

# Motor Drives and Different Topologies in Electric Vehicles

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**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, and PHEVs, and 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 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.

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 a higher fuel economy and efficiency, with a longer range in pure electric propulsion mode. The summary and conclusions are presented in Section V.

## 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 on board the vehicle and being externally charged by the utility grid, thus increasing the range when operating in pure electric mode.

### 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.

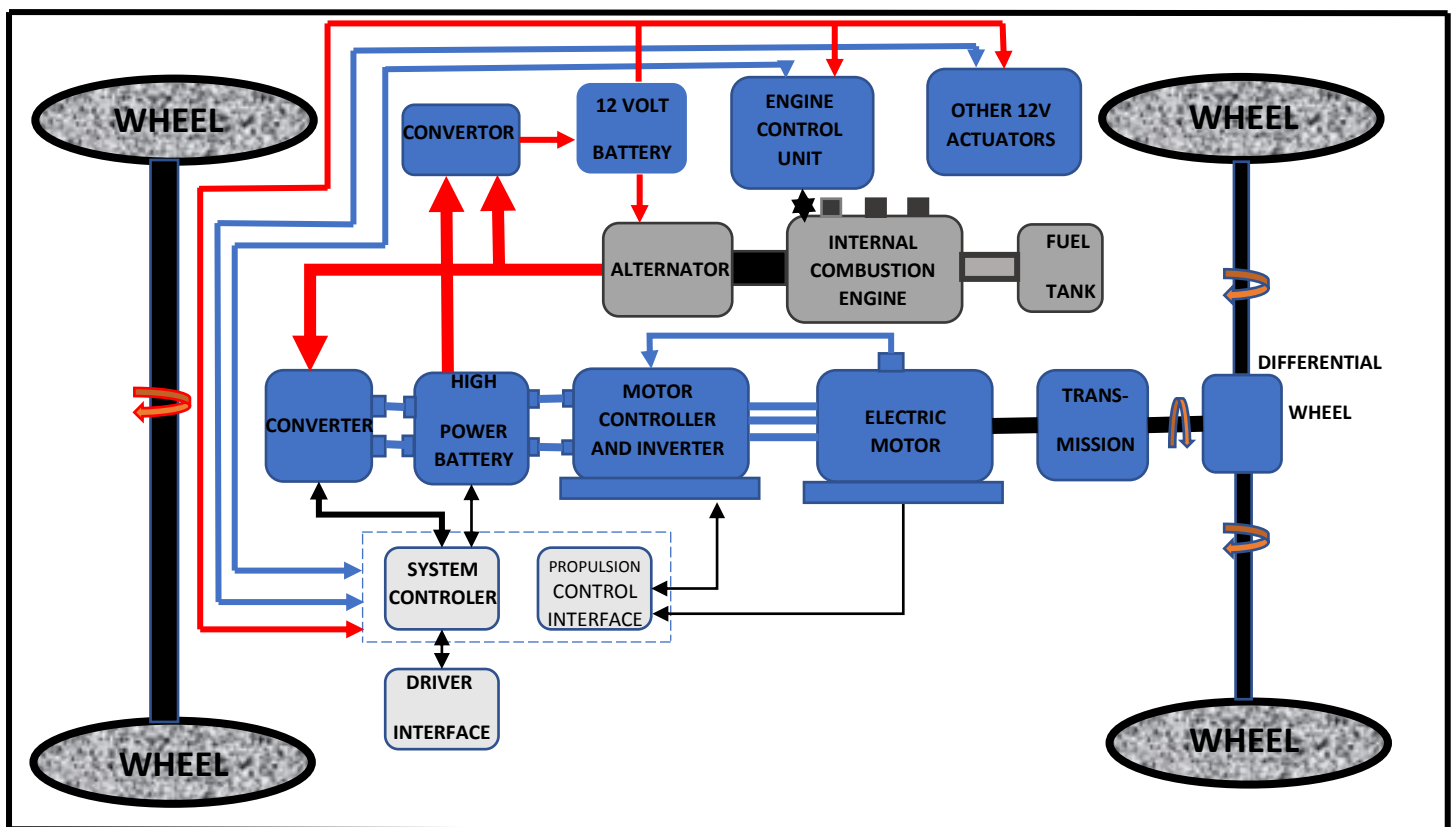


Fig 1. Series hybrid vehicle propulsion system [25].

### 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 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 takeoff (PTO) function can provide onboard electric power for 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 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

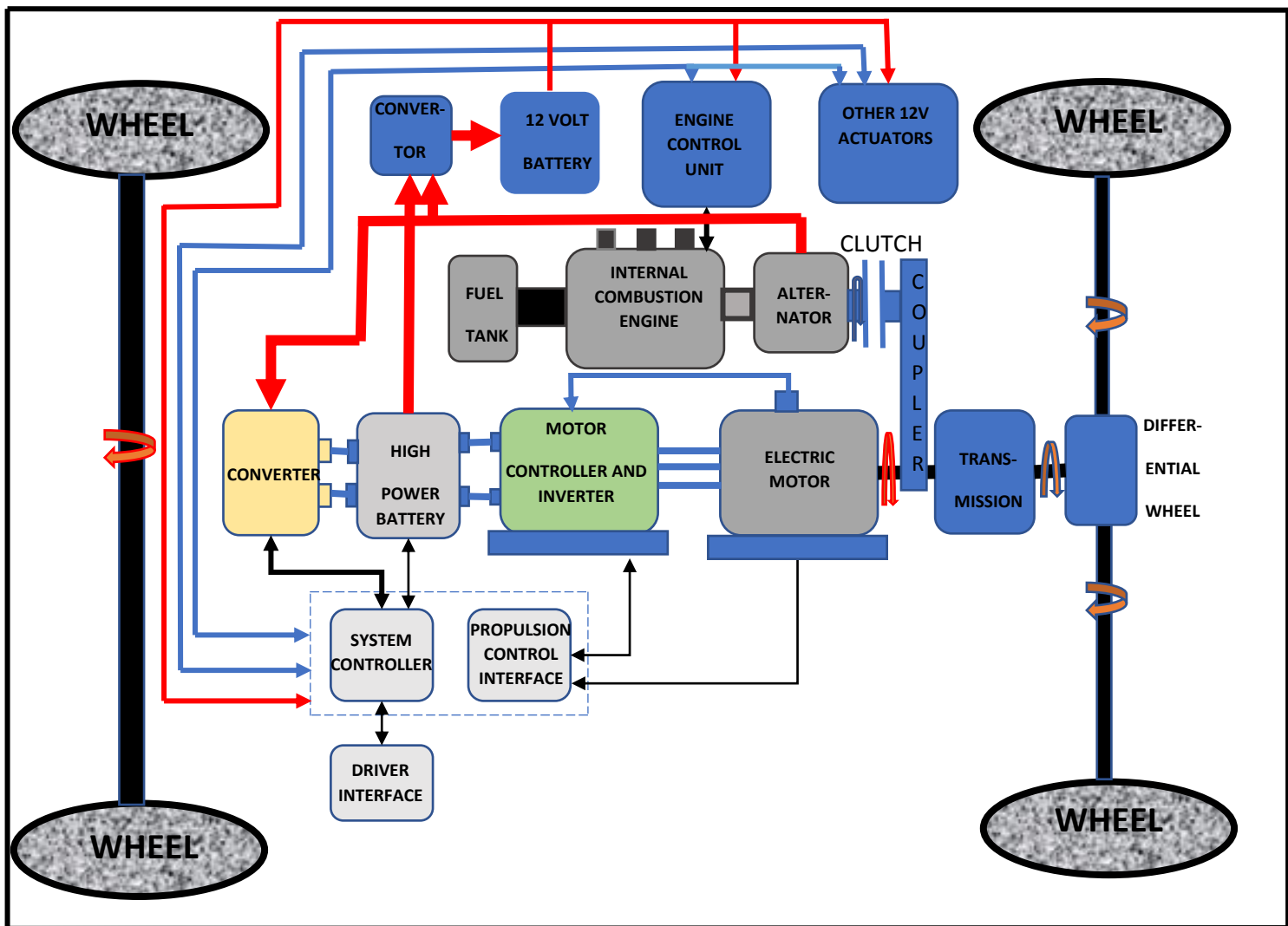


Fig 2. Parallel hybrid vehicle propulsion system [25].

devices is low during generation mode, they still need to be designed to meet the requirements of the starting current in motoring mode. The battery must be able to supply that amount of electrical power at the respective ambient temperatures as well.

### 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. 2. 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 [25]. Moreover, auto manufacturers are considering and preparing for the introduction of HEVs 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 [3]-[24].



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.

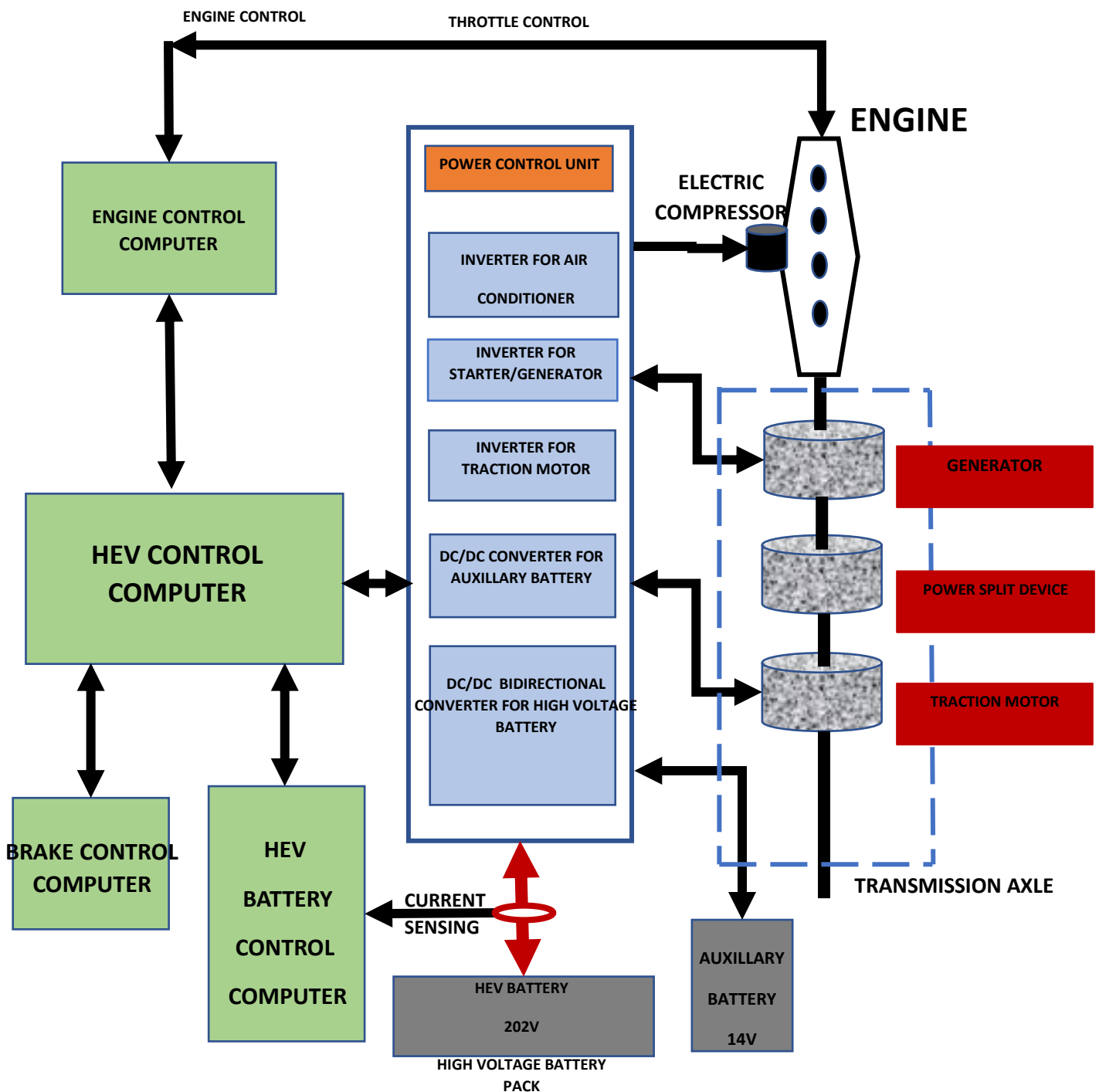


Fig 4. Power Control Unit (Toyota Hybrid Synergy) [25]

- 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.

#### 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. 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 150000-mi vehicle lifetime.



## V. CONCLUSION

In this paper we have studied the motor drives and various topologies in hybrid electric vehicle. The most reliable topology is Plug-in Hybrid Electric Vehicle. 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. 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 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.

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