Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles

Ali Emadi, *Senior Member, IEEE*, Young Joo Lee, *Student Member, IEEE*, and Kaushik Rajashekara, *Fellow, IEEE*

***Abstract*—With the requirements for reducing emissions and improving fuel economy, automotive companies are developing electric, hybrid electric, and plug-in hybrid electric vehicles. Power electronics is an enabling technology for the development of these environmentally friendlier vehicles and implementing the advanced electrical architectures to meet the demands for increased electric loads. In this paper, a brief review of the current trends and future vehicle strategies and the function of power electronic subsystems are described. The requirements of power electronic components and electric motor drives for the successful development of these vehicles are also presented.**

***Index Terms*—Electric machines, electric vehicles, fuel-cell vehicles, hybrid vehicles, motor drive, plug-in hybrid vehicles, power electronics, propulsion systems, vehicle strategy.**

I. Introduction

With the increasing demand for environmentally friendlier and higher fuel economy vehicles, automotive companies are focusing on electric vehicles, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel-cell vehicles. These vehicles would also enable meeting the demands for electrical power due to the increasing use of the electronic features to improve vehicle performance, fuel economy, emissions, passenger comfort, and safety. In electric vehicles, HEVs, PHEVs, and fuel-cell vehicles, the challenges are to achieve high efficiency, ruggedness, small sizes, and low costs in power converters and electric machines, as well as in associated electronics [1], [2]. In particular, in fuel-cell vehicles, a power-conditioning unit such as a dc–dc converter for matching the fuel-cell voltage with the battery pack may also be necessary. In steer-by-wire and brake-by-wire applications, a fast-response motor, inverter, and control system are essential and must be able to operate in adverse environmental conditions. Furthermore, the integration of actuators with power electronics not only improves the overall system reliability but also reduces the cost, size, etc. In addition to power electronics, the technology of the electric motor plays a major role in the vehicle's dynamics and the type of power converter for controlling the vehicle operating characteristics.

Manuscript received February 7, 2008; revised March 20, 2008.
A. Emadi and Y. J. Lee are with the Electric Power and Power Electronics Center, Illinois Institute of Technology, Chicago, IL 60616 USA (e-mail: emadi@iit.edu; ylee35@iit.edu).
K. Rajashekara is with Rolls-Royce Corporation, Indianapolis, IN 46268 USA (e-mail: ksrajashekara@ieee.org).
Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.
Digital Object Identifier 10.1109/TIE.2008.922768

This paper is organized as follows. In Section II, the introduction and general classification of HEVs are presented. Series and parallel configurations, as a general classification, are explained. In addition, detailed illustrations of an integrated starter–generator (ISG), which is one of the main topics in electric machines for hybrid vehicles, are shown. In Section III, the fundamental concept of plug-in hybrid vehicles is introduced with the conversion of HEVs into PHEVs, which are able to attain higher fuel economy and efficiency, with a longer range in pure electric propulsion mode. In Section IV, a fuel-cell-based vehicle propulsion system and a fuel-cell-based auxiliary power unit (APU) for vehicles are illustrated with the general classification of fuel cells for the automotive applications. In Section V, the requirements for power electronics, such as electric machines, sensorless control, high-power semiconductors, new switching topology, manufacturing process, etc., are discussed. The summary and conclusions are presented in Section VI.

II. HEVs

Hybrid vehicles have two or more sources of energy and/or two or more sources of power onboard the vehicle. The sources of energy can be a battery, a flywheel, etc. The sources of power can be an engine, a fuel cell, a battery, an ultracapacitor, etc. Depending on the vehicle configuration, two or more of these power or energy sources are used. Hybrid vehicles save energy and minimize pollution by combining an electric motor and an internal combustion engine (ICE) in such a way that the most desirable characteristics of each can be utilized. Hybrid vehicles are generally classified as series hybrids and parallel hybrids. In a series hybrid vehicle, the engine drives the generator, which, in turn, powers the electric motor. In a parallel hybrid vehicle, the engine and the electric motor are coupled to drive the vehicle. A series hybrid vehicle can offer lower fuel consumption in a city driving cycle by making the ICE consistently operate at the highest efficiency point during frequent stops/starts. A parallel hybrid vehicle can have lower fuel consumption in the highway driving cycle, in which the ICE is at the highest efficient point while the vehicle is running at constant speed. Hybrid vehicles are also divided into mild hybrids, power hybrids, and energy hybrids, according to the role performed by the engine and the electric motor and the mission that the system is designed to achieve [3]. A plug-in hybrid vehicle can be a series or parallel hybrid, with the battery being charged onboard the vehicle and being externally charged by the utility grid, thus increasing the range when operating in pure electric mode.

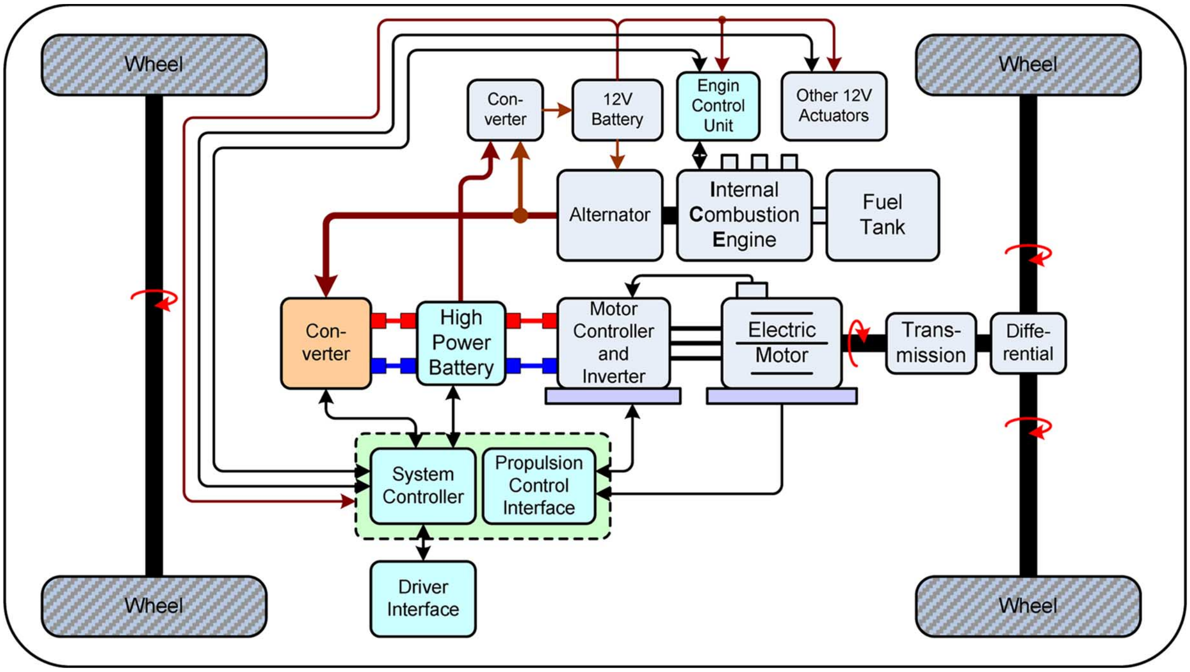

Fig. 1. Series hybrid vehicle propulsion system.

A. Series Hybrid Vehicles

A typical configuration of a series hybrid propulsion system is shown in Fig. 1. A series hybrid vehicle is essentially an electric vehicle with an onboard source of power for charging the batteries. In general, an engine is coupled to a generator to produce the power to charge the batteries. It is also possible to design the system in such a way that the generator could act as a load-leveling device that provides propulsion power. In this case, the size of the batteries could be reduced, but the sizes of the generator and the engine need to be increased. The power electronic components for a typical series hybrid vehicle system are: 1) a converter for converting the alternator output to dc for charging the batteries and 2) an inverter for converting the dc to ac to power the propulsion motor. A dc–dc converter is required to charge the 12-V battery in the vehicle as well. In addition, an electric air-conditioning unit needs an inverter and associated control systems.

B. Parallel Hybrid Vehicles

Parallel hybrids can offer the lowest cost and the option of using the existing manufacturing capability for engines, batteries, and motors. However, a parallel hybrid vehicle needs a complex control system. There are various configurations of parallel hybrid vehicles, depending on the roles of the electric motor/generator and the engine. In a parallel hybrid vehicle, the engine and the electric motor can be used separately or together to propel a vehicle. The Toyota Prius and the Honda Insight are some examples of parallel hybrid systems, which are commercially available [3]. A typical configuration of a parallel hybrid propulsion system is illustrated in Fig. 2.

C. Crankshaft-Mounted ISG System

Many automotive companies are working on the development of crankshaft-mounted-ISG-system-based hybrid vehicles. The ISG concept provides the ability to reduce fuel consumption through the use of engine off during coast-down and idle times, early torque converter lockup with torque smoothing, regenerative braking, and electric launch assist. The feature stop–start, which means ICE off at idle, integrates quiet starting and high-power generation into one single machine [4]–[6]. This specific feature offers a high potential for reducing fuel consumption, exhaust, and noise as a whole, compared to general vehicles in which ICE suffers from an extremely low miles per gallon (MPG) during stops/starts and the cold start of the ICE is the most polluting region of operation. In addition, ISG provides the capability for generating higher power than today's conventional automotive alternators. This higher power would enable us to incorporate features such as electric power steering, electric heating ventilation air-conditioning, electric valve trains, mobile ac power, and many entertainment features. The typical fuel economy gain by incorporating various functions is shown in Fig. 3 [1].

A typical architecture of an ISG system is shown in Fig. 4 [1]. The vehicle has a parallel hybrid architecture in which the electric machine and ICE can each provide torque to the drive wheels separately or simultaneously. The electric machine assists the IC engine by providing additional torque in the operating regions where the engine is less efficient. The system replaces the conventional vehicle's flywheel, alternator, and starter motor with an electric machine that fits between the engine and the transmission. The system has a power generation capability in the 5–10-kW range. The electric power take-off (PTO) function can provide onboard electric power for

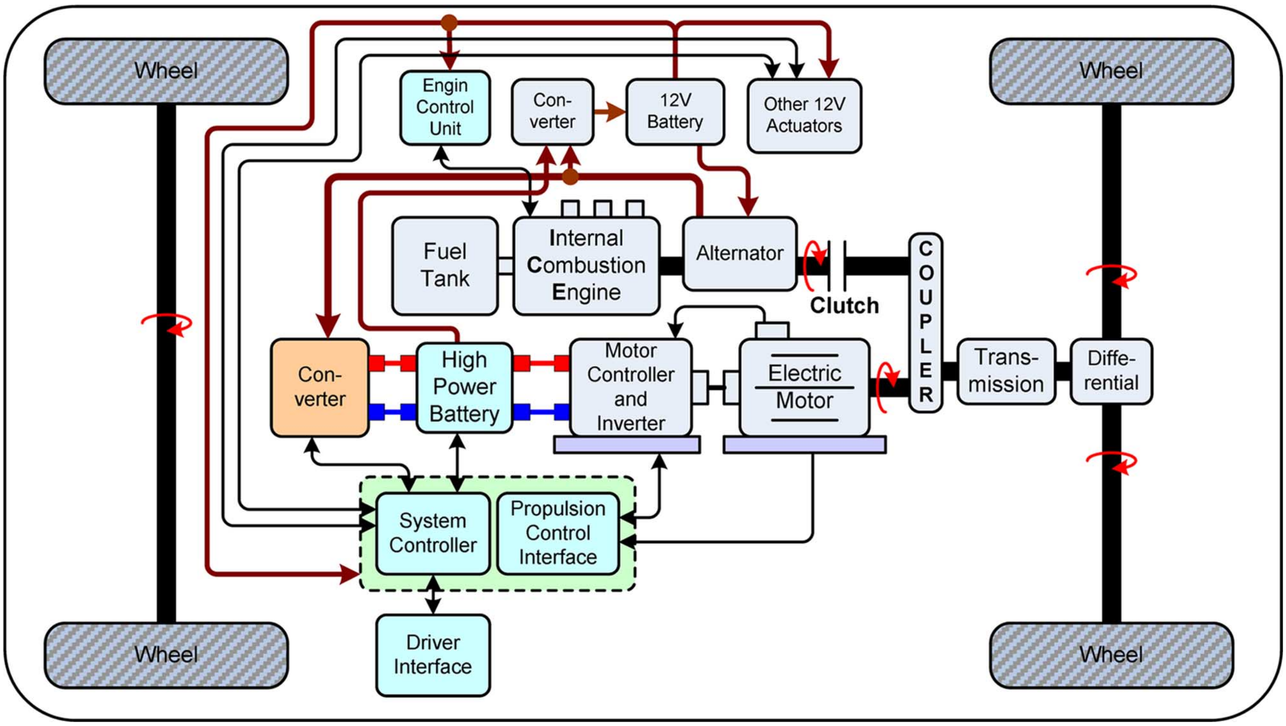

Fig. 2. Parallel hybrid vehicle propulsion system.

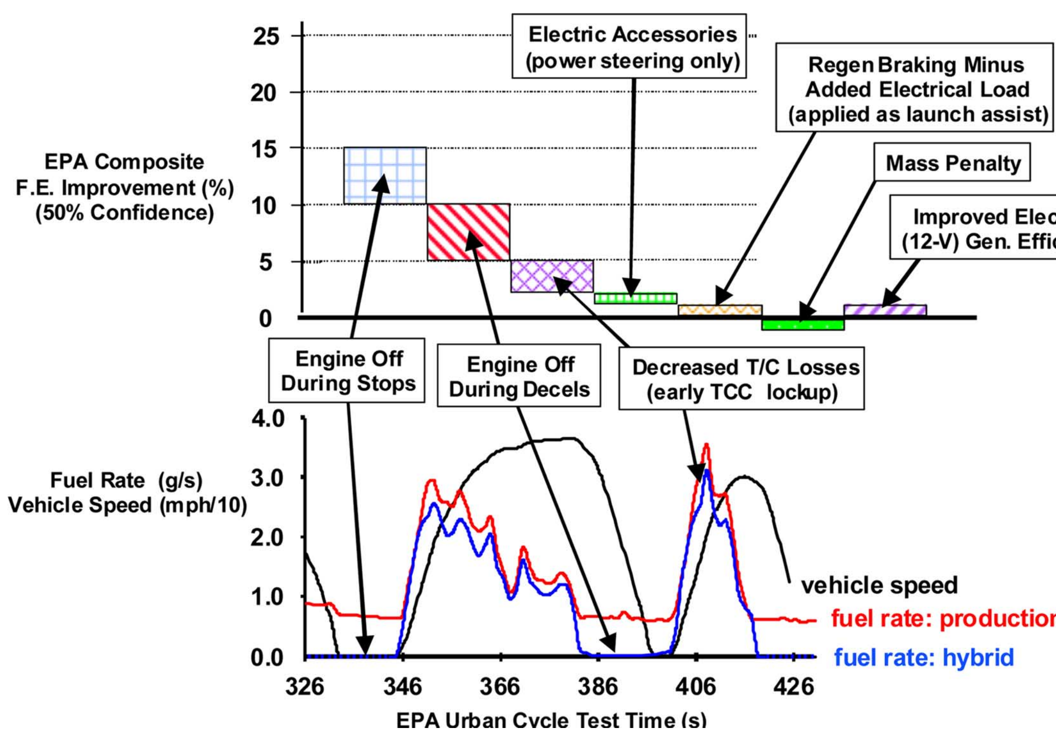

Fig. 3. Typical fuel economy gains for an ISG system. T/C—torque converter. TCC—torque converter clutch.

powering the appliances on the fly and when the vehicle is parked. PTO consists of a single-phase inverter for converting 42-V dc to 120-V/240-V ac power. The typical rating of the inverter is about 2.4 kVA. Depending on the functionality of the vehicle, this power could go as high as 20 kW (with a higher dc bus voltage). The requirements with respect to the starting mode can be very different from those during the generation mode. The result is that between the generator functionality and the motor functionality, the current level has to be raised by a factor of three. Although the current requirements for the silicon power devices is low during generation mode, they still need to be designed to meet the requirements of the starting current in

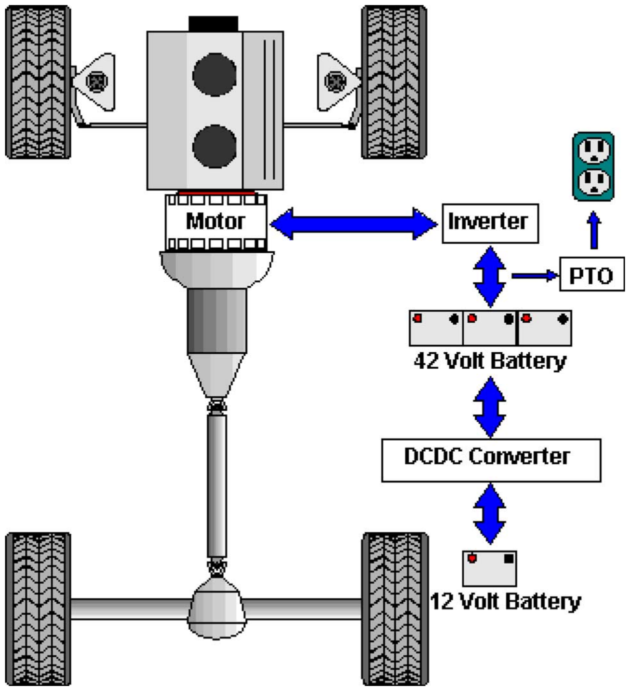

Fig. 4. ISG based on Energen-10 system architecture.

motoring mode. The battery must be able to supply that amount of electrical power at the respective ambient temperatures as well.

D. Side-Mounted ISG

Recently, there has been an increasing interest in the side-mounted ISG, i.e., the belt-driven starter–generator system. The side-mounted ISG can be realized using the conventional generator of today's vehicle. With the addition of position sensors and a three-phase inverter, the generator can be operated as a motor and can provide enough torque through the belt to the combustion engine to perform a fast and quiet restart for a warmed-up engine. On smaller engines, it is possible to cold crank the engine, eliminating the conventional starter. Further improvements in the generator and power electronics technology will increase the system efficiency, the power generation, and the cranking torque to fulfill future requirements and also allow the cold cranking of larger engines. The benefits of this system are: 1) low cost; 2) simple implementation; 3) minimal changes in the electrical system; and 4) use of the present belt-driven machine. The electronic system consists of a three-phase MOSFET bridge inverter with the associated gate drives and control electronics. Although the normal generation current is much lower, the power electronics need to be designed for higher starting currents. The packaging and the cooling of the devices need special consideration.

The Saturn Vue hybrid vehicle by General Motors is a typical example of a belt-driven starter–generator system. Saturn Vue's hybrid system reduces fuel consumption by:

- shutting off the engine when the vehicle is stopped to minimize idling;
- restarting the engine promptly when the brake pedal is released;
- enabling early fuel shutoff during vehicle deceleration;
- capturing vehicle kinetic energy during deceleration (regenerative braking) to charge an advanced nickel-metal hydride battery;
- performing intelligent battery charging when it is most efficient.

III. PHEVS

PHEVs have been considered as a significant advancement of the hybrid vehicle technology in both the industry and the academia [7] and even by various government agencies around the world. PHEVs have a battery pack of high energy density that can be externally charged and, hence, can run solely on electric power for a range longer than regular HEVs, resulting in a better MPG [8]–[12]. The battery pack can be recharged by a neighborhood ac outlet charger or in the garage. PHEVs improve the utilization of utility power because the charging of the batteries is done during nighttime.

A representative architecture of a plug-in parallel hybrid vehicle architecture is shown in Fig. 5. The conversion of conventional HEVs into PHEVs is being tried as a transient technology in many companies in order to enhance the efficiency of HEVs. Moreover, auto manufacturers are considering and preparing for the introduction of PHEVs into the commercial market. The conversion is achieved either by adding a high-energy battery pack or by replacing the existing battery pack of HEVs in order to extend the all-electric range. In either case, the high-energy battery pack must be able to store enough electrical energy from external charging as well as from regenerative braking and must be able to supply the stored electrical energy to a traction motor system. AC outlet charging should inevitably need a battery charger composed of an ac–dc converter with power factor correction (PFC) and a programmable digital controller with a proper voltage–current profile for high-energy battery packs. A bidirectional dc–dc converter and charge–discharge profile is also necessary so as to transfer energy between the battery and the traction motor system.

To make PHEVs available to consumers, there are several issues to be addressed. For example, the stability of utility power with regard to using a great number of high-power battery chargers with PFC at the same time and the choice, safety, thermal management, and cell-balancing of high-energy batteries such as NiMH and lithium batteries for automotive applications are some of the important issues [13]–[29].

IV. FUEL-CELL VEHICLES

A. Fuel-Cell-Based Vehicle Propulsion System

With the advancement in the technology of fuel cells, there is an increasing interest in using fuel cells for propulsion, onboard power generation, and stationary power generation applications. The advantages of fuel-cell vehicles compared to ICE vehicles are [30] the following.

- It makes use of direct energy conversion (no combustion).
- It has no moving parts, is quiet, and has fuel flexibility.
- It uses low energy, produces low air pollution, and utilizes alternative fuels.

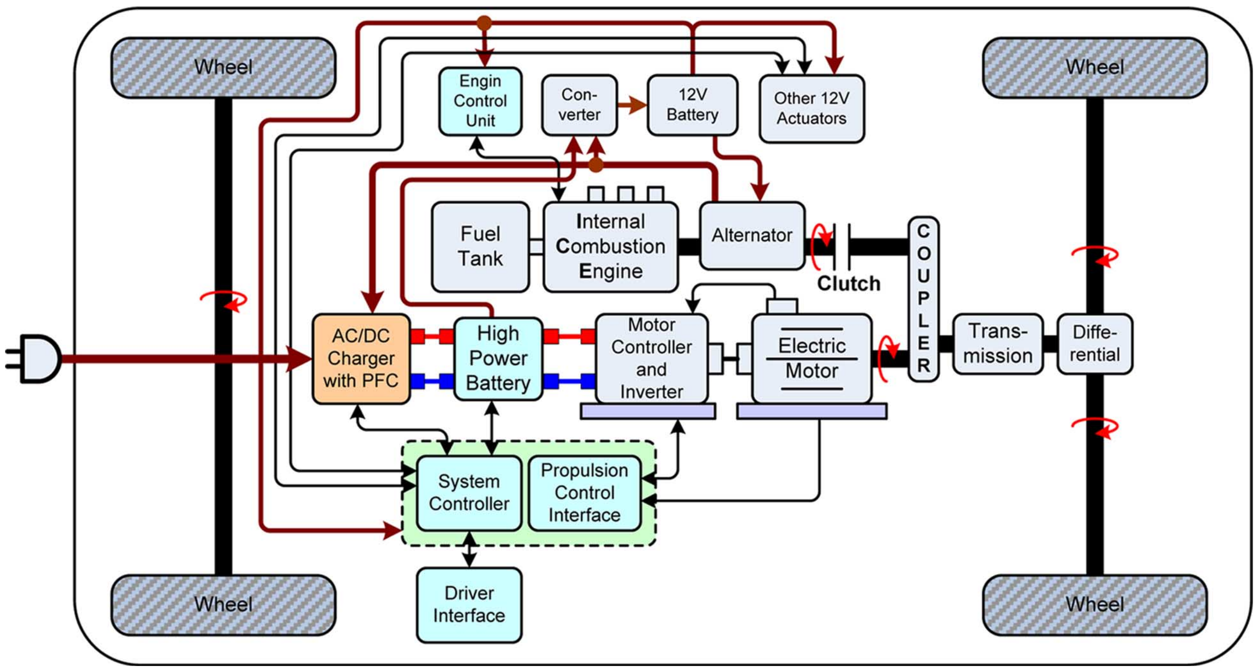

Fig. 5. Plug-in hybrid electric vehicle (parallel configuration).

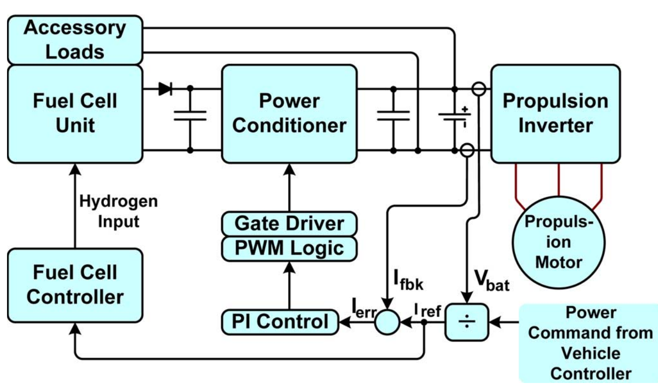

Fig. 6. Typical fuel-cell vehicle system.

- It has no sharp change in efficiency according to the size of the system and part load.
- It reduces CO_2 emission by about 75% and other toxic substances.

A fuel-cell system designed for vehicular propulsion applications must have a weight, a volume, a power density, a start-up, and a transient response similar to present-day ICE-based vehicles. Other requirements are: 1) very high performance for a short time; 2) rapid acceleration; 3) good fuel economy; and 4) easy access and safety considerations with respect to fuel handling. The cost and the expected lifetime are also very important considerations.

A typical fuel-cell vehicle propulsion system is shown in Fig. 6. The output voltage of the fuel-cell stack is conditioned to be compatible with the battery voltage using a power conditioner, which could be a step-up or step-down converter, depending on the voltage levels of the fuel cell and the battery. An inverter is used to convert the dc to variable voltage and variable frequency to power the propulsion motor. A battery or an ultracapacitor is generally connected across the fuel-cell system to provide supplemental power and for starting the system. Among several kinds of fuel cells such as proton exchange membrane (PEM) fuel cells, alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and solid oxide fuel cells (SOFCs), PEM fuel cells are gaining importance for automotive propulsion applications for the following reasons:

- easy start at ordinary temperatures below 100 °C;
- relatively high power density and smaller size;
- simple structure and maintenance;
- ruggedness to the shock and vibrations.

On the other hand, the problems in PEM are the following.

- The carbon monoxide (CO) concentration in the fuel should be reduced to less than 10 ppm, which causes deterioration in cell performance.
- Typically, expensive precious-metal catalysts are required, and low overall fuel economy from hydrogen generation should be addressed.

B. Vehicles With Fuel-Cell-Based APU

The power for the various electrical loads in an automobile is generally obtained using a belt-driven alternator driven by an ICE, producing power only while the engine is running. However, the fuel cell can produce onboard power independent of the engine operation, which can result in the elimination of an alternator and low emissions while maintaining passenger comfort such as heating. High-temperature SOFCs are particularly suitable as an APU in automotive applications because of the potential for internal reforming of more conventional petroleum fuels—with a simple partial oxidation reforming process into hydrogen (eliminating the need for an external reformer), less stringent requirements for reformate quality (directly using carbon monoxide as a fuel), and less sensitive to contaminants such as sulfur.

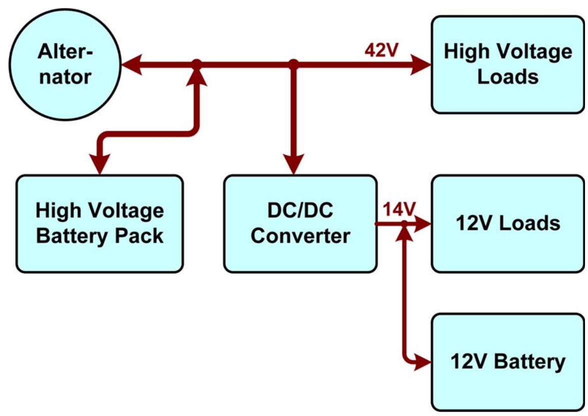

Fig. 7. Dual-voltage system with generator as power source.

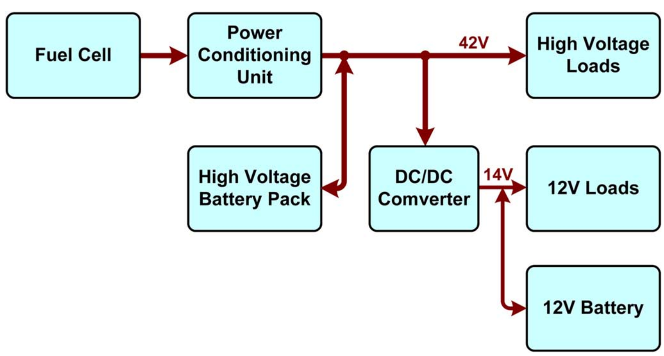

Fig. 8. Dual-voltage system with fuel cell as power source.

A dual 42-V/14-V architecture using an alternator is shown in Fig. 7. In this architecture, a generator feeds a 42-V bus having 42-V loads and a battery. A dc–dc converter connects this bus to the conventional 14-V bus having 12 V loads and a 12-V battery. The architecture for a dual-voltage electrical system that contains a fuel-cell power source is shown in Fig. 8.

The alternator in Fig. 7 is directly replaced by the fuel cell, and a new box, labeled "Power Conditioning Unit" is added, as shown in Fig. 8. The functions of the power-conditioning unit are to make the fuel-cell-stack output voltage compatible with the required load voltage, to protect the fuel cell from overload and short circuit at the output, and to prevent current from flowing back into the fuel-cell stack. The power-conditioning unit could be a buck, a boost, or a buck–boost dc–dc converter, depending on the output voltage of the stack.

V. Power Electronic Requirements

The power switching devices, electric motors, and associated control systems and components play a key role in bringing hybrid and fuel-cell vehicles to market with reliability and affordability. The power electronic system should be efficient to improve the range of the electric vehicles and fuel economy in hybrid vehicles. The selection of power semiconductor devices, converters/inverters, control and switching strategies, the packaging of the individual units, and the system integration are very crucial to the development of efficient and high-performance vehicles. In addition to power devices and controllers, there are several other components such as capacitors, inductors, bus bars, thermal systems, etc., that form a major portion of a power electronic unit. The packaging of all these units as one system has significant challenges. The U.S. Department of Energy, the U.S. Navy, and other organizations have funded the development of power electronics building blocks (PEBBs) to develop modular power electronic systems that ranges from 10 kW to several megawatts of power. Fig. 9 shows a "Power Control Unit" similarly functioning as a PEBB, which is mounted on a Toyota Hybrid Synergy Drive II system and is composed of an inverter for the air conditioner, an inverter for the starter and the generator, an inverter for the traction motor, a dc–dc converter for the auxiliary battery, and a dc–dc bidirectional converter for the high voltage battery. The goals of the U.S. Partnership for a New Generation of Vehicles for power electronics and electric machinery are quite challenging and are given in Table I.

To meet the requirements of the automotive environment, several technical challenges need to be overcome, and new developments are necessary, from the device level to the system level.

A. Development and Research on Switches and Diodes for High-Switching-Frequency, High-Power, and High-Temperature Applications

- The development of a power device that combines the MOS gate control characteristics with the current carrying capability and voltage drop characteristics of a thyristor-type structure whose forward voltage drop, even at higher currents (> 400 A), must be less than 2 V and, at the same time, can be operated at switching frequencies higher than 10 kHz is necessary.
- Furthermore, the development of a new power diode with superior dynamic characteristics, such as a MOS-controlled diode, should be carried out at the same time.
- The research on silicon carbide needs to be accelerated to make possible their application to high-power switching devices at higher operating temperatures.
- The devices and the rest of the components need to withstand thermal cycling and extreme vibrations.

B. Power Switch Packaging Technologies

The technologies related to device packaging need to be investigated by the semiconductor industry to develop a power switch, as the automotive industry is becoming one of the primary customers for power electronic devices. Wire bonding, device interconnections, etc., are the barriers to the development of high-current-density power units. Technologies such as topside power connection without wire bonds, minimizing wire bonds, dynamic matching, heat-sinking both sides of the die, direct bond copper on alumina and aluminum-nitride substrates, interconnect solutions for large-scale manufacturing, etc., need to be investigated as well. The reliable operation of power modules and other related packaging technologies needs to be studied. The power electronic systems available in the market are still bulky and difficult to package for automotive applications.

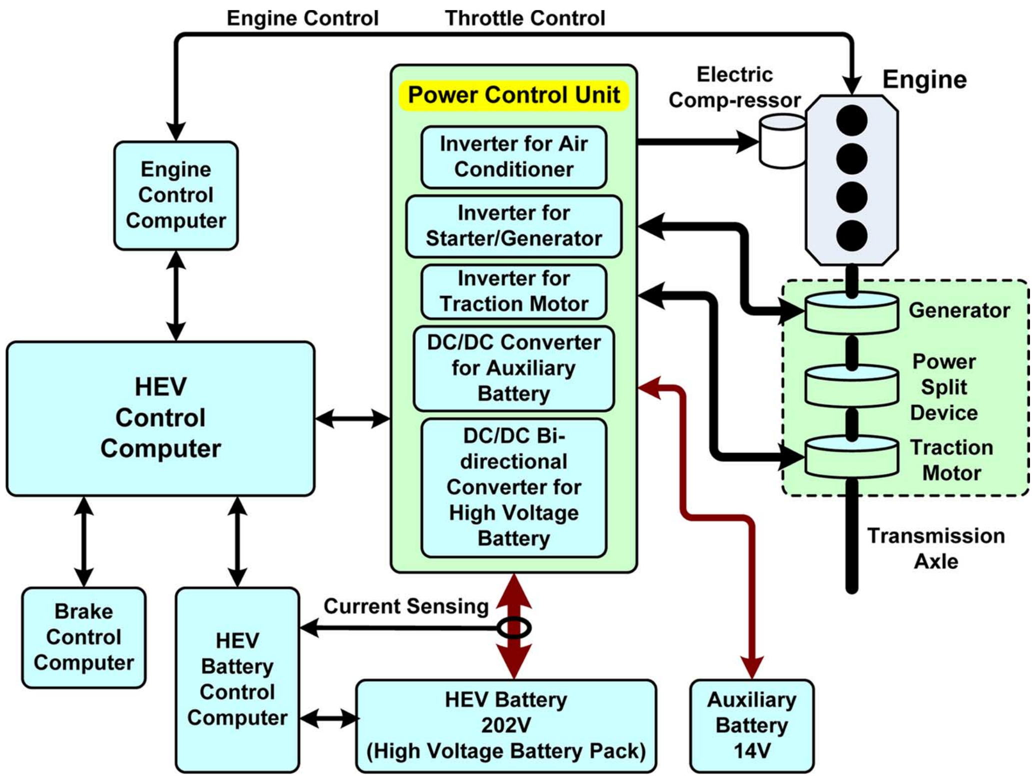

Fig. 9. Power control unit (Toyota Hybrid Synergy II).

TABLE I
TECHNICAL TARGETS OF ELECTRIC MACHINES AND POWER ELECTRONICS (INCLUDING ACTIVE MATERIALS, MOTOR GEARS, AND HOUSING)

(a)

Characteristics	2010 Target
Peak Power to Weight Ratio [kW/kg]	> 1.3
Peak Power to Volume Ratio [kW/liter]	> 5
Cost/Peak [$/kW]	< 7
Efficiency (@10% to 100% of max. speed)	>93
Nominal Voltage [V]	325
Maximum Current [Arms]	400

(b)

Characteristics	2010 Target
Peak Power to Weight Ratio [kW/kg]	> 12
Peak Power to Volume Ratio [kW/liter]	> 12
Cost [$/kW]	< 5
Efficiency [%]	97
Coolant Inlet Temperature [°C]	105
Lifetime [years]	15

C. Other Component Technologies to Meet the Application

In the past ten years, the technology of power semiconductor devices, magnetic components, and capacitors has significantly advanced to be used in high-frequency power electronic applications. The capacitors with high-frequency and high-voltage operations, low equivalent series resistance, high operating temperatures, and high ripple current capabilities need to be further developed. Hence, improved dielectric materials need to be investigated. The technology of laminated bus bars with high isolation voltage and low inductance needs further work to meet the automotive operating environment. To meet the packaging goals, the components must be designed to operate over a much higher temperature range. A novel way of cooling the entire unit needs to be examined to quickly take away the heat from the devices. The current heat management techniques are inadequate to dissipate heat in high-power-density systems. In addition, the impact of current intensiveness in a system on lower efficiency, larger passive components such as inductors and capacitors, and a thicker wiring harness among the components should be properly taken into consideration at the stage of system design.

D. New Switching Method, Integrated EMI Filter, and Fault-Tolerant Topology

Although soft-switching inverters have the advantage of lower switching losses and low electromagnetic interference (EMI), they need more components, higher operating voltage devices (depending on the topology), and more complicated control compared to hard-switched inverters. Hence, a soft-switched inverter application is limited to very special types of needs. There is a need to develop an inverter topology that achieves the performance of a soft-switched inverter but with less components and simplified control. Topologies with two or more integrated functions such as an inverter, a charger, and a dc/dc converter and with minimum use of capacitors need to be developed. In the area of dc–dc converters, further development is needed to obtain 12 V from 42 V and higher voltages. Integrated EMI filters for the control of EMI generated due to the switching of the devices needs to be a part of the inverter/converter topology. Fault-tolerant topologies and control techniques need further investigation. The system needs to be fault tolerant and provide limp-home capability.

E. Robust Sensorless Control and Low-Cost High-Temperature Magnets of Electric Propulsion Machine

In the area of propulsion motor and other motor control technologies, methods to eliminate speed/position sensors, inverter current sensors, etc., have been under investigation for several years. These technologies have not yet been proven to be practical for automotive applications [31]–[37]. The technology development effort needs to be focused on the sensorless operation of electric machines and the reduction or elimination of current sensors in inverters. Controllers need to be developed for the robust operation of all vehicle subsystems. The development of low-cost high-temperature magnets would lead to the widespread use of permanent magnet (PM) motors. PM motors have higher efficiency and need lower current to obtain the same torque as other machines. This would reduce the cost of power devices as well.

F. Development of New Manufacturing Processes

The cost of developing new manufacturing processes and packaging techniques are prohibitive for low production volumes. Generally, manufacturing technologies are taken for granted. Hence, low-cost manufacturing of power electronic systems needs a major work. The units have to be rugged and reliable for a 150 000-mi vehicle lifetime.

VI. Conclusion

Several technologies are in the horizon to be implemented in the next generations of automobiles. There are still a lot of technology challenges to overcome, particularly in the area of fuel-cell vehicles. Major obstacles must still be overcome in the areas of weight, volume, and cost to achieve the expected efficiency and performance. Other issues are manufacturability, reliability, safety, and durability, and the most important is the value to the customer as a function of the cost.

The barriers to the introduction of a "More Electric Vehicle" depend on the economics and not much on the technology. The value of a hybrid or plug-in hybrid vehicle has to be greater than the cost. This value equation includes the payback in fuel cost savings for the extra cost of the vehicle, adding to the manufacturer's corporate average fuel economy value, vehicle performance and boost, amount of onboard electric power for entertainment features and other conveniences, emissions reduction, and, finally, the image for the original equipment manufacturer.

Progress has been made in the area of power electronics and rotating machines to reduce the cost and improve the efficiency of the system. The issues related to power conversion and rotating machines are similar in electric, hybrid, and plug-in hybrid vehicles. The cost of the power electronics and the motor drive system is being reduced more to make the hybrid and plug-in hybrid vehicles at par with ICE-based vehicles.

References

[1] K. Rajashekara, "Power electronics for the future of automotive industry," in *Proc. PCIM Eur.*, Nuremberg, Germany, May 2002.

[2] A. Emadi, K. Rajashekara, S. S. Williamson, and S. M. Lukic, "Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, pp. 763–770, May 2005.

[3] J. Walters, H. Husted, and K. Rajashekara, "Comparative study of hybrid powertrain strategies," in *Proc. SAE Future Transp. Technol. Conf.*, Costa Mesa, CA, Aug. 2001.

[4] P. Bajec, D. Voncina, D. Miljavec, and J. Nastran, "Bi-directional power converter for wide speed range integrated starter-generator," in *Proc. IEEE Int. Symp. Ind. Electron.*, May 2004, vol. 2, pp. 1117–1122.

[5] L. Chedot, G. Friedrich, J. M. Biedinger, and P. Macret, "Integrated starter generator: The need for an optimal design and control approach. Application to a permanent magnet machine," *IEEE Trans. Ind. Appl.*, vol. 43, no. 2, pp. 551–559, Mar./Apr. 2007.

[6] A. K. Jain, S. Mathapati, V. T. Ranganathan, and V. Narayanan, "Integrated starter generator for 42-V powernet using induction machine and direct torque control technique," *IEEE Trans. Power Electron.*, vol. 21, no. 3, pp. 701–710, May 2006.

[7] G. Zorpette, "The smart hybrid," *IEEE Spectr.*, vol. 41, no. 1, pp. 44–47, Jan. 2004.

[8] S. S. Williamson and A. Emadi, "Comparative assessment of hybrid electric and fuel cell vehicles based on comprehensive well-to-wheels efficiency analysis," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, pp. 856–862, May 2005.

[9] S. S. Williamson, S. M. Lukic, and A. Emadi, "Comprehensive drive train efficiency analysis of hybrid electric and fuel cell vehicles based on motor-controller efficiency modeling," *IEEE Trans. Power Electron.*, vol. 21, no. 3, pp. 730–740, May 2006.

[10] S. S. Willamson, A. Emadi, and K. Rajashekara, "Comprehensive efficiency modeling of electric traction motor drives for hybrid electric vehicle propulsion applications," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 1561–1572, Jul. 2007.

[11] M. Amrhein and P. T. Krein, "Dynamic simulation for analysis of hybrid electric vehicle system and subsystem interactions, including power electronics," *IEEE Trans. Veh. Technol.*, vol. 56, no. 3, pp. 825–836, May 2005.

[12] T. Katrasnik, F. Trenc, and S. R. Opresnik, "Analysis of energy conversion efficiency in parallel and series hybrid powertrains," *IEEE Trans. Veh. Technol.*, vol. 56, no. 6, pp. 3649–3659, Nov. 2007.

[13] A. Affanni, A. Bellini, G. Franceschini, P. Guglielmi, and C. Tassoni, "Battery choice and management for new-generation electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1343–1349, Oct. 2005.

[14] C. Alaoui and Z. M. Salameh, "A novel thermal management for electric and hybrid vehicles," *IEEE Trans. Veh. Technol.*, vol. 54, no. 2, pp. 468–476, Mar. 2005.

[15] K. Kutluay, Y. Cadirci, Y. S. Ozkazanc, and I. Cadirci, "A new online state-of-charge estimation and monitoring system for sealed lead-acid batteries in telecommunication power supplies," *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1315–1327, Sep. 2005.

[16] J. H. Aylor, A. Thieme, and B. W. Johnso, "A battery state-of-charge indicator for electric wheelchairs," *IEEE Trans. Ind. Electron.*, vol. 39, no. 5, pp. 398–409, Oct. 1992.

[17] Y.-H. Kim and H.-D. Ha, "Design of interface circuits with electrical battery models," *IEEE Trans. Ind. Electron.*, vol. 44, no. 1, pp. 81–86, Feb. 1997.

[18] M. Coleman, C. K. Lee, C. Zhu, and W. G. Hurley, "State-of-charge determination from EMF voltage estimation: Using impedance, terminal voltage, and current for lead-acid and lithium-ion batteries," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2550–2557, Oct. 2007.

[19] J. Moreno, M. E. Ortuzar, and J. W. Dixon, "Energy-management system for a hybrid electric vehicle, using ultracapacitors and neural networks," *IEEE Trans. Ind. Electron.*, vol. 53, no. 2, pp. 614–623, Apr. 2006.

[20] S. T. Hung, D. C. Hopkins, and C. R. Mosling, "Extension of battery life via charge equalization control," *IEEE Trans. Ind. Electron.*, vol. 40, no. 1, pp. 96–104, Feb. 1993.

[21] L. A. Tolbert, P. Fang Zheng, T. Cunnyngham, and J. N. Chiasson, "Charge balance control schemes for cascade multilevel converter in hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 49, no. 5, pp. 1058–1064, Oct. 2002.

[22] J. Chatzakis, K. Kalaitzakis, N. C. Voulgaris, and S. N. Manias, "Designing a new generalized battery management system," *IEEE Trans. Ind. Electron.*, vol. 50, no. 5, pp. 990–999, Oct. 2003.

[23] C. Liang-Rui, "A design of an optimal battery pulse charge system by frequency-varied technique," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 398–405, Feb. 2007.

[24] L. Yuang-Shung and C. Ming-Wang, "Intelligent control battery equalization for series connected lithium-ion battery strings," *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1297–1307, Oct. 2005.

[25] G. O. Cimuca, C. Saudemont, B. Robyns, and M. M. Radulescu, "Control and performance evaluation of a flywheel energy-storage system associated to a variable-speed wind generator," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1074–1085, Jun. 2006.

[26] Z. Jiang and R. A. Dougal, "A compact digitally controlled fuel cell/battery hybrid power source," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1094–1104, Jun. 2006.

[27] S. Lemofouet and A. Rufer, "A hybrid energy storage system based on compressed air and supercapacitors with maximum efficiency point tracking (MEPT)," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1105–1115, Jun. 2006.

[28] M. Ortuzar, J. Moreno, and J. Dixon, "Ultracapacitor-based auxiliary energy system for an electric vehicle: Implementation and evaluation," *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 2147–2156, Aug. 2007.

[29] H. Matsuo, L. Wenzhong, F. Kurokawa, T. Shigemizu, and N. Watanabe, "Characteristics of the multiple-input DC-DC converter," *IEEE Trans. Ind. Electron.*, vol. 51, no. 3, pp. 625–631, Jun. 2004.

[30] K. Rajashekara, "Propulsion system strategies for fuel cell vehicles," presented at the SAE World Congr., Detroit, MI, Mar. 2000, Paper 2000-01-0369.

[31] B. Fahimi, A. Emadi, and B. Sepe, Jr., "Position sensorless control," *IEEE Ind. Appl. Mag.*, vol. 10, no. 1, pp. 40–47, Jan. 2004.

[32] S. Ichikawa, M. Tomita, S. Doki, and S. Okuma, "Sensorless control of synchronous reluctance motors based on extended EMF models considering magnetic saturation with online parameter identification," *IEEE Trans. Ind. Appl.*, vol. 42, no. 5, pp. 1264–1274, Sep. 2006.

[33] Y. A. Kwon and S. H. Kim, "A new scheme for speed-sensorless control of induction motor," *IEEE Trans. Ind. Electron.*, vol. 51, no. 3, pp. 545–550, Jun. 2004.

[34] J.-H. Jang, J.-I. Ha, M. Ohto, K. Ide, and S.-K. Sul, "Analysis of permanent-magnet machine for sensorless control based on high-frequency signal injection," *IEEE Trans. Ind. Appl.*, vol. 40, no. 6, pp. 1595–1604, Nov./Dec. 2004.

[35] P. Guglielmi, M. Pastorelli, G. Pellegrino, and A. Vagati, "Position-sensorless control of permanent-magnet-assisted synchronous reluctance motor," *IEEE Trans. Ind. Appl.*, vol. 40, no. 2, pp. 615–622, Mar./Apr. 2004.

[36] M. Ehsani and B. Fahimi, "Elimination of position sensors in switched reluctance motor drives: State of the art and future trends," *IEEE Trans. Ind. Electron.*, vol. 49, no. 1, pp. 40–47, Feb. 2002.

[37] N. Arthur and J. Penman, "Induction machine condition monitoring with higher order spectra," *IEEE Trans. Ind. Electron.*, vol. 47, no. 5, pp. 1031–1041, Oct. 2000.

[38] P. Bajec, B. Pevec, D. Voncina, D. Miljavec, and J. Nastran, "Extending the low-speed operation range of PM generator in automotive applications using novel AC-DC converter control," *IEEE Trans. Ind. Electron.*, vol. 52, no. 2, pp. 436–443, Apr. 2005.

[39] C. C. Chan, K. T. Chau, J. Z. Jiang, W. Xia, M. Zhu, and R. Zhang, "Novel permanent magnet motor drives for electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 43, no. 2, pp. 331–339, Apr. 1996.

[40] M. Ehsani, K. M. Rahman, and H. A. Toliyat, "Propulsion system design of electric and hybrid vehicles," *IEEE Trans. Ind. Electron.*, vol. 44, no. 1, pp. 19–27, Feb. 1997.

[41] J.-S. Lai, "Resonant snubber-based soft-switching inverters for electric propulsion drives," *IEEE Trans. Ind. Electron.*, vol. 44, no. 1, pp. 71–80, Feb. 1997.

[42] P. Melin and O. Castillo, "Intelligent control of complex electrochemical systems with a neuro-fuzzy-genetic approach," *IEEE Trans. Ind. Electron.*, vol. 48, no. 5, pp. 951–955, Oct. 2001.

Ali Emadi (S'98–M'00–SM'03) received the B.S. and M.S. degrees from Sharif University of Technology, Tehran, Iran, in 1995 and 1997, respectively, and the Ph.D. degree in electrical engineering from Texas A&M University, College Station, in 2000. He is a Professor of electrical engineering and the Director of the Electric Power and Power Electronics Center and Grainger Laboratories at the Illinois Institute of Technology (IIT), Chicago, where he has established research and teaching facilities as well as courses in power electronics, motor drives, and vehicular power systems. In addition, he is the Founder and Chief Technology Officer of Hybrid Electric Vehicle Technologies, Inc. He is also the Founder, Director, and Chairman of the Board of the Industry/Multi-University Consortium on Advanced Automotive Systems. He is the author or a coauthor of more than 200 journal and conference papers as well as several books, including *Vehicular Electric Power Systems* (Marcel Dekker, 2003), *Energy Efficient Electric Motors* (Marcel Dekker, 2004), *Uninterruptible Power Supplies and Active Filters* (CRC Press, 2004), and *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles* (CRC Press, 2004). He is the Editor of the *Handbook of Automotive Power Electronics and Motor Drives* (Marcel Dekker, 2005).

Dr. Emadi is the recipient of numerous awards and recognition. He has been named the Eta Kappa Nu Outstanding Young Electrical Engineer of the Year 2003 (single international award) by virtue of his outstanding contributions to hybrid electric vehicle conversion by the Electrical Engineering Honor Society. He is also the recipient of the 2005 Richard M. Bass Outstanding Young Power Electronics Engineer Award from the IEEE Power Electronics Society. In 2005, he was selected as the Best Professor of the Year by the students at IIT. He is the recipient of the 2002 University Excellence in Teaching Award from IIT as well as the 2004 Sigma Xi/IIT Award for Excellence in University Research. He directed a team of students to design and build a novel motor drive, which won the First Place Overall Award of the 2003 IEEE/DOE/DOD International Future Energy Challenge for Motor Competition. He is the Chair of the Power Electronics Technical Committee of the IEEE Industrial Electronics Society. He is also the Chair of the IEEE Vehicle Power and Propulsion Steering Committee and the Technical Committee on Transportation Power Electronics of the IEEE Power Electronics Society. He was the Chair of the 2007 IEEE International Future Energy Challenge. In addition, he was the founding General Chair of the First IEEE Vehicle Power and Propulsion Conference in 2005, which was colocated under his chairmanship with the SAE International Future Transportation Technology Conference.

Young Joo Lee (S'07) received the B.S. degree in electrical engineering from the Korea University of Technology and Education, Cheonan, Korea, in 1996, and the M.S. degree from Gwang-Woon University, Seoul, Korea, in 2003. He is currently working toward the Ph.D. degree at the Electric Power and Power Electronics Center, Illinois Institute of Technology, Chicago. His Ph.D. research has been focused on integrated bidirectional converter for plug-in hybrid electric vehicles.

In 1995, he joined SunStar R&C, Incheon, Korea, which is highly specialized in industrial sewing machines and motors and controllers for industrial sewing machines. He then joined Genoray Company, Ltd., Seongnam, Korea, which manufactures X-ray fluroscopy equipment for medical surgery. He has more than ten years of experience in the industrial field and has developed numerous commercial system controllers for sewing machines and medical X-ray fluroscopy equipment, which require control over BLDC motors, PMSM motors, induction motors, stepper motors, high-frequency full-bridge converters, X-ray electron tubes, and other electriopneumatic actuators.

Kaushik Rajashekara (M'86–SM'89–F'99) received the B.Eng., M.Eng., and Ph.D. degrees from the Indian Institute of Science, Bangalore, India, in 1974, 1977, and 1983, respectively.

From 1977 to 1985, he was an Assistant Professor with the Indian Institute of Science. In 1978 and from 1984 to 1985, he was with Asea Brown Boveri, Zurich, Switzerland, working on power electronics systems. In 1982, he was a Visiting Scientist with the Technical University of Dresden, Dresden, Germany. In July 1989, he joined Delphi Corporation, which was a division of General Motors. At Delphi Corporation, he held various technical and managerial positions and was the Technical Fellow and Chief Scientist for propulsion, fuel-cell, and advanced energy systems. In May 2006, he joined Rolls-Royce Corporation, Indianapolis, IN, where he is currently the Chief Technologist for propulsion and power systems engineering. He has published more than 80 papers in international journals and conference proceedings. He is the holder of 22 patents. He has been a keynote speaker at several conferences. He has given invited speeches and conducted tutorial courses at various universities and local IEEE chapters. He has done extensive research in the area of power conversion for transportation, propulsion systems for electric, hybrid, and fuel-cell vehicles, and fuel cells for transportation and power generation, and more-electric aircraft applications.