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Supercapacitors for the energy management of electric vehicles

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Abstract

The integration of the on-board energy source of an electrically propelled vehicle with a supercapacitor bank (SB) as a peak power unit, can lead to substantial benefits in terms of electric vehicle performances, battery life and energy economy. Different architectures may be envisaged, to be chosen according to technical–economical trade-off. A research activity, supported by the European Community in the frame of the Joule III program and titled 'Development of Supercapacitors for Electric Vehicles' (contract JOE3-CT95-0001), has been in progress since the beginning of 1996. The partners involved are SAFT (project leader), Alcatel Alsthom Research (France), Centro Ricerche Fiat (Italy), University of Kaiserslautern (Germany), Danionics (DK) and ECN (Netherlands). Its objective is to develop a SB and its electronic control and to integrate them in two different full-scale traction systems, supplied, respectively, by sealed lead traction batteries and by a fuel cell system. Through the bench tests, it will be possible to evaluate the impact of the SB on both traction systems. In this paper, a project overview will be given; the power management strategy principles, the supercapacitor's control electronic devices, the system's architecture and the supercapacitor's requirements on the base of the simulation results, will be examined. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Supercapacitor bank; Fuel cell; Electric vehicle

1. Introduction

The mission of road electric vehicles, especially in urban areas, is typically characterised by variable power demand of the drive train.

The power profile shows high peaks during traction and braking phases to be supplied, or respectively, recovered by the on-board electric energy source. The energy delivery at strongly variable power and the need of effective energy recovery, addressing the reduction of consumption, can conflict with the optimum utilisation of the board energy source in terms of functional behaviour, energy performance and endurance.

These considerations are applicable to electric drive trains fed by electrochemical storage batteries, or electrochemical generators (fuel cells) or electro-thermal engine generators (for series hybrid systems).

The release of the energy source operating conditions from the traction power demand in real time offers the possibility of optimising the system, or some components of it, according to specific objective or requirements.

A supercapacitor bank (SB), made up of single cells connected in series and in parallel, featuring appropriate parameters of energy density, power density, with high charging–discharging efficiency and affordable cost, ap-

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Table 1

Electrode material	Carbon	Carbon	Metallic oxides
Electrolyte	Aqueous electrolyte	Organic electrolyte	Aqueous electrolyte
Maximum voltage [V]	1	3	1
Specific power [kW/kg]	0.8–2.6	1.5–5	0.5
Specific energy [W h/kg]	0.2–1.3	3–6	1

pears to be a suitable device to support the energy source of an electrically propelled vehicle, thus providing an optimised energy management.

2. General characteristics of supercapacitors

A supercapacitor differs from conventional capacitors both in the physical phenomena and the materials of which it is made.

In the supercapacitor, the dielectric is an electrolyte interposed between two electrodes. When a voltage is applied, a double layer of charges is formed at the interface between the electrodes and the electrolyte. In this case, the distance between the charges corresponds to the thickness of the double layer, that is, only a few Angstroms. This accounts for the difference in terms of capacitance per square centimetre between a conventional capacitor (order of magnitude nF/cm^2) and a supercapacitor (order of magnitude 50 $\mu F/cm^2$).

The way to increase the energy stored in a conventional capacitor is to operate at high voltages (up to 3000 V), consistent with the dielectric breaking voltage. In supercapacitors, the voltage to be applied must be limited by either the solvent or the organic electrolyte decomposition voltage (1.23 V and 3.5 V, respectively); in this case, the only way to increase the stored energy is to raise the capacitance value adopting electrode materials with very high specific area. In particular, active carbon may reach, through suitable chemical processes, a specific area of 10^3 m^2/g, leading to a specific capacitance of 10^2 F/g. In addition, it is possible to reach very low values of the internal resistance, that allows the device to provide high output power [1].

So far, only supercapacitors operating on the basis of a charge separation phenomena due to the application of an external voltage between the electrodes have been considered. There is another type of supercapacitor, called Redox supercapacitors, in which reduction and oxidation reactions occur during charge and discharge phases. The electrodes are made of metallic oxides (ruthenium, iridium) and electrolytes are liquid.

The characteristics of the supercapacitor may be synthesised in Table 1 [2].

3. Integrating a SB with the on-board energy source

Because of their high specific power rate, supercapacitors may be integrated with an electrochemical energy source [5] to supply the power peaks required by the vehicle during the mission. The potential benefits of an integrated system SB-electrochemical energy source are the following:

– to improve the vehicle efficiency and energy economy over variable power driving conditions;
– to assure high performance and good vehicle behavioural response independently from the status of the energy source (including age);
– to improve the endurance of the energy source to the extent of its dependence on the high rate power demand;
– to extend the vehicle's range at full performance as a consequence of the combined effect of load levelling of the on-board energy source and of better efficiency of energy recovery.

These potential benefits are, in general, applicable to both types of energy source, storage batteries and fuel cells. It should be noticed that, in the case of a fuel cell, the integration of the SB is an essential implement for the function of energy recovery during braking.

A strong market acceptance feature of the electric vehicle is, besides the range, the high acceleration performance to achieve good characteristics of traffic compatibility and operational effectiveness. The integration of a SB in both cases of storage battery and fuel cell, allows a system design optimised according to mission requirements, by making the specific power and specific energy parameters of the energy source independent of each other.

As a consequence of this consideration, it will be possible to design the storage battery with respect to energy storage capability and life requirement, without taking into account the power requirement. In the case of a fuel cell, it will be possible to size and appropriately design the energy generation apparatus (stack, reformer, auxiliary devices) according to a low power demand, with

[5] Considering the lead acid technology as a reference, its specific power is 0.1–0.4 kW/kg and its specific energy is 30–35 W h/kg.

Table 2

	EV#1	EV#2
Curb weight (kg)	1215	1575
Payload (kg)	200	320
Cx	0.314	0.35
Maximum speed (km/h)	110	100
Acceleration time from 0 to 50 km/h (s)	8	8

consequent economical benefits, to be considered as a trade-off case with the whole system [3,4].

4. Activity in the frame of the JOE III project 'Development of Supercapacitors for Electric Vehicles'

4.1. Reference vehicles and cycles

In order to evaluate the impact of the SB on a traction system, the project 'Development of Supercapacitors for Electric Vehicles' has been in progress since the beginning of 1996, with the purposes described in the abstract.

To define the energy and power requirements of the traction systems, two reference vehicles have been considered: a city car (EV#1) as a vehicle supplied with traction batteries, and a Van (EV#2) as a vehicle supplied with fuel cells, whose main characteristics are reported in Table 2.

As a reference cycle, the urban part of the ECE15 cycle has been considered. In order to evaluate higher-performance EVs, which the buffer introduction can make more feasible, the acceleration time has been reduced from 26 to 8 s. This modified cycle can be assumed for energy evaluation for systems based on energy/power source splitting.

For the EV#1, an urban cycle, based on real mission profile, has also been considered (Figs. 1 and 2).

4.2. Energy flows management

The use of a power buffer in a traction system requires an accurate energy flow management between the power source (SB) and the energy source (traction battery or fuel cell system). The following points are part of the energy management strategy:

– the battery should deliver the energy at a power rate as far as possible constantly and smoothly in the transient phases, up to a value corresponding to the power required from the vehicle at the maximum constant speed;
– the peak power unit, upon traction demand, should deliver power exceeding the abovementioned power level and should recover the braking energy;
– if the energy demand exceeds the energy deliverable by the peak power unit, defined on the base of its

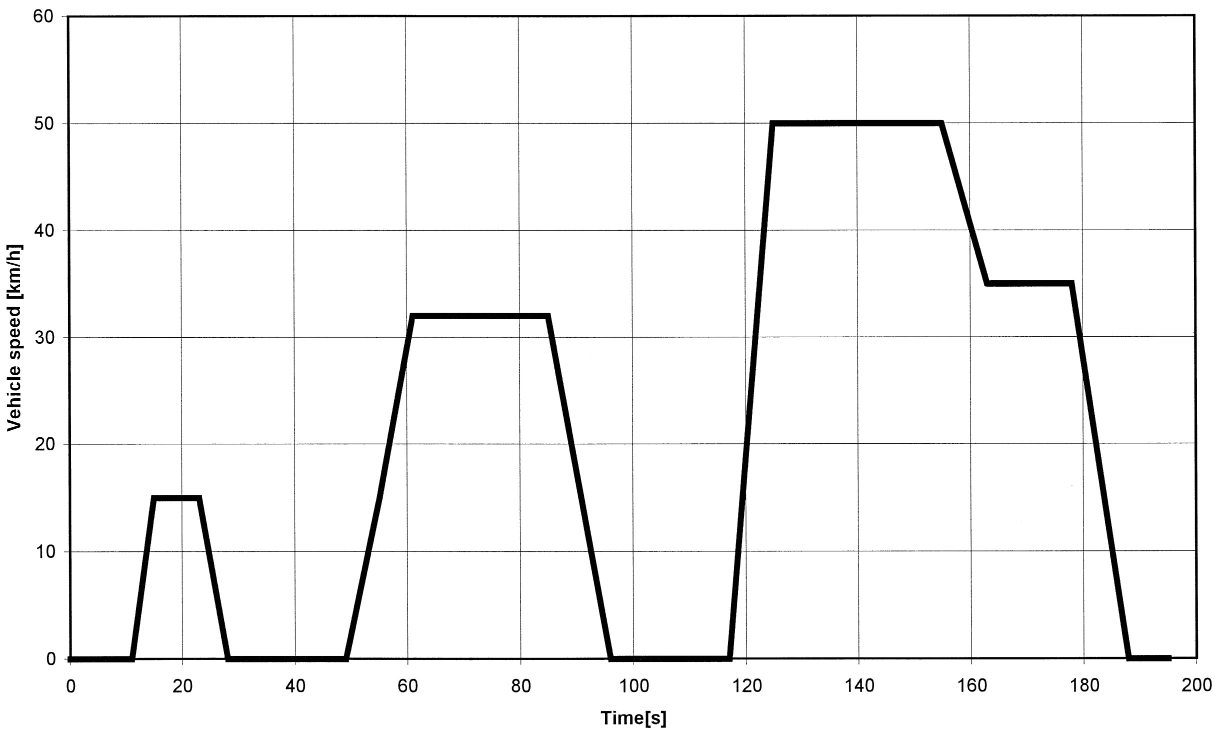

Fig. 1. ECE15 urban-enhanced cycle.

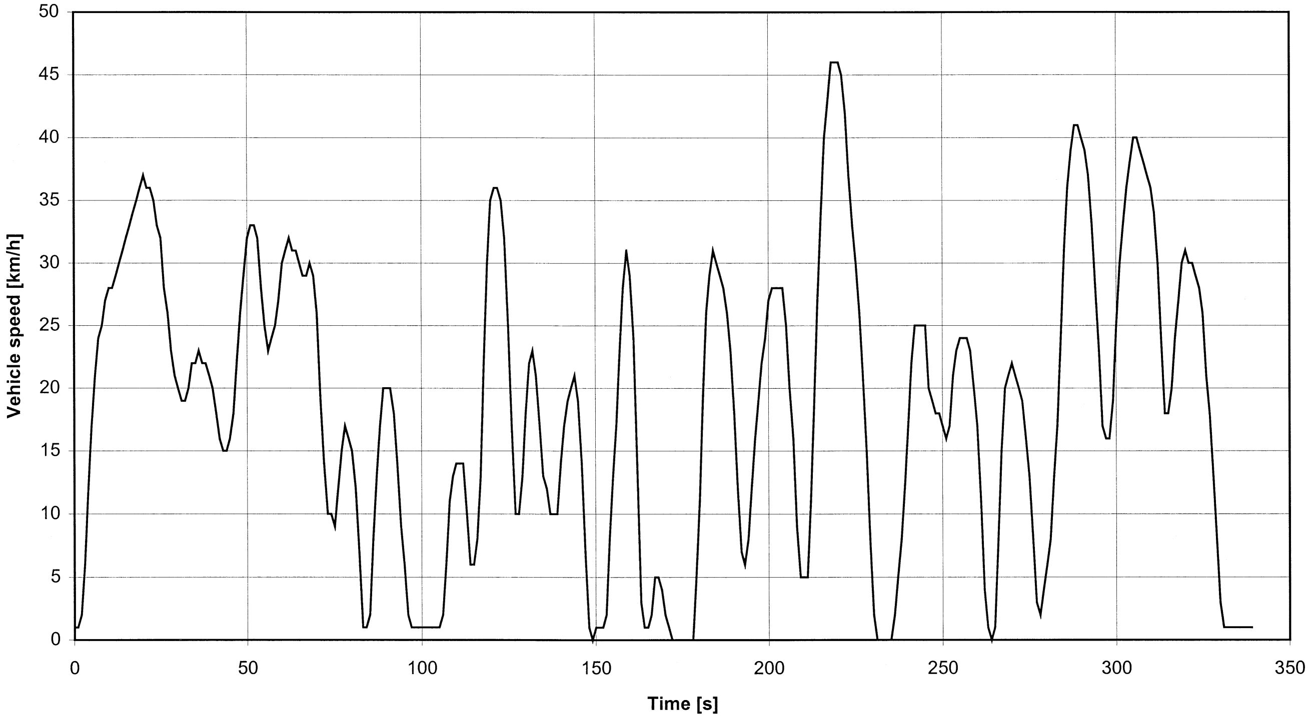

Fig. 2. Urban cycle of Fiat500 Elettra.

operating voltage range, the battery should take over the energy supply to the traction system;
– the SB should be recharged by the vehicle kinetic energy and, by the energy at low power rate provided by the traction battery for the portion covering the efficiency losses;
– if the peak power unit is in the fully charged situation, the energy recovered should be sent directly to the battery from the drive train system;
– the overall energy efficiency over the vehicle mission should be maximised, according to the trade-off between the losses deriving from the energy transfer and the load levelling benefit.

In order to perform the energy management strategy, the SB voltage is imposed as a function of the vehicle speed according to the following formula:

$$W_{max} = W_{nom} + W_{kin} = 1/2CV_{Scap} + \eta 1/2mv^2,$$

where W_{max} is the energy corresponding to the maximum SB operating voltage; W_{nom} is the energy corresponding to the vehicle speed; η is the overall efficiency of the components between the vehicle wheels and the SB; and m and v are the vehicle mass and speed, respectively.

4.3. Power train system architecture

An architecture conceived with the electronic interface between the SB and the traction battery on the SB line has been chosen (Fig. 3).

The main characteristics of this architecture are:
– the DC/DC converter has to be dimensioned for the maximum power flow into and out of the SB;
– the SB voltage may be kept always lower than the minimum traction battery voltage: as a consequence, a simpler DC/DC converter design may be obtained. The DC/DC converter may operate only in step-up mode during the traction phase and only in step-down mode during the braking phase;
– a lower operating voltage implies a lower number of cells connected in series and a reduced complexity of the electronic module of the SB;
– possibility to add an auxiliary generator (auxiliary power unit configuration) without modifying the existing structure.

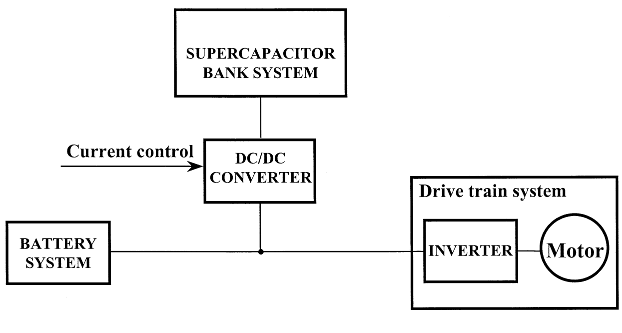

Fig. 3. Power train structure with DC/DC converter and SB series connected.

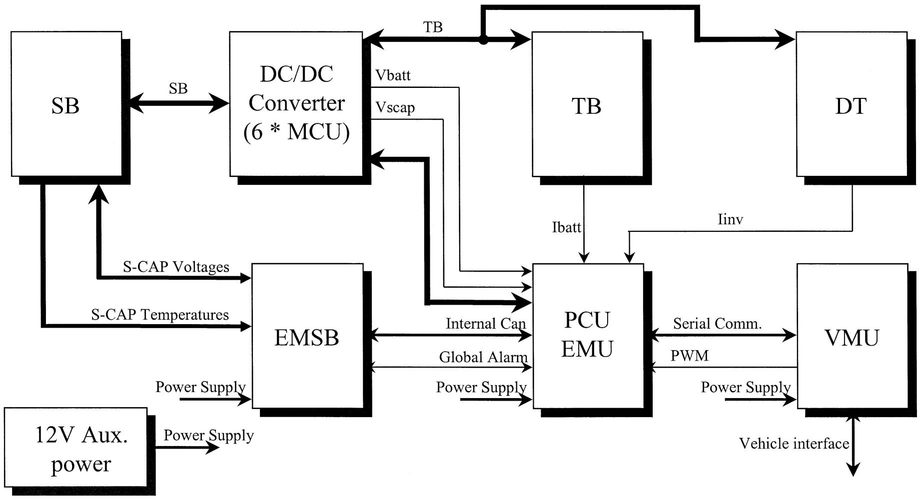

Fig. 4. EV#1 traction system supplied by traction batteries.

4.4. Control electronic devices

The control electronic devices are an essential part of the SB system. They allow to manage the energy flow among the system components and both to check and adjust the SB cell conditions during the vehicle operation through a balancing system.

Three electronic devices must be included in a traction system with a SB: a DC/DC converter, an electronic module for the SB (EMSB) and an energy management unit (EMU).

The DC/DC converter interfaces the SB bank and the traction battery. In absence of the DC/DC, it would be impossible to control the energy flow between the SB and

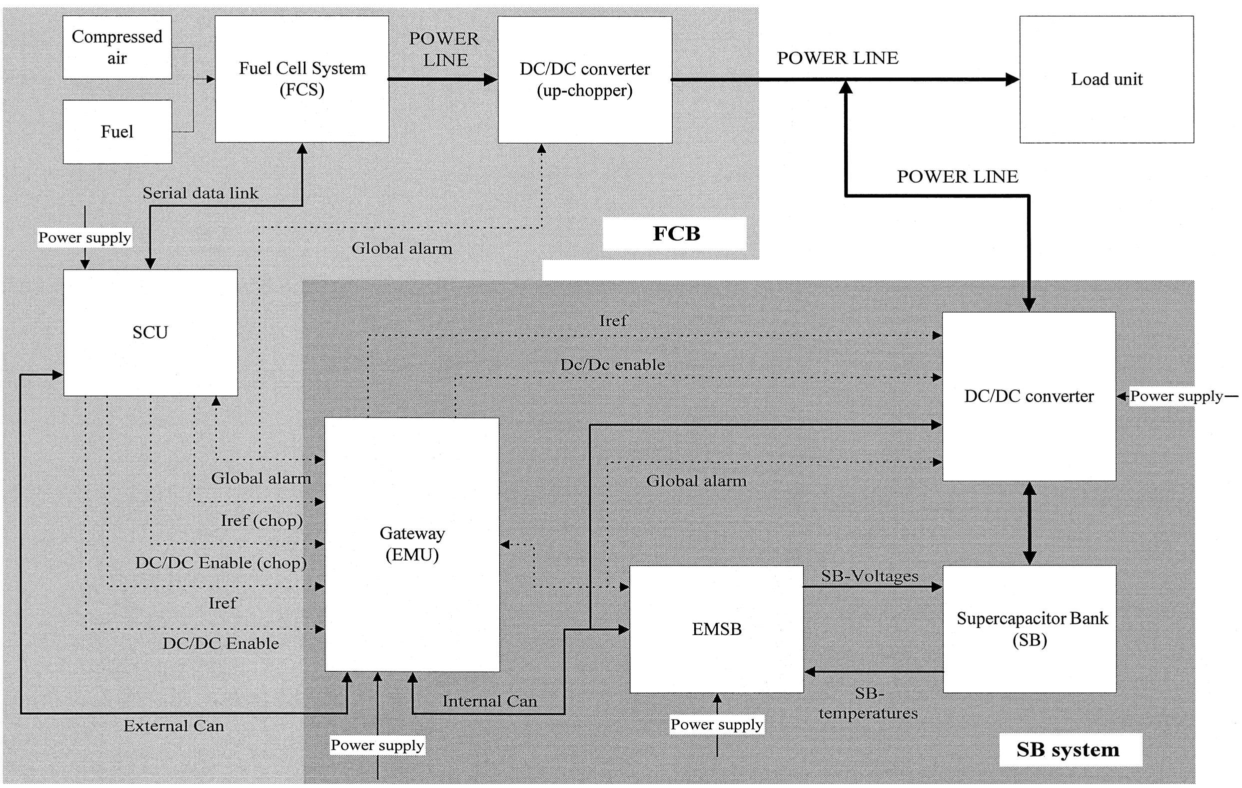

Fig. 5. EV#2 traction system supplied by fuel cells.

Table 3

	EV#1	EV#2
V_{bat} operating range	140–280 V	–
V fuel cells operating range	–	76–140 V
$V_{SC\ nominal}$	135 V	135 V
$V_{SC\ maximum}$	150 V	150 V
SC capacitance	87.6 F	87.6 F
SC internal resistance	50 mΩ	50 mΩ
Maximum battery power	10 kW	–
Maximum fuel cell system power	–	16 kW

Table 4

	EV#1	EV#2
SB maximum power	36 kW	38 kW
SB maximum power losses	10 kW	11 kW
SB cell voltage variation	2.2–2.76 V	1.7–2.7 V
SB provided energy	160 W h	110 W h
SB energy losses	12.8 W h	17 W h
SB efficiency	92%	85%

the traction battery, that would depend on their voltages and internal resistance values. With a current-controlled DC/DC converter and on the base of the power required by the drive train and of the SB state of charge, it is possible to regulate the power rate from and to the SB according to a defined strategy.

The main task of the EMSB is to manage the current flow on each cell in order to limit the voltage unbalancing between cells. In fact, keeping the different cells voltages in a range as small as possible, the possibilities for destructive overcharge phenomena (due to the overcoming of the decomposition voltage either of the organic solvent or of the liquid solution) are limited. In addition, the uniformity of the voltage distribution among the cells affects the energy quantity provided by the SB.

Two main factors cause the unbalancing between cells: differences in terms of capacitance and of leakage current. For this reason, a fairly good series connection should require low tolerance in terms of capacitance value.

Two main solutions may be adopted to achieve cell balancing, using active or passive elements. The first solution implies the charge of the lowest voltage cells through suitably sized DC/DC converters; this solution is expensive and the design is very complex. The second solution implies the discharge of the highest voltage cells through passive elements (resistances) connected in parallel, and it is much cheaper than the previous one.

In addition to this, the EMSB may carry out a real-time temperature monitoring of the SB, and the temperature measures on a defined number of cells could also be useful to implement system protection strategies.

The energy management unit supervises the complete traction system energy flow carrying out the following operations:

– energy management during transient phases through the DC/DC activation strategy;
– over temperature protection of the DC/DC converter;
– global alarm request grant and controlled operation shut-off in case of cell over-voltage, over-temperature or safety critical malfunction detection.

4.5. General traction systems schemes

On the base of the considerations previously made, hereafter, are reported the general schemes of the two traction systems considered, including the connections among their main components (Figs. 4 and 5).

4.6. Simulation results

The simulations on the systems including the SB have been carried out according to the input data listed in Table 3.

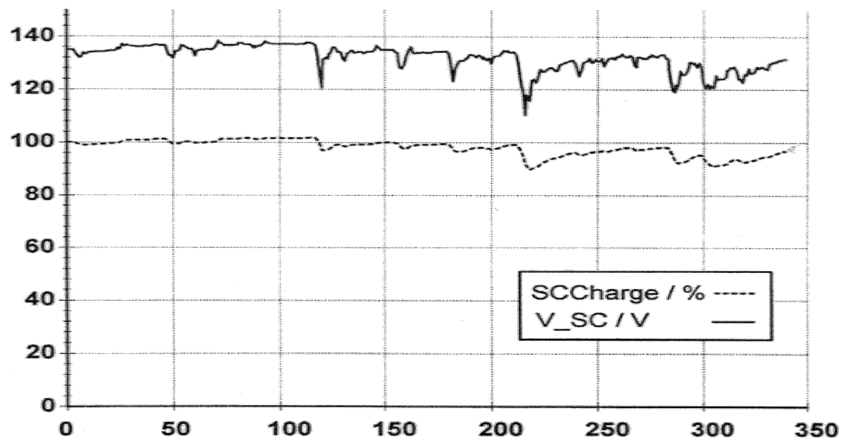

Fig. 6. EV#1 on urban cycle. SB SOC and voltage behaviour.

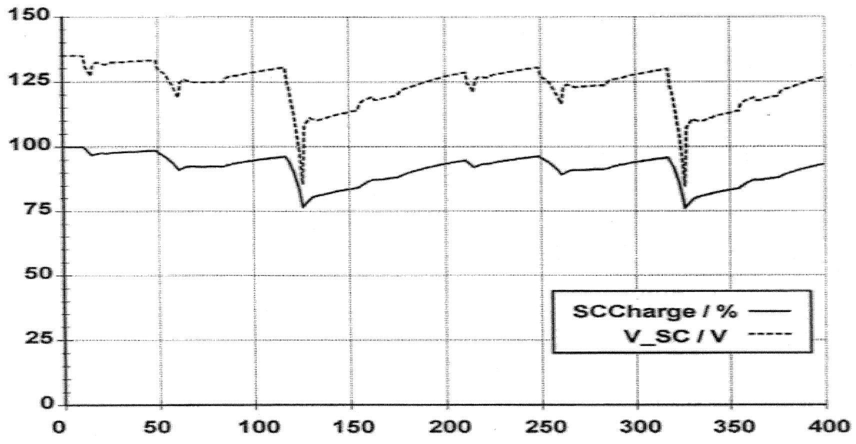

Fig. 7. EV#2 on ECE15 cycle. SB SOC and voltage behaviour.

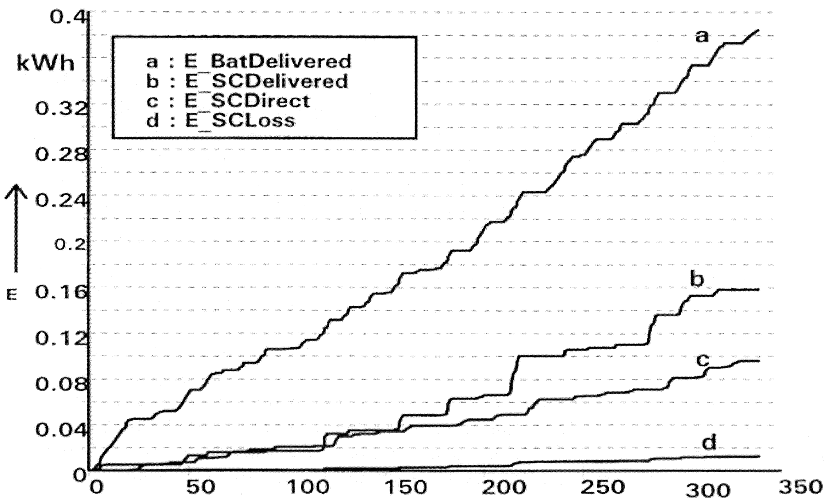

Fig. 8. EV#1 requirements on urban cycle.

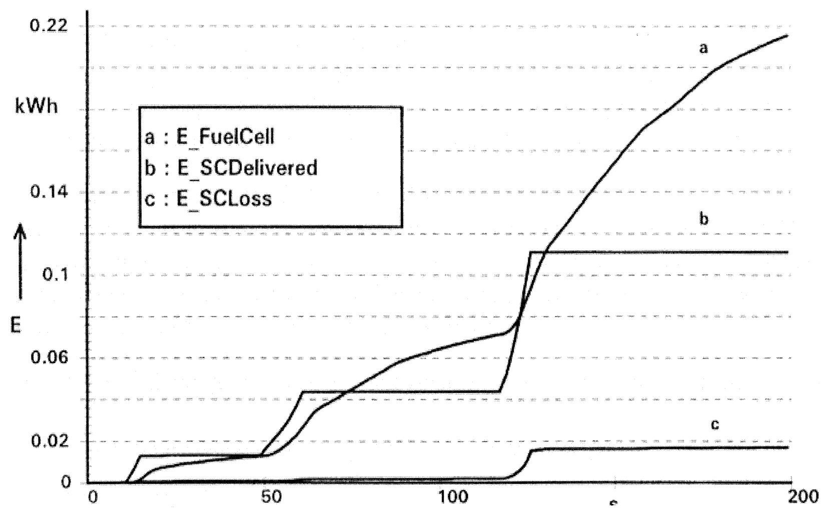

Fig. 9. EV#2 requirements on ECE15 cycle.

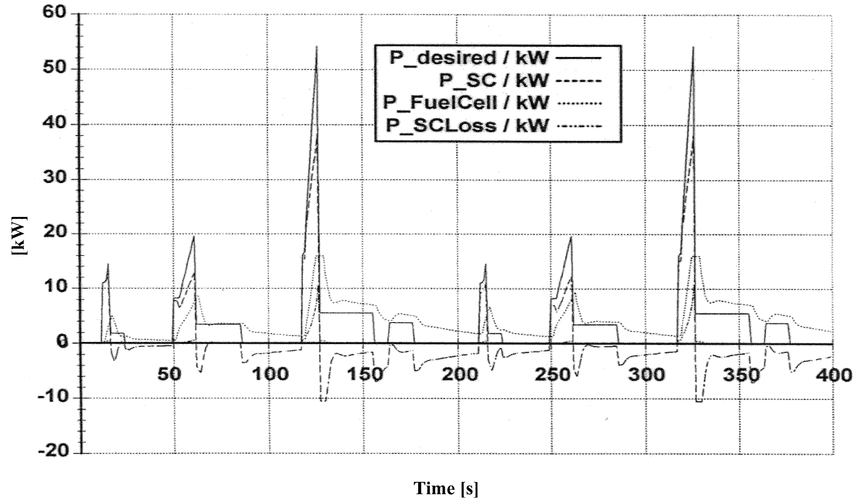

Fig. 10. EV#2 on ECE15 cycle power profiles.

The SC voltage has been defined according to the considerations made in Section 4.3, and the capacitance on the base of preliminary simulations carried out in order to know the inverter input requirements in terms of power and energy. The efficiency map of the drive train had been defined in bench tests carried out in CRF.

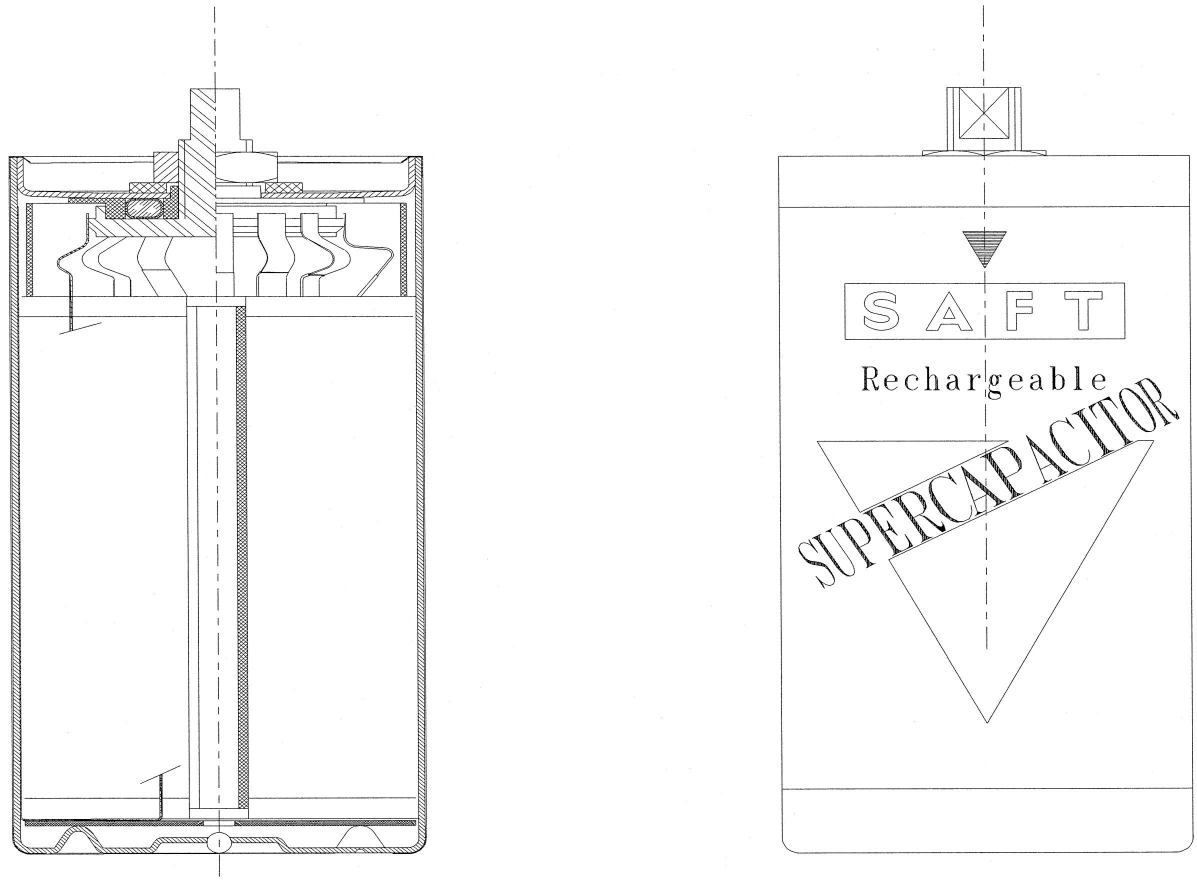

Fig. 11. Supercapacitor cell 33680.

Table 5

	Capacitance (5 s)	ESR (5 s)	Capacitance (20 s)	ESR (20 s)
Average	320.8 F	4.4 mΩ	367.3 F	6.5 mΩ
Scattering	9.42	0.35	8.95	0.35

The results related to evaluation of the EV#1 system on an urban cycle, more severe than ECE15, and of the EV#2 system on ECE15 enhanced are listed in Table 4.

The behaviour of the most significant quantities according to the simulations are shown in Figs. 6–10.

4.7. SAFT supercapacitor cells characteristics

The basic cell of the SB is made in format 33680: 33 mm in diameter and 68 mm in height. The electrodes are made by active carbon and an organic electrolyte is used. The cell can is made of stainless steel (Fig. 11).

A small size element has been chosen for the following reasons:

– the same basic element may be used for different applications;
– a small size element allows a parallel connection, thus providing a better balancing management;
– the chosen format allows to use technologies already adopted for accumulators and for primary batteries.

The most recent tests on single cells have been carried out; cycling the cells themselves at 20 A, in a voltage range between 1.4 and 3 V, with a rest time of 10 s after discharge and a steady condition at 3 V for 60 s before discharge. Different electrolyte volumes have been considered. The results are described in Table 5.

These results lead to 4.8 W h/kg, 7.8 W h/dm^3, 3.4 kW/kg, 5.5 kW/dm^3 for a nominal voltage of 3.0 V, average cell weight (without connections) of 95 g. An aluminium can would lead to 5.6 W h/kg and 4 kW/kg.

The test results will be completed with high discharge current rate tests and a self-discharge test.

5. Conclusions

The application of SB to electric traction systems can lead to substantial benefits in terms of electric vehicle performances, battery life and energy economy. Different system architectures can be envisaged, according to a technical–economical trade-off. The next step of this activity will be to go on evaluating the technical characteristics of supercapacitors (in terms of specific energy, specific power, energy density, power density, internal resistance, self-discharge rate, life cycle, evolution of the technical characteristics with temperature and ageing) in different operating conditions and at different temperatures. Then, the systems, including the SB, will be bench tested to evaluate the overall energy efficiency, the storage system life and the vehicle range extension. Particular attention will be paid to the problem of cell balancing and to the effectiveness of the energy flow management.

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