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**POWER ELECTRONICS AND ELECTRIC MACHINERY
CHALLENGES AND OPPORTUNITIES IN ELECTRIC AND
HYBRID VEHICLES**

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ABSTRACT

The development of power electronics and electric machinery presents significant challenges to the advancement of electric and hybrid vehicles. Electronic components and systems development for vehicle applications have progressed from the replacement of mechanical systems to the availability of features that can only be realized through interacting electronic controls and devices. Near-term applications of power electronics in vehicles will enable integrated powertrain controls, integrated chassis system controls, and navigation and communications systems. Future applications of optimized electric machinery will enable highly efficient and lightweight systems.

This paper will explore the areas where research and development is required to ensure the continued development of power electronics and electric machines to meet the rigorous demands of automotive applications. Additionally, recent advances in automotive related power electronics and electric machinery at Oak Ridge National Laboratory will be explained.

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POWER ELECTRONICS AND ELECTRIC MACHINERY CHALLENGES AND OPPORTUNITIES IN ELECTRIC AND HYBRID VEHICLES

INTRODUCTION

The development of power electronics and electric machinery presents significant challenges to the advancement of Hybrid Electric Vehicles (HEV). Despite all that is enabled by recent accomplishments in power electronics, cost remains the primary barrier.

Research & Development (R&D) is required in the following areas to ensure the continued development of power electronics and electric machines to meet the rigorous demands of automotive applications.

a. **Materials and Manufacturing Technologies**

Manufacturing equipment and processes are needed to make advanced technology vehicles cost-competitive in high-volume markets. Cost-effective materials and processes are needed to meet unique automotive environmental demands.

b. **Power Generation Systems**

New generation technologies like turbines or fuel cells need to interface with the vehicle's power and control system to cleanly and efficiently respond to power system load requirements. Energy storage systems which buffer these new generation technologies need to efficiently interface with the power system.

c. **Propulsion Drive Motors**

Improved motor magnetics are needed to reduce cost and weight of the traction system. New designs and control methods are required to broaden the range at which the propulsion motor operates at its highest efficiency, for varying load conditions typical of automotive drive cycles.

d. **Accessory Drives**

Subsystem accessories require small, light-weight, efficient motors to replace analogous belt or vacuum driven subsystems.

e. **Power Electronic Controls**

Interfacing components, including wiring, switches, and transformers, for power management and distribution account for a large fraction of electronic losses; as well as substantially contributing to the weight and cost of the overall system. New strategies are required to reduce the losses or to eliminate the need for the devices.

The principle challenge in all of these areas is affordability; then come robustness and performance, primarily as efficiency and driver acceptance.

POWER ELECTRONICS

Power electronics enabling technologies must be developed that will dramatically reduce the cost and the weight of electric propulsion system technologies and high-power accessories. A high degree of functional integration must be added while maintaining high efficiency and reliability for automotive industry applications.

Power electronics must be provided for the HEV for power system control management, bi-directional traction drive, power generation dc-dc converters, and auxiliary motor drives (e.g., heating, ventilation, and air conditioning (HVAC), power steering, suspension, energy storage sub-systems, engine valves operation, etc.). Specifically, the challenges are to reduce cost (present: \$35/kW, target: \$7/kW, etc.), reduce weight and volume, improve efficiency, ensure safety (<50V), and improve packaging.

POWER ELECTRONICS CHALLENGES

- a. Materials technology is inadequate for cost-effective production of power electronics and electric machines for automotive applications.

Processing, characterization, and optimization of components for high-temperature operation, including materials with wider band gaps and devices with higher power densities are needed. For example, power electronic components are not sufficiently resistant to RF interference to meet regulatory demands and recently developed lead-free solders are not adequate for temperatures above 150°C. Automotive environments reach temperatures between -40°C and 150°C, but commercially available power electronic component packaging is only rated for operation up to 120°C. Packaging accounts for 70 percent of the cost of silicon devices, capacitors, sensors, and inductors. Current packaging is bulky, and generally designed for fixed-location, low moisture, low electromagnetic interference (EMI), and ambient temperature environments.

- b. Current thermal management techniques are inadequate for high-power density microsystems.

High-power density concentrates heat generation. New technologies are needed to dissipate the heat and to ultimately remove it from the module to meet reliability requirements for 150,000 miles.

- c. Power electronic components are not adequately miniaturized or optimized.

Current power electronic technology is bulky and heavy. For example, off-the-shelf 100-kW system controllers are 7.5 ft³ and weigh nearly 70 lb (13.3 kW/ft³ and 1.4 kW/lb). State-of-the-art technologies are about 0.6 ft³ and 25 lb (167 kW/ft³ and 4 kW/lb). While this progression shows improvement, more is needed to meet the demands of the HEV industry. 275 kW/ft³ and 7 kW/lb are reasonable expectations in the next few years. Materials for electronics have not been optimized for cost, volume, and weight. Each power device needs an isolated power supply for its control which multiplies system complexity and cost. Integration of these components is needed to reduce cost, size, and weight. The development of miniaturized ultra-capacitors would contribute considerably to the size reduction of power converters.

- d. As a safety issue, it is desirable to hold the voltage below 50 volts.

The automotive industry is looking for a new technology to satisfy this safety requirement while simultaneously accomplishing motor control and battery charging with high efficiency.

OAK RIDGE NATIONAL LABORATORY (ORNL) ACTIVITIES IN POWER ELECTRONICS

ORNL, a U.S. Department of Energy research facility, has two new patented inverter topologies to tackle the challenges:

1. Soft-switching technology, such as the Resonant Snubber Inverter (RSI), which provides negligible switching loss, low EMI, and high power density.
2. Cascade inverter, which provides high efficiency, improved safety, low distortion, and low EMI.

Resonant Snubber Inverter (RSI)

The U.S. Partnership for a New Generation of Vehicles (PNGV) has set an efficiency goal of an 80-mpg automobile when driven at a constant 40-mph [1]. This same vehicle, with an added 800-W electrical load of today's electrical systems, is reduced in fuel economy to 65-mpg. This demonstrates why a substantially improved electrical system is required if the automobile is not to be stripped of amenities in order to meet the PNGV goal.

Challenges lie in the serious consideration of the system implications of these new electrical loads, in part, because of the conventional 12-V battery remaining the standard and in the cost evaluation, and market acceptance. The 12-V infrastructure must be maintained to transition to new designs; however, a higher voltage power distribution bus will be required [1].

Performance goals for the electric propulsion drive system soft-switching inverter have been proposed [2] as follows:

- efficiency > 98% peak and > 80% at 10% vehicle speed;
- cost < \$10/kW;
- power density > 100-kW/ft³;
- switching frequency > 20-kHz;
- robustness, redundant with limp home mode;
- EMI, zero emission and no interference;
- $dv/dt < 1000\text{-V}/\mu\text{s}$; and
- reliability, no failure before the end of vehicle life.

ORNL designed and built the 100-kW RSI, three-phase inverter (Fig. 1) and has tested this unit up to 40-kW into a three-phase inductive load in order to measure efficiency performance. Improved efficiency is an absolute must in view of the PNGV goal of 80-mpg and the new electrical technologies described above. The RSI efficiency versus load current for a 200-VDC link voltage is plotted in Fig. 2. Performance of the RSI was characterized as follows for comparison with the above target goals.

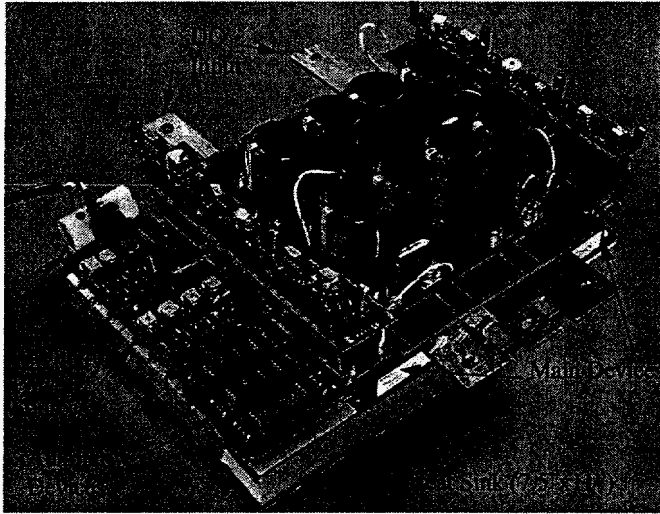


Fig. 1. Photograph showing a 100-kW D-configured RSI.

- efficiency $> 96\%$ at 40% maximum power or 54-hp and $> 80\%$ at 15% maximum power or 20-hp;
- $dv/dt \cong < 1000\text{-V}/\mu\text{s}$ at 300-A load current;
- power density = $167\text{-kW}/\text{ft}^3$; and
- switching frequency uncontrolled $< 10\text{-kHz}$, was not forced to 20-kHz, but the capability exists.

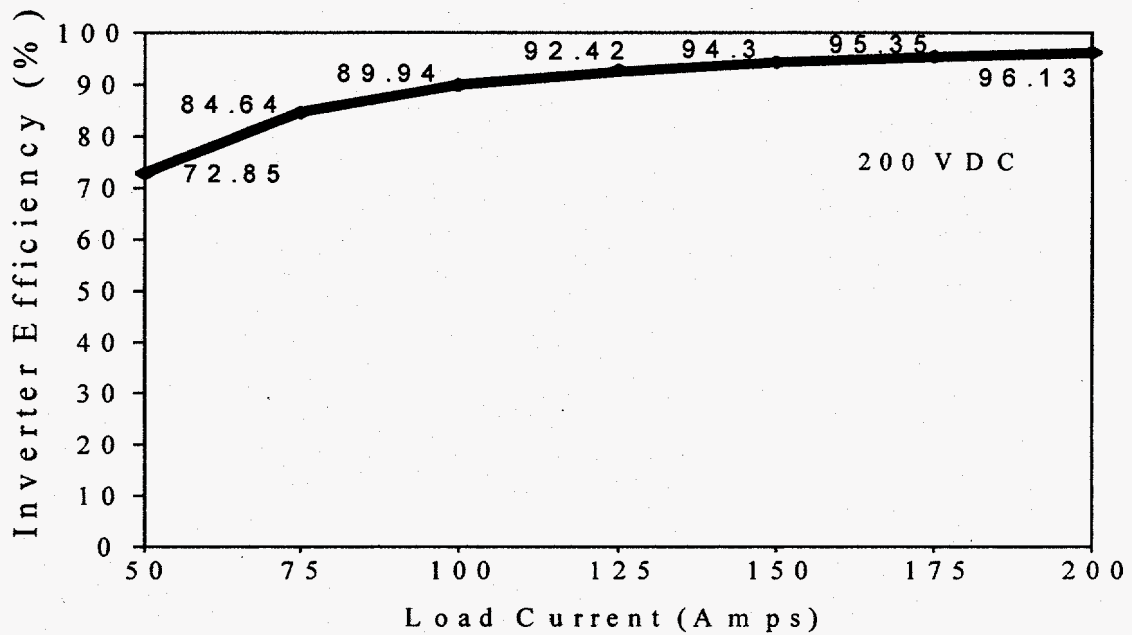


Fig. 2. Resonant snubber inverter efficiency vs load current at 200 volts.

The RSI efficiency obtained compares favorably to that proposed in Ref. 2. The Laboratory is presently modifying the soft-switching control to maintain a constant dv/dt of $600\text{-V}/\mu\text{s}$ independent of load current direction and magnitude. Power density exceeds that which has been proposed. For the tests, switching frequency was not controlled but the current error comparator, which generates the pulse width modulation, is being modified for fixed 20-kHz frequency operation.

Cascade Inverter

Figure 3 shows the structure of a cascade inverter for traction drive and battery charging. Compared to a traditional 2-level inverter, the advantages are listed below:

- staircase voltage waveform is almost sinusoidal and output current waveform is pure sinusoidal, as shown in Fig. 4,
- EMI is low,
- switching frequency is low ($\sim 60\text{ Hz}$),
- each H-bridge inverter unit has its own isolated dc source (48V). This feature resolves the safety issue since the batteries are disconnected from each other when the switching devices are turned off,
- there is no charge imbalance problem as is inherent in the traditional series string of battery cells since each H-bridge can regulate its dc (battery) voltage, thus reducing damage to battery cells and dramatically increasing battery life, and
- cascade structure supports easy packaging and modularization for manufacturing and mass production.

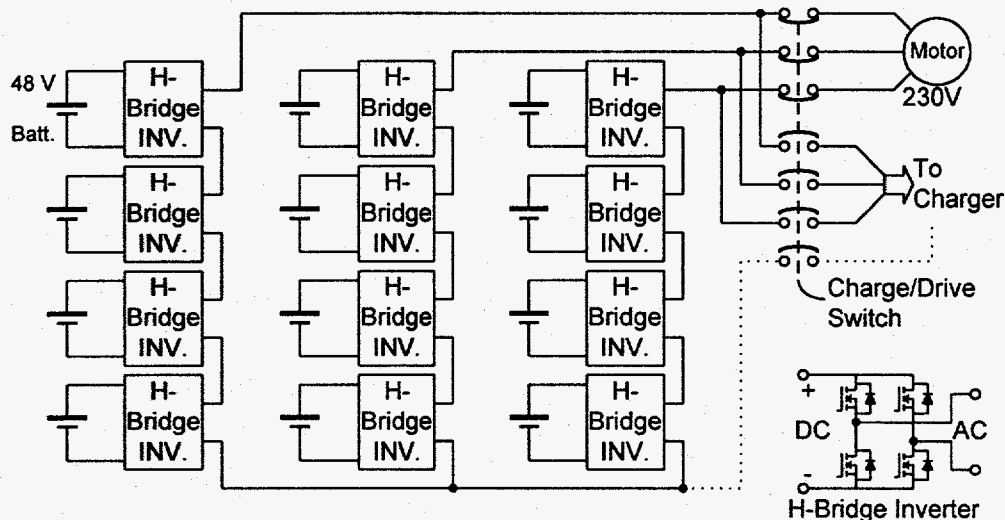
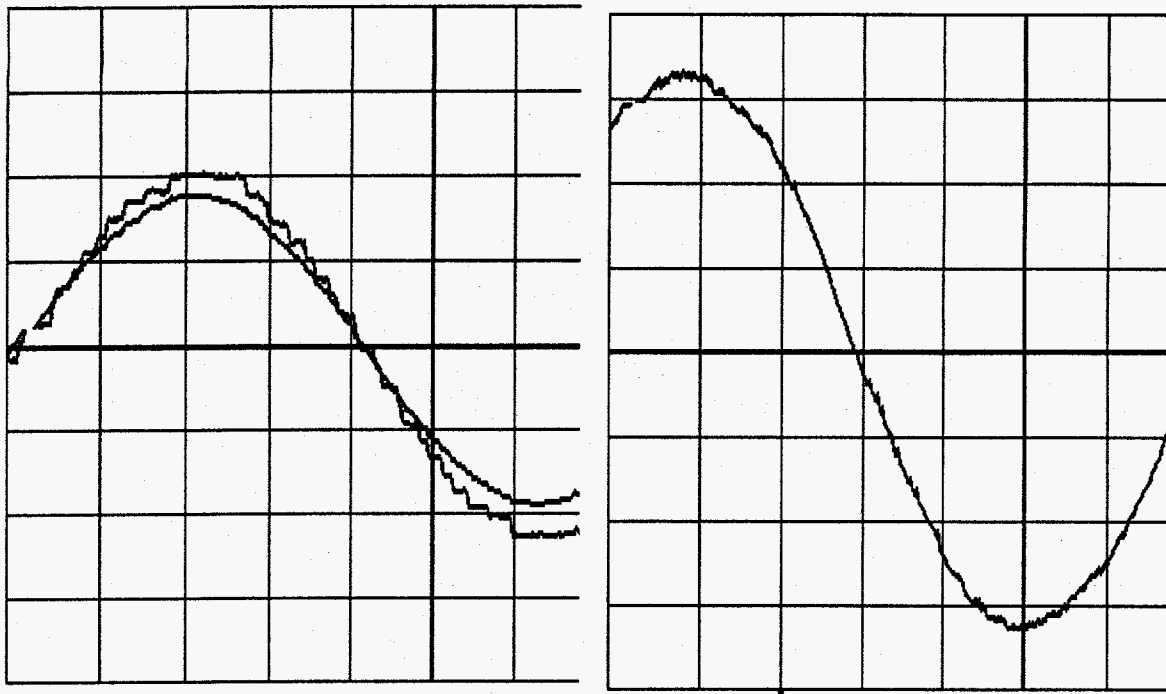


Fig. 3. Cascade inverter structure for HEV drive and battery charge.



(a) Line-to-line voltage waveforms

(b) Line current waveform

Fig. 4. Experimental voltage and current waveforms of the cascade inverter for motor drive.

ELECTRIC MACHINES

As for power electronics, electric machines must also be provided for the HEV for bi-directional traction drive, power generation, and auxiliary motor drives (e.g., HVAC, power steering, suspension, energy storage sub-systems, engine valves operation, etc.).

On the basis of development history, the electric machine technologies are more mature than the power electronics. However, revolutionary electric machine technologies must be developed which will enable significant reduction in cost, weight, size, and increase in efficiency and reliability in order to meet the PNGV goals. The motor and its power electronic control must be viewed as a unit for their overall cost and performance evaluation.

The development outlines of various electric machines are discussed below.

a. Induction Motors

Presently, development in the industry appears to be focused on induction motors for electric vehicle drives. Under a given supply frequency, an induction motor has a peak torque speed close to the full load speed. This unique torque-speed curve is desirable because the motor can easily maintain a nearly constant speed while the vehicle is running on a road with frequent uphill and downhill perturbations.

b. High-Speed Permanent Magnet (PM) Motors

The high-speed PM motors are being developed. The PMs with high maximum-energy product can increase the power density of motors. Unfortunately, high-quality PMs are expensive. However, this might not be a major problem for high-speed PM motors. Since all dimensions become smaller for high-speed motors, the cost for the permanent magnets required in a high-speed PM motor may very well be affordable.

c. Low-Cost PM Motors

Low-cost PM motors also attract interest. There are recent reports in the literature discussing the use of lower cost PMs for motors and published in the *Record of the 1996 Industry Applications Society 31st Annual Meeting*. There is always a balance required when considering cost, size, and performance issues.

d. Switched Reluctance Motors

Switched reluctance motors are relatively cost effective for the entire drive unit. However, they can be more noisy than induction and permanent-magnet motors. Noise and torque pulsation are areas for further improvements.

e. New Types of Direct Current Motors

Conventional dc motors are costly but do not require the even more costly inverters for their operation. The cost of the overall drive without an expensive power electronic section may become attractive to consumers. However, the conventional dc motor requires that the brushes be changed frequently and has strong EMI.

Homopolar motors and the soft commutating dc motors being developed at ORNL are not expected to have severe EMI problems. As dc motors, they do not require inverters for their operation. ORNL is actively pursuing these motors to explore their hidden potential for electric vehicle drives. Brushes remain as a maintenance item for this type of motor; however, the cycle for brush maintenance on these motors may be much longer than on the conventional dc motors.

GENERIC AREAS FOR MOTOR TECHNOLOGY DEVELOPMENTS

Cost, efficiency, dimension, weight, maintenance, smoothness, noise, acceleration, robustness, and hop-along characteristics are important evaluation criteria for HEV motors. The following generic areas for motor technologies are also being pursued by ORNL and other R&D centers.

Reducing Motor And Drive System Manufacturing Cost

a. Copper Rotor for Induction Motors

As compared with aluminum rotors, copper rotors can increase efficiency at least two percentage points. However, copper rotor manufacturing technology is lacking in the areas of life

expectancy of dies. ORNL is working on the copper rotor technology.

b. High-Speed Induction Motors

High-speed motors with gears can reduce the size and weight of the drive system. However, gears consume power. The drive system as a whole must be evaluated for the optimal speed that meets the size and overall efficiency requirements.

c. Direct Drive Motors

Although most present prototype vehicles are using high-speed motors, it is still possible to develop direct wheel drive motors. The size of a direct wheel drive motor would be larger than a high-speed motor, but the transmission train can be simplified.

d. High Temperature Electrical Insulations

A motor's life expectancy depends on the temperature rating of its electrical insulation. ORNL is actively engaged in high-temperature insulation research.

e. Compressed-Powder Cores and Amorphous Low Loss Cores

Manufacturing cost and core loss of motor core materials and production are important for electric vehicle motors.

f. Metal Matrix Composites for High Thermal Conductivity Motor Frames

g. Others, such as Cooling, Packaging, etc., are also Important Development Areas.

Improving Electric Motor Efficiency, Performance, and Controls

When reducing motor manufacturing cost, further research to increase efficiency, reduce torque ripple, reduce EMI, optimize power conversions, reduce or compensate for audible noise, and to help lower control cost must be iterated.

Shown below is an example of the high-efficiency traction drive machines developed at ORNL, where we are pursuing cost-effective solutions with innovations.

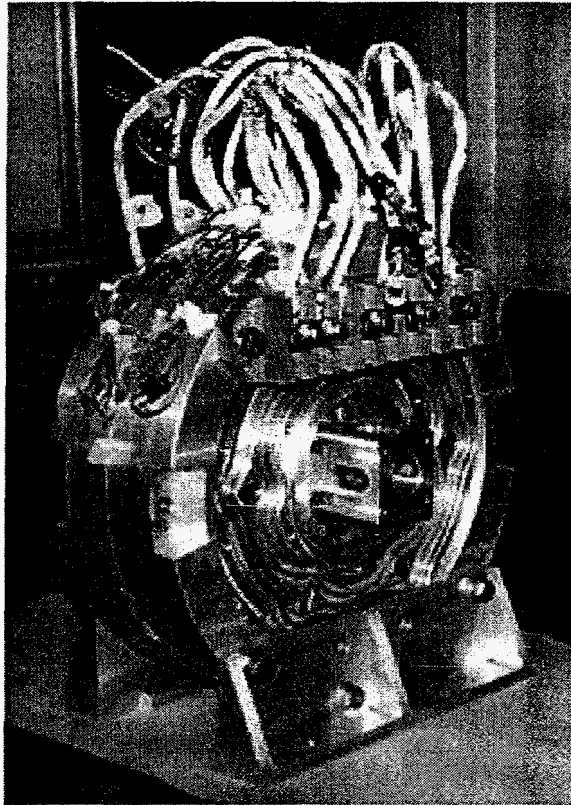


Fig. 5. 40 kW axial gap permanent magnet traction drive motor.

CONCLUSION

The one parameter of greatest concern in automotive power electronics and electric machinery is cost. While the requirements of performance, efficiency (range), weight, and size must be met to some degree, the overriding concern is cost. The HEV must be affordable for the average consumer. R&D in advanced materials development, manufacturing techniques, and value engineering, as well as new technologies in power converter and electric machinery can meet these requirements. Specifically, the primary challenges are materials and processing technologies, thermal management, and miniaturization of components. However, all of these advances must work in concert to meet the system needs of motion control.

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