Energy Storage Scheme for Rail-guided Shuttle using Ultracapacitor and Battery

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***Abstract* - *An energy storage system based on a combination of batteries and ultracapacitors for rail-guided shuttle is investigated. The control schemes according to the various power requirements in shuttles and the differing characteristics of these storage devices are proposed to manage the energy and optimize the power supply system performance. The power electronic converters connecting ultracapacitors, batteries and DC-link are studied. Simulation and measured results are presented, revealing that the separation of the dynamic load from batteries yield improvements in lifecycle, availability and long term costs and volume*.**

I. INTRODUCTION

Electrical energy storage units are the necessary elements for the operation of hybrid electric vehicles or rail guided shuttles. At present in most of these applications, the high energy density batteries, sized to provide both the energy and power required, are usually applied as the energy storage component. In load cases such as acceleration or driving on a bumpy road with a vehicle facilitated with an active suspension, the power required is relatively higher than the normal driving conditions, and the periods of peak power are relatively short, generally less than 30 seconds. Therefore a peak power energy storage unit is required, which can drastically relieve the dynamic stress of the battery [3][5].

Recently the advances of ultracapacitors technologies indicate that these commercially available devices are used effectively for hybrid energy storage in electric vehicles. Ultracapacitors, showing lower energy density but larger power density and longer life cycles than batteries, represent one of the latest innovations in the field of electrical energy storage, and find their place in many applications where alternative energy storage is needed. They release the costly battery from peak power, help in smoothing strong and short-time power solicitations of a distribution network, extract greater efficiency from existing power sources, and increase battery life [4][6].

In this contribution, a hybrid energy storage system based on batteries and ultracapacitors is designed and implemented for the energy supply system in an electric rail guided shuttle. The energy storage system structure is shown in Fig. 1. High energy density batteries are usually applied as the primary energy storage component to provide the continuous power. Ultracapacitors are responsible for the transient demand of power.

To ensure the reliable and effective operation of the energy distribution, the control schemes are investigated to store and deliver the electrical energy and are tested by simulation in order to achieve an optimal solution for both power and energy.

The bidirectional DC-DC converters were designed and implemented to realize the control of the energy flow to the ultracapacitors and batteries.

This energy storage system represents one part of the infrastructure used to validate a novel self-optimizing scheme outlined in [7].

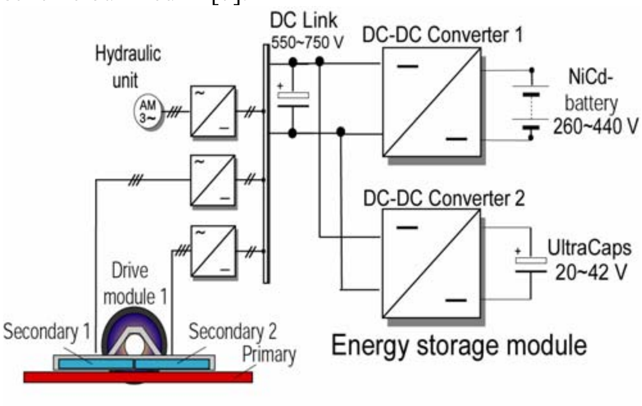


Fig.1 Energy Supply System Structure

II SHUTTLE ENERGY STORAGE SYSTEM

A. Power requirements of shuttle

In electric rail guided shuttles, developed within project NBP (Neue Bahntechnik Paderborn), the railway-driving vehicle technology is using a doubly-fed linear motor [1]. A test track in scale 1:2.5 and with a total length of about 530 m was established at the University of Paderborn for various investigations. The tested shuttles are designed to drive with a maximum speed of about 36 km/h, have a height and a width of about 1.2 m and a mass nearly 1200 kg.

The energy consumers, which are the linear motor secondary side driving module, hydraulic unit and 24V auxiliary power supply for the control system, are coupled via the DC link. The power requirements of these units are shown in table 1.

TABLE1: SHUTTLE CHARACTERISTICS

Parameters	value
Motor driving module	2.2 kW
Hydraulic unit	2.5 kW
24V auxiliary power supply	1.3 kW

B. Power supply system configuration

The on-board power supply system, which was designed especially for the demands of the doubly-fed drive structure, is shown in Fig. 1. The energy storage module consists of batteries, ultracapacitors and the dc-dc converters, which are required to have bidirectional capability interfacing energy storage element and the DC link. The individual control of the bidirectional converters provides the flexibility of the energy distribution. While batteries supply the continuous power, ultracapacitors are designed to absorb high regenerative braking energy and provide the demand of peak power during the acceleration of shuttle, thus limiting the otherwise very high charging current to the battery. In this way the negative effects of the characteristic limits of battery, such as limited life cycle, cold intolerance and critical charging rates are reduced. Therefore this energy storage system provides an efficient means to optimize the energy system management using a combination of different power sources, moreover provides the possibility to optimize the volume and weight of the energy storage system.

C. Energy storage element

1). Batteries

For an electric vehicle, the main energy needed to drive the vehicle must be stored in the main batteries. The batteries are constructed by 280 Ni/Cd battery cells connected in series. The specifications of the batteries are given in Table 2.

TABLE 2: BATTERY SPECIFICATIONS

Parameters	value
Energy Density	21Wh/kg
Energy	2.4 kWh

TABLE 3: 42V ULTRACAPACITOR MODULE SPECIFICATIONS

Parameters	value
Capacitance	145F
Rated Voltage	42V
Maximum Current	600A
Stored Energy	128 kJ
Maximum Series Resistance	10 mΩ
Weight	16 kg
Cycliablity	500,000

2). Ultracapacitors

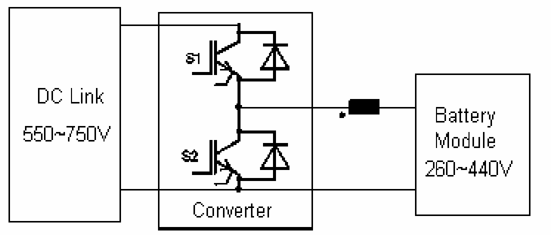
The primary disadvantage of ultracapacitors is their relatively low energy density (Wh/kg and Wh/l) compared to batteries. Hence, it is necessary to know the usable energy storage (Wh) and the maximum power requirements. In this study, the energy requirement is calculated based on the maximum power of 6 kW for 15 seconds, and assuming that 75% of the energy stored in the ultracapacitors is useable. This results in a total energy storage requirement of 33.3Wh or 120 kJ for the shuttle.

Presently ultracapacitor devices have cell voltages of 2.5 ~ 3V. The energy densities of commercially available large device (450 ~ 2600 F) have usable energy densities of 2.1 ~ 4.3 Wh/kg with peak power capability of 3 ~ 4 kW/kg. The standard modules are manufactured for voltages of 14, 28 and 42V. Each module shows the typical characteristics of the individual device, namely a high energy and power density [4].

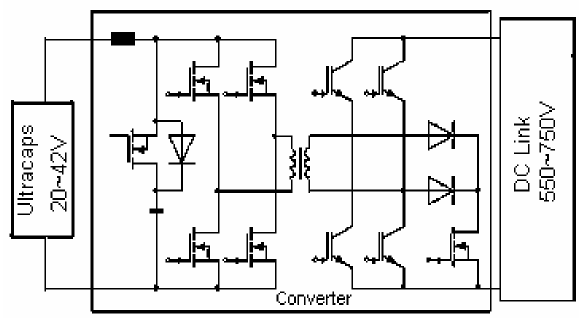
According to the energy requirement, a commercial ultracapacitor modules provided to the use of 42V systems in electric vehicle applications is selected. Such a 42V module could store 35.6 Wh or 128 kJ of energy. The peak pulse power is calculated about 18 kW when the voltage is 30V. The specifications of the 42V ultracapacitor module are given in Table 3.

III BIDIRECTIONAL DC/DC CONVERTER

As discussed above, in order to control the energy stored in ultracapacitors and batteries, both the voltage and current of the storage devices should be controlled through the bidirectional converters. And the voltage of DC link should also be controlled by one of the energy storage converters. To realize the controlling concept, two types of bidirectional converters control the energy flow between these energy sources are designed and implemented, shown in Fig.2.



(a) Converter between Batteries and DC-link



(b) Converter between Ultracapacitors and DC-link

Fig. 2 Proposed Bidirectional DC-DC Converter Topologies

The single stage buck-boost topology and the full-bridge topology are considered as typical candidates for realizing the bidirectional DC-DC converters. Compared with the full-bridge type, the single stage buck-boost type topology is characterized by the following items: lower boost ratio, and non-isolation between input and output stage; but the circuit is simple, requires less components, and higher efficiency is achieved. On the other hand, the full-bridge topology could be employed in these cases, in which higher boost ratio and electrical isolation are required.

For these reasons, a buck-boost DC-DC converter is used to connect Batteries and DC-link. Moreover an isolated full-bridge bi-directional dc-dc converter using phase shifted PWM control is employed to control the peak power flow through ultracapacitors, By using adequate clamp circuits across both bridges the voltage transient spikes are limited, and all switches are operated at soft switching conditions. The topologies of the converters are shown in Fig. 2 (a) and (b).

As shown in Fig. 2, the single stage buck-boost bidirectional dc-dc converter and the full-bridge bidirectional dc-dc converter are operated in the boost mode, when electric power is supplied from batteries or ultracapacitors to the DC link, i.e. from the low to high voltage side. On the contrary, both work in buck mode at the time electric power is absorbed from the DC link.

The voltage control and average current control are used here to control the energy flow and to improve the converter dynamic behavior and stability.

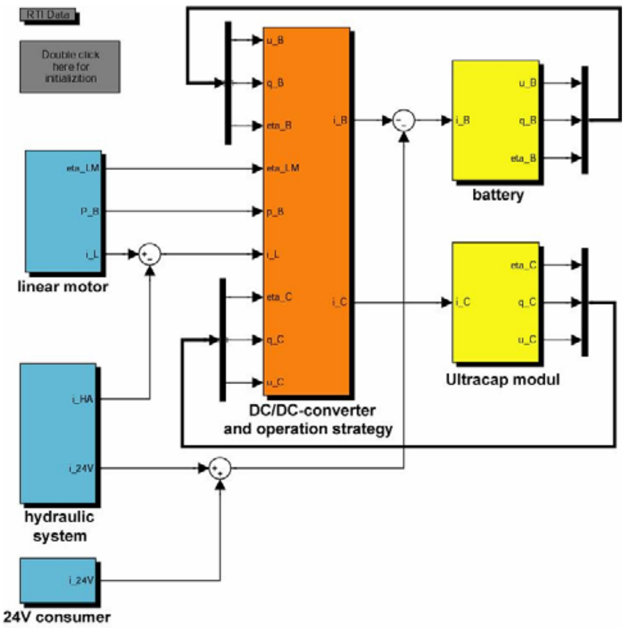


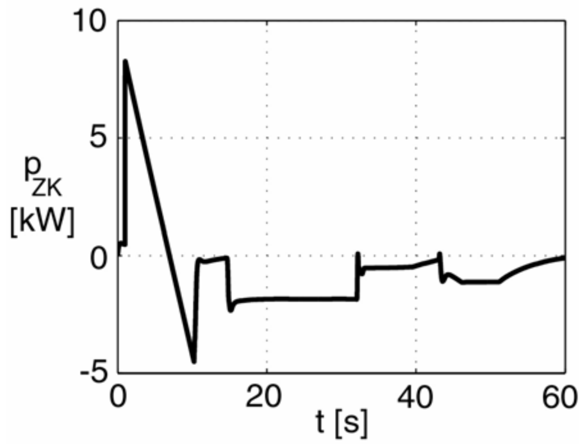
Fig. 3 Energy management simulation model

IV SIMULATION MODEL

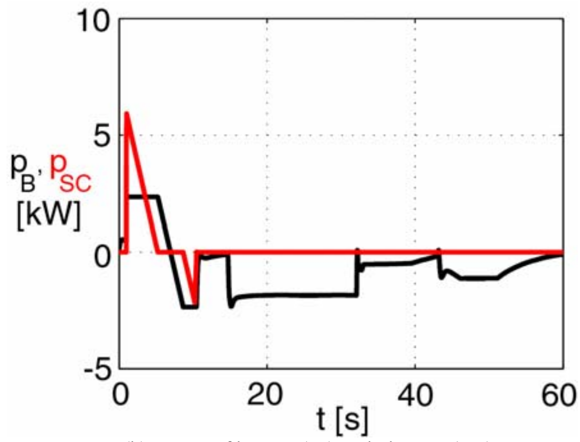
As initial step to design and verify the proposed energy storage system a simulation model is built in MATLAB/SIMULINK, shown in Fig 3. Energy management is performed via the controllers of bidirectional DC-DC converters using various strategies. The simulation comprises a number of subsystems, such as the linear motor, a hydraulic system, a, batteries and ultracapacitors.

The hydraulic system, 24 V consumers and the secondary of the linear motor fitted below the undercarriage of the shuttle are energized from the DC link with a voltage level of 650 V. The linear motor not only generates the thrust force to drive the shuttle, it can also be used to transfer energy from the primary into the secondary and by this way into the DC link. The value of this contactless transferred power depends on the operation point of the motor. The Influences like the high-profile of the track, friction and wheel flange contact have been accounted by the simulation.

The task of the energy management is to measure the energy storage state in batteries and ultracapacitors and power required in the DC link, and then control the energy flow through batteries and ultracapacitors, in order to obtain a constant voltage level of the DC link. To minimize the losses of these energy storages a simple strategy is employed: Charge or discharge the ultracapacitors only if the absolute value of the power in the DC link is larger than 2.3 kW ($5 \cdot I_5 \cdot U_R$ of the battery).



(a) DC link power



(b) Power of battery (P_B) and ultracap (P_{SC})

Fig. 4 Energy management simulation results

In Fig.4 the time dependent behavior of the DC link was simulated for a 60 s long drive of the shuttle around the oval of the NBP-test-track. Simulation results show, that the power in DC link is distributed by battery and ultracapacitor. The transient peak power are assigned to the ultracapacitor, whereby the power stress of battery are reduced.

V EXPERIMENTAL RESULTS

A test bed of the proposed energy storage unit was built and tested to verify the principle of operation. An assembly of the test bed comprising one dc-dc converter, measuring facilities and the batteries are shown in Fig.5.

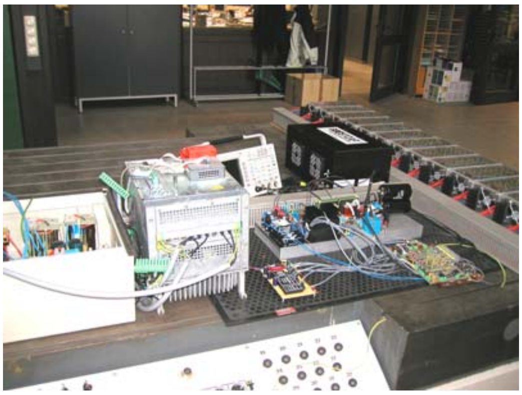


Fig.5 Energy storage system of the test bed

The battery consists of 280 cells connected in series and can provide continuous power of 10kW. Fig.6 and Fig.7 show DC Link voltage u_{ZK}, current i_b and battery power P_{Bat} and current i_{Bat} under a step response experiment.

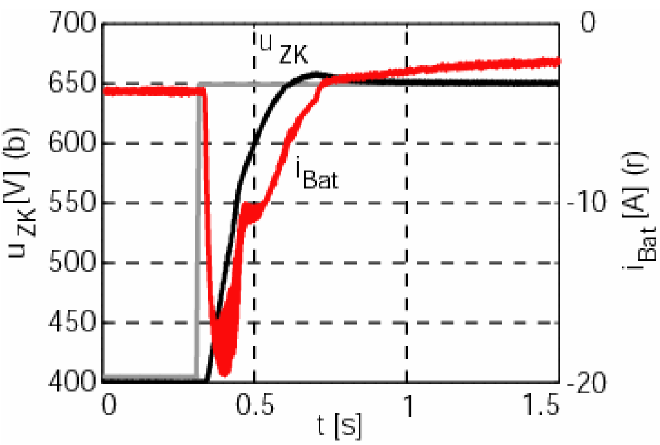


Fig.6 DC-Link voltage u_{ZK} (black) and current i_b (red)

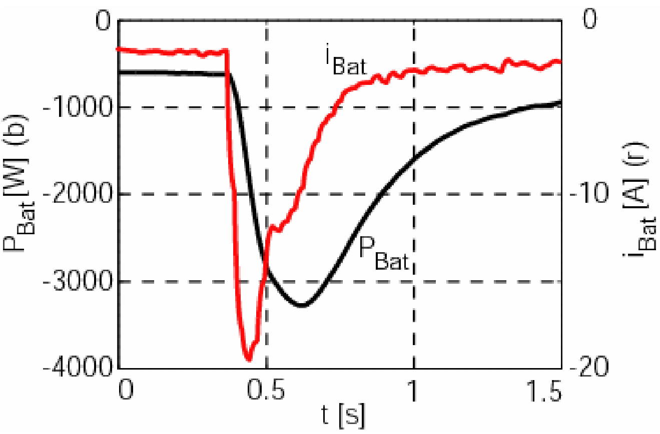


Fig.7 Battery power P_{Bat} (black) and current i_{Bat} (red)

As analyzed above, a 42V ultracapacitors module of type BMOD0115AV produced by Maxell is used to handle the peak energy. The ultracapacitors module working voltage range is 20~42V, in this range the usable stored energy satisfies the demand of peak energy analyzed above.

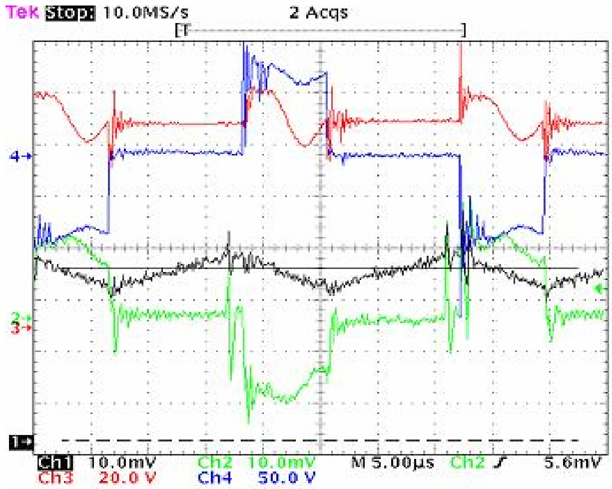


Fig. 8 Boost mode tests.

Ch1: ultracapacitor discharge current (20A/div).

Ch2: current-fed side transformer current (50A/div).

Ch3: voltage-fed side transformer voltage

Ch4: current-fed side transformer voltage.

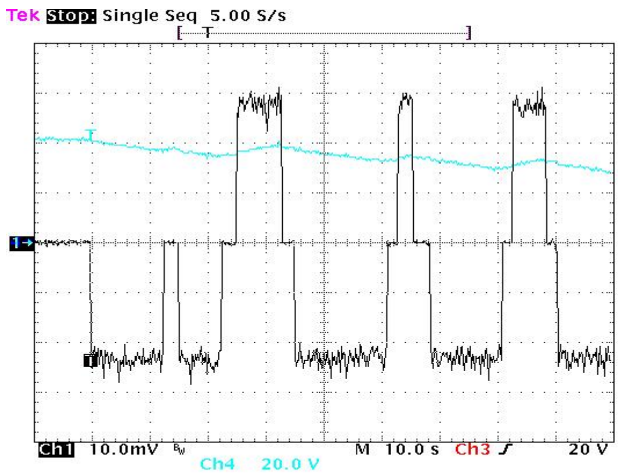


Fig. 9 Buck mode.

Ch1: Ultracaps current (20A/div).

Ch4: Ultracaps voltage.

A 3kW experimental converter prototype connecting ultracapacitors and DC link was built to verify the operation principle of the proposed full bridge bidirectional dc-dc converter. The current control loop of boost mode and buck mode are implemented by using analog current compensator and PWM modulator, while the voltage control loop is realized using a DSP controller.

The experimental waveforms of the input inductor current, the current-fed side transformer current and the voltage across the transformer at boost mode are shown in Fig.8. The operations of the ultracapacitor module are tested by the const charging and discharging current, the results are shown in Fig.9.

The output power is 3kW in this test and the measured efficiency is 88.5% at discharge mode and 90.5% at charge mode.

VI. CONCLUSION AND OUTLOOK

An energy storage system built by combining battery and ultracapacitor is presented in this paper. The design and configuration of battery and ultracapacitor module are presented after a detailed investigation about that storage structure and devices were performed. A simple control strategy is verified through a simulation model consisting of an energy storage module and power consumer. In order to control the energy flow bidirectional dc-dc converters were studied and implemented. The operation of the energy distribution is verified by measurements. The test results show that their correspondence to theoretical results.
It is intended to increase the efficiency of the bidirectional isolated full-bridge DC-DC converter by using a low leakage planar transformer and reduce ringing effects and transformer core losses by using matched snubber.

VII ACKNOWLEDGEMENTS

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