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TABLE OF CONTENTS

Technical Papers and Authors	Papers	Page No.

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Power Electronics for the Future of Automotive Industry

Kaushik Rajashekara
Chief Scientist, Energenix Center
Delphi Automotive systems
Mail Code ERC12/D35, P.O. Box 9005
Kokomo, IN 46904
USA

ABSTRACT

With the requirements for reducing the emissions and improving the fuel economy, the automotive companies are developing electric, hybrid, and fuel cell vehicles. Power electronics is an enabling technology for the development of environmentally friendly vehicles, and to implement the 42 V based electrical architecture to meet the demand for increased electric loads. In this paper, future vehicle strategies and the function of the power electronic sub-systems are described. The requirements of the power electronic components for the successful development of these vehicles are also presented.

1.0 INTRODUCTION

With the increasing demand from consumers, the automotive manufacturers are required to provide more electronic features in the vehicles, while continually striving to develop environmentally friendly and improved fuel economy vehicles. In order to reduce the emissions and to improve the fuel economy, research work is going on in the area of alternative power train technologies [1]. Some of these technologies are electric vehicles, hybrid electric vehicles, fuel cell vehicles, integrated starter/generator systems, and belt driven starter/generator systems. Progress is also achieved in the area of exhaust after-treatment to reduce emissions. The increasing use of electronic features to improve vehicle performance, fuel economy, emissions, passenger comfort, safety, and convenience has resulted in the growth of electrical loads in the vehicle. Hence a major change in the electrical architecture of the vehicles is on the horizon by going for a 42 V system from 14 V systems. The main reasons for switching over to 42 V are to meet the increased electrical demands of future vehicles, to lower the current drawn from the battery, and to implement additional safety and comfort features [2]. In addition, to reduce the mechanical and hydraulic components and to improve the design flexibility of the vehicles brake-by-wire and steer-by-wire technologies are being considered for the future automobiles.

Power electronics is an enabling technology for the development of cleaner, fuel efficient, and 42 V architecture based vehicles. In electric, hybrid, and fuel cell vehicles, the challenges are to have a high efficient, rugged, small size, and low cost inverter and the associated electronics for controlling a three phase electric machine [3]. In fuel cell vehicles, a power-conditioning unit such as a dc-dc converter to match the fuel cell voltage with the battery pack may also be required. Exhaust after-treatment units such as the one based on non-thermal plasma require a high voltage ac power supply of the order of 1 to 2 kW at 6 kV. In steer-by-wire and brake-by-wire applications, a fast response motor, inverter, and the control system are required and must be able to operate in adverse environmental conditions. The power electronics also has a major role in the 42 V architecture based vehicles. Also, the integration of actuators with power electronics reduces the overall systems cost. In addition to the power electronics, the technology of the electric motor plays a major role in the dynamics of the vehicles and the type of the power converter required for controlling the vehicle operating characteristics.

In this paper, the operating strategies of hybrid and fuel cell vehicles are described with the associated power electronics required for these systems. The functions of the power electronics sub-systems are presented. The challenges related to the power device selection, packaging constraints, topology selection, control issues, and cost issues will be discussed. The paper also examines how the automotive technology trends will evolve in the next 8 to 10 years.

2.0 HYBRID ELECTRIC VEHICLES

Hybrid vehicles have two or more sources of energy and/or two or more sources of power on-board the vehicle. The sources of energy can be battery, flywheel, etc. The sources of power can be engine, fuel cell, battery, ultracapacitor, etc. Depending on the configuration of the vehicle, 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 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 [4]. 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 used to drive the vehicle. Series hybrid vehicle offers lower fuel consumption in city driving cycle and the parallel hybrid vehicle has lower fuel consumption in the high way driving cycle. Hybrid vehicles are also classified as mild hybrids, power hybrids, and energy hybrids depending on the role played by the engine and the electric motor and the mission that the system is designed to achieve [5].

2.1 Series Hybrid Vehicles

A typical series hybrid propulsion system configuration is shown in Fig. 1. A series hybrid vehicle is essentially an electric vehicle with an on-board source of power for charging the batteries. Generally, 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 providing propulsion power. In this case, the size of the batteries could be reduced but the size of the generator and the engine need to be increased. The power electronic components required for a typical series hybrid vehicle system are: converter for converting the alternator output to dc for charging the batteries and the inverter for converting the dc to ac to power the propulsion motor. A dc-dc converter is required to charge the 12 volt battery in the vehicle. In addition, an electric air-conditioning unit needs an inverter and associated control systems.

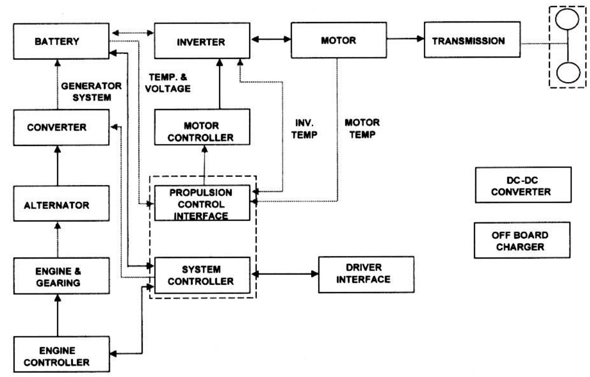

Fig.1 Series Hybrid Vehicle Propulsion System

2.2 Parallel Hybrid Vehicles

The parallel hybrid can offer the lowest cost and the option of using existing manufacturing capability for engines, batteries, and motors. But the parallel hybrid vehicle needs a complex control system. There are various configurations of the parallel hybrid vehicles depending on the role of the electric motor/generator and the engine. In the 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 of the examples of parallel hybrid systems, which are commercially available [6].

2.2.1 Crankshaft Mounted Integrated Starter –Generator System

Many automotive companies are working on the development of crankshaft mounted integrated starter-generator (ISG) system based hybrid vehicles. The ISG concept offers the ability to reduce fuel consumption through the use of engine-off during coast-down and idle, early torque converter lockup with torque smoothing, regenerative braking, and electric launch assist. The feature stop-start, which means IC engine off at idle, is integrating the quiet starting and the high power generation into one single machine. This specific feature offers high potential for reducing fuel consumption, exhaust and noise. In addition, the ISG provides the capability for generating higher power than today's conventional automotive alternators. This higher power would enable to incorporate features such as electric power steering, electric HVAC, electric valve trains, mobile ac power, and many entertainment features. The typical fuel economy gain by incorporating various functions is shown in Fig. 2 [2].

Delphi Automotive Systems has built and tested an SUV equipped with an Energen-10 ISG system [7], shown in Fig. 3. The vehicle has a parallel hybrid architecture in which the electric machine and IC engine 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 Energen-10 system replaces the conventional vehicle's flywheel, alternator, and starter motor with an electric machine that fits between the engine and transmission. The system has a power generation capability in the 5 to 10 kW range (hence the 10 in its name). The electric power take-off (PTO) function can provide on-board electric power for powering the appliances on the fly and when the vehicle is parked. The PTO consists of a single phase inverter for converting 42 V dc to 120V/240 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 peak (with a higher dc bus voltage), as in DaimlerChrysler's "Contractor Special" vehicle.

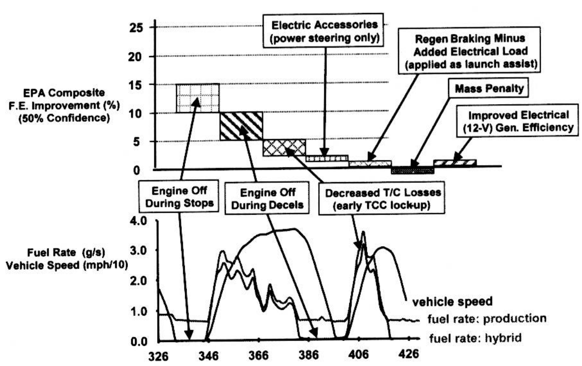

Fig. 2 Typical fuel economy gains for an ISG System

The requirements in respect to starting mode can be very different from the generation mode. The ratio of machine speed to engine speed is 1:1. The diagrams in figure 4 describe the current level requirements for a 5 kW induction machine in both modes. In order to generate the specified power level at a temperature of 125°C and at a 42 V system voltage, the maximum ac current level is almost reaching 150 A [8]. For starting the engine, a starting torque of about 200 Nm is required at the worst case condition, i.e. at a temperature of –30°C. To provide that torque with this machine design, stack length and rotor diameter, a current of more than 450 A has to be

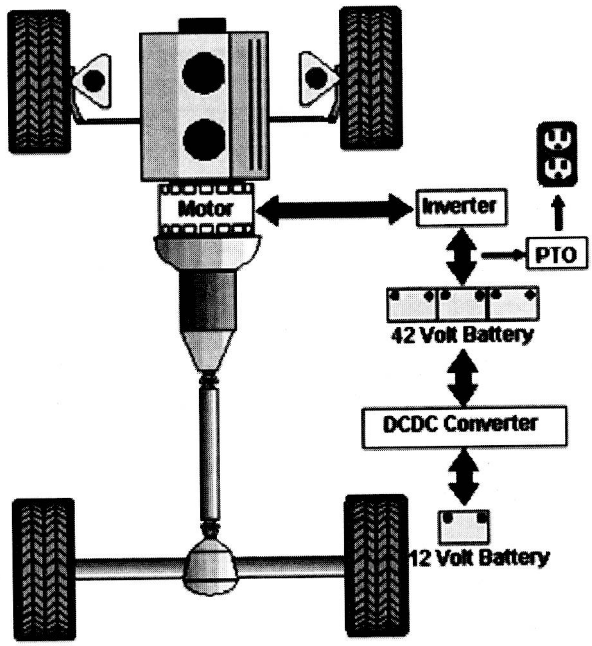

Figure 3 ISG based on Energen-10® System Architecture

supplied. The result is that, between generator and 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, still they need to be designed to meet the requirements of starting current. In addition the battery has to be able to provide that amount of electrical power at the respective ambient temperatures.

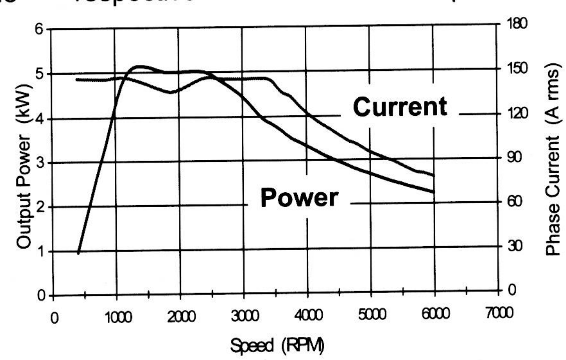

Figure 4(a) Generator requirements at 125°C

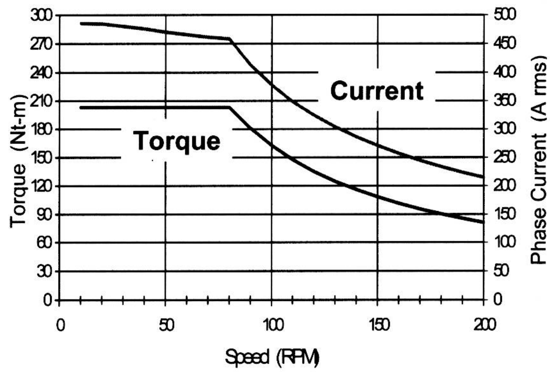

Figure 4(b): Starting requirements at -30°C

Another configuration of ISG system at a higher voltage and using a permanent magnet machine is shown in Fig. 5. This system has been implemented in DaimlerChrysler's ESX3 vehicle, which was part of the PNGV (Partnership for a New Generation of Vehicles) [2, 9]. The rating of the electric machine is 15 kW continuous and 20 kW peak power.

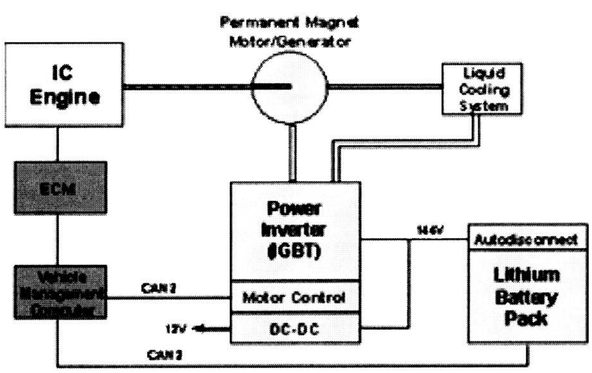

Fig. 5 ISG System based on 144 V dc and Permanent magnet machine

2.2.2 Side Mounted Integrated Starter-Generator

Recently, there has been lot of interest in the side-mounted ISG, that is, the belt driven Starter-Generator system [8]. 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 a quiet re-start for a warmed-up engine. This has been demonstrated by Delphi (Energen 5) and other companies in gasoline engines up to 1.6 liter displacement, using the conventional 12 volt battery. 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 allow also a cold-cranking of larger engines. The benefits of this system are: low cost, simple implementation, minimal changes in the electrical system, and 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. Though the normal generation current is much lower, the power electronics need to be designed for higher starting currents. The packaging and cooling of the devices need special consideration.

3.0 FUEL CELL VEHICLE PROPULSION SYSTEM

With the advancement in the technology of fuel cells, there is an increasing interest in using fuel cells for propulsion, on-board power generation, and for stationary power generation applications. The advantages of fuel cell vehicles compared to internal combustion engine vehicles are [10]:

- Direct energy conversion (no combustion).
- No moving parts in the energy converter, quiet, and fuel flexibility.
- The fuel cell vehicles can dramatically lower energy use, lower air pollution, and increase the use of alternative fuels.
- The fuel cell efficiency does not decrease sharply as the size of the system is decreased.
- The fuel cell efficiency does not appreciably change if the fuel cell operates at part load. Under comparable road load conditions, the fuel cell efficiency is significantly greater than the efficiency of internal combustion engines, especially at part load. At a nominal driving speed of 30 mph, the efficiency of fuel cell electric drive using Hydrogen from natural gas is about two times higher than that of a conventional engine.
- Replacement of ICE with fuel cell system could save 60% of the primary energy

consumption, the CO_2 emission can be reduced by about 75%, and release of toxic substances could be largely reduced.

A fuel cell system designed for vehicular propulsion applications must have weight, volume, power density, start-up, and transient response similar to the present day internal combustion engine based vehicles. Other requirements are: very high performance for short time, rapid acceleration, good fuel economy, and easy access and safety considerations with respect to fuel handling. Cost and expected life-time are also very important considerations.

A typical fuel cell vehicle propulsion system is shown in Fig. 6 [10]. Inside the fuel cell stack, the hydrogen and oxygen are combined to produce direct current electricity and heat. The output voltage of the stack is conditioned using a dc-dc converter to be compatible with the battery voltage. 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.

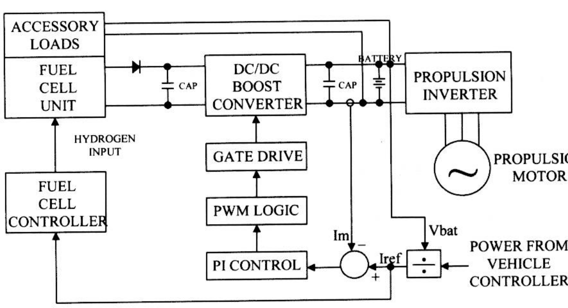

Fig. 6 Typical Fuel Cell Vehicle System

Various types of fuel cells are in the development stage. The most common classification of fuel cells is by the type of the electrolyte used. They are:

(1) proton exchange membrane (PEM, also called polymer electrolyte) fuel cell with an operating temperature of about 80° C
(2) alkaline fuel cell with an operating temperature of about 100°C
(3) phosphoric acid fuel cell with an operating temperature of about 200°C
(4) molten carbonate fuel cell with an operating temperature of about 650°C
(5) Solid oxide fuel cell with an operating temperature of 800°C to 1000°C.

PEM fuel cells are gaining importance as the fuel cell for propulsion applications because of their low operating temperature, higher power density, specific power, longevity, efficiency, relatively high durability, and the ability to rapidly adjust to changes in power demand. The PEM is more suitable for automotive applications for the following reasons.

- PEM can be started easily at ordinary temperatures and can operate at relatively low temperatures, below 100°C
- Since they have relatively high power density, the size could be smaller. Hence they could be easily packaged in the vehicles
- Because of the simple structure compared to other types of fuel cells, their maintenance could be simpler.
- They can withstand the shock and vibrations of the automotive environment because of their composite structure.

One problem in PEM is that the carbon monoxide (CO) concentration in fuel should be reduced to less than 10 ppm, because even small amounts of CO in fuels cause deterioration of the cell performance. Another problem is that they typically require expensive precious-metal catalysts.

4.0 VEHICLES WITH FUEL CELL BASED APU

The power required to feed the various electrical loads in an automobile is generally obtained using a belt-driven alternator driven by an internal combustion engine. The alternator can only produce power while the engine is running. The fuel cell can produce the on-board power when the engine is not running and thus would eliminate the need for an alternator. High-temperature solid oxide fuel cells (SOFC) are particularly suitable as an auxiliary power unit(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. It has less stringent requirements for reformate quality (using carbon monoxide directly as a fuel) and is less sensitive to contaminants such as sulfur.

A fuel cell APU is a high efficiency generator that runs with the engine on or off. It can be applied in conventional or mild hybrid configurations - and is not linked to a fully electric drive train. The use of a fuel cell as an electrical power source in vehicles has several key advantages [11]. First, power can be produced when the engine is not running. The fact that power can be made available in abundance with the engine off offers a host of possibilities including the ability to climate control the vehicle with the engine off. This capability alone could promote lower emissions while maintaining passenger comfort via the use of engine start-stop operation in cities. For over-the-road semi-trucks, nightlong idling of the stationary truck's diesel engine has been a common practice. The engine-independent fuel cell auxiliary power unit (APU) could provide power for heating/cooling as well as the host of convenience items found in today's semi-trucks, thus avoiding the necessity for running the engine idle for a long time. This would considerably reduce the emissions from the trucks.

A dual 42V/14V architecture using an alternator is shown in figure 7. In this architecture, a generator feeds a 42V bus having 42V loads and a battery. A dc-dc converter connects this bus to the conventional 14V bus having 12V loads and a 12V battery. The architecture for a dual-voltage electrical system containing a fuel cell power source is shown in figure 8. The alternator of figure 7 is directly replaced by the fuel cell, and a new box, labeled "Power Conditioning Unit" is

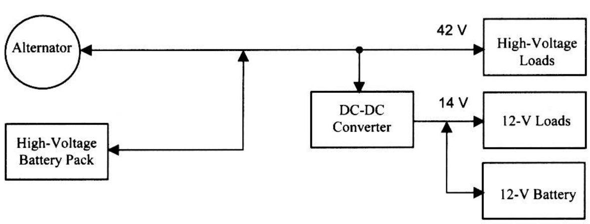

Fig. 7 Dual Voltage system with generator and as power source

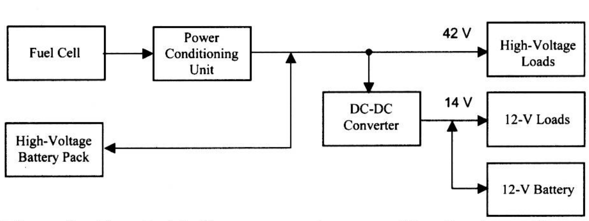

Fig. 8 Dual Voltage system with fuel cell as power source

added. The functions of the power-conditioning unit are to make the fuel cell stack output voltage compatible with the 42 V Powernet standards, 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, which would damage the cell. The power-conditioning unit could be a buck, boost, or a buck-boost dc-dc converter depending on the output voltage of the stack. Although in the long run, it may be possible to design the stack to meet the 42 V powernet standards, but in the short run a power conditioning unit is required.

5.0 NON THERMAL PLASMA (NTP): EXHAUST AFTER-TREATMENT

Non-Thermal Plasma (NTP) is a plasma in which the electron mean energies are considerably higher than those of the components of the ambient gas. NTP devices decrease polluting / toxic gases by producing energetic electrons which collide with the background gas molecules producing chemically reactive free radicals (O_2, N_2). These free radicals promote selective partial oxidation of NO to NO_2 in diesel or in gasoline lean-burn engines. NO_2 can be used to enhance NOx reduction when combined with reducing catalyst technology. NTP enables continuous particulate filter regeneration even at lower temperatures. With this technology, it is possible to have NOx emission reduction up to 70%, particulate mass reduction through reactor up to 30%, and NTP reactor is not affected by sulfur. A typical NTP based system architecture is shown in Fig. 9 [12].

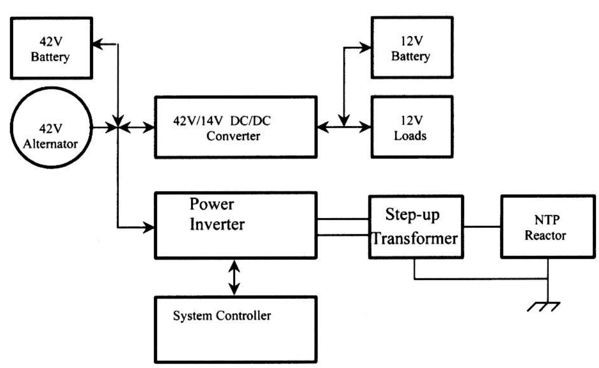

Fig. 9 NTP based Exhaust After-treatment System

The NTP power supply requires a 3 kV (peak) adjustable sinusoidal voltage of about 1000 W continuous power into the reactor, variable frequency, and synchronization with the resonance frequency of the reactor. It should be capable of pulse density modulation. The efficiency and cost play a major part in incorporating this system into vehicles.

6.0 STEER-BY-WIRE AND BRAKE-BY-WIRE

Steer-by-wire is a fully electric engine independent steering system. A typical steer-by-wire system consists of a steering wheel module, the steering rack module, the electronic control unit and the battery module [13]. The steering wheel module determines the input from the driver and gives the driver the same steering feel and feedback of a typical, normal vehicle. An electric motor (typically 600W) with integrated power electronics is connected to the steering wheel to provide the desired steering feel and steering torque. The steering rack module transmits the driver's commands into steering motion on the two front wheels and determines the feedback forces from the wheel/road contact. Two motors, one on either side, drive the pinion of the steering rack through the transmission unit with the control unit (CPU) applying the angle data from the steering wheel and steering rack to determine the control signals for the actuators. Simultaneously, the control unit monitors all system components and links up with the electronic stability system to take necessary action in times of emergency. Steer-by-wire provides more precise steering feel and performance, speed sensitive steering, and up to about 4% fuel economy improvement on small engines. It is environment friendly eliminating hydraulic fluids and rubber hoses. As an added safety, it provides power assist even if engine stalls.

Automotive companies are also working on the development of electric brake-by-wire systems based on four electro-mechanical brake (EMB) calipers. A motor and a mechanical reduction mechanism generate the clamp force. Permanent magnet motors and switched reluctance motors are the major candidates for brake-by-wire applications. Switched reluctance motors and associated power electronics would help to reduce the cost and improve the fault tolerant capability. The brake-by-wire has the advantages of improved braking efficiency, enhanced vehicle stability, eliminating vacuum booster, integrating electric park brake, and has no fluids, no hoses, and has fewer parts for dismantling.

7.0 POWER ELECTRONICS REQUIREMENTS

The power switching devices, electric motors, and the associated control systems and components play a major 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, packaging of the individual units, and the system integration are very important for the development of efficient and high performance vehicles. In addition to the power devices and controllers, there are several other components such as capacitors, inductors, bus bars, thermal system, etc., form a major portion of the power electronics unit. The packaging of all these units as one system has significant challenges. The US Department of Energy, US Navy, and other organizations have funded the development of Power Electronics Building Blocks (PEBB) to develop modular power electronic systems ranging from 10 kW to several MW of power. The PNGV goals for power electronics and electric machinery are quite challenging and are given in Table 1 [14].

To meet the challenges of the automotive environment, several technical challenges need to be overcome and new developments are needed from device level to system level. There is a strong need for a power device which combines the MOS gate control characteristics with the current carrying capability and voltage drop characteristics of a thyristor type structure. The device forward voltage drop even at higher currents (>400 A) must be less than 2 V and at the same time be able to be operated at switching frequencies higher than 10 kHz. The first device to meet these requirements was MCT, but it did not meet the expectations of the power electronics community. In addition to the switching device, there is a need for development of a new power diode with superior dynamic characteristics such as MOS diode (MCD). The research on Silicon Carbide needs to be accelerated to enable 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.

Table 1: Technical Targets: Power Electronics and Electric Machines
(For 47.5 kW Hybrid Propulsion Drive)
Electric Motor/Generator

Characteristics	Units	2000	2004	2006
Specific Power at Peak Load	kW/kg	1.5	1.6	1.6
Volumetric Power Density	kW/L	4	5	5.5
Cost(100,00 units/year)	$/kW	6	4	4
Efficiency(10% to 100% Speed, 20% rated torque)	%	92	96	97

Power Electronics (Inverter and Controller)

Characteristics	Units	2000	2004	2006
Specific Power at Peak Load	kW/kg	4	5	5.5
Volumetric Power Density	kW/L	10	12	13
Cost(100,00 units/year)	$/kW	10	7	6
Efficiency(10% to 100% Speed, 20% rated torque)	%	95	97-98	98

(The above values are for a typical power level, but the values are not linear with respect to power level)

The technologies related to device packaging need to be investigated for developing a power switch. Wire bonding, device interconnections, etc. are the barriers to development of high current density power units. The 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. The reliable operation of power modules and other related packaging technologies needs to be studied. The power electronic systems available in the market are bulky and difficult to package for automotive applications.

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 operation, low ESR, high operating temperature, and high ripple current capability need to be further developed. Hence improved dielectric materials needs 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.

Although soft switching inverters have the advantage of lower switching losses and low EMI, they need more components, higher operating voltage devices (depending on the topology), and complicated control compared to hard-switched inverters. Hence the soft-switched inverter application is limited to very special types of needs. There is a need to develop an inverter topology to achieve the performance of the soft-switched inverter with less components and simplified control. Topologies with two or more integrated functions such as inverter, charger, dc/dc converter, and with minimum use of capacitors needs to be developed. In the area of dc-dc converters, further development is needed to obtain 12 Volt from 42 Volt and higher voltages. Integrated EMI filters for control of EMI generated due to switching of the devices needs to be 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.

In the area of propulsion motor and other motor control technologies, methods to eliminate the speed/position sensors, inverter current sensors, etc. have been under investigation for several years. These technologies have not yet proven to be practical for automotive applications. The technology development effort needs to be focused on sensorless operation of electric machines and reduction or elimination of current