ISSN 2032-6653

Peak Power based Fuel Cell Hybrid Propulsion System

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Hybrid electric propulsion systems are interesting solutions to increase the energy efficiency of the road transportation technology. In this paper, several series hybrid propulsion system topologies are analysed in the Vehicle Simulation Programme (VSP). Especially the use of a DC/DC converter connected between the DC-bus and a energy source like a battery or the fuel cell stack, the supercapacitor or both are investigated together with its control algorithms in the validated VSP model. Both the advantages and drawbacks of the different topologies are presented. On the basis of experimental results, the proposed power management control strategy is also validated, which can ensure the main power supply (e.g. fuel cell) only providing the moving average power.

Keywords: Supercapacitor; Converter; Controller; Modelling and Simulation

1. INTRODUCTION

The results presented in this paper are based on a powerful simulation tool and experimental results. The Vehicle Simulation Programme (VSP) is a modular user-friendly interactive programme that allows simulating the behaviour of electric (battery, hybrid and fuel cell) as well as internal combustion vehicles (petrol, diesel, CNG, etc.). The model has been validated. The comparison of both simulated and measured parameters demonstrates a good correlation. The relative error is less than 5 % [1].

The validated model of the battery electric passenger car power system has been adapted to a series hybrid propulsion system with a supercapacitor pack and a fuel cell system. The component simulation models are described in [2].

2. THE ROLE OF THE SUPERCAPACITOR

The Series Hybrid Propulsion System (SHEV) can be presented by Fig. 1. The main energy management strategy can be summarized as follows:

The main power supply system (e.g. fuel cell) provides the mean power for driving. This power does not have to be constant but corresponds to a slow moving average.

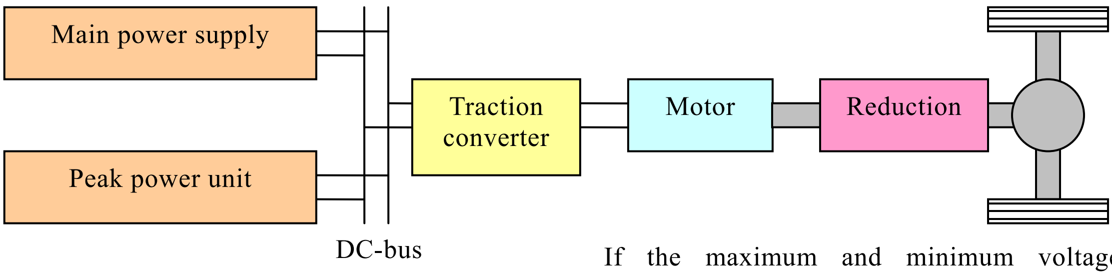

Fig. 1 SHEV with peak power unit

The Peak Power Unit (PPU) (e.g. supercapacitor based energy storage system) delivers the remaining required peak power for accelerating or regenerates the braking power.

Assuming the mass of a passenger car (M) is 1.2 ton and the speed of the passenger car (v) is in the highest speed 90 km/h (in this example of a small city car), the kinetic energy of this car can be calculated on the basis of equation (1).

$$E_{kin} = ½\ Mv^2 = 375\ [kJ] = 104\ [Wh] \tag{1}$$

Neglecting all driving losses (transmission, aerodynamic drag, rolling resistance, etc.), this kinetic energy can be stored in a supercapacitor energy storage while braking. If C is denoted the capacitance of the supercapacitors, and U is denoted the rated voltage of this energy storage, then the stored energy can be expressed by equation (2).

$$E_{cap} = ½\ CU^2 \tag{2}$$

If the maximum and minimum voltages of the supercapacitors are U_{max} and U_{min}, then the exchanged energy in the supercapacitors can be expressed in (3).

$$\begin{aligned} E_{cap} &= ½\ CU^2_{\max} - ½\ CU^2_{\min} \\ &= 443\ [kJ] = 123\ [Wh] \end{aligned} \tag{3}$$

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In the presented analysis the supercapacitor pack consists of 70 series connected cells with a nominal voltage of 2.5V and a capacitance of 2700 F each, resulting in a stack capacitance of 38.6 F. In order to efficiently use the supercapacitor, the voltage variation of the supercapacitor pack can be specified to be between 100% and 50% of its nominal voltage (e.g. 175V in the presented example). This corresponds to 75% of the energy storage capacity of the supercapacitor. This example shows that in this case the supercapacitor is big enough to store the regenerative braking energy when reasonably decelerating from 90 km/h[1]. Hence the energy management system must take into account that the capacitor should be 50% discharged at high speeds to allow recuperating the braking energy and charged at stand still to be able to deliver the acceleration power.

Next to the kinetic energy the supercapacitor can also be used to store potential energy (E_{pot}), e.g. while driving downhill. Equations (4) and (5) shows that with the capacitor pack one can drive downhill with an altitude difference (h) of almost 40m (when neglecting all driving losses). This result illustrates the restrictions of supercapacitors. For driving in a hilly environment other energy storage systems, like batteries, are more appropriate.

$$E_{pot} = gMh \tag{4}$$

$$h = \frac{E}{gM} = 38\,[\mathrm{m}] \tag{5}$$

3. VEHICLE SIMULATION PROGRAM RESULTS

In this section the usefulness of a supercapacitor pack as peak power unit will be further described on the basis of some simulation results.

Several topologies for the power system (consisting of a main power supply and a peak power unit) are possible and are investigated by the use of the Vehicle Simulation Programme (VSP). Both the advantages and drawbacks of the different topologies are highlighted.

One can consider two main approaches:

1. The topology with peak power unit that is based on a parallel configuration of the supercapacitors, connected to the DC-bus through a dedicated DC-DC converter. The converter allows a power flow control, optimising the global propulsion system efficiency and its dynamic performances. This feature enables braking energy recuperation into the peak power unit. However a very high efficiency of this converter is required. A Bi-directional zero voltage switching (ZVS), quasi-zero current switching (Quasi-ZCS) resonant converter would be a good solution to reach this high efficiency.
2. In a second configuration the supercapacitor is directly coupled to the DC-bus. A high efficient DC-DC converter connected to the supercapacitor is hence not required. It is a cheaper solution. However the amount of energy stored in the supercapacitor depends of its voltage. For optimal usage the supercapacitor as a peak power unit the DC-bus voltage should not be kept constant. The DC-bus voltage can be controlled by the DC-DC converter connected to the fuel cell. However when the DC-bus voltage is low the available power for traction is also small. This control strategy would reduce the acceleration performance of the vehicles propulsion system.

The topologies for the power systems are implemented in the Vehicle Simulation Programme to evaluate the overall efficiency of the different propulsion system. The VSP simulation tool, developed, in the LabView® graphical program environment, is used to analyse different propulsion system topologies and control strategies of a peak power unit in the series hybrid electric vehicle (SHEV) propulsion system.

Fig. 2 shows the modular configuration of the VSP simulation model of the series hybrid electric drive train. A case structure allows the selection of the different topologies: peak power unit with or without DC-DC converter and energy source with or without DC-DC converter. A 1.2 ton passenger car, from the example of previous section 2, is simulated. The fuel cell stack delivers up to 10kW and the supercapacitor consists out of 70 series connected cells with a nominal voltage of 2.5V and a capacitance of 2700 F each. The DC-DC converter connected to the supercapacitor has an efficiency of 95% and the DC-DC converter connected to the fuel cell has an efficiency of 90%.

The ECE-15 drive cycle is used as the reference speed cycle for the simulations. The control strategy of the peak power unit was investigated, by means of the VSP simulation tool. A maximum power variation of the fuel cell was set to 200 W/s. When no peak power needs to be delivered by the supercapacitor, it is charged by the fuel cell with a power of 500 W.

[1] In the example the vehicle has a front drive system. For high braking power only a part of the braking energy can be regenerated since the electric motor is only connected to 2 wheels. The mechanical brakes will assure a safe braking on the 4 wheels together.

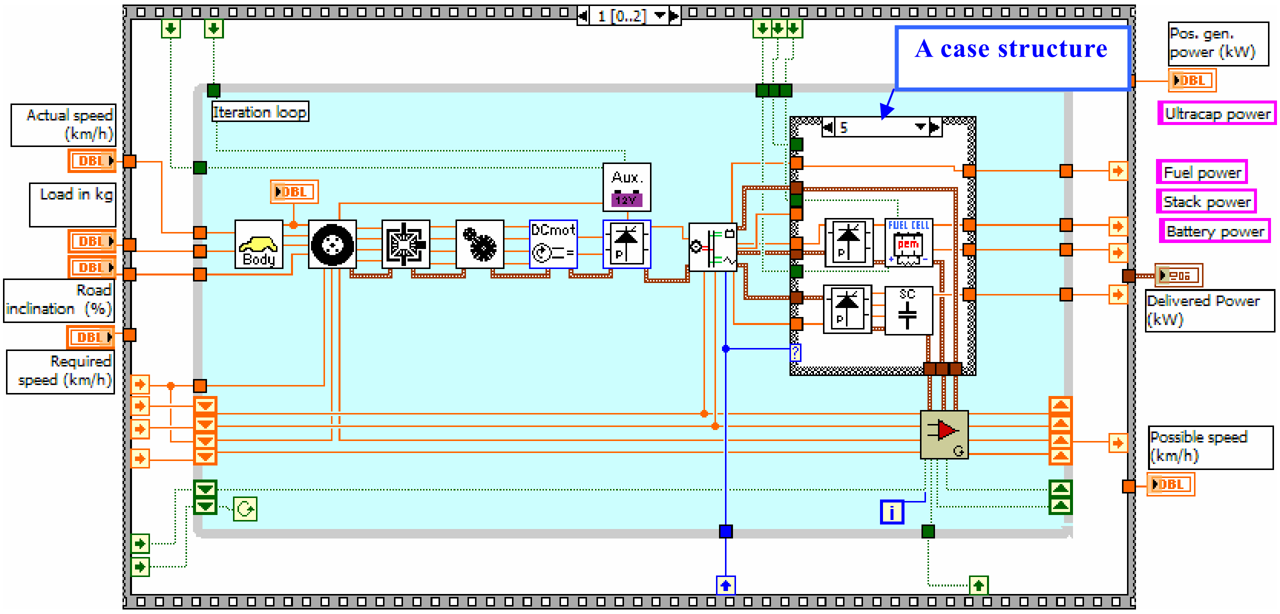

Fig. 2 SHEV drive train model in VSP with two DC/DC converters in this case [3]

Fig. 3 shows the simulation results of the power flow in the different components of the series hybrid fuel cell and supercapacitor topology with two DC-DC converters (one connected to the fuel cell and one connected to the supercapacitor). Ptrac is the required traction power, Pdcdcsc is the power delivered by the DC-DC converter connected between the DC-bus and the supercapacitor, Pdcdcfc is the power delivered by the DC-DC converter connected between the DC-bus and the fuel cell system, Psc is the power delivered by the supercapacitor and Pfc is the power delivered by the fuel cell system.

One can recognise the start-up of the fuel cell the first 7 seconds. Next a constant power of 1500 W is delivered by the fuel cell (Pfc) to charge the supercapacitor with a power of 475 W (Psc). This corresponds to 500 W delivered by the DC-DC converter of the supercapacitor (Pdcdcsc) minus the power consumed by the vehicles' auxiliaries. After 11 seconds the vehicle starts accelerating. The fuel cell output power is slowly increasing with 200 W/s. The remaining power for acceleration is delivered by the supercapacitor. From 15 seconds the vehicle is driving 15 km/h constant speed and the supercapacitor is charged again. At the time of 23 seconds the vehicle starts braking. The regenerative braking energy is recuperated into the supercapacitors with a high charging power (Ptrac). From 28 seconds the vehicle is standing still again. The fuel cell power is further reduced with 200 W/s until the supercapacitor is charged with 500 W (time stamp 29.6 seconds), also corresponding to the power management strategy.

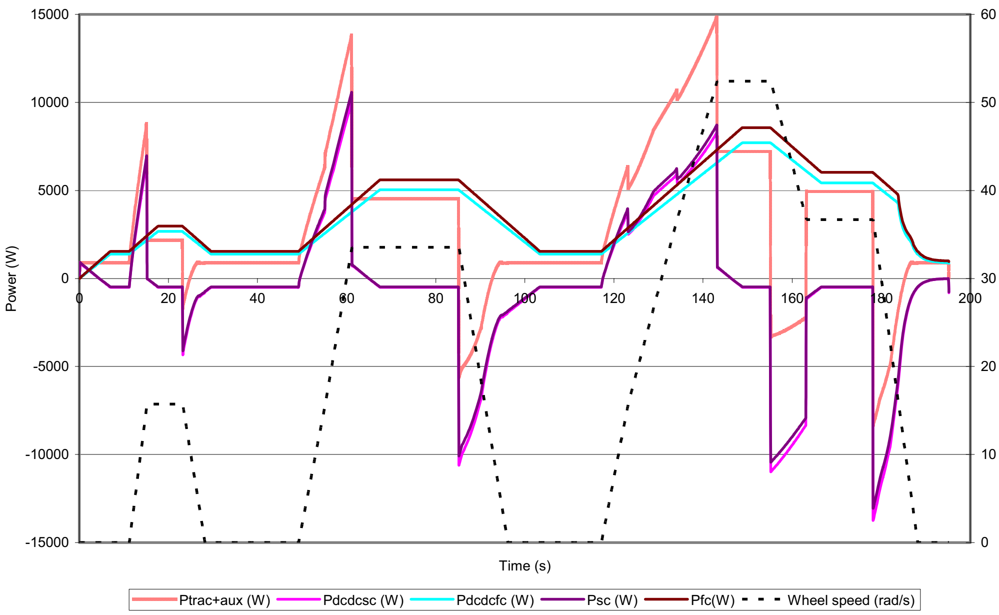

Fig. 3 Power flow in the series hybrid fuel cell and supercapacitor topology with both DC-DC converters [4]

ISSN 2032-6653

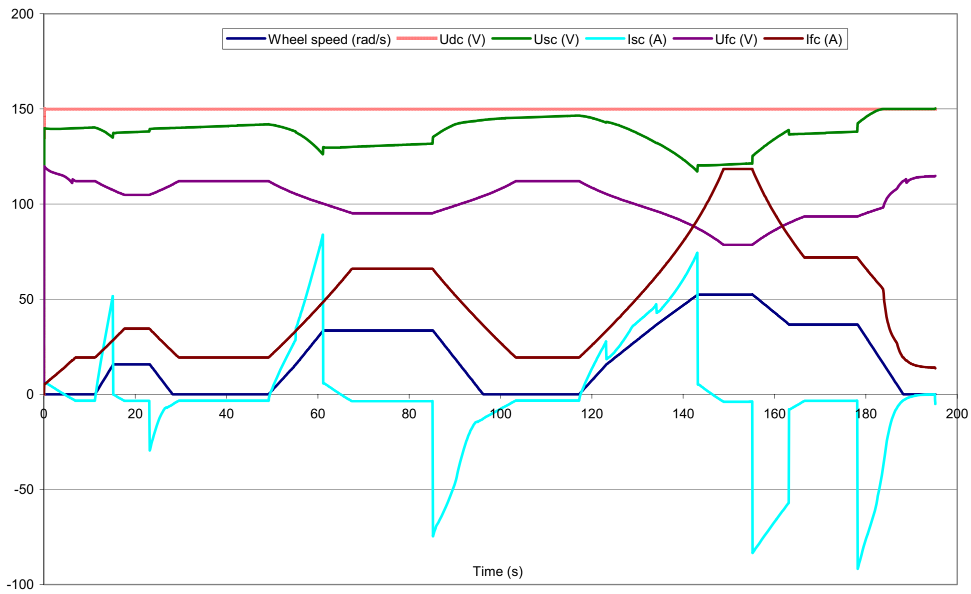

Fig. 4 Currents, voltage and speed of the series hybrid fuel cell and supercapacitor topology with both DC-DC converters [4]

At the end of the ECE-15 cycle the supercapacitor voltage reaches the maximum allowed DC-bus voltage and can not be further charged. At this moment fuel cell power is faster reduced than 200 W/s by the unique iterative algorithm of the VSP tool (see [4]) that takes into account the maximum voltage limitation of the supercapacitor (from time stamp 184 to 194 seconds).

Fig. 4 shows some additional simulation results. It illustrates the wheel speed (in rad/s), the DC-bus voltage (Udc), the voltage of the supercapacitor (Usc), the current of the supercapacitor (Isc), the voltage of the fuel cell system (Ufc) and its current (Ifc).

By using two DC-DC converters, one controlling the fuel cell system power and another one controlling the supercapacitor power, it is possible to keep the DC-bus voltage constant independent from the supercapacitor voltage or fuel cell system voltage, as can be seen in this figure. When discharging the supercapacitor the supercapacitor voltage drops and vice versa. Also the voltage of the fuel cell system drops when high currents are delivered by the fuel cell system. However also other topologies for the power system are possible and will be described in the following section.

4. POWER SYSTEM TOPLOGIES

A first topology is described in Fig. 5. The topology corresponds with the simulation results of previous section.

The peak power unit is a parallel configuration of the supercapacitor, connected to the DC-bus through a dedicated DC-DC converter. The converter allows a power flow control, optimising the global propulsion system efficiency and its dynamic performances [4] [5]. If a DC-DC converter is located between the supercapacitor pack and the DC-bus, the use of a bi-directional function is necessary to allow power transfer in both directions [6]. This feature enables braking energy recuperation into the peak power unit. However a very high efficiency of this converter is required. A Bi-directional ZVS, Quasi-ZCS resonant converter would be a good solution to reach this high efficiency.

Another DC-DC converter is connected in-between the fuel cell and the DC-bus. This allows controlling the DC-bus voltage independent from the power delivered by the fuel cell system.

The amount of energy that can be stored in the supercapacitor system is limited. Especially for driving downhill (see section 2), when a high amount of energy can be recuperated in the supercapacitor, its storage capacity would need to be very high. For this purpose it could be interesting to additionally use a battery pack.

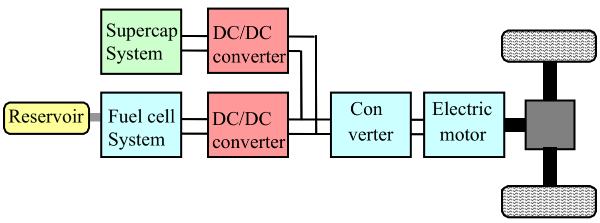

Fig. 5 A series hybrid fuel cell and supercapacitor topology with two DC-DC converters [4]

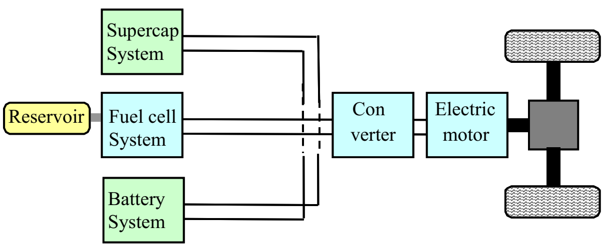

Fig. 6 A series hybrid fuel cell and supercapacitor topology without DC-DC converter [4]

One can consider connecting directly all sources in parallel to the DC-bus (see Fig. 6). Several solutions are possible: connecting a supercapacitor parallel to a battery pack (no fuel cell is used in this case), connecting a supercapacitor parallel to a fuel cell or using only a fuel cell with a battery. Since no DC-DC converters are used the division of the power flows between the components depends of their internal characteristics and the required load power only. This is the cheapest solution, but braking energy regeneration can not be optimised (see [4]).

Another approach is described in Fig. 7. In this configuration the supercapacitor is directly coupled to the DC-bus. The amount of energy stored in the supercapacitor depends of its voltage (see equation (2) in §2). For optimal usage the supercapacitor as an peak power unit the DC-bus voltage should not be kept constant. Normally a supercapacitor voltage may range from 50% to 100% (fully charged) of its nominal voltage to keep an acceptable efficiency of the energy transfer.

The DC-bus voltage can however be controlled by the DC-DC converter connected to the fuel cell (see Fig. 7. However when the DC-bus voltage is low the available power for traction is also small. This control strategy would reduce the acceleration performance of the vehicles propulsion system.

Another idea could be to only use a DC-DC converter only between the DC-bus and the supercapacitor system as described in Fig. 8. This would allow a better usage of the energy stored in the supercapacitors. Again a high efficient bi-directional DC-DC converter is required. The DC-bus voltage in this configuration depends of the output voltage of the fuel cell energy conversion system.

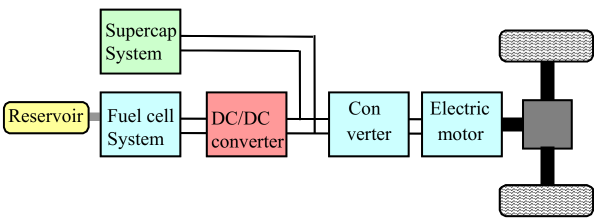

Fig. 7 A series hybrid fuel cell and supercapacitor topology with one DC-DC converter connected to the fuel cell [4]

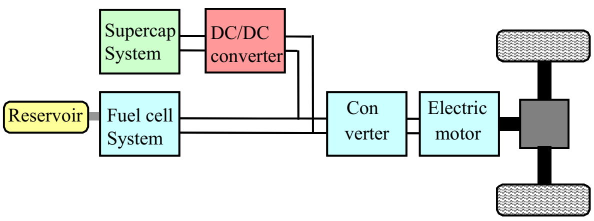

Fig. 8 A series hybrid fuel cell and supercapacitor topology with one DC-DC converter connected to the supercap [4]

5. ENERGY EFFICIENCY ASSESSMENT

A drawback of using both DC-DC converters is the losses they additionally introduce. In this section the energy efficiency of the different topologies described above will be assessed.

Based on the VSP tool, the simulations of the series hybrid vehicle driving the ECE-15 cycle have been done. The results show that the vehicle with both converters (corresponding to the topology of Fig. 5) has the fuel consumption of 0.96 kg/100km of hydrogen, the same vehicle with only one DC-DC converter at the side of the fuel cell system (corresponding to the topology of Fig. 7) has the fuel consumption of 0.92 kg/100km, and the vehicle with only one DC-DC converter between the supercapacitor and the DC-bus [4] (corresponding to the topology of Fig. 8) has the lowest fuel consumption of 0.76 kg/100km.

However one should verify the influence of the state of charge (SoC) of the supercapacitor. In hybrid vehicles the SoC at the end of the simulated speed cycle can be different from the SoC at the beginning. When comparing the results of the three topologies only a minor SoC deviation of 2% was observed.

By integrating the power delivered by the fuel cell system and the power delivered by and/or stored in the supercapacitor one can calculate the energy delivered (stored) by the supercapacitor. This can be added to the energy delivered by the fuel cell to compensate the delta SoC of each simulation result. This gives 189.5 Wh/km for the topology of Fig. 5, 174.4 Wh/km for the topology of Fig. 7 and 148.4 Wh/km for the topology of Fig. 8 [4]. Hence the conclusion stands for the investigated propulsion system: lowest energy consumption when only a DC-DC converter is used connected to the supercapacitor.

6. HYBRID POWER CONTROL STRATEGY

In this section the series hybrid propulsion system, with a power unit consisting out of a supercapacitor connected to the DC-bus via a DC-DC converter and a fuel cell system, will be further investigated.

The Hybrid power control strategy, proposed for this configuration, is based on three measurements: the load current (the current of the traction system), the voltage of the supercapacitors and the voltage of the DC bus.

According to the load current, its moving average i_{loadf} is obtained in the propose software and hardware model, by using a LPF (low pass filter). The load current minus its moving average is defined as the required peak current of the load i_{loadh}. The proposed methodology of multiple energy sources control and management are based on following rules [7]:

According to the moving average of the load current i_{loadf} and the DC bus voltage u_{dc}, the source current from the fuel cell to the DC bus i_{fc} is controlled.

According to the peak current of the load current i_{loadh}, the injection current from the supercapacitor to the DC bus i_{sc} is controlled, if it is possible.

ISSN 2032-6653

According to the specified range of voltage variation of the supercapacitors, to control the charging current from DC bus to the supercapacitors is controlled, if it is possible.

In order to efficiently use the supercapacitor, the voltage variation of the supercapacitor pack can be specified to be 100% to 50% of its nominal voltage. According to the voltage of the supercapacitors u_{sc}, a charging demand can be defined by:

If (u_{sc}< 50%) or ((charging=1) and (u_{sc}< 100%)), then charging=1, otherwise charging =0.

It is not necessary to charge the supercapacitor immediately which means that the priority of charging supercapacitor will be lower than the priority of providing the mean power of the traction system and the priority of maintaining DC bus voltage.

Since there is only the DC/DC converter connected to the supercapacitor (no DC/DC converter connected to the fuel cell), one can directly control power of the supercapacitor and only indirectly control the power of the fuel cell. The DC bus voltage u_{dc} will be used to evaluate the control result of the DC/DC converter of the supercapacitors and the control result of fuel injection in fuel cell. Although there is no DC/DC converter of the fuel cell system, it is still important to introduce a feed forward signal i_{loadf} (that corresponds to the moving average of the load current).

In order to ensure the current from the main power supply system is changing slowly and not higher than 1 per unit (the nominal current of the main power supply system), the reference of the output current of the main power supply system i_{fc1_ref} should be estimated as described in Fig. 9.

The summation of the feed forward signal i_{loadf} and the current demand of charging supercapacitor i_{sc1f_demand} is the input of a limiter. The output of the limiter is the reference of the output current of the fuel cell i_{fc1_ref}. This reference will be used in the control system of the DC/DC converter connected to the supercapacitor. As a result, the main power supply system (e.g. fuel cell) is indirectly controlled by the DC/DC converter in Fig. 8.

The reference of the output current of the DC/DC converter of the supercapacitors i_{sc1_ref} corresponds to a slow reference i_{sc1f_ref} and a fast reference i_{sc1h_ref}. The fast reference of injection current from the DC/DC converter i_{sc1h_ref} is defined as the load current i_{load} extracting its moving average component i_{loadf} as expressed in equation (6).

$$i_{sc1h\_ref} = i_{load} - i_{loadf} \qquad (6)$$

The slow reference of the injection current from the DC/DC converter i_{sc1f_ref} is calculated according to the reference of fuel cell i_{fc1_ref} and the moving average of the load current i_{loadf} as described in equation (7).

$$i_{sc1f\_ref} = -(i_{fc1\_ref} - i_{loadf}) \qquad (7)$$

Due to above definition, the priority of charging supercapacitor is lower in comparison with the priority of providing the mean power of the traction system. The summation of the fast reference i_{sc1h_ref} and the slow reference i_{sc1f_ref} is the reference of the output current of the DC/DC converter i_{sc1_ref} (see equation (8)).

$$i_{sc1\_ref} = i_{sc1h\_ref} + i_{sc1f\_ref} \qquad (8)$$

This analysis results in the output current reference of the DC/DC converter of the supercapacitor expressed in equation (9).

$$i_{sc1\_ref} = i_{load} - i_{fc1\_ref} \qquad (9)$$

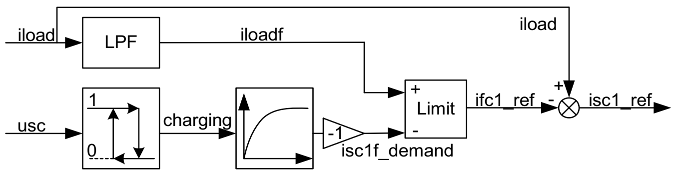

Fig. 9 Current reference of the supercapacitor [7]

7. EXPERIMENTAL VALIDATION OF THE HYBRID POWER CONTROL STRATEGY

The proposed power management strategy for the series hybrid vehicle with a fuel cell as main power supply system and a supercapacitor, connected to the DC-bus via a DC-DC converter, as peak power unit, is validated on the basis of experimental results.

To validate the simulation results an test rig of the hybrid propulsion system has been developed. This platform allows analysing the system behaviour with real components as well as on the basis of Hardware in the Loop simulation (HIL). The test platform is controlled by a PCI eXtensions for Instrumentation (PXI) system with Field-Programmable Gate Array (FPGA) to control the firing of the Insulated Gate Bipolar Transistors (IGBT's). With the help of an Signal Conditioning Extension for Instrumentation (SCXI) system the different parameters are measured and will be compared with simulation results. The set-up is described in Fig. 10.

The laboratory setup is somewhat different from the vehicle simulated with VSP, however the control principles could be validated.

The experimental test consisted out of a stepwise DC load current increasing/decreasing as described in Fig. 11. One can see that the supercapacitor current i_{sc} is a little higher than the DC load current i_{dc}. (The supercapacitor current multiplied the duty cycle of converter would be the same as the DC load current). The batteries current i_{ba} is slowly increasing.

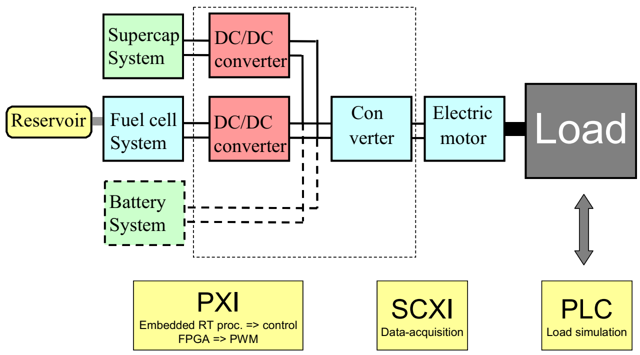

Fig. 10 Test setup of the series hybrid propulsion system using a fuel cell as energy source and a supercapacitor as peak power unit

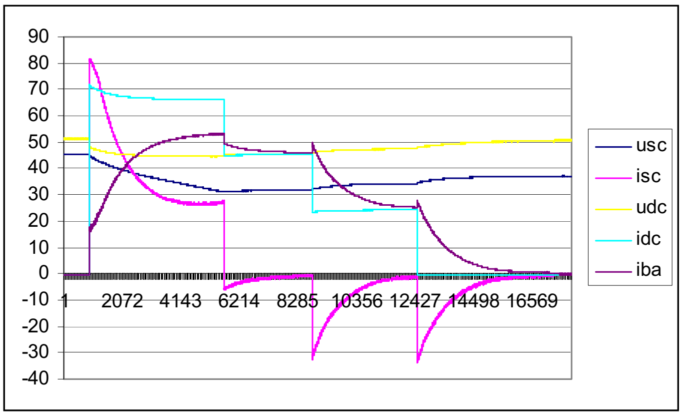

Fig. 11 Waveforms of voltage and current in case only with a DC/DC converter of the supercapacitors (10ms/dot) [7]

In Fig. 11, it is also shown that the battery current i_{ba} is limited (around 50A). This means that the main power supply system only needs to provide the slow moving average current for the load. The differences of the supercapacitor current i_{sc} and the DC load current i_{dc} are almost the same before and after stepwise decreasing load current as described in Fig. 11. This means that the power supply system only needs to provide the continuous current.

The experimental results clearly demonstrates the ability of the power management strategy to slowly control the moving average of the fuel cell power while delivering the required peak power by the supercapacitor via a current controlled DC-DC converter.

8. POTENTIAL APPLICATION

For the practical application an existing commercial electric vehicle is considered as test platform. This commercial vehicle has originally a 100Ah/120V NiCd battery and a DC motor with a nominal power of 11kW (20kW maximum power). For the new hybrid propulsion system the battery is replaced by a 10kW fuel cell connected in parallel to a supercapacitor via a DC-DC converter. To improve the acceleration performance of the existing battery electric vehicle, especially at high speeds, a rated power of 35kW for this DC-DC converter is required.

In the new propulsion system the battery of 250kg will be replaced by a power source of 170 kg corresponding to 100 kg for the fuel cell; 40 kg for the supercapacitor pack and 30 kg for the DC-DC converter. The traction motor power can hence be increased to 45kW, which gives an additional weight of about 50kg. This assessment clearly illustrates the potential applicability of the hybrid power source in a passenger car application.

9. CONCLUSIONS

The simulation and experimental results described in this paper show the possibility of analysing the power flow in the series hybrid propulsion system on the basis of different topologies and different power management strategies. The Vehicle Simulation Programme is an important tool for these assessments.

Supercapacitor based energy storages are very suitable as peak power units. The selection of the appropriate propulsion system topology is very important. One needs to weight the advantages and drawbacks of the different solutions. Using DC-DC converters allows keeping the DC-bus voltage as high as possible to have a good acceleration power. At the other hand DC-DC converters induce additional losses resulting in higher fuel consumptions.

The simulation results show the possibility to select an adequate power management. They also indicate that a topology, with a high efficient DC-DC converter connected between the supercapacitor and the DC-bus and a direct parallel connection of the fuel cell system to the DC-bus, results in the lowest fuel consumption for the considered application.

The different configurations of the energy sources and the supercapacitor based energy storage have been analyzed. The proposed power control algorithm has been validated on the basis of experimental results from a HIL test rig. With the proposed control, the main power supply system (fuel cell) can be controlled to provide, only the moving average power of the traction system.

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BIOGRAPHIES

Prof. Dr. ir. Joeri Van Mierlo (EPE and IEEE member) graduated in 1992 as electro-mechanical engineer at the Vrije Universiteit Brussel, V.U.B. His master thesis was devoted to the development of the PLC automatisation of a dynamic roll bench to test electric vehicles.

As a research assistant, at the department of Electrical Engineering and Energy Technology (ETEC) of the V.U.B, he was in charge of several national and international research projects mainly regarding the test and evaluation of electric and hybrid electric vehicles. He was engaged in different boards of the V.U.B. as well as in several demonstration and PR projects of CITELEC and AVERE, European scientific association hosted by the University on the bases of contracts.

He finished his PhD, entitled "Simulation Software for Comparison and Design of Electric, Hybrid Electric and Internal Combustion Vehicles with Respect to Energy, Emissions and Performances", in June 2000 with greatest distinction.

From October 2004 Joeri Van Mierlo has been appointed as a fulltime professor at the Vrije Universiteit Brussel. Currently his research is devoted to the development of DC-DC converters for hybrid propulsion systems as well as traffic and emissions models and environmental comparison of vehicles with different kind of drive trains and fuels.

Jean-Marc Timmermans graduated in 2003 as electro-mechanical engineer at the Vrije Universiteit Brussel, VUB. As a research assistant at the department of electrical engineering (ETEC) he is involved in a national research project regarding the comparison of the environmental damage of vehicles with different kind of drive trains and fuels.

Dr. ir. Peter Van den Bossche graduated as civil mechanical-electrotechnical engineer from the Vrije Universiteit Brussel, and got involved in the research activities on electric vehicles at that institution. Since its inception in 1990, he has been co-ordinating the international association CITELEC, more particularly in the field of electric and hybrid vehicle research and demonstration programmes. Furthermore, he has a particular research interest in electric vehicle standardization issues on which he finished a PhD work. He is currently lecturer at the "Erasmus Hogeschool Brussel" which is a member of the University Association of Brussels, and co-ordinator of common research programmes with the Vrije Universiteit Brussel

Prof. Dr. ir. Gaston Maggetto was the founder of the department Electrical Engineering and Energy Technology at the Vrije Universiteit Brussel, which he led from 1970 to 2004. He had been involved in the management of several international associations such as AVERE, CITELEC, EPE (of which he was the founder), and KBVE/SRBE. he was vice-president of AVERE and Vice-president of the Advisory Commission "Mobility" of the Brussels Capital Region. Prof. Em. Dr. Ir. Gaston Maggetto recently has passed away on 09 February 2007. His pioneering work laid the foundations for many new ideas that helped develop a community of engineers both in Europe and World-wide.