Grid Power Quality Improvements Using Grid-Coupled Hybrid Electric Vehicles with a Dual Energy Storage System

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Abstract

The paper discusses the use of a dual energy storage system based on batteries and supercapacitors in hybrid electric vehicles (HEV). The battery has a large energy density, enabling an all-electric driving range of 100 km, while the supercapacitor has a large power density and provides peak power during acceleration and regenerative breaking. The paper discusses the benefits and drawbacks of both storage systems and the specific requirements imposed by the hybrid drive train. Coupling such a HEV to the grid allows interaction between grid and HEV, providing the grid with a controllable load. Depending on the communication between the hybrid fleet and the grid, this load can be controlled by adjusting the electricity price in order to allow a higher penetration of intermittent renewable energy sources such as wind parks in the grid and if the communication allows the transmission system operator to reduce the load imposed on the grid by the hybrid fleet, the hybrid fleet can become part of the secondary frequency control reserve. In case of sudden demand or supply fluctuations, the hybrid fleet can assist in primary control of the grid. Due to the dual energy storage system the HEVs can also provide fast load tracking to keep the voltage in microgrids at the desired set point. An experimental setup with a battery, grid coupling and induction machine proves the feasibility of the concept.

Keywords: *HEV (hybrid electric vehicle), Li-ion battery, supercapacitor, grid coupling*

1 Introduction

As society becomes more aware of the problems associated with the use of fossil fuels, solutions are sought to reduce the emissions of vehicles. One possible solution is the use of hybrid vehicles, relying both on electric motors and internal combustion engines to propel the vehicle. While these vehicles have proven to be able to reduce emissions, further emission reduction, as far as the vehicle is concerned, can be achieved by implementing a sufficiently large battery that allows a certain all-electric range and is charged by electric energy from the grid. This requires a grid coupling that allows the charging of the battery. Furthermore this grid coupling allows the provision of certain services by the hybrid fleet to the grid, such as primary and secondary frequency control and the use of a large controllable load. In absence of the grid the HEV can be used as stand-alone generator or as part of a microgrid.

2 Energy storage in hybrid electric vehicles

2.1 Energy storage in batteries

Current hybrid electric vehicles (HEVs) mostly use NiMH batteries with a limited energy content of about 1 to 2 kWh. These batteries have a limited lifetime of about 1500 charge-discharge cycles with a 25 % depth of discharge [1]. To extend the lifetime of the battery to the lifetime of the vehicle, the depth of discharge (DOD) has to be limited considerably, resulting in no more than approximately 25 % of the total capacity being used. This makes the batteries currently used in HEVs expensive and heavy in comparison with their energy content.

The most promising technology to overcome the limited energy content of batteries is the Li-ion battery [1]. So far this battery has not been used in HEVs due to its high price per kWh, which is about one third more expensive per kWh than NiMH, and its limited lifespan, restricted to about 3 tot 5 years. One of the main problems that has to be addressed by the battery of HEVs is the high power/energy ratio. Whereas low power devices such as laptops use lithium cobalt oxide (LiCo) positive electrodes, these are not suitable for HEVs because their power/energy ratio is limited to 1. This means that a 15 kWh battery (see later) is only able to provide a continuous power of 15 kW, which is insufficient for a vehicle that is supposed to be able to drive in all-electric mode. Therefore batteries in HEVs are based on lithium manganese oxide (LiMn) cathodes. Due to its three-dimensional spinel structure these batteries have a lower internal resistance which enables fast charging and high-current discharging. The resulting power/energy ratio is 10, but the main drawback of this battery is the lower energy density of about 120 Wh/kg, whereas the LiCo battery can go as high as 190 Wh/kg. A compromise between the high energy density of LiCo chemistry and high power/energy ratio of LiMn is provided by nickel-cobalt-manganese (LiNiCoMn) and phosphate (LiP) chemistries. These batteries have an energy density of 120-140 Wh/kg, while the power/energy ratio is 5 for LiNiCoMn and up to 35 for LiP batteries. This makes the LiNiCoMn battery suited for all-electric propulsion using batteries starting from 10 kWh, while the LiP battery can provide all-electric propulsion using batteries starting from 1,5 kWh. We consider a vehicle capable of all-electric propulsion when it has sufficient power to drive solely on its batteries and electric motor both in city-traffic and on highways. An arbitrary minimal requirement concerning the amount of power required to do this is set at 50 kW.

Apart from the higher power/energy ratio, batteries such as the LiNiCoMn battery have the advantage of a higher thermal stability. These batteries are provided with safety mechanisms within the cell, such as a PTC-resistor and circuit interrupt device against current surges and safety vents against overpressure. Furthermore, battery packs are provided with an electronic circuit protection such as solid state switches that cut the current path of the battery pack if any individual cell is subjected to an overvoltage during charging or an undervoltage during discharging and a fuse that cuts the current flow if the skin temperature exceeds a certain limit, e.g. 90 °C. The combination of a high thermal stability, the inclusion of various safety mechanisms within the cell and an external electronic protection circuit ensure that these batteries are safe to operate in a HEV. The characteristics of the most important battery types for HEV applications are given in Table 1[1,2,3,4].

Table 1: Characteristics of various battery types

Battery type	Specific energy	Efficiency E_{in}/E_{out}	Lifetime (small DOD)	Cost	Self-discharge
	Wh/kg	%	Cycles	$/kWh	%/month
VRLA	30-40	75-90	> 1000	± 125	-
NiCd	50-55	70-85	1000-2000	± 300	20-30
NiMH	40-80	65	800-1500	± 300	30-35
Li-ion	110-160	> 90	2000-3000	± 400	3-5

Through the ongoing development of especially Li-ion batteries, the cost per kWh diminishes while the specific energy content rises. As a consequence, in the future larger amounts of energy can be stored in an economic way for the electric propulsion of HEVs and larger distances can be traveled in an all-electric “emission free” mode. An estimated 85 % of fossil fuel (not energy) savings can be achieved if the vehicle has an all-electric driving range of 100 km [8]. A HEV capable of driving 100 km (or 60 mile) in all electric mode is known as HEV60.

To attain this all electric driving range of 100 km requires at least 10 kWh of electric energy. Under the assumption that state of the art power electronics (96 % conversion efficiency) and batteries (Li-ion) are used, the energy efficiency of the battery system reaches 90 % with a DOD of 80%. Current Li-ion batteries would only last 400 to 500 charge-discharge cycles at this DOD, but future batteries should be able to reach longer lifetimes at this DOD. A battery of 15 kWh is thus required to compensate for the energy losses in the battery and converter and the limited DOD. Prototypes of this kind of vehicles already exist like the Mercedes Sprinter with a 14.4 kWh Li-ion battery. Like other batteries the number of charge-discharge cycles of the Li-ion battery is limited and depends amongst others on the depth of discharge (DOD) and the charge and discharge currents. With current technology this battery would weigh over 100 kg and cost at least 5000 €, which is too expensive to implement in existing HEVs. Within the next decade, energy density is expected to rise to 400 Wh/kg and specific costs should drop to 120 €/kWh. In that case the proposed battery would weigh only 38 kg and cost 1800 €.

An intermediate solution in expectation of a cheaper Li-ion battery could be found in molten salt batteries like the Zebra battery [5]. These batteries are already used in battery electric vehicles (BEVs) such as the Newton truck and Edison van of Smith Electric Vehicles and the electric version of the Smart currently tested in the UK. These batteries consist of a nickel based positive electrode and a molten sodium negative electrode with molten chloroaluminate ($NaAlCl_4$) as electrolyte. These batteries operate at 250-350 °C. A standard battery pack of 0,13 m^3 weighs 195 kg and operates between 186 and 278.6 V. The peak power of such a standard battery pack is 32 kW, which is insufficient for any speed above city traffic, but the energy content is satisfactory at 16,2 kWh for high current discharges. This example demonstrates yet again the difficulties concerning a sufficiently high power/energy ratio. Another problem associated with these batteries is that they require to be left under charge, in order to keep the battery temperature high. If shut down, a reheating process must be initiated that may require up to two days to restore the battery pack to the desired temperature, and full charge.

2.2 Energy storage in supercapacitors

A second element for energy storage is gaining interest in transport applications: the supercapacitor [9]. Supercapacitors consist of activated carbon electrodes separated from each other by a separator and an electrolyte. The electrolyte generally contains an organic solvent and a salt that supplies the ions for the energy storage. Energy storage in supercapacitors is based on the accumulation of electrical charge by electrostatic forces in the double layer between the activated carbon electrodes and the ions of the electrolyte. The stored electrical energy is based on the separation of charged species in an electric double layer across the electrode/electrolyte interface.

The supercapacitor is best suited for applications requiring a high power density. Furthermore the supercapacitor has a lifetime of several hundreds of thousands of charge-discharge cycles and a high efficiency due to its low equivalent series resistance (ESR). The drawback of the supercapacitor is the low cell voltage, which is limited to 2.5-2.7 V. This necessitates the series coupling of several tens of cells in a supercapacitor stack to obtain a useful voltage. In order to limit overvoltages on individual cells, the stack is equipped with a voltage balance circuit. High-duty cycle applications, such as a HEV driving in city traffic where frequent acceleration and braking can be expected, necessitate the use of an active balancing circuit in order to ensure a fast and accurate equalization of the cell-voltage distribution. At the same time the active cell balancing minimizes parasitic losses in the balancing circuit. The drawback of the active balancing circuit is its higher cost compared to passive balancing circuits. A second drawback of the supercapacitor is the decrease of the voltage when the stack is discharged. Typically the stack is discharged until the voltage reaches half of the nominal value. The consequence is that only 75 % of the maximal energy content can be utilized. The third drawback of the supercapacitor is the fast self-discharge, resulting in a useful energy content of approximately 40 % of the maximal energy content after one day.

The supercapacitor has a very low energy density compared to batteries. The energy density for supercapacitor modules, including the casing, protection and balancing equipment, is limited to 3-4 Wh/kg, but the power density reaches 2-3 kW/kg, which is a 3 to 4 times better than Li-ion batteries optimized for energy storage. Although the power density is only 3 to 4 times larger than batteries, supercapacitors are capable of delivering the high currents associated with these power bursts several hundreds of thousand times, while these power bursts would be very detrimental for the lifetime of batteries. A good example of the usefulness of supercapacitors in HEVs would be the high power fluctuations associated with the frequent acceleration and regenerative braking of the vehicle in city traffic. As before, we require 50 kW of power to drive the vehicle. This power could be delivered for instance by two series coupled Maxwell BMOD0145 P048 modules. Operating between 96 and 48 V, these modules could deliver or receive 50 kW during more than 6 seconds. During acceleration this allows the battery to smoothly adopt to the new required power output, while during regenerative braking the battery does not have to cope with high charge currents. The maximal energy content of the 27 kg series connected modules is 94 Wh, enough to absorb the kinetic energy of a 1300 kg vehicle driving at 80 km/h.

Even more promising are the hybrid charge-storage devices in which a faradaic, rechargeable battery-type electrode is combined with a non-faradaic, double layer type of electrochemical capacitor electrode [6][7]. These asymmetric supercapacitors have the charge storage mechanism of a battery at one electrode, such as a PbO_2, NiOOH or $Li_4Ti_5O_{12}$ electrode, and that of an activated carbon electrode at the other electrode. Proper dimensioning of the electrodes and the use of low-resistance organic electrolytes such as acetonitrile allows a compromise between the power density of the activated carbon electrode and the energy density of the rechargeable battery-type electrode. These asymmetric supercapacitors have a flatter voltage profile than symmetric supercapacitors, using two activated carbon electrodes, due to the higher charge acceptance per mole of the battery-type electrochemical reagents. This flatter voltage profile, e.g. going from 3 V at full charge to 2 V at 80 % depth of discharge, makes it easier to design a DC/DC converter that is able to transform the descending voltage of the asymmetric supercapacitor into an appropriate DC voltage for the DC-bus voltage. This flatter voltage profile also results in a higher specific

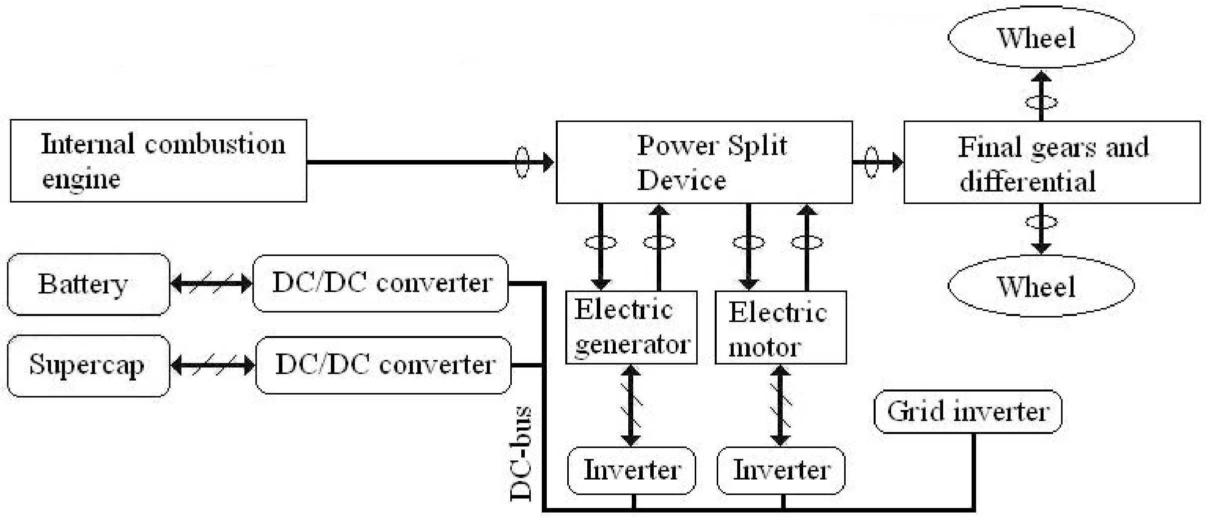


Figure 1: Diagram of a series-parallel hybrid with dual battery-supercapacitor energy storage and grid coupling

energy density for the asymmetric supercapacitor compared to the symmetric supercapacitor. At 80 % efficiency, these asymmetric supercapacitors have an equal power density compared to symmetric supercapacitors of approximately 1 kW/kg, while their energy density is about two times higher; 9 Wh/kg for the asymmetric supercapacitor compared to 4 Wh/kg for the symmetric supercapacitor. Besides the higher energy density and the flatter voltage profile, a third benefit of the asymmetric supercapacitor is the lower self-discharge, retaining 80 % of its original capacity after 200 hours. The main drawback of the asymmetric supercapacitor is the limited lifetime, which is expected to be around 10.000 charge-discharge cycles. After these 10.000 charge-discharge cycles the remaining energy density is approximately 80 % of the original energy density.

As of today only asymmetric supercapacitors using an aqueous electrolyte are commercially available. Due to the use of the aqueous electrolyte, the cell-voltage is limited to 1,5-1,7 V. Compared to symmetric supercapacitors using an aqueous electrolyte their energy density is 3-4 times greater, but compared to symmetric supercapacitors using an organic electrolyte and operating at 2.5-2.7 V they lack sufficient energy and power density.

2.3 Dual energy storage

Rather than limiting the energy storage in HEVs to batteries, much benefit can be expected from a dual energy storage system compromising batteries and supercapacitors. Due to its limited energy storage, the supercapacitor is unable to replace part of the battery, so the HEV60 still requires a 15 kWh Li-ion battery. As stated before, two series coupled Maxwell BMOD0145 P048 modules would be complementary with the battery. The supercapacitors are able to absorb and deliver the power peaks associated with the driving of the vehicle and in this way they are able to reduce the wear and tear of the battery. Due to the different voltage profiles during charging and discharging and the different nominal voltages of the battery-stack and the supercapacitor modules, both require a separate DC/DC converter to be coupled to the common DC-bus. A possible layout of a HEV is pictured in Figure 1.

3 Interaction between grid and hybrid electric vehicles

3.1 Grid coupling

Vehicles are found in vast numbers around the world. In industrial countries the combined power of all cars largely exceeds the installed electric power in power plants. Vehicles for personal transportation are at standstill for more than 95 % of the time on average. Even in situations where “everbody” is caught in traffic, 90% or more of the vehicle fleet actually is not on the road. This indicates that vehicles in theory are available for grid coupling during most of the time. In order to charge the battery and to ensure the interaction between the grid and the hybrid fleet, the grid coupling is dimensioned at 10 kVA. This is based on a regular 230 V/40 A single-phase grid connection. The grid coupling costs about 300 € and enables people to charge their vehicle at home [10][11].

3.2 Interaction 1: Battery charging and controllable load

As an example of the impact of a fleet of hybrid electric vehicles on the grid we consider Belgium. The Belgian fleet of vehicles consists of about 5 million vehicles, each traveling 41 km a day on average. A situation is assumed where the hybrid vehicles drive in all-electric mode as much as possible to minimize the use of fossil fuels. Maintaining some reserve and taking into account the losses in the grid and the energy conversion losses, an average of 6 kWh a day is required for each car. Multiplied by 5 million cars this gives a total energy consumption of 30 GWh a day. Such an amount of electrical energy cannot be supplied to the grid at random as an additional load without causing overloads.

Therefore, the vehicles are best charged at night, when the grid load is less and electric energy prices are down. In Belgium the night rate lasts 9 hours, resulting in an average power of 3400 MW when all vehicles are charged overnight. Thereby the overnight power consumption by the vehicles raises the overnight base load to a level comparable with the daytime base load.

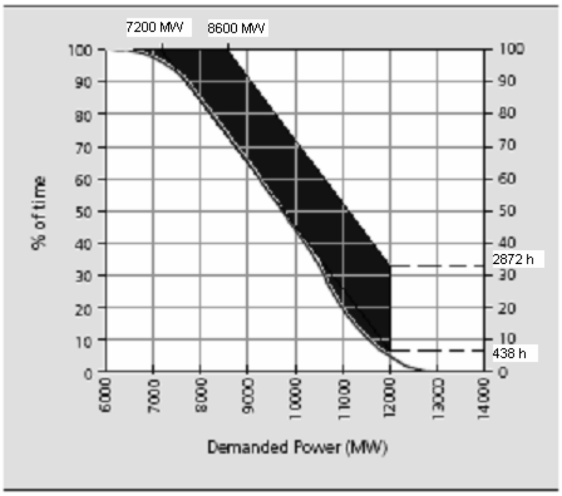
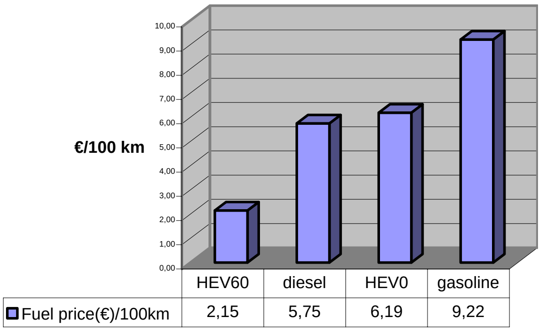


Figure 2: Load increase due to battery-charging of plug-in hybrid electric vehicles

The resulting load transition caused by the fleet of hybrid electric vehicles is pictured in Figure 2. When the load curve is moved in parallel with the current load curve and taking into account a maximal generation of 12.000 MW, then the black zone is obtained. This black zone represents the annual energy consumption of the hybrid fleet. In theory, this energy can be delivered with the existing grid and power stations, but the base load rises from 7200 MW to 8600 MW and during one third of the year a relatively large power of 12.000 MW has to be delivered. This additional base load calls for a shift in the generation unit technology, because with the higher utilisation the cost effectiveness of a power plant shifts. From an economic point of view, it now becomes more attractive to build a base load plant. A base load plant of 1400 MW with a utilisation of 85 % has an annual energy production of 10 TWh, matching the energy consumption of the hybrid electric fleet.

In Europe, where fuel is expensive and electric energy relatively cheap, driving electric would be financially attractive. First we have to make a distinction between HEV0 and HEV60 vehicles. These vehicles both have a dual petrol-electric propulsion, but the battery of the HEV0 is not designed to drive the vehicle on its own, whereas the battery of the HEV60 is capable of driving the vehicle solely on electric propulsion for 60 miles or 100 km. Such a HEV60 can run in all electric mode for 85 % of the time. If the fuel cost of both hybrid electric vehicles is compared to those of conventional diesel and gasoline powered cars (Figure 3), it becomes obvious why HEV0 vehicles like the Toyota Prius have such a low market penetration in Europe compared to diesel vehicles, but it also shows the benefit of the HEV60: after 10 years and an annual traveling distance of 15.000 km, the discounted value of the difference between the conventional car and the HEV60 amounts to more than 4500 €. This clearly indicates that the difference between conventional cars and hybrid electric vehicles can be partially compensated by the lower energy cost.



	HEV60	diesel	HEV0	gasoline
■ Fuel price(€)/100km	2,15	5,75	6,19	9,22

Figure 3: Fuel cost per 100 km for different vehicle types.

By implementing the necessary telematics in the grid coupling, the charging of the battery can be controlled by the electric energy price [8]. One possible solution is that one central server is connected to the HEVs of one or more low voltage feeders. Each car has its own demand profile, linking the electricity price to a certain amount of electric power used to charge the battery. These servers aggregate the demand curves of the HEVs connected to them and are connected to higher-level servers. Furthermore these low-level servers take into account the limitations posed by the distribution grid, such as the power ratings of the low voltage distribution grid and of the medium voltage distribution grid feeding the low voltage transformers. Based on the aggregated demand curves of the different servers, an equilibrium price is calculated, which is send back to the servers and the HEVs. The equilibrium price of the electricity is transmitted to the onboard controller, which controls the amount of power supplied through the grid coupling. When a shortage of electrical energy is imminent, the equilibrium price will rise, which stimulates the controller to charge the battery at a lower power level or postponing the charging to a later moment. If the price lowers afterwards, the controller can increase the power used to charge the battery. The amount of power extracted from the grid depends on some parameters imposed by the driver; minimal range, distance and time of departure of the next trip and maximum price of the electric energy for charging the vehicle. In this way the controller can decide to partially charge the battery to provide only the minimum range when prices are high, whereas the controller can decide to fully charge the battery when prices are low.

This controllable load is very interesting to balance supply and demand in a grid with a high penetration of renewable energy sources. These forms of supply have a stochastic (but predictable on the short term) generation profile, so balancing supply and demand can only be attained by a load reacting on the change in the supply. With a grid coupling capable of extracting 10 kW from the grid, only a relatively small number of cars is necessary to absorb the power generated by e.g. a wind park. In 2004 Germany had an installed capacity of 16.629 MW of wind turbines and 45 million passenger cars. To absorb the entire power production of these wind turbines, only 3,7 % of the vehicles is required to be grid coupled. The annual energy generation of these wind turbines (25 TWh in 2004) can be absorbed by the hybrid fleet if 60 % of all vehicles became HEV60, proving that a large controllable load such as a hybrid fleet can deal with both the power and the energy of a grid with a high penetration of renewable energy sources.

3.3 Interaction 2: services provided by the hybrid electric fleet to the grid

3.1.1 Service 1: Reactive power

The power electronic converter enables the conversion of the alternating current of the grid to the direct current of the battery. The power electronics on the grid side can deliver reactive power, independently from the exchanged active power as long as the total apparent power does not exceed the 10 kVA maximum, and without a negative impact on the service life of the battery, using only the power electronics of the grid interface. Currently, this delivery of reactive power is forbidden for distributed generation units, but in the future it can become a necessity. The power factor of the installation can be improved when the grid coupling acts as a small Statcom, providing the reactive power other loads need. This is not important for domestic users, but may be for commercial users.

3.1.2 Service 2: Primary and Secondary Control

Hybrid vehicles can also be put in service to deliver reserve power on (very) short notice in order to keep the frequency on the target value by maintaining balance between supply and demand in the grid (control area) or for an individual access responsible party. This reserve must be able to put power on the grid at very short notice, usually after the loss of a large power station, wind energy fluctuations or in the event of large load changes. Preferably the primary and secondary control is performed by large power stations, because the electrical energy supplied by HEVs isn't economically competitive with the electric energy supplied by large power stations. In extreme situations where frequency control cannot be achieved by lowering the demand, e.g. the HEVs act as controllable load and stop absorbing electric energy from the grid, further action is required. When the frequency falls below 49,8 Hz, the HEVs should be obliged to take part in the primary and secondary control, supplying electric energy to the grid in order to prevent black-outs. In this case the dual energy storage system can prove its value by using the quick response time of the supercapacitors to aid in the primary frequency control. If the disturbance lasts no more than 30 seconds, the hybrid fleet will only deplete its supercapacitors. This means that disturbances limited to 30 seconds, which is considered the timeframe of primary frequency control, can be resolved by using the proposed supercapacitors and do not result in extra wear of the battery. For secondary control the batteries are used, but this should only be done in emergency situations, due to the high costs associated with using the batteries to supply power to the grid (see service 3).

When the HEV fleet is able to act as a controllable load, as discussed before, it should be considered as negative spinning reserve, which provides capacity that can be switched off quickly to compensate a fluctuation in energy demand. If the communication between the HEV and the servers is extended such that the transmission system operator (TSO) can reduce the load on request, the HEV fleet actually becomes part of the secondary frequency control reserve.

To illustrate the potential of HEVs: assume that the loss of a large power station (1000 MW) has to be compensated for 4 hours: If a vehicle is capable of delivering 5 kWh, half of the capacity of the proposed battery, it can provide 10 kW of power during half an hour. To provide 1000 MW 100.000 cars have to be grid coupled and after 4 hours a total of 800.000 cars has been used. This would be particularly interesting for countries with limited interconnection capacity like the UK. With a total of 27 million cars, only 0,4 % of the cars has to be connected simultaneously, in total requiring only 3 % of the fleet to provide the 1000 MW for 4 hours. It has to be stressed that the situation in this example goes beyond primary and secondary control, the latter typically lasting no more than 15 minutes.

3.1.3 Service 3: Peak-shaving

A hybrid electric vehicle can deliver electric power for peak shaving to the grid by injecting power from the battery or by producing electric energy with the onboard generator driven by the internal combustion engine (ICE). Neither option is economically viable. The battery could be charged at night rate (±0,1 €/kWh) and deliver power during daytime, but the high cost of the battery (5000 €) and the limited number of charge-discharge cycles (±500 cycles at 80 % DOD, a few thousand cycles at 30% DOD), increases the price of the stored electricity by approximately 0,5-1 €/kWh, augmenting the total cost of the electricity to 0,6-1,1 €/kWh, far higher than the normal daytime rate.

Table 2: Fuel cost of electricity generated by the combustion engine

fuel type	energy density	generation efficiency	fuel cost	electricity price
	Wh/l		€/l	€/kWh
Diesel	10700	0,4	1	0,234
Heating oil	10700	0,4	0,5	0,117
Biodiesel	9844	0,4	0,5	0,127
Biodiesel	9844	0,4	1,2	0,305
Petrol	9700	0,286	1,25	0,451
Ethanol (E85)	6100	0,315	0,4	0,208
Ethanol (E85)	6100	0,315	1,31	0,682
LPG	7000	0,295	0,5	0,242
CNG (in -/kg)	12100	0,311	0,67	0,178

In Table 2 the price of electricity is calculated for different types of fuel, when the ICE is used to drive the onboard generator [12]. For biodiesel and ethanol, the prices are very different depending on the source (waste, feedstock,…), size of the production facility, tax regulation and so on; therefore both are calculated with a low and high price. The electricity prices range from 11,7 to 68,2 c€/kWh, which is substantially more than industrial customers and most domestic costumers have to pay. Both options become interesting when they can replace the existing peak power plants used only a few hundred hours a year employing expensive fuel, although this idea has to be investigated further to make the peak power plants dispatchable. As discussed in 3.1.2 this would ask for an extension of the communication to allow the TSO to communicate with the hybrid fleet.

3.1.4 Service 4: Additional services, independent from the grid

Besides the delivery of electrical energy in competition with grid supplied energy, the hybrid car can also deliver electric energy in absence of the grid. They can perform as mobile generators on construction yards or remote locations and as back-up generator in case of a black-out, avoiding the acquisition of a separate generator. Thanks to the optimised energy efficiency and strict emission regulations (certainly in Europe) for car engines, they perform with greater efficiency and lower emissions than current small power generators. An additional benefit of vehicles is the high mobility, so they can be used as temporary solution when other kinds of distributed generation are not available in time.

Besides the true stand-alone applications, hybrid electric vehicles can play a vital role in microgrids [12], e.g. when part of the grid has been isolated. In this microgrid one or a few DG units use a voltage/frequency (Vf) control scheme, thus providing the reference voltage for the microgrid. Other DG units use an active and reactive power (PQ) control scheme or, more commonly, an active power and voltage (PV) control scheme. The DG units equipped with Vf control are essential for the stability of the microgrid since there is no grid voltage available for reference. This Vf control does not only depend on the applied control scheme of the power electronic interface, but also a suitable sized storage should be included on the DC bus to insure fast response to any power change. The hybrid electric vehicle equipped with a dual battery/supercapacitor energy storage system fits this profile, with peak powers and fast load tracking delivered by the supercapacitors, delivering the 10 kVA power rating of the grid coupling in milliseconds, while the batteries can smooth out lower frequency load changes.

The fast response of the dual energy storage system ensures a more stable microgrid voltage and enables fast load tracking. Other DG units such as diesel generators, stationary fuel-cells and microturbines have a reaction time in the order of seconds, which is too slow for many loads. If the vehicle is located outside, the ICE can be used to produce electrical energy to recharge the battery and to provide long term supply, since a grid connection delivering 10 kW consumes approximately 2,4 l diesel or 3,6 l gasoline hourly. As stated before (Table 2) the electrical energy thus provided is rather expensive.

4 Experimental implementation

The experimental setup (Figure 4) consists of 2 power electronic converters [13], a battery, a three-phase induction machine used both as generator and as motor and finally a DC machine used as load or to simulate the combustion engine that drives the generator. The induction machine and DC machine are displayed on the left, the battery in the lower right corner and the grid connection centrally on the right. The converters are connected back to back by connecting their capacitors and both consist of four half-bridges using IGBTs. One converter is coupled to the induction machine through 3 half-bridges, the other uses one half-bridge for the buck-boost connection with the battery and two

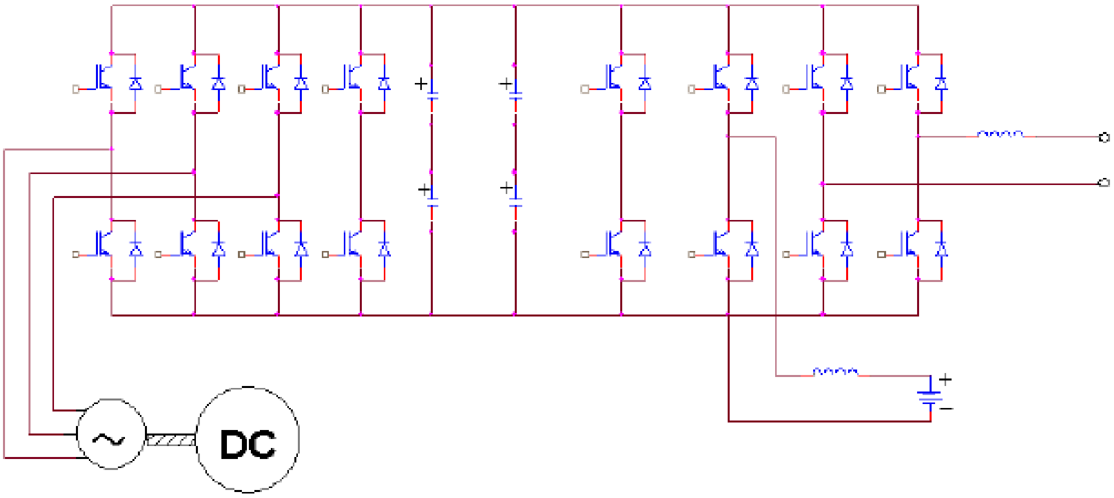


Figure 4: Scheme of the experimental setup

half-bridges for the grid connection. One half-bridge on both converters is not used. The remaining half-bridges can be used for the connection with the supercapacitors, but so far this has not been implemented.

The control of the induction machine is based on the stator frequency (scalar control); the induction machine works as a motor or generator respectively when the stator frequency is above or below the speed of the DC machine. When the induction machine is in motor mode, the torque can be controlled, when the induction machine is in generator mode, the delivered power can be controlled. The control of the grid connection enables a bidirectional energy flow: from the grid to the DC-bus to keep the voltage of the DC-bus at 400 V and from the DC-bus to the grid to deliver a controllable amount of active and reactive power. A bi-directional energy flow between battery (18*12 V) and DC-bus is established through a buck-boost connection. In the boost mode the control scheme keeps the DC-bus voltage at 400 V, in the buck mode the battery is charged.

Table 3: overview of the different modes of energy flows

	M 1	M 2	M 3	M 4	M 5
Induction motor	x				
Induction generator				x	x
Battery charging			x	x	
Battery discharging	x	x			
Grid as load		x			x
Grid as supplier			x		

The control scheme was built in Matlab/Simulink. This control scheme is downloaded on a DSP, which is connected to a FPGA, controlling the switching of the IGBTs of both converters and provides the interface with current and voltage measurements. The control scheme allows experiments in 5 different modes (M1-5). A summary of the modes is given in Table 3.

Every mode represents a different application of the grid coupled hybrid electric vehicle. In the first two modes, the battery is discharged to supply power to the electric motor simulating the vehicle while driving or to supply power to the grid. In the third and fourth mode, the battery is charged with respectively energy from the grid and from the onboard generator. In the fifth mode the onboard generator is used to directly supply power to the grid, simulating the use of the HEV as mobile generator. Thanks to the external mode of Matlab/Simulink online changes in power can be achieved, thus testing the dynamic response of the setup. During tests all modes performed well, proving the technical feasibility and the promising possibilities of the interaction between hybrid electric vehicles and the grid.

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