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Energy Storage System for Electric Vehicle

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Abstract: In this paper an alternative energy storage system in the drive train of a hybrid electric vehicle is investigated. In particular, it concentrates on the potential reduction of the stresses of the battery when electrochemical capacitors, a.k.a super capacitors, are added as high power energy storage. Different control strategies are evaluated and an estimation of the performance is given. In order to verify the simulation results, a downscaled HEV drive train consisting of NiMH batteries, electrochemical capacitors, a DC/DC converter and an external load, is built and tested. The results show a significantly reduction in battery stresses and a good agreement between the models used in simulations and the laboratory system. Finally, a weight optimization of such a system is briefly discussed.

Keywords: Capacitive energy storage, Electrochemical devices, Energy management, Energy storage, Power electronics, Road vehicle electric propulsion, Road vehicle power systems.

1. INTRODUCTION

The motorised vehicle is more than a hundred years old and has been continuously developed. Today, politicians and consumers are more and more considering the environmental effects of vehicular traffic and accordingly there is an interest in exchanging the conventional mechanical drive train with an electrical one and making the vehicle to either an all-electric vehicle (EV), or a hybrid electric vehicle (HEV). An EV has no internal combustion engine (ICE), but instead a large battery, charged from an external source when the vehicle is at rest. The HEV has a smaller battery, charged from either a generator driven by an on board ICE, or a fuel cell (FC).

Unfortunately, energy density [Wh/kg] and power density [W/kg] of conventional batteries are often dependent on each other. Batteries with high energy density have poor power density and vice versa. In addition, large charge and discharge currents cause losses and heating of the battery, which significantly decreases the battery lifetime. For these reasons, batteries must be oversized in terms of energy capacity to meet the power requirements of an HEV.

EC's, also called super capacitors or ultra capacitors, have extremely high capacitance compared to conventional capacitors (kF compared to μF). In contrast to batteries, EC's have high power density and poor energy density. Furthermore, they have almost negligible losses and a comparably long lifetime. Consequently, a combination of these two types of energy storage will in theory yield an equivalent energy storage system with both high energy density and power density, where energy is stored in the battery and peak power is supplied by the EC's.

However, since the charge and discharge profiles of the batteries and EC's are fundamentally different, they cannot be combined efficiently without a DC/DC converter. Adding this component also implicate the possibility to separately control the power flow between load, battery and EC's. With this ability, the high currents needed during acceleration and breaking can be supplied / absorbed by the EC's, potentially increasing the battery lifetime. Moreover, with the EC's supplying peak power, batteries with lower power density and higher energy density can be used, thus reducing the total weight.

This battery-EC system has been proposed already in the early nineties [1], but has not been put into production due to the complexity and, onto now, expensive design. Development has,however, accelerated during the past decade, yielding better performance and lower prices [2].

The aim of this paper is to investigate the battery-EC system in an HEV drive train. In particular, it concentrates on the potential reduction of the stresses of the battery. Finally a goal is to verify the results experimentally.

2. DRIVE TRAIN OF A HYBRID ELECTRIC VEHICLE

A. Drive train overview as a first step in the investigation of the battery-EC system, the drive train of an HEV is simplified in order to find appropriate models of each component. In general, there are two main design topologies of an HEV, the series design and parallel design. The parallel hybrid vehicle has an ICE and an electric motor arranged in parallel. The vehicle can be directly driven from the ICE or the electric motor, or both at the same time. When not used as a traction motor, the ICE can charge the battery via a generator. In the series hybrid vehicle, the traction motor is electric, with its electrical energy supplied from both a battery and an ICE driven generator or an FC. Using the series hybrid design, the ICE or FC can be kept at their optimum driving conditions and only operating when the battery needs to be charged. Moreover, when an ICE is used it can be made much smaller than a conventional traction ICE, since the battery supplies the peek power needed during acceleration. On the other hand, containing several energy conversions, the overall efficiency of the series HEV might be low compared to that of a parallel design HEV.

The series HEV drive train used in this investigation is presented in Fig. 1

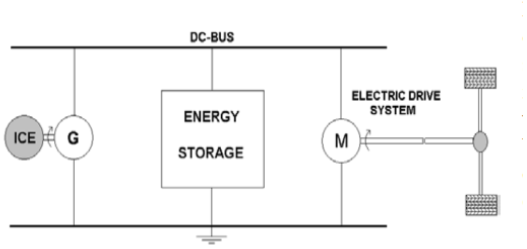

Fig. 1. Model of a series HEV drive train.

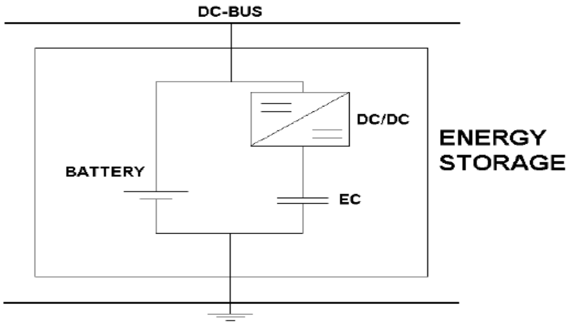

Fig. 2. Battery-EC energy storage system.

B. Battery

The battery is the main energy storage for electrical energy and is directly connected to the DC-bus. Consequently, charge and discharge is directly dependent on the DC-bus voltage and the open circuit voltage (VOC) of the battery. The VOC depends on several conditions, including battery type, number of cells, temperature and state of charge (SOC). During normal operating conditions, the variation in VOC is rather small. The SOC is a parameter describing the relative amount of stored energy in the battery. In other words, a SOC equal to 1 corresponds to a fully charged battery and a SOC equal to zero a fully discharged battery. Battery capacity is often measured in C_{Bat} [Ah].

C. DC/DC Converter

As mentioned earlier, a DC/DC converter is necessary to connect the EC’s to the DC-bus and to control the power flow between the battery and the EC’s. Ideally, the DC/DC converter transfers electric power between two sources having different voltages. Unfortunately, it possesses losses and restrictions on voltages and currents. These losses affect the overall efficiency of the system, and require a proper cooling system.

D. Electrochemical Capacitor

The peak power needed for acceleration and produced during regenerative braking is delivered / absorbed by the EC’s, connected via the DC/DC converter to the DC-bus. In other words, the EC is used as temporary energy storage for short intervals of large power. The capacitance of each EC is in the order of kF. The drawback is that the RWV (rated working voltage) of an EC is typically in the range of 2-2.7 Volt. Therefore, the EC’s consist of a large number of series connected elements but can in most aspects be treated as one equivalent, called “EC bank”.

However, energy and charge transferred to such systems will not be evenly distributed to the capacitors due to small differences in component parameters. When working with high power applications, this phenomenon can cause severe damage to elements exposed to over-voltages. There are several solutions to this problem [3]. In the simplest, passive balancing method, a resistance in the order of 1/10 –1/100 of the equivalent parallel resistance (see Figure 4) of the EC is connected in parallel with each capacitor, forming a voltage divider to distribute the charge evenly to the capacitors. These resistors must be rather small to ensure sufficient balancing, which in turn yields ohmic losses and fast self discharge of the EC-bank. Therefore, the more complex active balancing method has proved to be the only alternative in high-power applications with focus on performance and efficiency. Both passive and active balancing are used in the experiments, see section IV.

E. Dimensioning strategy

Generally, to dimension an energy storage system, a power profile for a typical driving cycle is required [4]. With such a profile at hand, the maximum power and energy that the system should be able to deliver can be calculated.

The ICE must be able to deliver enough energy to satisfy the maximum continuous demand of the vehicle, depending on speed and transport capacity etc. The ICE must also be able to efficiently charge the battery whenever needed.

During urban driving, it is desirable to drive short distances on battery only. In such cases, the battery should deliver the maximum steady-state power required, assuming that the EC’s supply the energy and power needed during acceleration. This maximum required specific power for urban driving, is obtained from the typical driving cycle used.

Moreover, if the ICE is assumed to have a relatively short start-up time, it is possible to exclude the conventional battery from the energy storage system. In that case, the EC’s are dimensioned to deliver the maximum energy and power required during acceleration from zero to maximum speed. This implies that the all-electric driving time becomes very short compared to an energy storage system containing batteries.

The energy and power demands of the EC’s depend on the control strategy. One general design rule and first assumption can however be that the EC’s should be able to deliver the peak power and energy required during the highest acceleration.

The voltage levels of the battery and the EC's depend on the maximum rated current of the components in the system and the peak power needed. Generally, the voltage of each component should be as high as possible to reduce currents and the ohmic losses associated to them.

3. MODELLING OF THE SYSTEM

Consisting of two or more energy sources, the drive train in an HEV is a complex system. In order to control the power flow between the traction motor and energy storage, the dynamic behaviour of each component of the simplified system, presented in Fig. 3, must be investigated. In this section, the origin and implementation of models are presented.

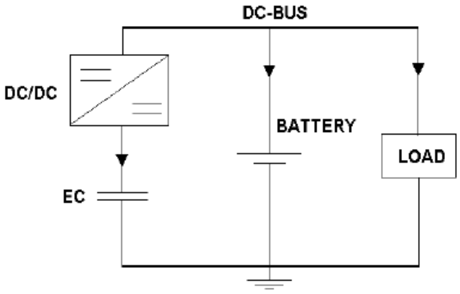

Fig. 3 . Simplified drive train of an HEV.

A. Electrochemical Capacitors

One of the simplest, but still quite accurate way of modelling the EC, is to model it as a generic capacitor, having one resistance in parallel and one in series with the capacitor (Fig. 4) [5],[6].

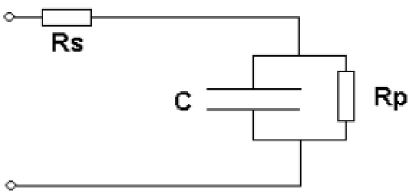

Fig. 4. Simplified equivalent circuit of the EC.

B. Battery

Compared to the EC, a battery is much more complicated to model. Internal temperature and SOC are two examples of important parameters difficult or practically impossible to measure. Therefore, a model developed by Advisor [7] is used in combination with experimental data in the simulations. Basically, this model is a Thevenin equivalent with parameters dependent on current, temperature and SOC etc. (see Fig. 5). In addition, using the model it is possible to calculate the total power losses, which is a valuable parameter for the evaluation of the system. A comparison between the voltage of the simulated battery model and measurements on the real battery is presented in Fig. 5.

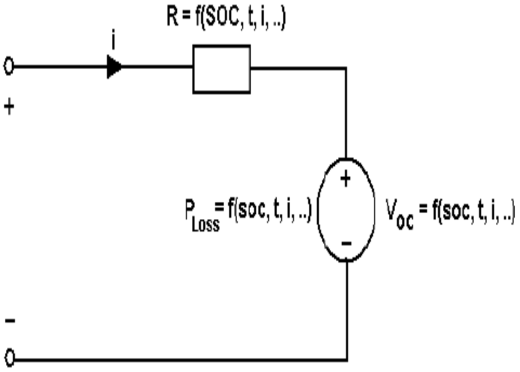

Fig. 5. Battery model used in simulations.

D. Load

The load used in the experimental set-up was Digatron thyristor based two-quadrant converter and could be modelled as a time dependent power source, using values according to the specific driving cycle and vehicle. In simulations and experiments, the required power is scaled by the system voltage, resulting in a component equivalent to an ideal current source. The required power is here calculated using ECE15-L power profile [4], widely used in life cycle tests for battery systems.

4. EXPERIMENTAL LABORATORY SET-UP

A downscaled test system was built using a NiMH battery, EC's, DC/DC-converter and a dSPACE system. In this section, the system (Fig. 6) is described including controllers, measurement system and computer interface.

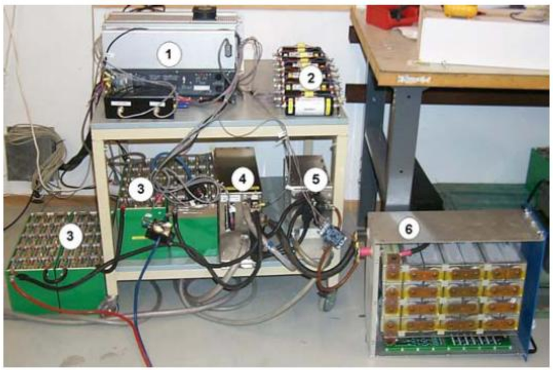

Fig. 6. The laboratory system used in tests of the *Size I* and *Size II* systems: 1. Power supply, opto-coupling card, dSPACE interface.2. EC Bank with passive balancing, used in the *Size I* system. 3. NiMH Batteries 4. DC/DC Converter 5. Inductance for the DC/DC Converter 6. EC Bank with active balancing, used in the *Size II* system.

The used batteries were of 20-cell each (1.25 V / cell), and the EC's were available in either ten separate elements or one package of 28-cells (referred to as Size I and Size II respectively). In practice, this means that the maximum voltage of the EC's was 25 V or 56 V, thus limiting the system performance in combination with the current limit of the DC/DC converter of 300 A. Since the battery voltage, due to the design of the DC/DC converter, must be higher than the EC bank voltage, two (Size I) or four (Size II) NiMH batteries were connected in series.

A. Control and Measurement System

To control the system, a dSPACE□ system was used and since the dSPACE® system are sensitive to over-voltages an analogue galvanic separated optocoupling card was used. This 8-channel component includes filtering, amplification (or attenuation) and galvanic protection of the computer – dSPACE□interface.

Voltage measurements were performed by adding a simple voltage division circuit at the input of the optocoupling card. Current measurements were performed using LEM modules. A simple schematic layout of the measurement system is shown in Fig. 7.

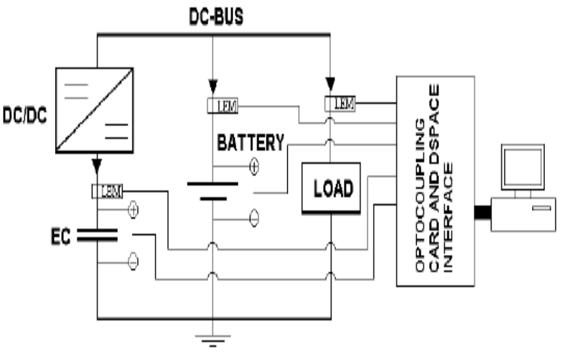

Fig. 7. Schematic layout of the measurement system.

A. To reduce the noise level, a filter having a cut-off frequency of 450 Hz was added directly on the optocoupling card's output terminals. The current measurements showed to be especially sensitive to interference. To further reduce this noise, another filter having a cut-off frequency of 1 kHz was added on the outputs of the LEM-modules.

B. Control of the DC/DC Converter

The only difference between the simulated and experimental control systems is the control of the DC/DC converter. In simulations, the converter is assumed to be an ideal DC-transformer. Therefore, the needed battery current is assumed to be the actual one as long as the converter is operating within its limits.

In the experimental set-up, the DC/DC converter is controlled by a reference voltage for the high voltage side. An internal circuit in the converter controls the switching of the IGBT's. The input signal to this controller is a PWM signal with the duty cycle proportional to the output voltage. Another internal controller limits the current at the low voltage side.

The reference voltage is set by a separate battery current controller implemented in MATLAB□/SIMULINK□. This controller receives the reference battery current and controls the DC/DC via the PWM input and a standard PI-controller. The optimum values of the controller parameters were determined after several tests.

5. EXPERIMENTAL RESULTS

Subsequent system simulations, numerous experiments were performed on two set-ups, Size I and Size II. Firstly, the models were verified and some parameters, like total series resistance in the EC bank, were determined. The control system developed was implemented and adopted to the MATLAB□/SIMULINK□/dSPACE□ environment.

1) Electrochemical Capacitors

The total series resistance, Rs, of the EC bank was measured by applying a current step and observe the immediate associated voltage step. The second component parameter, the leakage resistance, Rp, is in the order of a hundred times higher than the resistance used in the passive balancing circuitry. Therefore, it was not verified. For the EC's used, the equivalent series resistance (ESR) is approximately 0.6mΩ / capacitor element. The leakage resistance is approximately 1kΩ (data supplied from manufacturer).

2) DC/DC Converter

As mentioned earlier, the DC/DC converter is controlled by a PWM signal. The relation between the pulse width and the actual output voltage was obtained from several early experiments. The losses in the converter are dependent on several parameters such as current at high and low voltage side and the voltage conversion ratio. The loss function is, however, modeled to only depend on the current at the low voltage side. This function is determined from experimental data.

B. Size I System

As a first step, the Size I system was tested. Several tests were performed to find the highest possible EC voltage (using passive balancing). Two capacitor voltages are monitored individually to avoid over voltages. After each test, performance parameters are calculated and compared with simulated values.

In Fig. 8, the battery power and load power from simulation are shown and in Fig. 9 results from both simulation and experiment are shown. The experimental values show a slight time shift and differences in the load power magnitude. However, the main characteristics are very similar. This experiment is performed to verify the models and to point out the discovered drawbacks of the passive balancing method rather than to give a realistic estimation of the performance of a real system. In the next experimental set-up, the Size II system, the measurement system is re-calibrated to obtain better accuracy of the load power.

In Table 2, the performance parameters of the experimental system are presented together with results from the corresponding simulations.

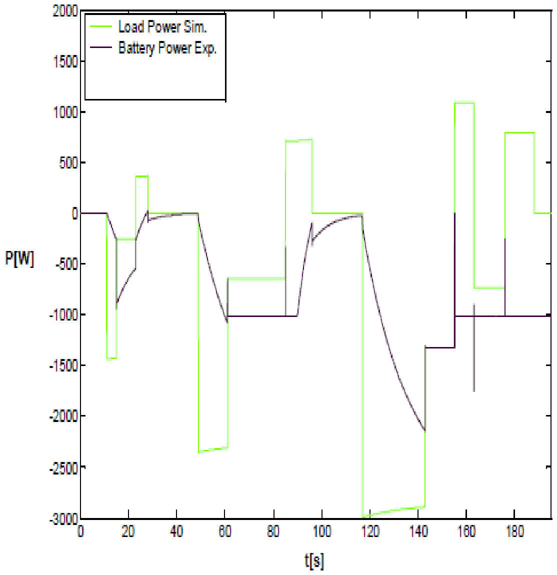

Fig. 8. Battery and load power from simulation with the *Size I* system.

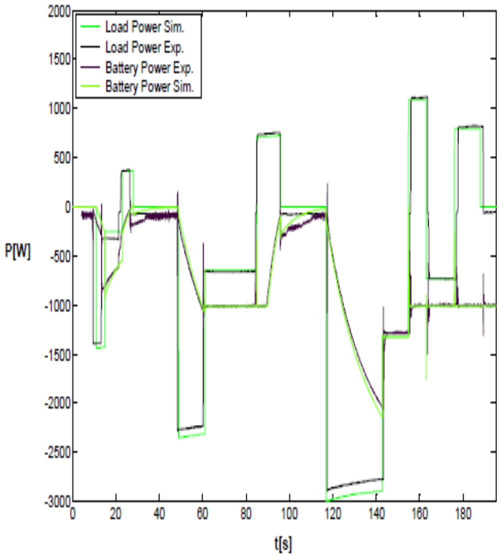

Fig. 9. Battery and load power from experiment and simulation for the *Size I* system.

TABLE 2 THE *SIZE I* SYSTEM PERFORMANCE.

Performance parameter	**Experiment**	**Simulation**	**Unit**
RMS battery Current	70	67	Reduction ratio in %
Power Loss in Battery	41	41	Reduction ratio in %
Total Energy Efficiency	81	81	%
Charge Control (average value)	84	83	% of reference voltage
Control parameters			
Initial EC voltage	88	88	% of RWV
Filter constant	20	20	S
EC Charge current	0.33	0.33	C_{Bat}

C. Size II System

Subsequent the Size I test series, the experimental laboratory system was re-built according to the Size II specification described earlier. Since this EC bank has active balancing, no upper voltage level other than the RWV is present. Consequently, the initial EC voltage can be set at the RWV. The results are discussed in section D.

When the results from simulations and experiments are compared (see Fig. 10), they are found to be in good accordance expect the time shift of the load power curve. This difference is due to the difference in battery voltage between simulations and experiment, as seen in Fig. 11.

D. Discussion

From the performance values (Table 2 and Table 3) and the power profiles presented in Fig. 9 and Fig. 10, it can be concluded that the models and assumptions used in the simulations are in good agreement with the real system. In other words, the simulated system offers a good estimate of how a real battery-EC system will perform. Three particular differences can be pointed out though:

- The time shift between the load power profiles is a consequence of the limited rise time for the current drawn / supplied by the Digatron□ converter. Moreover, the current direction cannot be altered instantaneously, resulting in a short period of zero current during each transition from acceleration to regenerative braking.
- The difference in magnitude of the load power during high currents, for example during the period t=120 to 140 s, has two reasons. Firstly, the calibration of the current measurements in the Size I system is made using relatively low currents and having the Digatron□converter as reference. This might cause inaccuracies in the current measurements, together with possible interference from strong electro magnetic fields during the test. The current measurement system is re-calibrated before the Size II system is built. Secondly, the battery model used in the simulations does not include the temporary decrease of VOC associated to high battery currents. This behaviour is shown in Fig. 11. The difference is not significant in the tests performed within this project, but during longer tests, this must be accounted for.
- The loss function used for the DC/DC converter is merely an estimation of the actual losses in the real system, causing additional inaccuracies in the simulations.

Compared to the results from the experiments of Size I, the over all efficiency of the Size II system is, as expected, increased due to the higher voltage levels, which decrease the relative system losses. In addition, the battery losses is further reduced in the Size II system, since the relation between the battery and the EC capacity is more in accordance with the reasoning in section II E.

It is possible that the performance of a real battery-EC system is further enhanced, since the necessary cooling of the batteries is decreased when the maximum battery power is decreased. Moreover, the total efficiency of the energy storage system could possibly be improved, compared to a conventional battery system, when the internal losses associated with large battery power are reduced. This could compensate for the added losses in the DC/DC converter and the EC bank.

WEIGHT OPTIMISATION OF A BATTERY-EC SYSTEM

As discussed above the battery-EC system could reduce the battery stresses. If the battery lifetime is already satisfying, another goal could be to minimize the weight of the system to be able to deliver a specific power and energy. One way of doing this is to plot the specific energy versus specific power [5] over the battery-EC system.

However, since this plot should show the power and energy densities for the entire system, the weight of the DC/DC converter must somehow be included. Here, assuming.

6. CONCLUSIONS

In this paper it was shown theoretically as well as experimentally that a battery-EC system can be used instead of a pure battery system with the same performance but with benefits such as reduced weight and reduced battery stresses. The reduced battery stresses are important in order to increase the lifetime of the battery.

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