

Assessment of Behaviour of Super Capacitor-battery System in Heavy Hybrid Lift Truck Vehicles

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Abstract

This paper represents an alternative energy storage system in the drive line of a hybrid electric vehicle. The effect of the use of an 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 is investigated. In this work a topology is presented where the performances of a battery pack in parallel with supercapacitors are evaluated in terms of stress and extending battery lifespan. According to this association the battery current drawn is reduced and the supercapacitor source supplies the majority of transient current and as a result the battery stress is reduced up to 30 %. Other laboratory tests showed a fourfold improvement over stand alone lead acid battery pack under a Dynamic Endurance Test in which the lifetime of the battery is increased with 30 %. This work has been carried out on computer simulations. Finally the simulations results are validated on a test bench.

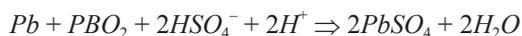
Keywords

battery model, simulations results, electrical double layer capacitors, lead acid, dynamic endurance test

1. INTRODUCTION

As the global economy begins to strain under the pressure of rising petroleum prices and environmental concerns have spurred research into the development of various types of Hybrid Electric Vehicles (HEV's). 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 [Emadi et al., 2005]. The battery pack (lead acid) in conventional fork lift trucks, is sized for peak power demand. Cycling the battery at high power rates leads to [Bockeris et al., 1981]:

- (1) To reduce available capacity. This reduced capacity is caused by the isolation of active material due to the blocking of PbSO₄ molecules by sulphate deposition during high rate discharge, which has twice the volume of the PbO₂.



The number and the position of these molecules depend on the reaction speed which is linked to the discharge current value. These molecules have the properties of bad conductors. So the battery capacitance value is lower than with small cur-

rents. The higher the current, the less are the amperes hours (Ah's) furnished by the battery. This effect has been already investigated by Peukert [Bockeris et al., 1981; Kozawa, et al., 2005].

- (2) Physical degradation of the battery structure. High discharge currents normally encountered by the battery lead to higher RMS currents, with accompanying higher operating temperatures.

This gives rise to considerably shorter battery lifetime, due to increased grid corrosion, and increased gassing within the battery, leading to separator dry out, and eventual cell failure [Adam et al., 2006].

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. Therefore the lifetime of the batteries should be extended. Another potential benefit of minimizing battery currents is increased reliability of the batteries by reducing the chance of a catastrophic failure through short circuiting or thermal runaway [Adam et al., 2006; Achaibou et al., 2008; Cooper et al., 2009].

Under such background, a hybrid energy storage system consisting of a battery with high specific energy and supercapacitor with high specific power will be proposed.

In this study, the topology consisting of a battery pack connected directly in parallel to the supercapacitors is

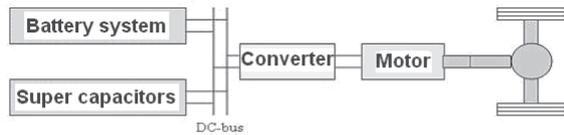


Fig. 1 A parallel connection of batteries to EDLC

investigated (Figure 1). The goal of this association is to reduce battery stress in order to extend the lifespan of the battery pack.

2. TRUCK DESCRIPTION

The vehicle system considered in this study is an electric lead-acid powered fork lift truck (CAREER R45 NCF). This vehicle is designed to drive with a maximum speed of about 16 km/h. It can lift max. 4,500 kg. Further, it has two DC-motors; one is used for driving the vehicle 17 kW and the other one for lifting 15 kW. The mast is hydraulically operated by one or more hydraulic cylinders. The battery pack has a capacity of 960 Ah and the operating voltage is 80 V.

3. METHODOLOGY

To model HEV systems is quite a complex task. There are several software environments suitable for analysing such systems. For this task the Matlab® Simulink® software program has been used to model the vehicle system. It is at present a widely spread simulation program both in industry and in academia. Other accessible simulations models are Modelica, Advisor, CRUISE, Vehicle Simulation Program (VSP) [Van Mierlo, 2000], SIMPLEV and EHVSP.

A simulation program based on the “effect cause” also called the “wheel-to engine” has been developed [Van Mierlo, 2000]. 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 bat-

tery pack and from the supercapacitors pack. Figure 2 shows a detail of the lift truck model inside the simulation program.

4. SIMULATION MODEL

To evaluate the behavior of supercapacitors connected in parallel to batteries, a simulation model based on the circuit as displayed in Figure 3 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.

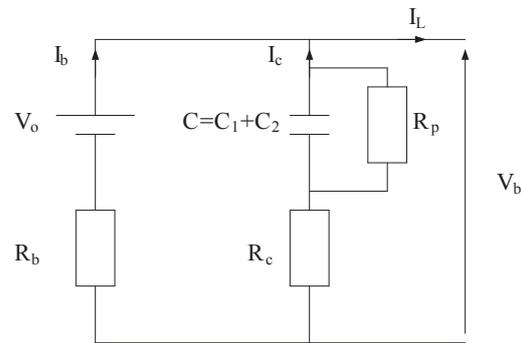


Fig. 3 Parallel setup of supercapacitors and batteries

To use supercapacitors as an energy storage device in vehicles, several cells in series or parallel-series are needed because of their low voltage. The pack model can be simplified by modeling a single cell and choosing the type of cell association to design the pack [Barrade *et al.*, 2003]. The supercapacitor model is made up of an internal resistance R_c and a resistance in parallel R_p representing resistance the self discharge [Van Mierlo *et al.*, 2003].

The leakage resistance R_p can be ignored without much error, the supercapacitor model can simply be presented by a series RC-circuit. The model has further an equivalent capacitance C that has two compo-

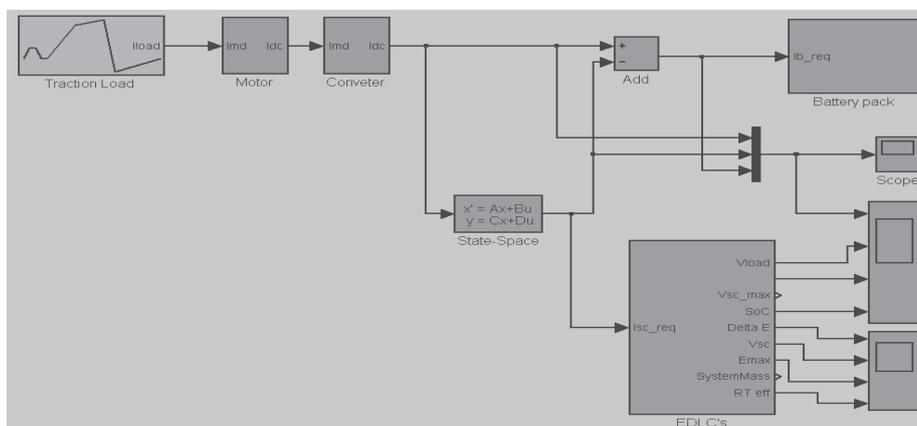


Fig. 2 Simulation model of lift truck according to topology presented in Figure 1

Tabel 1 Maxwell cell parameters [Maxwell, 2009]

Name	Symbol	Value	Unit
Cell Number in series	N_R^S	30	-
Cell resistance	ESR	0.8	mΩ
Initial capacitance	C	650	F
Rated cell voltage	V_{cell}	2.7	V

nents: 1) C_1 , which changes as function of voltage and has as a role to give the evolution of energy during the times of charge and discharge, and 2) C_2 , which describes the internal distribution of energy after the charge or discharge.

The battery is modelled by an equivalent electric circuit. It is composed of a voltage source V_0 with an internal resistance R_b . It is not easy to develop a general model that takes into account all the battery phenomena as physics and chemical because of their relative complexity. The existing models in the literature for lead-acid technology are generally complex to implement, because several parameters have to be determined. The used battery model is represented in Figure 3.

Table 2 Battery parameters

Name	Symbol	Value	Unit
Capacity	C_b	960	Ah
Voltage	V_b	80	V
Internal resistance	R_b	80	mΩ

5. SIMULATION RESULTS

Simulations were performed using a realistic current profile of battery powered lift truck as presented in Figure 4. This figure illustrates the division of current between the battery and supercapacitor in function of the time. The red line represents the required current while the blue and green lines represent the battery and supercapacitor current. It can be seen that

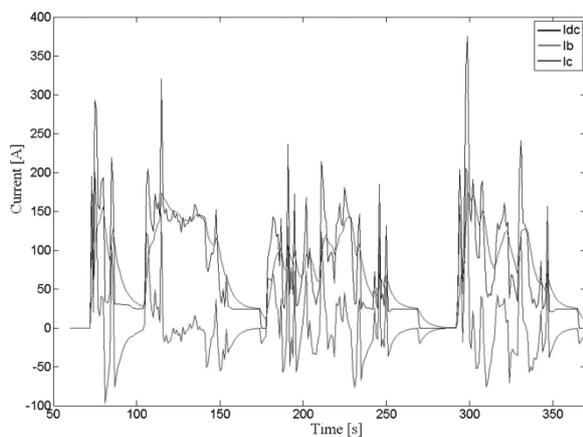


Fig. 4 Current flow versus time

the short time constant of the supercapacitor allow to 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 1.

$$I_b = I_L - \frac{I_L \cdot R_b}{R_b + R_c} e^{-t/\tau} \tag{1}$$

Where: $\tau = C (R_b + R_c)$ is the time constant

Further, noticeable in Figure 5, the supercapacitor voltage V_{sc} follows the pulse immediately, while after the pulse the supercapacitor voltage begins to rise because the battery is charging the supercapacitor due to the interaction between the supercapacitor and battery packs. The battery current remains in break times positive while the supercapacitor current becomes negative. The battery is effectively charging the supercapacitor during these periods until the supercapacitor voltage is equal to battery voltage.

One can observe that this approach results in a reduction of battery voltage excursions compared with the unassisted battery pack as presented in Figure 5. It is clear that this association allows reducing the battery stress. Consequently, this approach makes it possible to increase the lifetime of the battery and to improve the performances.

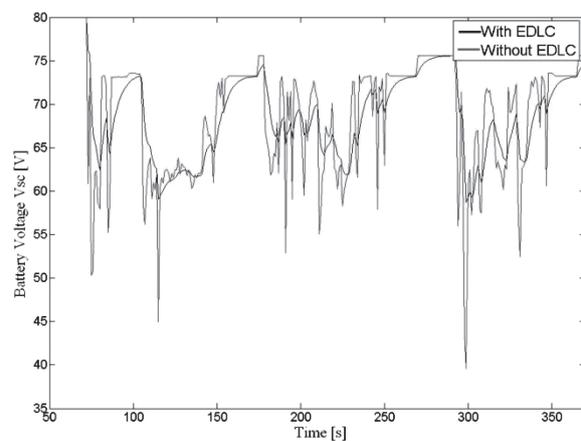


Fig. 5 Battery voltage versus time

6. TEST BENCH DESCRIPTION

To evaluate the performances of the battery and the super capacitor system an experimental test platform of hybrid electric vehicles has been used as presented in Figure 6. This platform consists of:

- A battery module of 4 12 V VRLA batteries of Energysys®, 2.5 mΩ in series (2);
- Different super capacitors modules (650 F and 2 × 650 F), of 24 cells Maxwell® (5);
- DC motor LEM200 (6), the motor in the test plat-

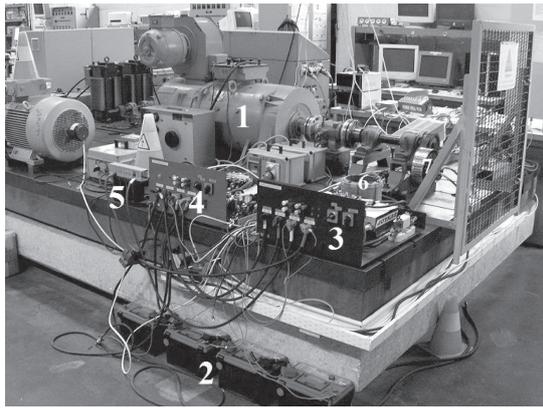


Fig. 6 Test platform of hybrid electric vehicles

form 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”. 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);

Due to the permissible current through the controller of the motor, limited to 200 A, the load profile (see Figure 4) has been scaled with a factor 2.

7. EXPERIMENTAL RESULTS

A first measurement was performed considering a direct connection of the batteries with a supercapacitor 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 40 mΩ (see Figure 7). The relative error is less than 5 %. The mentioned R_b in the supplier data sheet is often based on static tests. It doesn't take in account that this parameters is in function of the state of charge and temperature [Van Mierlo *et al.*, 2003].

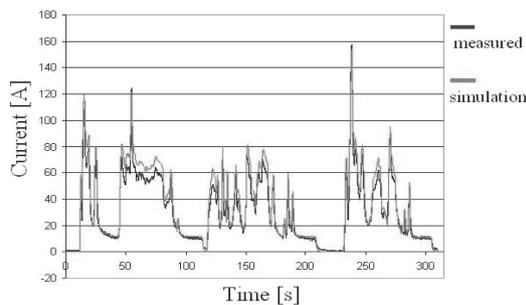


Fig. 7 Measured and simulated current versus time

This value could be used further to analyze the behaviour of the battery pack with supercapacitor unit in a simulation model.

When considering the current coming from the battery pack (I_b), one can observe that the battery pack has been relieved with 20 % of peak currents (see Figure 8).

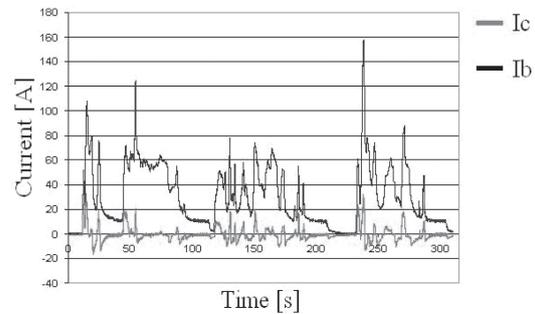


Fig. 8 Measured battery and supercapacitor current versus time for SC capacity 27.3 F

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

$$C = C_{cell} \frac{N_R^P}{N_R^S} \quad (2)$$

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 from 20 % 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 ($R_b \cdot I_b^2$). Minimising this heating (through minimising battery current) will have beneficial effects on the battery lifespan, as gassing and also grid corrosion, are all temperature dependant [Sugimoto *et al.*, 1998].

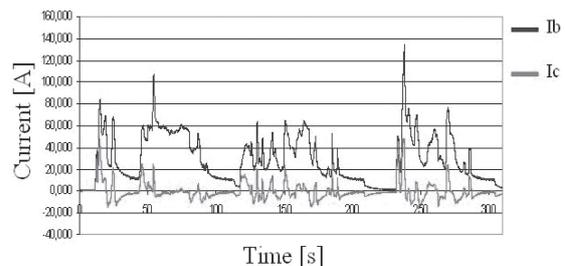


Fig. 9 Measured battery and supercapacitor current versus time for SC capacity 54.6 F

8. LIFE CYCLE ANALYSIS

We have seen in the previous chapters that the supercapacitors result in reducing the current 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 [Angers, 2005]. Due to the failures more tests would be necessary to determine this. To evaluate this aspect, accelerated life cycle testing was performed using two ENERSYS 12 V lead-acid batteries with a rated capacity of 57 Ah (C_{5h}). Both batteries were subjected to the same current profile: battery only, i.e. case 1, and 2×6 cells 600 F super capacitors in parallel i.e. case 2. The testing was conducted simultaneously using a Digatron BTS600 testing device (see Figure 10).



Fig. 10 Testing device digatron

For evaluation, the Dynamic Endurance Test (DET) according to IEC 61982-2 was used as reference as shown in Figure 11. This test is consisting of a micro-cycle with [Van den Bossche et al., 2007]:

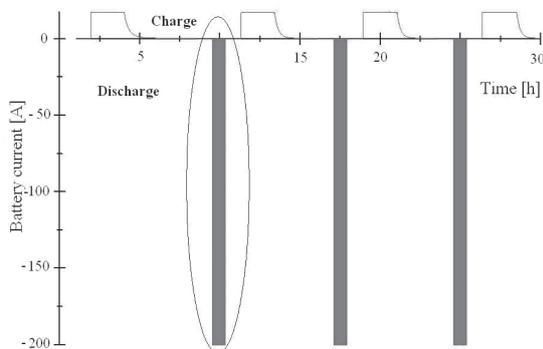


Fig. 11 DET-test

- A high current to simulate acceleration (200 A during 10 s) (see Figure 12),
- A low current to simulate constant speed (50 A during 20 s),

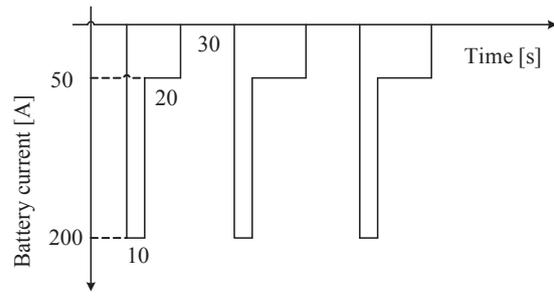


Fig. 12 Micro-cycles during discharge

- No current for pause period (30 s)
- Both batteries will be charged and discharged until battery capacity drops to 80 % rated capacity which considers the end of life of battery [Van den Bossche et al., 2007]. The benefit of the supercapacitor to extend the lifetime of the battery has been investigated. In Table 3, one can observe that the battery with a supercapacitor pack in parallel has done 65 cycles compared to 50 cycles without supercapacitors.

Table 3 Results of cycle life analysis

	# cycles
Without SC	50
With SC	65

9. LIMITATION

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 (3):

$$E = \frac{1}{2} C (V_{max}^2 - V_{min}^2) \tag{3}$$

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 [Hesam et al., 2008].

10. CONCLUSION

In this paper we have proposed a topology where the performances of a battery pack in parallel with supercapacitors are evaluated in terms of stress and extending battery lifespan. According to this association the battery current drawn is reduced and the supercapacitor source supplies the majority of transient current. According to the simulations and experimental results, the battery stress can be reduced up to 30 %. Other

results showed that this approach offers a fourfold improvement over stand alone battery pack in sense of battery voltage excursions. At least accelerated life cycling tests have proved the benefit of this topology in increasing the life time of battery pack with 30 %.

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