Advances in Propulsion Systems of Hybrid and Electric Vehicles

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1. Introduction

Mid-term expectation for reduced availability of oil compared to market demand and environmental concerns being spread throughout public opinion worldwide are leading disputed, but somewhat unavoidable, technological transition to novel configurations of propulsion systems for road vehicles in order to overcome today's vehicles driveline based on the use of an internal combustion engine (ICE). To this goal, propulsion systems using electric motor drives are widely recognized to be the ultimate solution provided that the electric energy required for traction could be efficiently and cost-effectively made available on board the vehicle. Despite of the best efforts to produce pure battery-powered vehicles (EVs) since the beginning of the last century, up to date the long-standing problem of battery range remained insurmountable. With EVs destined for a niche role in the car industry, attention is now increasingly focused on fuel-cell and hybrid technologies as a way of producing breakthrough vehicles with alternative power plants. A number of auto makers see fuel-cell powered electric vehicles (FC-EVs) as the ultimate route to achieving sustainable long-term alternative propulsion systems. However, commercial production of FC-EVs is still several years away and considerable debate is still raging as to the optimum way to produce and safely store on board a vehicle the hydrogen necessary to power the fuel-cell generator. On the other hand, vehicles equipped with a hybrid drive-train (HEVs) are yet being developed by most of the auto makers to be offered as a commercial product, and thereby in a short-term vision HEVs may prove to be the way forward for the time being at least, until FC-EV technology is fully developed.

This paper outlines some advances in vehicle propulsion systems resulting from research developments in motor drives and power electronics. Rather than providing an exhaustive overview of such a wide field, this paper aims to give author's vision of future trends in road vehicle drivelines and reports examples of technology developments being undergoing at the Power Electronics and Drives laboratory of the University ROMA TRE, Rome, Italy.

2. Propulsion Systems in Next-Generation Vehicles

A significant number of electric and electronic power apparatus are yet employed in today's road vehicles for ancillary loads and the use of such devices will be further increased in a short term period. In order to meet the growing auxiliary electric power requirements a higher output power alternator is needed and it has been proposed that this same machine also be used to start the engine since the motoring and generating torque requirements are gradually converging as the alternator power requirements increase. Using an integrated starter/alternator (ISA) could produce a lower system cost as well as provide extra functionality such as allowing the engine to be automatically stopped when it would otherwise be idling and then restarted simply by pressing the accelerator pedal. This could provide significant fuel savings and reduce emissions in city traffic conditions. The ISA-equipped car is also of interest because it represents a halfway point between conventional propulsion systems and HEV drivelines which use higher power electric drive systems and require larger energy storage capacity on board. Then, in parallel with development of ISA systems, since the past decade the international research and development efforts have been increasingly focused on a wide variety of hybrid drive-train configurations in which the required traction power is achieved from the combined operation of both the ICE and an electric traction drive. In these hybrid configurations the electric traction drive has power rating that generally falls in the range from 10 kW to 100 kW depending on the vehicle size and the propulsion drive configuration. Hybrid configurations in which the electric drive is used to assist ICE operation only during vehicle acceleration transients are often referred to as "mild" hybrids, whereas in "full" hybrid drive-trains the electric drive provides a substantial portion of the vehicle traction power.

Compared to conventional vehicles, HEVs potentially offer attractive advantages in terms of fuel savings and reduced emissions. In fact, hybrid drivelines allow the use of an engine having reduced power rating and, further to that, such an engine can actually be designed to be operated in the torque-speed range over which it would be most efficient. Even though full hybrid configurations would actually give the greater benefits, to date mild hybrid arrangements are drawing considerable attention as they result in minor modifications of the driveline of conventional vehicles and require the use of energy storage having substantially lower capacity compared to full hybrid architectures. Fig. 1 shows a mild hybrid configuration in which an electric machine, usually having power rating in the range from 10 kW to 15 kW, is mounted in place of the conventional flywheel between the ICE and transmission. In such a hybrid drive-train the ICE provides most of the traction power and the electric drive is used to provide leveling of the ICE torque load. Thereby, the electric machine would be required to operate as either motor or generator over a wide range of speed in order to process the bi-directional peak power flows resulting from vehicle motion transients. Further to that, ICE idling would be avoided by using the electric machine as engine starter.

In mild hybrid configurations the electric traction drive is fed through an energy storage that would be recharged whenever the vehicle is either cruising or decelerating. The energy storage could arranged by combining together electrochemical battery and ultracapacitors and would use a dc-to-dc converter as power interface between the electric traction drive and the energy storage devices. Further discussion on such an energy storage arrangement is provided herewith after in this paper.

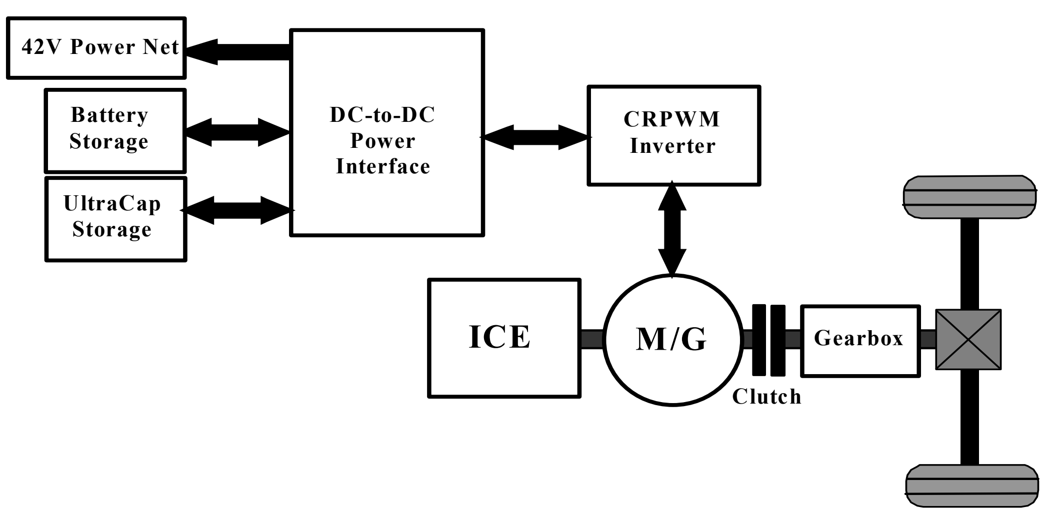


Figure 1 Mild hybrid propulsion system.

Recent advances in fuel-cell technology have significantly revived interest in propulsion systems that are entirely electric. This represents a major reversal of the trends away from such systems caused by the growing pessimism about the prospects for electrochemical batteries to provide the necessary vehicle range between recharging at an acceptable cost. Despite of some drawbacks in terms of number of electrical components being used and relatively larger capacity of the on-board energy storage being required, compared to hybrid drivelines the "entirely electric" propulsion systems offer the most effective solution for achieving zero emissions vehicle drive-trains. Even in the case that the on-board electric generator is being accomplished by means of an ICE-driven alternator (in such a misleading way, in literature the propulsion systems that use an ICE-driven alternator as on-board electric energy generation unit are often referred to as "series hybrid" systems even though in these driveline arrangements the ICE is not used for traction purposes), significant reduction of emissions could actually be achieved as the engine would be operated independently from traction requirements. This is a great feature for those vehicles purposely designed to operate mostly on urban driving cycles, such as vehicles for public transportation and compact pickup cars for door-to-door delivery.

The propulsion system architectures adopted for entirely electric traction drivelines are not as varied as those for HEVs. While to date the use of a single electric traction motor is most popular as a means of minimizing total system cost, it is envisaged that future vehicles would use as many as four traction motors, one built into each wheel and due to that in literature often referred to as "wheel motors". As example of such a novel concept, Fig. 2 shows a propulsion system architecture that would be suitable for electric traction in 2-wheel-drive vehicles. In this propulsion system an electric generator (i.e., either a fuel-cell stack or an ICE-driven alternator) would be used together with a combined ultracapacitor-battery energy storage to supply the two wheel traction drives. The electric generator would be operated to deliver the average traction power requested by the driving cycle, whereas the energy storage would be required to handle the bi-directional peak power flows resulting from vehicle operations. Further discussion on both wheel motor technology and use of combined battery-ultracapacitor energy storage in propulsion systems is given in the following.

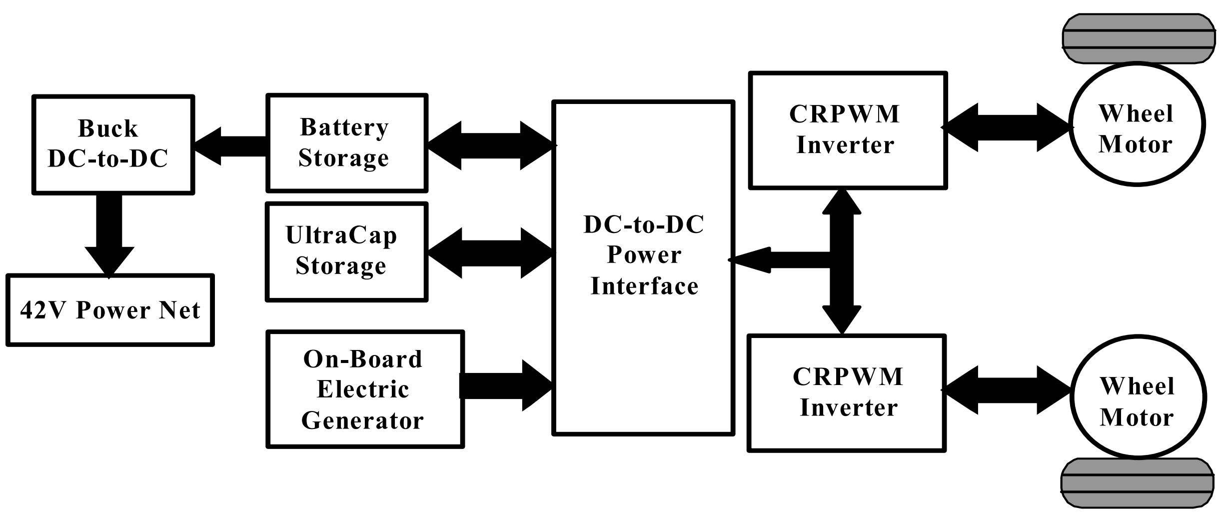


Figure 2 Electric traction propulsion system.

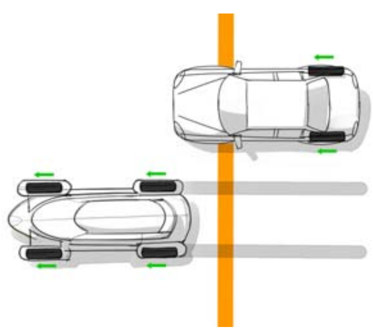
3. Wheel-Motor-Based Traction Drives

Fuel cell electric vehicles require an electric propulsion system to transform electrical energy into electromagnetic torque to propel the vehicle. In most conventional applications, a central high speed electric motor is mechanically coupled to the wheels by a single speed reduction gearbox and a mechanical differential. An innovative alternative utilizes low speed, high torque, gearless, electric motors being mounted completely inside the rim of the wheels to provide instantaneous torque. These wheel motors have many advantages including no mechanical linkages and independent and precise torque control. This leads to some interesting potential applications.

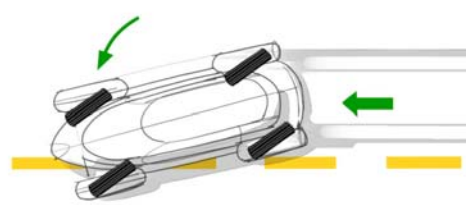
Wheel motors offer a significant vehicle packaging advantage over conventional electric motor architectures. By placing the traction motors in the wheels, there is no intrusion into the vehicle chassis. This frees up valuable chassis space for passengers, components, or cargo. Since the wheel motors are completely self contained, there are no drive shafts, constant-velocity joints, or axles to contend with. As shown in Figure 3a, adding two wheel hub motors to a conventional 2-wheel-drive (2WD) vehicle would be fairly straightforward and produce all-wheel-drive (AWD) vehicles without excessive modifications to existing chassis structures and without adding a mechanical transfer case, driveshaft, and secondary axle. The precise control of torque at each corner presents new opportunities for enhanced vehicle stability controls under all weather conditions not possible with mechanical AWD systems. This includes far better enhancements to antilock braking systems.

The freedom of mechanical linkages will permit greatly improve turning radius and suspension travel. Figure 3b shows how four steerable wheel motors can be used for 4 wheel steering. These motors can be mechanically steered, electronically torque steered, or a combination of both. This could provide new opportunities for advanced vehicle controls in lane keeping, collision avoidance, and stability controls. It would even be possible to counter-rotate left and right side wheels to make the vehicle turn on its own axis. One can imagine how this can be used to get into and out of tight parking spots. Torque is controlled independently to each motor, so differential speed control while cornering is provided electronically. Precise torque and speed control are inherent with the drive system. This will permit splitting torque, front-to-rear or side-to-side, far easier than with a mechanical system. If combined with an internal combustion engine, it is possible for the electric motor to compensate for torque oscillations induced by engine vibrations and driveline gear-shift torque disturbances to enhance driver comfort.

Most of the major car manufacturers are now seriously considering use of wheel motors in future either fuel-cell or hybrid vehicle configurations and to date a number of research programs are being under development at least for validating motor technology and improve drive performance. As example of such a novel concept for vehicle propulsion systems, the GM’s wheel hub motor research project is summarized herewith in the following.



(a)



(b)

Figure 3 Adding wheel motors to a conventional vehicle creates all-wheel-drive system (a) and this introduces new opportunities for enhanced vehicle stability controls (b).

3.1 The GM's Wheel Hub Motors [1, 2]

The work herewith described was performed at General Motors Advanced Technology Center, Torrance, CA in cooperation with Lucchi Elettromeccanica, Rimini, Italy, two Universities of Rome, "La Sapienza" and "ROMA TRE", Italy and Quantum Technologies, Irvine CA. The GM direct drive system is targeted for use in the GM's fuel-cell vehicle platform shown in Fig. 4, even though it would be used also in dual-mode hybrid vehicle propulsion systems having an internal combustion engine driving the front wheels and wheel motors on the rear wheels.

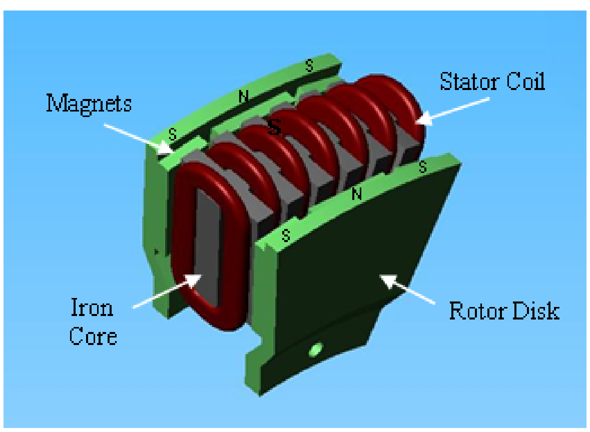
The GM direct drive system does not require reduction gears. This means the mechanical losses induced by the gearbox can be eliminated as well as acoustic noise and gear backlash. The torque generated by the electric machine is transferred directly to the tire. In practice these motors produce no noise other than a very slight high frequency hum from the power inverter. The torque is extremely smooth and without noticeable cogging.

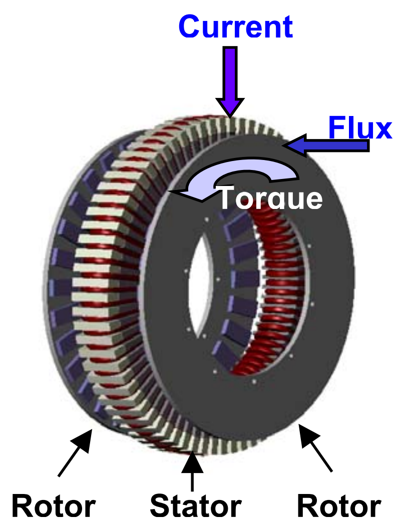
GM's direct drive system offers significant advantages such as instantaneous torque production, improved system efficiency, independent control of each wheel, ease of packaging, and enhanced drive and ride comfort. The goal of direct drive called for a high torque, low speed motor. Following an extensive trade study, a surface permanent magnet machine was selected for the high torque per volume ratio. In order to achieve high torque density and high efficiency, a single stator, dual rotor, axial flux machine design was chosen. The high torque produced by these motors make them particularly well suited for in-wheel applications without gears. The first generation of the GM wheel hub motor was designed to prove the practicality of the axial flux permanent magnet motor technology. Thus, more emphasis was given to robustness and durability rather than low machine mass. The added mass for the motors is approximately 15 kg per wheel compared to standard wheel mounting. Future work will further reduce unsprung mass. Careful suspension tuning can compensate for most of the effects of this additional mass.

Figure 4 GM's fuel-cell powered vehicle platform.

Figure 5 shows the basic construction of an axial flux permanent magnet motor. Axial flux machines can have extremely high torque density, and are more forgiving to mechanical displacement from road disturbances, especially in a geometry which has a large diameter. Because the basic geometry favors a disk, these machines are ideal candidates for in-wheel applications. These machines have discs for both rotor and stator geometries. The wheel hub motors selected have a single stator in the middle with a slotted magnetic core and a rotor with distributed magnets on each side. This type of design provides higher torque density because it utilizes copper from both surfaces of the stator for torque production. Magnetic flux from the permanent magnets flows parallel to the axis of rotation. Torque is the product of air-gap flux multiplied by stator current. Since the flux is fixed by the permanent magnets, the high peak torque requires a high stator current which generates heating losses due to winding resistance. To keep the stator temperature within the ratings of the materials used, a liquid cooled thermal system is used on the stator. An aluminum ring with internal coolant passages surrounds the end winding of the outer stator winding to maximize the cooling surface. In addition to this, high thermal conductivity epoxy is used in the end winding to further improve cooling efficiency and to attach the coolant ring to the stator core.

The basic requirements for each wheel hub motor are shown in Table 1. The machine and power-inverter-module have been designed, manufactured, dynamometer tested, and publicly shown on a S-10 truck demonstration test vehicle. Each motor was designed to be driven by a GM three phase inverter operating from a nominal 320V battery pack. Figure 6 shows the basic motor assembly before mounting. The three black leads provide AC power from the inverter module. The red wires are signal leads from the resolver type position sensor, and the two red caps are the coolant connections. A standard wheel rim is bolted to the 5 bolt hub which was modified from a production GM vehicle. This motor was mounted directly to the solid axle of the S-10 truck using custom fabricated mounting brackets.





a) (b)

Figure 5 Axial flux permanent magnet machine topology selected for the GM's wheel hub motors: a, basic layout of machine active parts with rough indication of torque production mechanism; b, slice of machine active parts showing a single stator in the middle with winding coils being housed in a slotted magnetic core and a rotor discs with distributed magnets on each side.

Table 1. GM's wheel motor requirements.

Max. Speed (Operating)	1200 rpm
Max. Mechanical Speed (Non-Operating)	1500 rpm
Base speed	750 rpm
Peak torque, 30 sec.	500 Nm
Peak power, 30 sec.	25 kW
Continuous torque	200 Nm
Continuous power	16 kW
Max. overall diameter	390 mm
Max. overall length	95 mm
Max. mass	30 kg

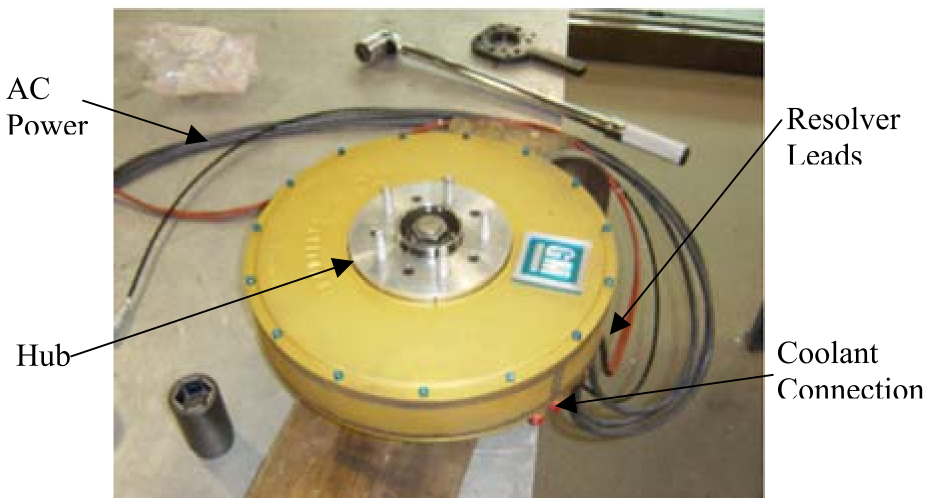


Figure 6 GM's wheel motor on bench.

Since the motors are attached to the wheels, they had to meet GM requirements for road shock, vibration, chemical exposure, temperature, etc. Each motor had to withstand water intrusion but not be waterproof. Once the machine prototype was built, it was necessary to characterize the machine parameters to develop optimal controls. The critical flux linkages were measured as a function of current. These values were used to develop an accurate machine model which includes the effects of magnetic non-linearity and cross-coupling effects. The optimal control parameters were then stored in a look-up tables within the digital controller. Figure 7 shows the measured torque-speed curve of the prototype wheel hub motor. The upper lines are for motoring operation and the lower lines are for regenerative operation. The baseline requirement is shown by the light blue line. As shown in Figure 7, the design requirement was achieved even with the lowest dc link voltage of 250V. With higher bus voltages the torque remained constant almost to 1200rpm. Overall the measured performance was in close agreement with the predicted simulations. Table 2 presents design data of the first generation GM's wheel hub motors.

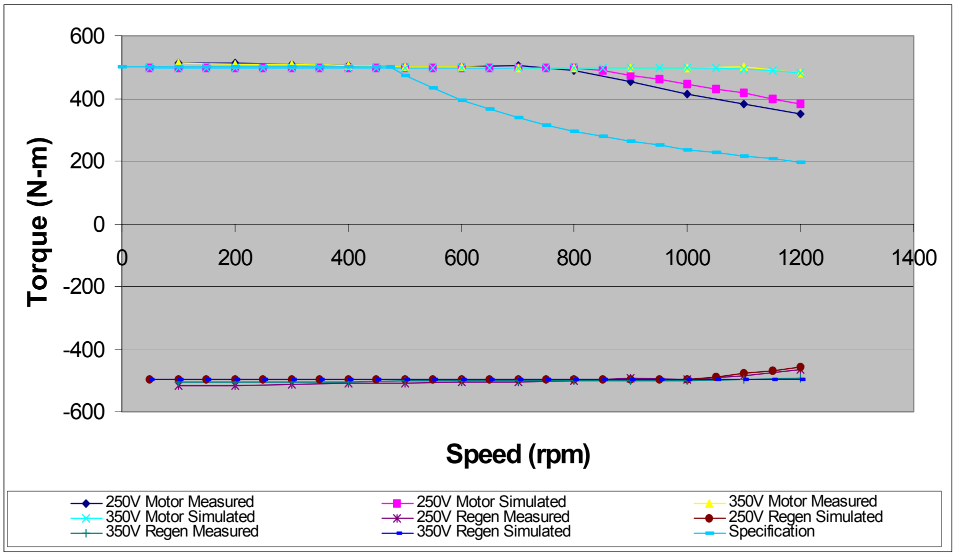


Figure 7. Measured Torque vs. Speed.

Table 2. GM's wheel motor design parameters.

Number of phases	3
Number of poles	24
Peak torque	500 Nm
Stator outer diameter	340 mm
Max. axial length	75 mm
Peak machine power	25 kW
Nominal bus voltage	280V
Peak machine current	150 Arms
Maximum machine speed	1200 rpm

Two wheel motors were mounted to the solid rear axle of the S-10 vehicle and suspension was the standard leaf spring assembly. The S-10 chosen already had a conventional 70 kW electric traction motor for the front axle and a battery pack which made conversion easy since most of the components were already onboard. Two GM inverters and radiators were mounted under the truck bed. The inverters were connected to the existing nominal 320V battery pack and the motor controllers were connected to a special vehicle controller provided by Quantum Technologies. The vehicle was outfitted with instrumentation equipment, data acquisition hardware, and an operator control that allowed the driver to select between front, rear, or both traction systems. Overall performance of wheel motors was so impressive that it was decided to unveil this technology to the public. A press demonstration took place at Irwindale Speedway in California during August 2003. The press members were invited to drag-race the demonstration vehicle against conventional Chevrolet S-10 trucks and a high performance GM vehicle. In head-to-head racing the electric S-10 outperformed its competitors in the ¼ mile. Figure 8 shows the demonstration vehicle at the racetrack. In the following months the S-10 demonstration vehicle toured with other GM high technology vehicles at GM Tech Tours throughout the United States and Asia. Over 1000 individual drivers drove the demo vehicle at these events. Almost all of them used this opportunity to experience its excellent acceleration. Over several thousand miles of hard use, there were no problems with the wheel motors. This is an excellent initial indicator of mechanical and electrical robustness.

(a) (b)

Figure 8. GM’s wheel hub motor (a) being mounted on a S-10 demonstration vehicle (b).

4. Combined Battery-Ultracapacitor Energy Storage

Fuel cell and hybrid vehicles require an energy storage in order to optimize the modes of operation of either the fuel-cell stack or the internal combustion engine in terms of efficiency and fuel consumption. A common approach to this problem relies on using an electrochemical battery which is required to either supply or absorb power in order to match on an instantaneous basis the power being requested for traction with the power delivered by the prime source. As a consequence, in such propulsion systems the electrochemical storage has to deal with high power peaks being on demand during acceleration or braking transients. Peak currents are supplied at the expense of relatively lower efficiency and increased heating rate and such highly stressing modes of operation substantially reduce the battery charging-discharging cycling life and lead to accelerated aging.

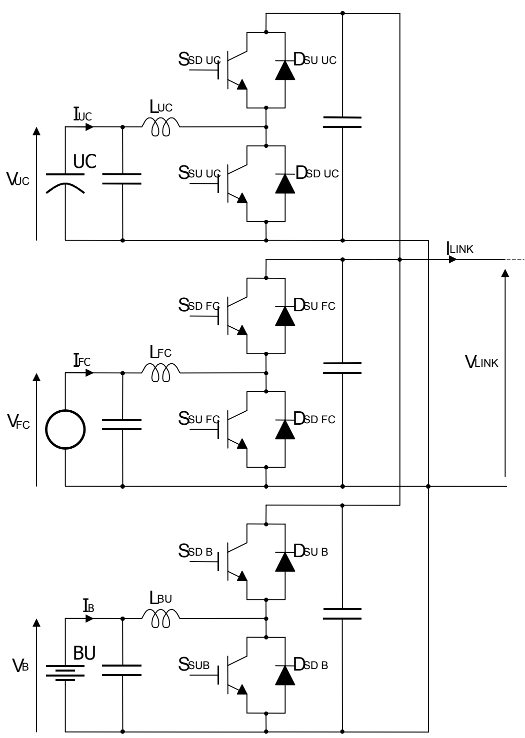
In order to achieve suitable leveling of the battery load in propulsion systems, since the last decade the use of a combined battery-ultracapacitor energy storage has been proposed and investigated. Due to both much higher power density and lower equivalent series resistance compared to electrochemical batteries, ultracapacitors are capable to handle high peak currents, so that through an UC tank a relatively high amount of power can efficiently be either supplied or recovered during the sudden electric transients resulting from vehicle acceleration or braking. Therefore, the battery modes of operation can be substantially ameliorated in terms of reduced peak currents whenever a combined battery-ultracapacitor energy storage is used.

4.1 MIPEC Topology for Combined Battery-Ultracapacitor Energy Storage [3, 4]

In the last few years the University “ROMA TRE”, Rome, Italy and ENEA (the Italian National Agency for New Technologies, Energy and the Environment) have jointly carried out a research project devoted to the development of a suitable power converter interface for combined battery-ultracapacitor storages to be used in propulsion systems. It was proposed and experimentally investigated an original Multi Input Power Electronic Converter (MIPEC) arrangement for handling the bi-directional power flow between the on-board electric energy generating system – which would include low-voltage dc energy sources such as a fuel-cell stack (FC), a battery unit (BU) and an ultracapacitor tank (UC) – and the high-voltage dc link being used for the supply the vehicle traction system. Figure 9 shows the proposed dc-to-dc power converter arrangement and the first prototype built for the purpose of laboratory experiments.

As shown in Figure 9a, each dc energy source is connected to the MIPEC dc output terminals through a bi-directional step-up/step-down dc-dc converter; the step-up mode of operation is used for regulating the power flow from each energy source to the traction drive input terminals, whereas the step-down mode of operation is used for recharging the combined battery-ultracapacitor storage system whenever required. The power semiconductors of each step-up/step-down converter are connected among them to form a conventional "phase-leg" and thereby the converter layout can be accomplished by using a single three-terminal assembly available in the market as a dual-pack IGBT module. This solution was actually adopted for the first MIPEC prototype shown in Figure 9b. However, a more compact structure of the MIPEC arrangement would be arranged by using a single six-pack IGBT module, thereby reducing the converter overall dimensions. In this case, saving of volume would justify the useless presence of the step-down switch and diode in the FC-fed converter that actually would never be operated to recover vehicle braking energy.

The MIPEC switches are controlled in order to supply the output dc link according to the traction power demand. However, each on-board energy source would be managed to achieve the best exploitation of its own characteristics. Thus, the MIPEC control manager would command sharing of the power flow between the UC and BU on the basis of the instantaneous value of control variables such as the state-of-charge (SOC) of each storage device, the maximum-allowed time derivative of the current fed by each energy source and the efficiency map of each of the available sources. Current control would be adopted for both the FC-fed and BU-fed step-up/step-down converters. On the other hand, at any working condition of the traction drive system, the desired dc output voltage would be achieved through suitable modes of operation of the UC-fed converter.



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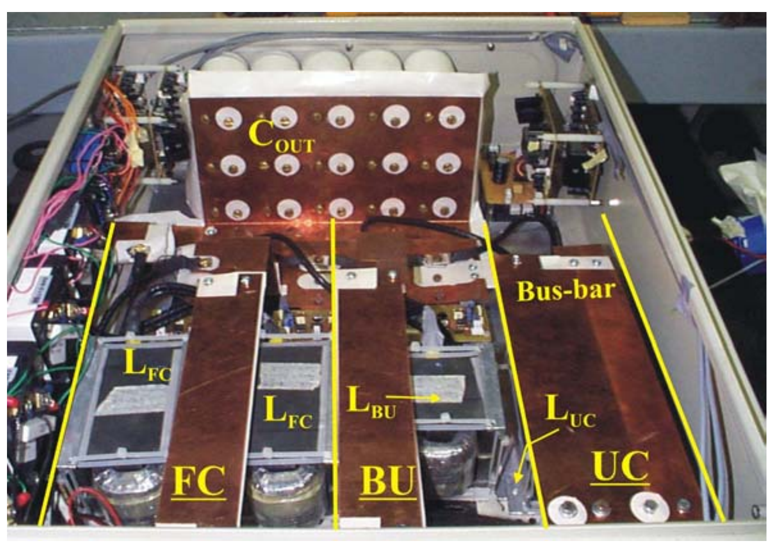

(b)

Figure 9 Proposed MIPEC arrangement: a, basic configuration; b, laboratory prototype.

In the MIPEC prototype shown in Figure 9b an air-forced heat-sink was used to make easier the setting up of the experimental rig. However, a MIPEC arrangement intended for use on board vehicles would use a water-cooled heat-sink in order to achieve the required compactness. Table 3 summarizes the leading characteristics of the power components used in the MIPEC prototype shown in Figure 9b.

To the goal of experimentally validating the MIPEC modes of operation a complete propulsion system was arranged in laboratory by using a 30kW rated traction drive and three energy sources having the electrical characteristics summarized in Table 4. In such a test rig the UC was arranged through the series connection of 3 modules each rated 42V - 145F, and the BU was accomplished by means of the series connection of 12 elements each rated 12V - 13Ah. In order to simulate the traction power requirement resulting in compact car whenever operated along urban driving cycles, laboratory experiments were carried out by operating the MIPEC prototype with output power up to 33kW.

Table 3. Characteristics of components used in the MIPEC prototype.

Power Semiconductors	PM300DSA060 (IPM dual-pack module)			
Rated Current [A]	300			
Rated Voltage [V]	600			
Inductors	L_{FC}		L_{UC}	L_{BU}
Inductance [μH]	130		52	160
Rated Current [A]	160		200	80
ESR [mΩ]	9.6		2.4	9.8
Capacitors	C_{OUT}	C_{FC-IN}	C_{UC-IN}	C_{BU-IN}
Capacitance [mF]	15	1	2	1
Rated Voltage [V]	385	385	385	385
ESR [mΩ]	5	74	37	74

Table 4. Electrical characteristics of the energy sources used for the MIPEC test campaign.

FC		UC		BU	
Power [kW]	16	Max Voltage (@ SOC=1) [V]	126	Rated Voltage [V]	144
Min Voltage [V]	100	Min Voltage (@ SOC=0.6) [V]	70	Min Voltage [V]	120
Max Voltage [V]	200	Max Current [A]	250	Max Voltage [V]	168
Rated Current [A]	160	Capacitance [F]	48.3	Capacity [Ah]	13

Figures 10 and 11 show the MIPEC dynamic performance resulting from sudden changes of the load current at the MIPEC output. Figure 11 refers to a step change of the MIPEC output current from the no load condition to load current of about 50 A whereas, starting from such a 50A current load condition, Figure 12 refers to a sudden loss of the MIPEC load. In the right-hand side of Figure 10 it can be noticed that at the end of the output load transient, further than supplying the traction load, the FC source is used to provide constant-current charging of the BU. As clearly appears from Figures 10 and 11, following sudden changes of the MIPEC load current the UC-fed converter acts in order to keep constant the MIPEC output voltage while both BU and FC follow the current change time derivative imposed by the MIPEC control system for adjusting their own output current to the modified traction load condition. If one notes that in both such figures the current scale of the BU current trace is half the one used for the UC trace, load levelling action provided by the UC is evident.

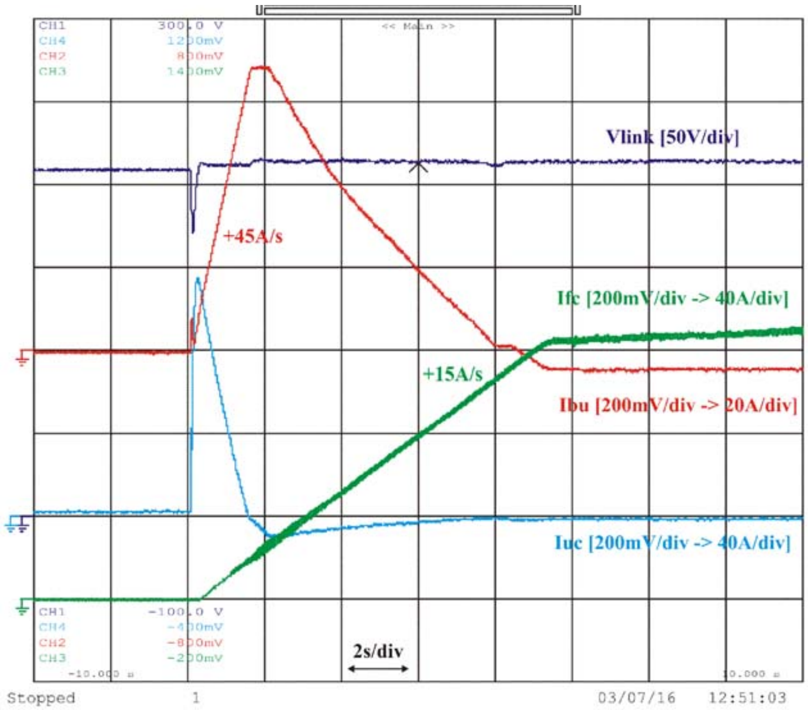

Fig. 10 MIPEC electrical quantities resulting from a step change of the output current from no load to load current of about 50 A (time scale: 2s/div): CH1, output voltage (scale: 50V/div); CH2, BU current (scale: 20A/div); CH3, FC current (scale: 40A/div); CH4, UC current (scale: 40A/div).

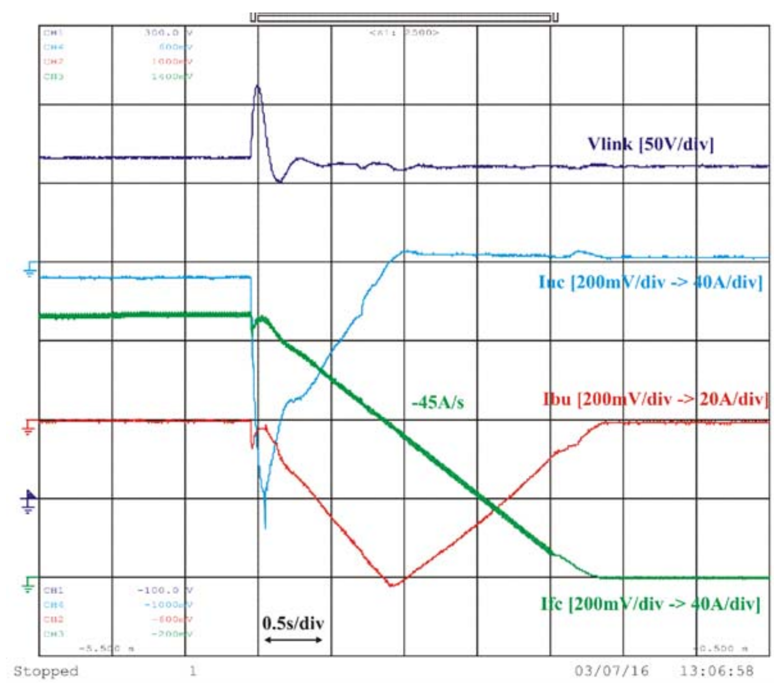

Fig. 11 MIPEC electrical quantities resulting from a sudden loss of 50A load current (time scale: 0.5s/div): CH1, output voltage (scale: 50V/div); CH2, BU current (scale: 20A/div); CH3, FC current (scale: 40A/div); CH4, UC current (scale: 40A/div).

Fig. 12 shows MIPEC input and output currents resulting from operation of the propulsion system along the urban ECE-15 driving cycle. Actually, in order to evaluate performance resulting from operation with a much heavier urban driving cycle than the original ECE-15, in the driving cycle used for experiments higher load acceleration transients were included. It should be noticed that the UC is actually required to operate during very short and severe accelerations and braking transients, whereas both BU and FC more gently adjust their output to load changes imposed by the driving cycle.

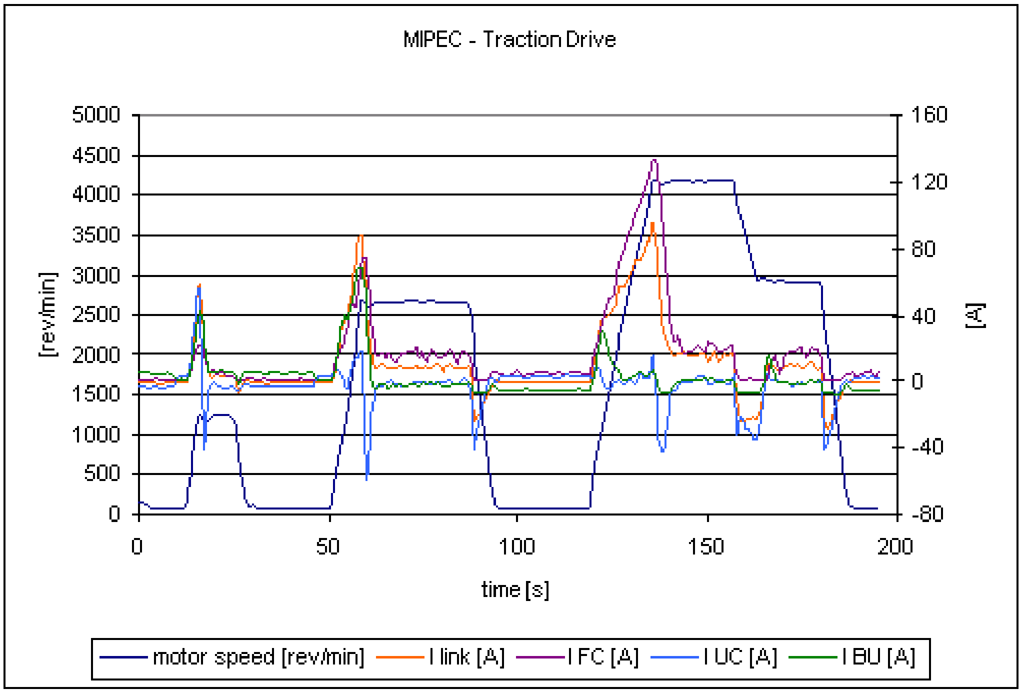

Fig. 12 Testing of the laboratory propulsion system over a modified urban ECE-15 driving cycle.

5. Use of Power Electronic Building Blocks in Automotive Applications

Improved packaging of the power electronics components and subsystems is expected to be one of the most active development areas because of the significant cost reductions that are achievable by modularizing the power electronics and automating its manufacturing. Wider acceptance of power electronics in automotive applications during coming years – both for traction and accessory applications – will likely provide a substantial boost for this trend by focusing the energies of the automotive industry on achieving these manufacturing economies.

A major barrier to further advancements in technology and required cost reduction of power electronics products is the striking lack of standardization, as the power electronics industry is often preoccupied with providing partial solutions for specified applications. The idea of a “building block” approach to power electronics design was conceived in the early eighties, influenced by the booming developments in the integrated circuit industry. The approach of constructing different power converters using a smaller number of integrated modules instead of discrete components was initiated by several power semiconductor manufacturers and proposed in some research laboratories. However, the initial attempts were mostly directed towards simplifying packaging of power converters and did not resulted in a complete shift of the design paradigm, as the concept of integrated circuits did in the signal processing industry.

The much more comprehensive concept of the Power Electronics Building Block (PEBB) originated in the nineties. The overall concept is to use intelligent and reconfigurable PEBBs with standardized power, thermal, and control interfaces to develop a multitudes of cost-affordable, reliable, and efficient power processing systems. In fact, unlike modern digital technology, which utilizes an array of developed components or cells to build a system, modern power converters still lack a high degree of integration and standardization. As a result, designers are often forced to build entire systems from scratch each time, which is costly in engineering time as well as system reliability. In order to remedy this situation, in the last decade the concept of PEBB has drawn considerable attention and major research centers are being investigating PEBB-based power converter arrangements devoted to a number of applications.

PEBBs are integrated power modules serving functions that would commonly be found in a wide number of power conversion systems. Depending on the type of energy conversion to be accomplished, the PEBB would be required to function as, for instance, a dc-dc converter, a voltage-source or current-source inverter, a synchronous rectifier, or a motor drive controller. The PEBB is envisioned to be scalable in the level of power processing and on-board intelligence. The goal of the PEBB development is to create a power-processing component that moves most of the design away from specific circuit topology consideration and moves up to a systems level power electronic switch and associated inductors, capacitors, and other ancillary components selection. In few words, the PEBB concept removes the low-level design problems and treats converters as a functional assembly.

As PEBB modules can be connected together to form several power system topologies, they would greatly reduce design efforts as well as would allow the achievement of increased system simplicity and reliability. The PEBB concept would also be the best choice for minimizing both the layout and packaging parasitics, as all the power semiconductor devices, control circuits, and busbar would be integrated together as a large power device. In addition, maintenance cost would be reduced as individual modules could be replaced easily and the number of stock spare parts would be reduced. Thus, the converter designer would be concerned most with information and control data flowing in and out of PEBBs and, in the larger power systems design, between PEBBs. This means that less specialty training in the field of power electronics would be required, thus opening the way for higher quality and efficiency, and increased use of power processing technology.

5.1 Low-Voltage Power Electronic Building Blocks [5]

Since the last few years at the Power Electronics and Drives laboratory of the University "ROMA TRE", Rome, Italy, investigation has been started concerning the potential use of the PEBB concept in low-voltage fed power converters, such as those being currently utilized in particular traction drives, such as fork-lift drives or wheelchair drives, or those being envisaged to be utilized on board automobiles together with a 42V electric power system. Concerning such specific vehicular applications, various power converter topologies having input voltage in the range from 24 V to 80 V and rating power from few kW up to 30 kW are likely to be used in order to accomplish bi-directional dc-dc or dc-ac power conversion. Thereby, the development of low-voltage PEBB (LV-PEBB) modules including standardized power, thermal, and control interfaces is expected to be of great interest for power converter manufacturers as it would lead to great simplification in converter design and assembly and thereby should allow substantial reduction of mass-production costs.

From a review of power converter topologies being used in fork-lift drives, wheelchair drives and 42V-fed automotive drives, such as starter/alternator systems and ultracapacitor-based storage systems, it was realized that the power section of the envisaged LV-PEBB should include a six-pack module based on MOSFET technology, temperature, current and voltage sensors, input and output filters. The six-pack module configuration was selected in order to form a 5-poles PEBB that, depending on both the specific type of power conversion application and converter power rating, would be used either as a single power converter or as a single “power switch” to be connected in parallel with other PEBBs for handling high current output.

As shown in Figure 13, further than a six-pack MOSFET module, in the proposed LV-PEBB a capacitor C_{PN} would be connected in parallel between the terminals P and N and a small-size inductor L_L would be connected in series with each of the other three PEBB terminals. Such inductors would allow that two or even all three switches of the same PEBB could be safely paralleled among them, as well as they would allow having two or more LV-PEBBs being connected in parallel among them to achieve a converter with higher power rating. Further to that, the inductors are responsible for limiting the time derivative of the phase current in case of short-circuits which are external to the LV-PEBB; besides, the proposed power electronics block includes software active protections for both over-current, over-voltage and over-temperature. The suitable combination of the protections’ operating time and phase inductor value makes possible a very small current de-rating for the power switches with respect to traditional power converter design.

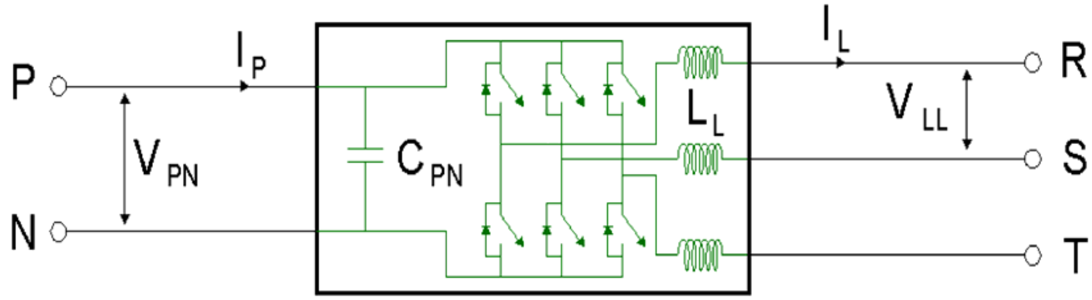

Fig. 13 Proposed LV-PEBB configuration

A simplified functional block scheme for the LV-PEBB being under investigation is shown in Fig. 14 in order to illustrate the concept of distributed control architecture. To the goal of minimizing the number of interconnections between the different control portions and in order to provide enough flexibility and modularity to the whole system, the control section of a generic power converter has been split into three subsections, such as: System Manager, Application Manager, Hardware Manager.

The System Manager (SM) would have control tasks being related to supervising the energy conversion overall system one or more LV-PEBB modules are part of, such as monitoring the entire process one or more electric drives are being devoted to. On the other hand, as a high-level application-related regulation device, the Application Manager (AM) would be intended to perform tasks such as either voltage and current control loops or speed and torque control loops of the power converter. As a consequence, the AM would process the main control strategy of the power converter itself, such as generating control reference signals, executing control loops and generating modulation pattern for determining the on state of the converter power switches.

The Hardware Manager (HM), which actually would be the core of the LV-PEBB control system, is intended to act as a local controller that would perform low-level hardware-oriented control tasks. To best perform such tasks the HM would be resident on the LV-PEBB itself and would be required to drive the LV-PEBB power circuitry. According to a given specific application the LV-PEBB would be used for and on the basis of the selected control strategy, the AM would provide the HM, in a digital form, the duty cycles to be applied to the power converter. Then, based on such inputs, the HM would adjusts the duty cycles in order to take into account the hardware characteristics of the LV-PEBB power circuit, such as providing the required blanking time, isolation of digital ground from analog ground, and so on.

Another important function the HM would be required to handle includes a software active protection of the LV-PEBB power switches against anomalous operating conditions resulting from over-current, over-voltage and over-temperature. In order to accomplish such a task the LV-PEBB would be equipped with transducers and sensors and thereby the HM would be required to perform processing of measured data including signal filtering and amplification, voltage level shifting and A/D and D/A conversions. Finally, the HM would also required to perform all the communication interfacing to the external world (either with the AM or with other PEBBs being used in the overall system) and thereby its circuit board should include the circuitry needed for handling the communication signals (i.e. serializer and deserializer, single-ended/differential converters, etc). As result of the various functionalities being required, the HM would be equipped with several components such as transducers and sensors, signal amplifiers and filters, ADCs and DACs, gate drivers and optocouplers, transmitters and receivers. Hence, in order to operate effectively each component would need stable and regulated supply voltage and thereby, starting from the main supply being available in the LV-PEBB module, the HM would be equipped with the necessary power distribution circuitry.

In a conceptual LV-PEBB prototype being under development, the HM functions are mainly accomplished by means of a Field Programmable Gate Array (FPGA), such as the Spartan-3 by Xilinx. The requirements for very fast programmable devices with moderate computational capabilities advise for a programmable logic IC rather than a Digital Signal Processor (DSP) or a microprocessor in order to perform the outlined functions. In fact, the HM is not called to elaborate complex control strategies and it has to be fast enough to protect the power switches against possible failure conditions.

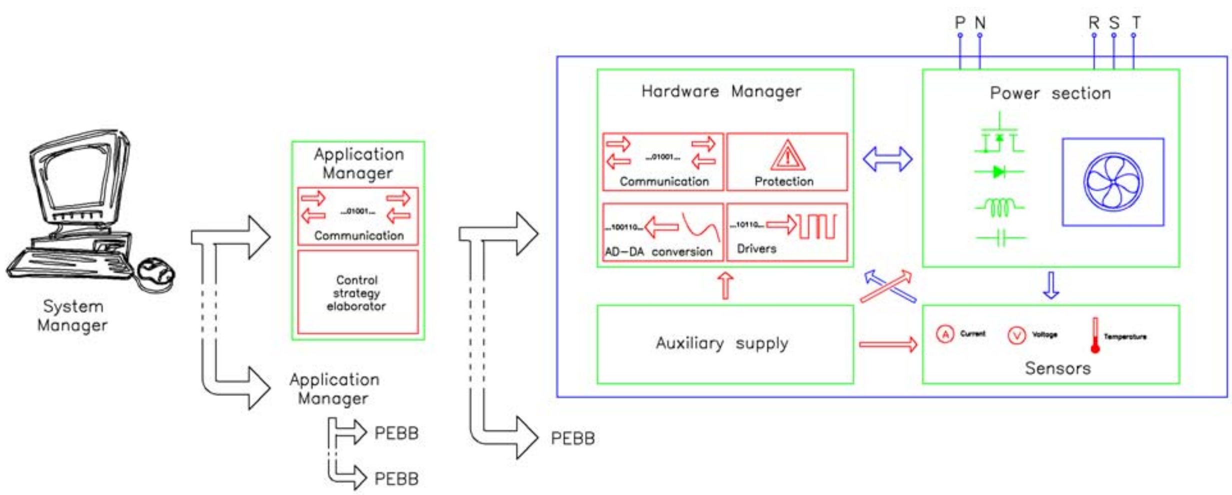

Fig. 14 Block scheme for a LV-PEBB based power converter system

Figure 15 shows the mechanical layout that has been developed for a LV-PEBB concept prototype being under construction. Such a PEBB prototype is equipped with a VWM340-0075 six-pack power module and uses a forced-air cooling system. The HM being used in this PEBB includes FPGA and PCBs suitably designed for data acquisition and for power circuit driving functions. This prototype will be used to evaluate electrical and thermal performance as well as to demonstrate the concept of distributed control architecture. Further attempts to reduce size and achieve higher integration of components will follow.

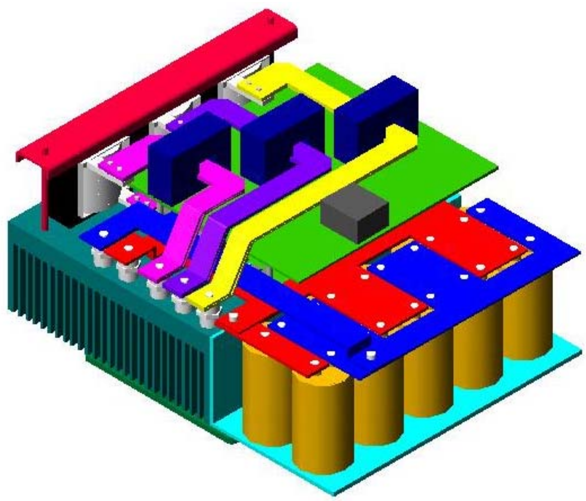

Fig. 15 Layout of a LV-PEBB concept prototype.

6. Conclusions

The last decade has witnessed significant advances in vehicle propulsion systems resulting from research developments in motor drives and power electronics. Continued improvements in the material properties and cost of rare-earth permanent magnets have opened great opportunities for more compact and efficient electric machines devoted to vehicle traction drives. In particular, since it has been made possible to achieve the machine torque densities required for the integration of the traction motor within a wheel rim, the availability of such wheel hub motors is leading to new concepts in the overall architecture of road vehicles, especially for those expected to use a fuel-cell fed power-trains.

On the side of energy storages being required in vehicle propulsion systems, the use of ultracapacitors in vehicular applications is expected to spread as fast as their cost will be reduced to an affordable level. Then, 42V ultracapacitor modules will probably be used in combination with electrochemical batteries for handling pulse power flows resulting from vehicle acceleration and braking transients, as well as for providing pulse power required in novel ICE-based drivelines that would use the start/stop function for avoiding ICE idling. For such combined battery-ultracapacitor energy storages bi-directional dc-to-dc power converters having acceptable compactness and cost will be necessary for use as power interfaces between storage devices required to have relatively low voltage rating and the dc input circuit of either the traction drive or the starter/alternator system that likely would be set at voltage level in the range from 250V to 400V.

Improved packaging of the power electronics components and subsystems is expected to be one of the most active development areas because of the significant cost reductions that are achievable by modularizing the power electronics and automating its manufacturing. Wider acceptance of power electronics in vehicle propulsion systems during coming years will likely provide a substantial boost for this trend by focusing the energy of the automotive industry on achieving these manufacturing economies. The application of the PEBB concept to power converters used in vehicle propulsion systems will probably be the way forward to achieve the reliability and cost being required for a wider acceptance of novel vehicle driveline arrangements.

Although specialized to the particular case of the research activities the Power Electronics and Drives laboratory of the University ROMA TRE, Rome, Italy, has been involved in the recent years, the advances outlined in this paper bear testimony to the significant effort that is being accomplished in applying motor drives and power electronics technologies to vehicle propulsion systems. The future of the novel arrangements expected for vehicle drivelines depends not only on advances in the technology but the economic and regulatory climate in which they are developing. Whether global concerns about transportation fuel economy and pollutant emissions levels will continue to increase during the coming years, there are many reasons to expect that the desire for further improvements in traction drives will place a high premium on advances in motor drives and power electronics technologies.

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