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Charge/Discharge Load Reduction of Lead Acid Batteries in Micro-Hybrid Vehicles Using Ultra-Capacitor Assistance

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Abstract

Micro-Hybrid-Vehicles get more and more influence on the German market because of the fast rising fuel prices. With the ability of starting and stopping the combustion engine up to 7% fuel can be saved. In this article a simulation of a complete micro hybrid drivetrain and the electrical on-board net with ultra-capacitor assistance is presented. The adaptive controller yields in additional fuel savings and a significantly reduced charge/discharge load of the battery which results in higher lifetime. Based on the simulation the optimal Ultra-Capacitor size is determined for the configuration presented.

lead-acid battery , EDLC, cycle life, HEV

1 Introduction

Micro-hybrid-vehicles are an attractive alternative to the more complex mild or full-hybrid vehicles because of the low cost of manufacture. They, too offer the ability of regenerative braking, start/stop of the combustion engine and even boosting the combustion engine (though to a limited extent only). This can lower the fuel consumption by up to 7% [1]. The micro-hybrid configuration is favoured especially for compact cars [5]. But there are not only benefits. The start/stop functionality results in a significantly higher relative charge exchange. Also batteries are limited in their ability to take up and provide bursts of high power during events such as regenerative braking and start-up of the combustion engine. This will cause a reduced cycle life of the battery. To handle these drawbacks a second energy storage with a high cycle lifetime to support the battery is beneficial. Especially ultra-capacitors [4] can easily deliver such high power peaks without noticeable aging. The system design of micro-hybrids benefits from the use of ultra-capacitors as a second energy store achievsa better on-board net stability and capturs more regenerative braking energy [3].

2 Micro Hybrid Configuration

2.1 Classical Micro Hybrid Configuration

The classical micro-hybrid configuration in figure 1 differs only a little from a conventional vehicles. The micro-hybrid works with a lead acid battery at a $14\,V$ voltage level. Only the generator can either be designed as a belt-driven generator or as a combination of a belt-driven starter and a generator. The functional range of the micro hybrid consists of starting and stopping the combustion engine and saving regenerative braking energy within the battery. For example, the "Smart MHD" is a typical representative of a micro hybrid drivetrain using a belt-driven starter/generator and a lead acid battery. BMW

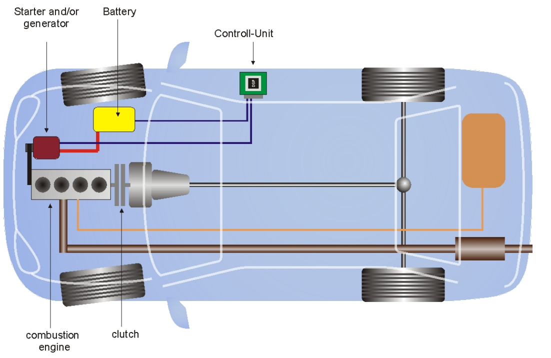

Figure 1: System design of a classical Mikro-Hybrid

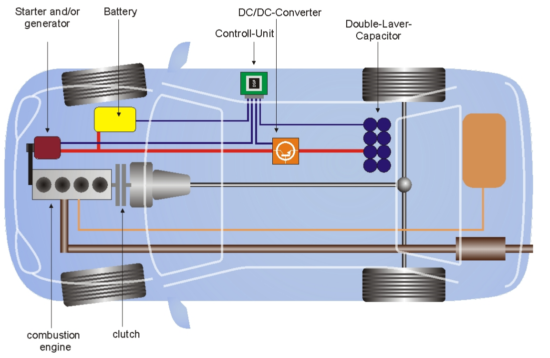

Figure 2: System design of micro hybrid configuration with DLC as a buffer

is using another technology in their vehicles with ”Efficient Dynamics”. Here the motor controlling unit is able to control the output voltage of the belt-driven generator and with it the energy exchange between the generator, the battery and the electrical on-board loads. So regenerative braking energy can be stored within the battery by increasing the generator output voltage. A normal crank-shaft starter is used for starting the combustion engine.

2.2 Double-Layer Capacitor as a Buffer in Micro Hybrid configuration

In figure 2 the system design of the double-layer capacitor-bufferd micro-hybrid vehicle is shown. The vehicle works with a typical lead acid battery at $14\,V$ voltage level and an ultra capacitor with a variable voltage level of up to $65\,V$. The double layer-capacitor (ultra-capacitor) is connected via a DC/DC converter with the $14\,V$ on-board electrical system to support the battery. Aslo a belt driven starter/generator is used. This configuration offersan additional degree of freedom because the double-layer-capacitor can be used as an additional energy source or energy sink in the electrical on-board net.

3 Simulation Environnent

The micro hybrid drivetrain was transferred to a MATLAB/SIMULINK simulation. The design was integrated into our hybrid vehicle simulator ”FAHRSIM” [2]. The simulation is structured in two parts shown in figure 3. One part represents the test vehicle, a gasoline operated Skoda Fabia III. Out of synthetic or real-world driving cycle data (block ”driving cycle data”), the speed profile, the altidude profile and the gear vector were extracted and fed into the block ”tire & gear”. In the block ”tire & gear” the rolling friction , the air resistance, the climbing resistance and the accelerating force were calculated using the characteristic vehicle parameters. The resulting engine speed and engine torque were scaled with the transmission ratio of the differential and manual gearbox. In the block ”combustion engine” the fuel consumption is calculated using an efficiency map. A positive engine torque will result in an actual fuel consumption. A negative engine torque below the total drag moment results in overrun fuel cut-off. For a detailed description of the FAHRSIM-toolbox the reader is referred to [2].

The second part represents the on-board electrical net with the generator, the battery, the electrical loads, the DC/DC-converter and the double-layer capacitor. Just like in a real car the electrical on-board net is connected to the drivetrain through the alternator only. The electrical on-board loads result in an additional engine torque which is added to the engine torque necessary to fulfilf the demands defined by the driving cycle data. Based on the equivalent circuits all components were simulated. Detailed descriptions of the models used can be found in [6]. The capacity of the ultra-capacitor model is variable. In table 1 an overview of the modelled on-board electrical components is given.

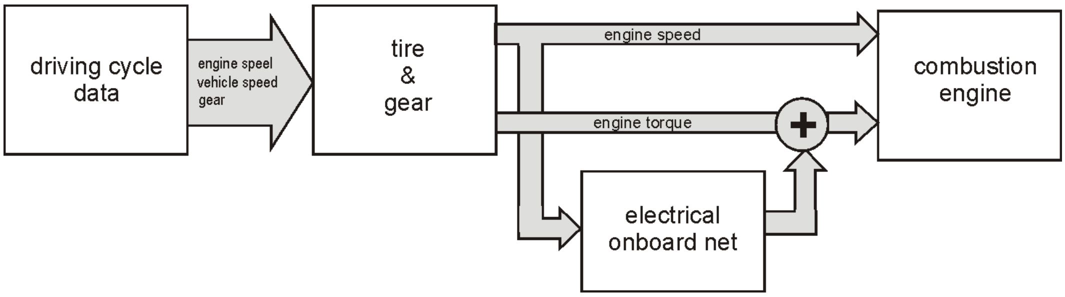

Figure 3: Overview of the simulation ”FAHRSIM”

Table 1: Components of the electrical on board net

Generator	**Bosch 14V 70-120A** Nominal level: $14\,V$ max. Current: $120\,A$
Battery	**Optima Yellow Top** Nominal level: $12\,V$ Capacity: $55\,Ah$
Ultra-Capacitor	**Based on Maxwell Boost-Cap** Nominal Voltage: $64,8\,V$ Capacity: $0 - 160\,F$ (variable)
DC/DC Converter	**3 phase DC/DC** max. Current @ 14V-side: $150\,A$ max. Current @ 64V-side: $50\,A$ max. continous power: $1500\,W$ efficiency: 90%

4 Simulation results

4.1 Simulation Results for the Classic Micro-Hybrid Configuration

Using start/stop mode in the classical micro-hybrid configuration offers a great fuel saving potential. In figure 4 the fuel saving potential is shwon over a constant electrical on-board net load using start/stop-mode in the NEDC compared to a conventional vehicle. The overall savings depend on the electric load. Higher electric loads result in a higher savings because of the better electrical efficiency of the generator. A higher electric load leeds to a higher additional combustion engine torque which also results in a higher mechanical efficiency of the combustion engine. One problem of the classical micro-hybrid configuration is a rapidly increasing charge exchange of the battery. The battery has to supply at least the necessary electrical loads like the motor controller during the stops of the vehicle when the combustion engine is off. Also components with vital functions like

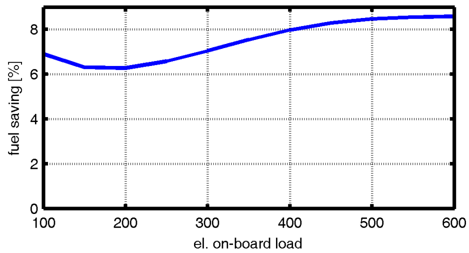

Figure 4: Fuel saving potential for the classical micro-hybrid configuration

the lights have to be supported. So every stop of the vehicle results in a discharging and later in a charging process of the battery. Figure 5 shows the load exchange of the battery in Ah for the NEDC driving cycle using start/stop-mode . This increased charge exchange affects the life

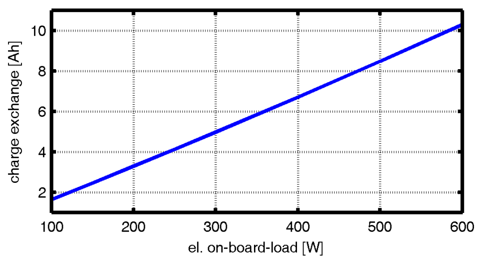

Figure 5: Charge exchange of the battery using start/stop-mode

time of the battery negatively. In figure 6 the correlation of the battery lifetime with an average electric load is shown. An average electric on-board net load of $300\,W$ will reduce the lifetime of a normal lead acid battery to less than 4 years with an estimated total mileage of the vehicle of $10,000\,km$ per year. $300\,W$ electrical load is a typical value representing only the absolutly necessary electrical components of a vehicle. The estimation is based on the NEDC driving cycle and the measurement done in [7].

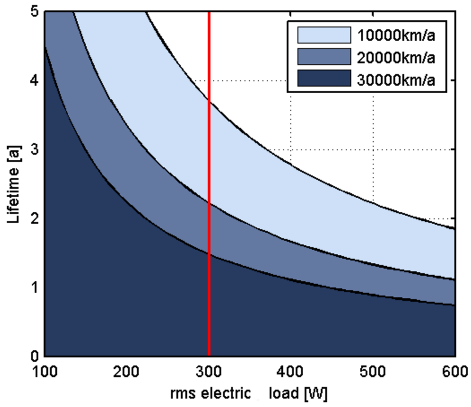

Figure 6: Estimated lifetime of a lead acid battery

4.2 Energy Management of the Double-Layer-Capacitor buffered Micro-Hybrid Configuration

Only two variables are used to manage the energy distribution in the electric on-board net of the double-layer-capacitor buffered micro-hybrid. The first is the output voltage of the generator. The second variable is the current of the DC/DC-converter on the $14\,V$ side. So the energy flow into and out of the capacitor can be controlled directly. The energy distribution between the generator, the battery and the electric loads is affected indirectly by the generator output voltage and the current flow of the capacitor. The capacitor is used to store as much regenerative braking energy as possible without affecting the state of charge of the battery. With that additional energy the battery can be supported during the stops of the car when no energy from the alternator is available. The strategy is implemented with a fuzzy controller [8].

4.3 Simulation Results of the Double-Layer Capacitor bufferd Micro-Hybrid Configuration

In figure 7 the overall fuel saving referenced to a non-hybridized vehicle is plotted over the size of the ultra-capacitor and the mean electric load. Obviously a higher electric load results in an increasing fuel saving. This is due to the rising generator efficiency. Of course, absolute final consumption increases with the electric load in both cases. The efficiency of the alternator varies from 20% up to 70% for the electric load values analyzed. With capacitances higher than $50\,F$ no more fuel saving improvement is obtained due to the limitations of the generator. Up to 10% of fuel saving can be achieved with a minimal capacity of Figure 8 shows the fuel saving in comparison to a ”classical” micro-hybrid employing start/stop mode. At low electric load, the fuel saving is very low because the stored regenerative braking energy cannot be spent. An optimal fuel saving can also be achieved at an electric load of about $300\,W$. For higher loads the fuel saving decreases due to the limitation of the maximum alternator current. Up to 2.5% additional fuel saving can be achieved using a capacity of $20\,F$.

Another very important issue is the stress for

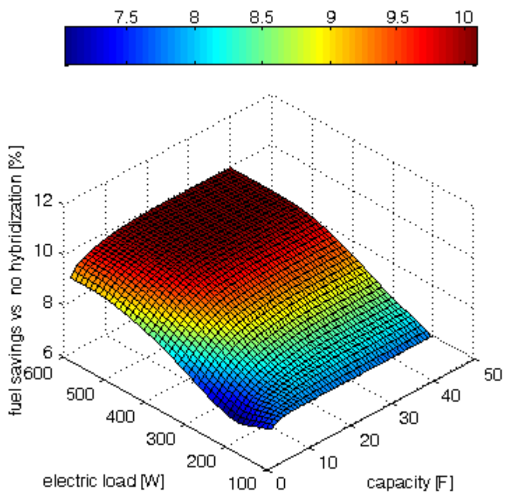

Figure 7: Fuel saving referenced to a non-hybridized vehicle

the battery in start/stop-mode. Figure 9 shows the relative transfer reduction of the charge to and from the battery over the mean electric load and the size of the ultra-capacitor, referenced to a micro-hybrid configuration using start/stop mode without a second energy storage. Up to 95% of the charge exchange can be done with the ultra-capacitor which reduces the stress on the battery by a factor of 20. This results in a significantly higher battery lifetime.

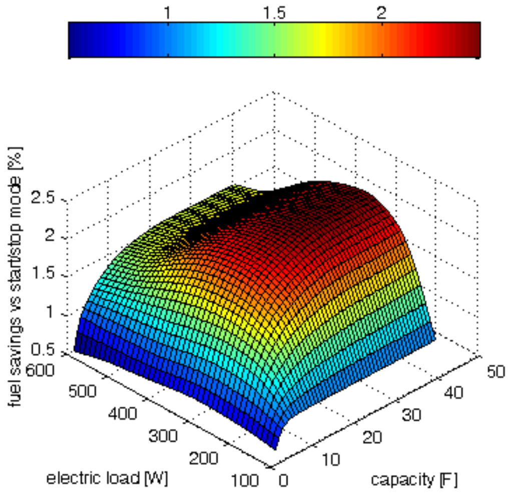

Figure 8: Fuel saving referenced to a ”standard” micro-hybrid employing start/stop mode

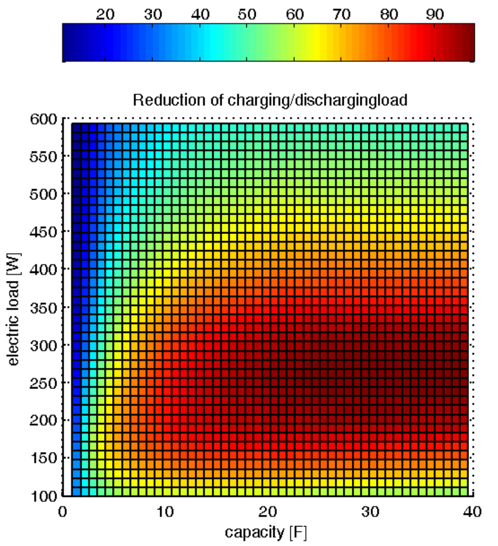

Figure 9: Relative reduction of the load exchange of the battery

5 Conclusions

The system design of micro-hybrid vehicles benefits from an additional ultra-capacitor energy storage. Not only the fuel saving can be improved up to an additional 2.5% in comparison to a ”classical” micro-hybrid in start/stop mode. Also charge transfer to and from the battery can be reduced to as little as 5%”. This results in a significantly higher lifetime of the battery. The overall fuel savings can be improved up to 10% instead of only 7.5% using start/stop-mode without ultra-capacitor assistance. The simulation results show that a capacitance of the additional energy storage of only $20\,F$ at $65\,V$ is sufficient.

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