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Effectiveness evaluation of a Supercapacitor-battery parallel combination for Hybrid Heavy Lift Trucks

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Abstract

In many hybrid configurations batteries continue to be the weakest component because they have a shorter lifespan than the vehicle. Large power demands in particular have a detrimental effect to a battery pack's lifespan. This paper investigates the effect of the use of a EDLC (Electrical Double Layer Capacitors) as a power buffer to smooth rapid power fluctuations in and out of the batteries of a hybrid electric heavy truck.

The study considers a simple configuration where the supercapacitors are directly connected in parallel with the batteries. A simple parallel connection is the easiest to arrange for trial purposes but depending on the specific application, it might not always be the most efficient. Such design of hybrid energy storage system is expected to result in substantial benefits to the well being of the battery system. The work has been carried out on computer simulations. Finally the simulations results are validated on a test bench.

Keywords: Battery Model, EDLC, Simulations

1 Introduction

With the growing demand from the world community to reduce the emission of carbon dioxide, and after a decade of intense research, Hybrid Electric Vehicles (HEV's) appear more an important attention than ever before. Due to their several on-board power sources, HEV's offer unprecedented possibilities to pursue low energy consumption, higher efficiency, increasing life time of energy sources as well as reducing size and cost. The battery bank (lead-acid) in conventional fork lift trucks, is sized for peak power demand [1,4]. Cycling the battery at high power rates leads to reduce available capacity. This reduced capacity is caused by the isolation of active material due to the blocking of pores by sulphate deposition during high rate discharge. Also the reaction rate may outstrip the diffusion rate causing a depletion of ions at the reaction surface [2]. In addition, high current pulses will create short low cell voltages due to the ohmic voltage drop caused by the cell's internal resistance. These low voltage pulses in turn may trip low voltage limit detection systems in closely managed battery packs. This results also in extensive heat inside the battery, which leads to increased battery internal resistance, lower efficiency and ultimately premature failure [1]. The problem of battery overheating and loss of capacity is more acute when batteries are near full state of charge (SOC) since they cannot accept large busts of current from regenerative braking without degradation at this stage. This results increasing the cost and size of the battery pack to ensure the battery life and to avoid thermal runaway problems [5,6].

Degradation of the active mass can be reduced by minimizing the currents in the batteries. Additionally, the temperature of the batteries will be lower and this will reduce corrosion and sulphation. The lifetime of the batteries should therefore be extended. Another potential benefit is increased reliability of the batteries by reducing the chance of a catastrophic failure through short circuiting or thermal runaway [1,2].

Limited by the development of battery technology, a single energy storage system can very difficulty meet the requirements of energy and power in heavy electric lift truck at the same time, together with reasonable cost. To solve these problems, a good way is to combine a high specific energy source with high specific power source. The use of hybrid energy can integrate the advantages of a variety of energy storage sources to complement each other, while it can also satisfy the dual requirements for energy and power in hybrid electric drive system and improve the power performances. Under such background, a hybrid energy storage system consisting of battery and supercapacitor will be proposed.

Supercapacitors or Electrical Double Layer Capacitors (EDLC) are energy storage technology dedicated to applications where high power density is needed [2] as presented in Fig. 1. EDLC are capable of very fast charges and discharges at high efficiency, and can typically be recharged up to million cycles, unlike conventional batteries which last for only a few hundred or thousand recharge cycles [3].

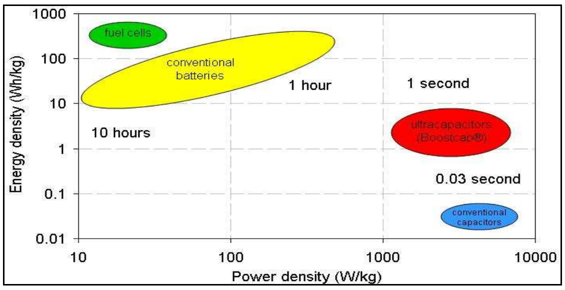

Fig. 1. Ragone chart comparing energy density versus power density [2]

Hybridizing a lift truck drive train with supercapacitors can have several purposes, depending on the particular aims, such as: energy savings, peak power shaving, [3, 4], etc. This study will focus on the development of a Peak Power Unit (PPU) oriented to extend the lifetime of the batteries and energy savings.

Different topologies of hybrid energy sources have been studied in the literature [10]. A parallel connection of two sources with a dc-dc converter between battery and supercapacitor bank, as well as two dc-dc converters sharing the same output are among conventional options. In this study, the topology consisting of a battery bank connected directly in parallel to the supercapacitors will be investigated (Fig. 2).

The goal of this association is to reduce the current when the vehicle accelerates in order to guarantee the best lifecycle of the battery.

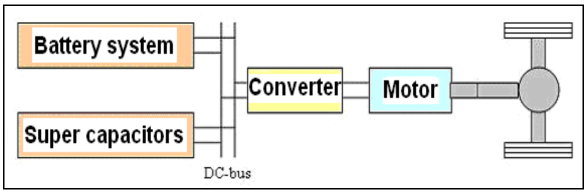

Fig. 2. A direct parallel connection of batteries to EDLC

2 Vehicle description

The vehicle system considered in this study is an electric lead-acid powered truck (CARER R45 NCF).

This vehicle is designed to drive with a maximum speed of about 16 km/h. It can lift max. 4500 kg. Further, it has two DC-motors, one is used for driving the vehicle and the other one for lifting. The mast is hydraulically operated by one or more hydraulic cylinders.

The battery bank has a capacity of 960Ah and the operating voltage is 80V. Due to the low voltage, the batteries have to provide hundreds of amperes.

Manufacturer, model	Carer, CARER R45 NCF
Rated capacity	4.5 ton
Power unit	Battery: -Voltage: 80V -Discharge cap. 960V
Speed -travel:(laden/unladen) -lifting:(laden/unladen)	 14.6/17.2 km/h 0.28/0.45 km/h
Service weight (incl. batteries)	6950kg
Electrical motor: - Drive - Lift	 17kW 15kW
Control system	Electronic
Operating pressure	160bar

Table 1. Specifications CARER R45 NCF

The modification of the drive line of the vehicle by using supercapacitor according to the topology in Fig. 2 will result in reducing the current drawn from the battery bank.

Fig. 3. Fork lift truck [5]

3 Methodology

A simulation program based on the “effect cause” also called the “wheel-to engine” has been developed in Matlab® Simulink® [6]. The simulation method goes upstream the vehicle components until it reaches the energy source. It can model the current flow in light, mild and heavy off-road vehicles. Starting from a given load profile, it calculates the current requested by the battery bank and from the supercapacitor banks. Fig. 4 shows a detail of the lift truck model inside the simulation program.

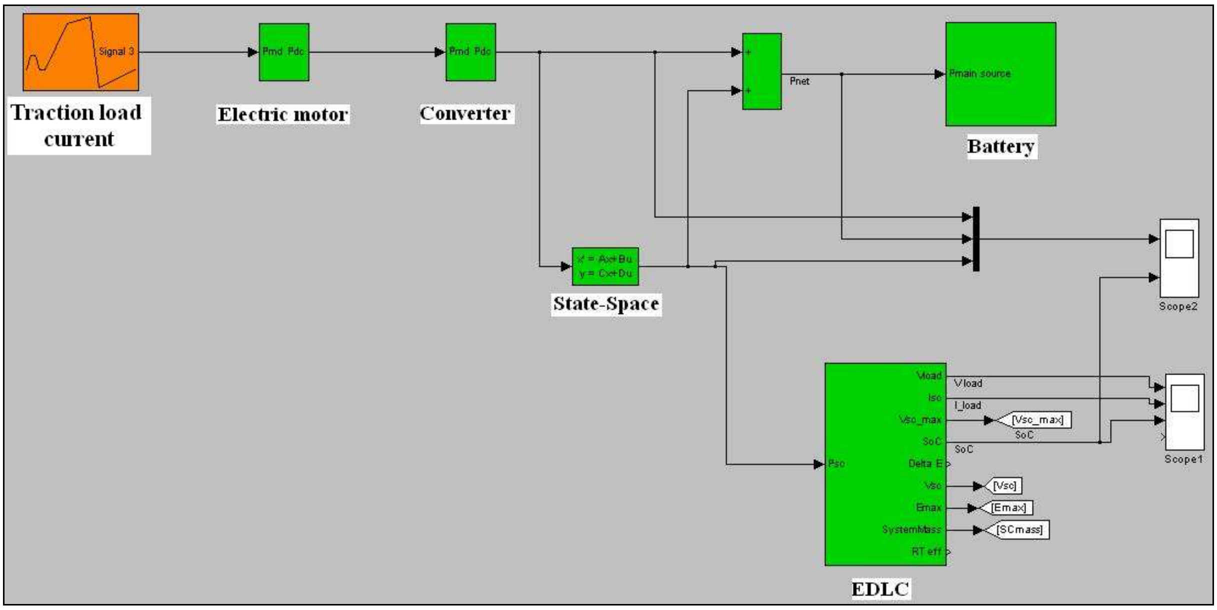

Fig. 4. Detail of lift truck model in simulation program

4 Models

4.1 Battery model

The simplified Thevenin model in Fig. 5 is used for this study with voltage source V_o in series with an internal resistance R_b which can be considered constant. Both, voltage and resistance values are generally functions of the battery State of Charge (SoC_b) and temperature. The state of charge of the battery can be expressed as [7]:

$$SoC_b = 1 - \frac{I_b^{\ k}}{(C_b * 3600)\left(\frac{C_b}{X_b}\right)^{k-1}} \qquad (1)$$

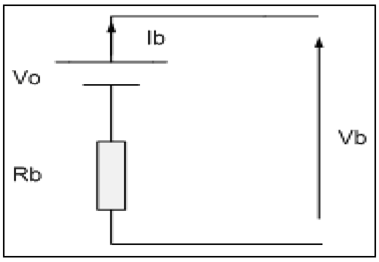

Fig. 5. Battery model [7]

Where C_b is the initial battery capacity, X_b is the rated ampere-hour and I_b is the battery current and k is the Peukert number.

The terminal voltage is given by:

$$V_b = V_o - I_b.R_b \qquad (2)$$

4.2 Supercapacitor model

One of the simplest ways of modelling supercapacitors is to model it as a generic capacitor, having a resistance in series R_s representing the charging and discharging resistance, a resistance in parallel R_P representing resistance the self discharge and a capacitor C.

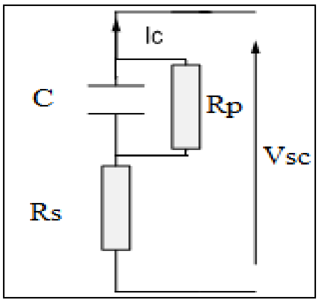

Fig. 6. Supercapacitor model [7]

The study under investigation is a short-current analysis of the current distribution between super capacitor bank and battery bank during acceleration and deceleration. Hence, the leakage resistance R_P can be ignored without much error, the supercapacitor model can simply be presented by a series RC-circuit.

The State of Charge (SoC) of the supercapacitor is the ratio of its instantaneous terminal voltage V_{sc} to the nominal voltage $V_{sc\text{-}max}$ [7].

$$SoC_{sc} = \frac{V_{sc}}{V_{sc-\max}} \qquad (3)$$

4.3 Simulation model

The term ‘hybrid energy storage system’ (HESS) means an energy storage system containing both a battery and a supercapacitor. The concept is generally successful because it exploits the strengths and compensates for the weaknesses of each storage device.

To evaluate the behaviour of such system, a simulation model based on the circuit as displayed in Fig. 7 is required. The model is enabled to calculate the current contribution of each branch to an imposed load profile. By giving the internal resistances of the battery and the supercapacitor pack, the supercapacitor capacitance and the starting voltage, the model can calculate the respective current distributions to the peak load.

Further the internal resistances in the model are assumed to be constant.

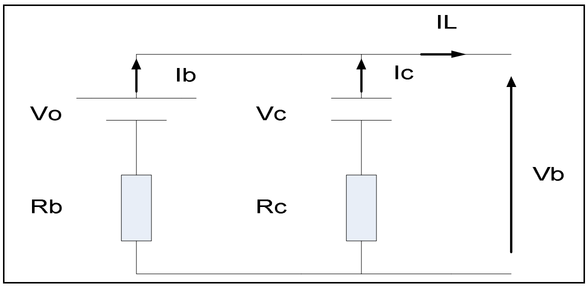

Fig. 7. Parallel setup of supercapacitors and batteries

Based on a certain current profile, the battery current I_b and supercapacitor current I_c are found by Kirchoff’s current and voltage laws.

$$I_L = I_b + I_c \qquad (4)$$

$$V_o - I_b * R_b = V_c - R_c * I_c \qquad (5)$$

$$I_c = -C\frac{dV_c}{dt} \qquad (6)$$

Substitution of (4) and (5) in (3) leads to the first order equation of $\frac{dV_c}{dt}$:

$$\frac{dV_c}{dt} = -\frac{R_b}{C(R_b + R_c)} I_L + \frac{1}{C(R_b + R_c)} V_o - \frac{1}{C(R_b + R_c)} V_c \qquad (7)$$

Substitution of (4) in (3) results to I_c:

$$I_c = \frac{1}{R_b + R_c} V_c + \frac{R_b}{R_b + R_c} I_L - \frac{V_o}{R_b + R_c} \quad (8)$$

The equations (6) and (7) can be implemented in Matlab Simulink® by using a *state space* [17] block as presented in Fig. 4.

The parameters R_b, R_c and V_o can be derived from the equations 9 to 11.

$$R_b = R_{bcell} \frac{N_R^S}{N_R^P} \quad (9)$$

$$R_c = R_{ccell} \frac{N_R^S}{N_R^P} \quad (10)$$

$$V_c = V_{cell} \frac{N_R^S}{N_R^P} \quad (11)$$

	Symbol	Value
Battery pack		
Capacity	C_b	960Ah
Rated cell voltage	V_{cell}	2V
Internal cell resistance	R_{bcell}	1mΩ [23]
Number cells in series	N_R^S	40
Supercapacitor pack		
Rated cell capacity	C	600F
Rated voltage	V_{cell}	2.5V
Number cells in series	N_R^S	30
Number cells in parallel	N_R^P	1
Internal cell resistance	R_{ccell}	0.8mΩ
Motor & converter		
Motor efficiency	η_{motor}	90%
Converter efficiency	$\eta_{convrter}$	91%

Table 2. Model specifications

5 Simulations results

Simulations were performed using a real current profile of battery powered lift truck as presented in Fig. 8.

Fig. 8 shows the current waveform in function of the time. The red line represents the required current while the blue and green lines represent the battery and supercapacitor current. One can observe that the supercapacitors supply most of the energy in transient state while in steady state the batteries current ramps up slowly and the supercapacitor current decreases according to equation 12.

$$I_b = I_l - \frac{I_L . R_b}{R_b + R_c} e^{-t/\tau} \quad (12)$$

Where $\tau = C(R_b + R_c)$ is the time constant
It is clear that this association allows reducing the battery peak current. Consequently, this makes it possible to increase the lifetime of the battery and to improve the performances.

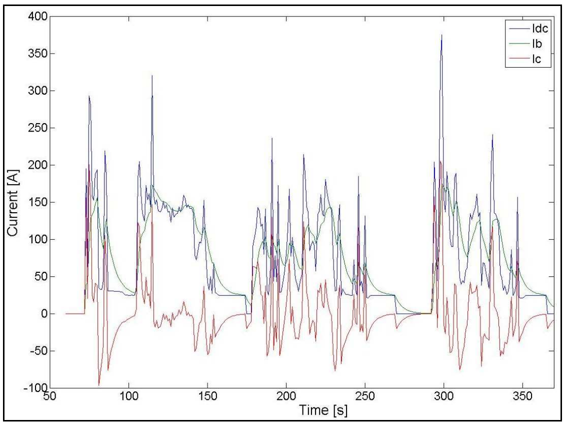

Fig. 8. Current flow versus time

Fig. 9 notices the supercapacitor voltage V_c follows immediately the pulse, while after the pulse the supercapacitor voltage begins to rise because the battery is charging the supercapacitor. It continues to rise until $V_b = V_{sc}$.

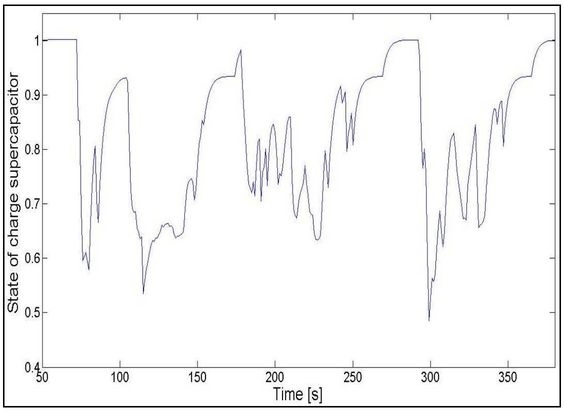

Fig. 9. SoC supercapacitor versus time

At least one can observe that the open circuit voltage is lower due to reduced battery current through the internal resistance with supercapacitors in parallel as shown in Fig. 10.

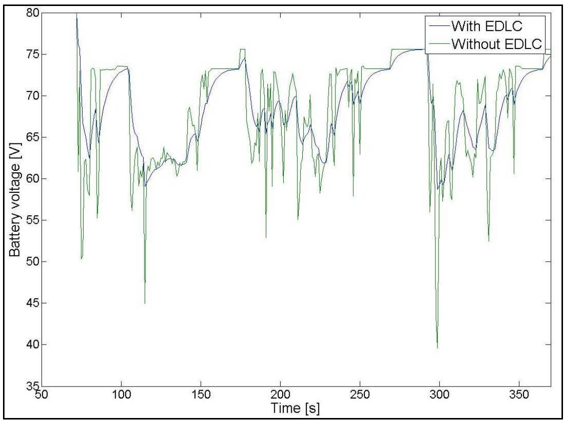

Fig. 10. Battery voltage versus time

6 Experimental results

To evaluate the performances of the battery and the super capacitor system an experimental test platform of hybrid electric vehicles has been used as shown in the photo in Fig. 11. This platform is consisting of:

- A battery module of 4 12V VRLA batteries of Enersys®, 2.5mΩ in series (2);
- Different super capacitors modules (650F and 2X650F,) of 24 cells (5) Maxwell®;
- DC motor LEM200 (7), the motor in the test platform is mechanically coupled to another electrical machine and which will function as the load of the drive train. This machine will be indicated as the "load machine" (1). When the motor of the electric drive train will accelerate, this load machine will have to apply a load torque which corresponds to the torque which would be acting on the motor when used in a vehicle.
- BRUSA® Motor controller (4);

The test bench is controlled by a real time controller, existing of a National Instruments PXI system with a reconfigurable I/O using FPGA for custom discrete and analogue control.

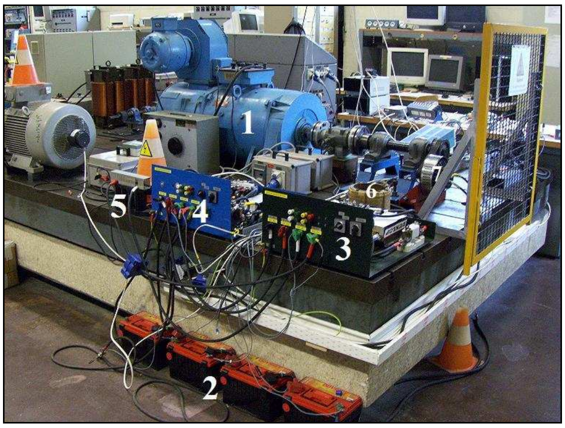

Fig. 11. Test platform of hybrid electric vehicles

Due to the permissible current through the controller of the motor, limited to 200A, the load profile (see Fig. 8) has been scaled with a factor 2.

A first measurement was performed considering a direct connection of the batteries with a supercapacitors unit to the DC-bus. Both the current coming from the main energy supply system in our case the battery pack (I_b) and the current coming from the supercapacitors (I_c) were measured and compared with the simulated results. The comparison of both simulated and measured parameters demonstrates a good correlation when the internal resistance R_b is 40mΩ (see Fig. 12). The relative error is less than 5 %. The mentioned R_b in the supplier data sheet is often based on statics tests. It doesn't take in account that this parameters is in function of the state of charge and temperature. This value could be used further to analyze the behaviour of the battery pack with supercapacitor unit in a simulation model.

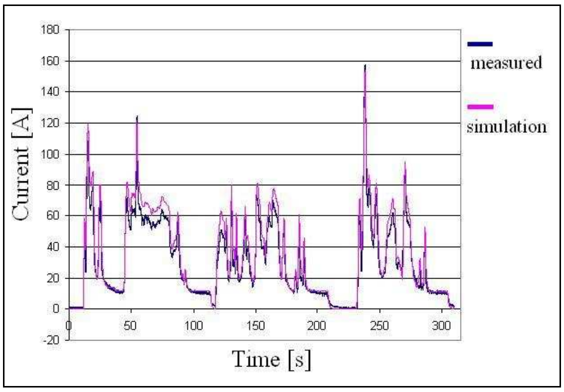

Fig. 12. Measured and simulated current versus time

When considering the current coming from the battery pack (I_b), one can observe that the battery pack has been relieved with 20%.

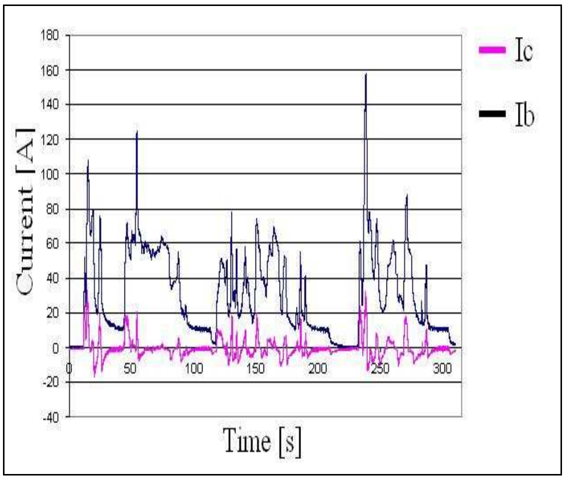

Fig. 13. Measured battery and supercapacitor current versus time for SC capacity 27.3F

Second test was performed considering 2 strings in parallel. According to equation (13) the capacity of the supercapacitor package will increase from 56.6F compared with 27.3F in previous association.

$$C_{tot} = C_{cell} \cdot \frac{N_R^P}{N_R^S} \tag{13}$$

Due to increasing the capacity, the supercapacitors will be able to provide more energy than before. So the relieving percentage of the battery pack is increased to 30%.

Confirmed by simulation and practical tests, this association makes it possible to reduce the battery current. These results to minimize the voltage drop across the internal resistance of the battery.

The rms current is responsible for the majority of the heating effects in the battery, through ohmic losses ($I_b.I_b^2$). Minimising this heating (through minimising battery current) will have beneficial effects on the battery lifespan, as gassing and hence electrolyte loss and also grid corrosion, are all temperature dependant.

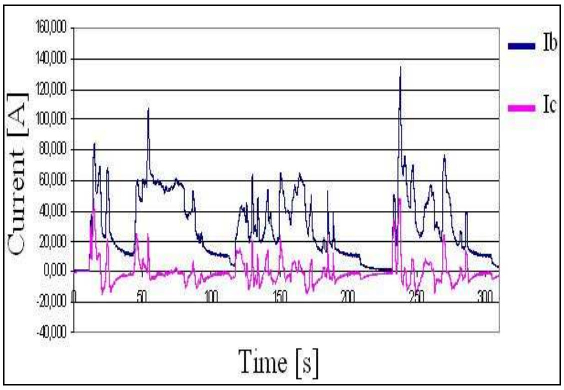

Fig. 14. Measured battery and supercapacitor current versus time for SC capacity 54.6F

This association has beside positive side also one negative point namely increasing of the battery consumption, due to increasing the total internal resistance of the whole system (R_b+R_c). This is presented in Table 3. But the increase is too little so it can be neglected.

Consumption [Ah]	Without SC	With SC 27,3F	With SC 54,6F
Measured	2.60	2.62	2.63
Simulations	2.59	2.60	2.60

Table 3. Battery discharge capacity

7 Life cycle analysis

We have seen in the previous chapters that the supercapacitors result reducing power rates from the batteries, which should extend their lifetime. However, an electric vehicle built by EVermont and tested at the Energy Technology Laboratory of Hydro Quebec found that the supercapacitors did not appreciably extend battery lifetime. However, three of the batteries in the battery pack had catastrophic failures compared to one battery in the supercapacitor assisted pack. Due to the failures more tests would be necessary to determine this. To evaluate this aspect, life cycle testing was performed using two ENERSYS 12V lead-acid batteries with a rated capacity of 57Ah (C_{5h}). Both batteries were subjected to the same current profile: battery only, i.e. case 1, and 2X6 cells 600F super capacitors in parallel i.e. case 2. The testing was conducted simultaneously using Digatron BTS600 testing device (see Fig. 15).

For evaluation, the Dynamic Endurance Test (DET) according to IEC 61982-2[1] was used as

[1] IEC 61982-2 specifies tests and requirements for capacity and endurance tests for secondary batteries used for vehicle propulsion applications. Its objective is to specify certain essential

reference as shown in Fig. 15. This test is consisting of a micro-cycle with [21, 22]:

- A high current to simulate acceleration (200A during 10s),
- A low current to simulate constant speed (50A during 20s),
- No current for pause period (30s)

Both batteries will be charged and discharged until 50 cycles.

Fig. 15. Testing device digatron

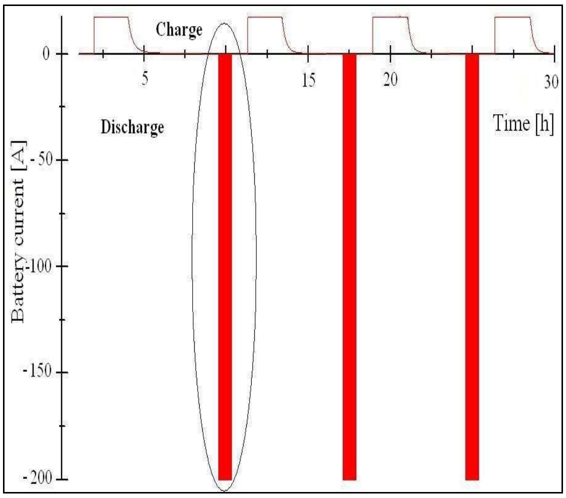

Fig. 16. DET-test

characteristics of cells and batteries used for propulsion of electric road vehicles together with the relevant test methods for their specification

7.1 Results

The benefit of the supercapacitor to extend the lifetime of the battery has been investigated. In table 4, one can observe that the battery with a supercapacitor pack in parallel has done 65 cycles compared to 50 cycles without supercapacitors.

	# cycles	Peukert constant	Begin battery cap. [Ah]	End battery cap. [Ah]
Case 1	50	1.22	40	31.9
Case 2	65	1.17	50	38.7

Table 4. Results of cycle life analysis

During the test the battery and supercapacitor currents have been measured as presented in Figures 13 and 14. Due to supercapacitors, the battery is providing only 0.46 PU while the supercapacitor is suppling 0.65 PU. With the time the battery current is increasing until 172A. Between 60 en 120s the battery current will not fall to zero but will decrease slowly to charge the supercapacitors until $V_b=V_{sc}$ is reached.
Here we recognise the advantage of the supercapacitor as a peak power unit to assist the batteries during high rates discharge and to avoid harmful phenomena as seen in chapter 1.

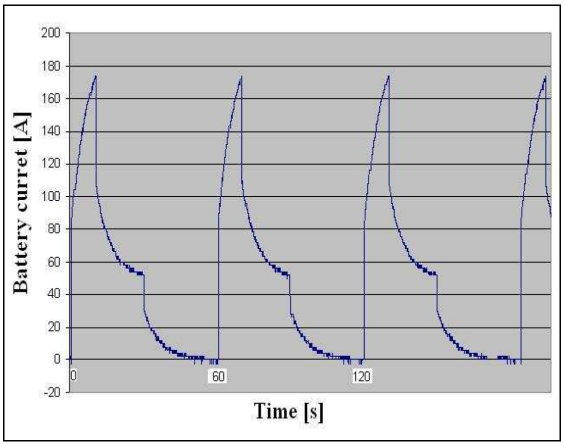

Fig. 17. Battery current versus time

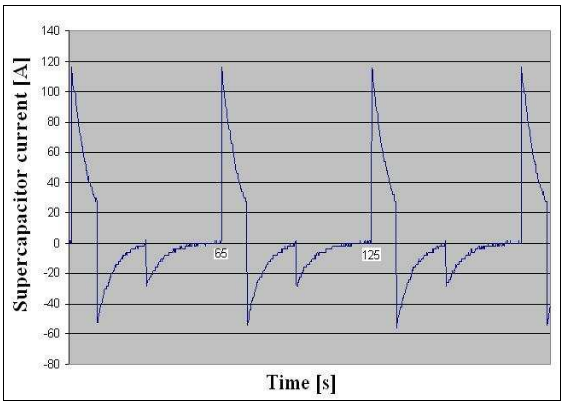

Fig. 18. Battery current versus time

Further in table 4 one can see that the battery capacity is 40Ah in case 1 compared to 50Ah in case 2. The difference in the capacity is mainly due to the Peukert effect. Peukert expresses the capacity of a battery in terms of the rate at which it is discharged. This is an empirical formula which approximates how the available capacity of a battery changes according to the rate of discharge as expressed in (14) [7].

$$C_p = I^k{}_{dis} . T_{dis} \quad (14)$$

Where C_p is the theoretical capacity of the battery expressed in Ah, I_{dis} is the discharge current, T_{dis} the discharge time and k is the Peukert constant. This equation shows that at higher discharge current, there is less available capacity in the battery. The Peukert constant indicates how well a battery performs under continuous heavy discharge current. A value close to 1 indicates that the battery performs well; the higher the value, the more capacity is lost when the battery discharge at high current. We see in table 3 again that due to supercapacitors the Peukert value is 1.22 in case 1 compared to 1.17 in case 2.

8. Conclusion

Due to their advantages, EDLC have many properties that make them well-suited for hybrid applications. A direct parallel configuration is a cheap and easy solution to be implemented. It reduces the battery stress by assisting with transients during acceleration and deceleration of the vehicle. As a result, this makes it possible to increase the lifetime of the battery, to achieve high global efficiency and to improve the energy performances of the whole system. Based on the life cycle analysis, this topology guarantees to extend the lifecycle of the battery with 30%.

The super capacitor is according to this configuration directly coupled to the DC-bus. An (expensive) DC-DC converter and associated management system are not required. However the amount of energy stored in the super capacitors depends on its voltage as expressed in equation 15.

$$E = \frac{1}{2} C.V^2{}_{\min} - \frac{1}{2} C.V^2{}_{\max} \quad (15)$$

For optimal usage, the super capacitor as a peak power unit, the voltage of the supercapacitor string should not be kept constant. Normally a super capacitor voltage ranges from 50% to 100% of its nominal voltage to keep an acceptable efficiency of the energy transfer.

The number of battery cycles can be extended more by implementation of a DC-DC converter. In order of a DC-DC converter the supercapacitors can be used optimal and the battery stress will be more reduced than in the topology proposed in this paper.

Finally, the selection of the appropriate propulsion system topology is very important.

8 Acknowledgments

This work was financial supported by Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT). The author would like to thank Enersys NV and Emrol NV for providing of both batteries and data.

9 List of abbreviations

Symbol	Explanation
C	Capacitor
C_b	Battery capacity
C_{cell}	Capacity of one supercapacitor cell
C_p	Theoretical battery capacity
E	Storend energy in supercapacitor
I_c	Supercapacitor current
I_{dis}	Battery discharge current
I_L	Total current (som of I_b+I_c)
$N_R{}^P$	Number of cells in parallel
$N_R{}^S$	Number of cells in series
R_b	Internal resistance battery
R_p	Parallel resistance of supercapacitor
R_s	Serie resistance of supercapacitor
SoC_b	State of charge battery
SoC_{sc}	State of Charge supercapacitor
T_{dis}	Discharge time
V_b	Battery voltage
V_o	Voltage source of battery
V_R	Rated voltage cell
V_{sc}	Supercapacitir voltage

V_{sc-max}	Maximal supercapacitor voltage
V_{sc-min}	Minimal supercapacitor voltage
X_b	Rated ampere hour
η_{motor}	Motor efficiency
η_{motor}	Converter efficiency
τ	Time constant

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