or terminate
9. Evaluate newly developed component technologies in an automotive inverter
10. **Go/no-go.** Validate improved thermal-management techniques resulting in size, weight, and cost reductions of at least 10% on components, or delay work on system-level electric-power management
11. Evaluate sensorless technology in an automotive application
12. Complete a common motor/inverter thermal-management system
13. Complete integrated motor/inverter system

Technology Program Output

1. Integrated inverter/motor to meet FreedomCAR goals to Vehicle Systems Analysis
2. Prototype AIPM to Vehicle Systems Analysis
3. Controller on a chip to Vehicle Systems Analysis
4. dc/dc converter to Vehicle Systems Analysis
5. Prototype AEMD to Vehicle Systems Analysis
6. Prototype internal PM motor to Vehicle Systems Analysis
7. Thermal-management system to Vehicle Systems Analysis

Supporting Input

1. Requirements for power, weight, volume, and cost for power electronic components and electric machines from industry
2. Battery targets for hybrid fuel cell vehicles from Energy Storage
3. Fuel cell performance characteristics from HFCIT