Energy Pack for Trolleybuses as an on-board Energy Storage System with Batteries and Supercapacitors

Maksimovic A.[1], Haerri V.V. [2]

[1]Aleksandar Maksimovic is with the Center of Competance IIEE, Lucerne University of Applied Sciences and Arts

(e-mail: aleksandar.maksimovic@hslu.ch)

[2]Vinzenz V. Haerri is with the Center of Competance IIEE, Lucerne University of Applied Sciences and Arts
(e-mail: vinzenz.haerri@hslu.ch)

Abstract

This paper presents “Energy Pack” as an on-board energy storage system with batteries and supercapacitors for the new generation of the trolleybuses. The "Energy Pack" is a combination of the “Super Accumulator Module”- SAM[1] energy storage system with a power electronics module and a energy management which interfaces with a trolleybus enabling autonomous operation, reduced energy consumption and stabilization of the line voltage. The first SwissTrolley3 to be equipped with an "Energy Pack" will enter service in Lucerne in 2013.

Introduction

Trolleybuses are the prime urban public transport solution in some 60 European cities. This system of transport is especially popular among customers and local residents due to its proven environmental advantages. Today more than 360 cities all over the world benefit from a modern trolleybus system. The trolleybus combines the basic advantages of the tram with those of a conventional diesel bus and represents one of the most economical forms of electric urban public transport systems. Moreover, the trolleybus offers an answer to current political and ecological issues such as local air pollution, ever-increasing contamination by fine dust in city centres and noise emissions. The high acceptance of this on-street zero-emission means of transport is also demonstrated by a higher ridership factor. Statistics from various public transport operators show that the ridership factor on trolleybus routes is up to 10-20% higher than on comparable diesel bus routes[2]. This is clearly attributable to the high level of comfort and pleasant ride provided by such vehicles, but also due to the visible indication of a regular public transport route indicated by the overhead line. These features enhance passenger trust in the punctuality of the system.

Some members of the public feel that the overhead lines are a visual intrusion, particularly in historic city centres, and would like them to be removed. Autonomous operation away from an overhead line is possible by placing an energy storage device on board the vehicle. The stored energy enables the trolleybus to operate even during power failures, around temporary obstructions or road works, and in the absence of overhead lines. In addition, trolleybus operators can experiment with possible new route extensions using trolleybuses but prior to erecting the necessary infrastructure.

Beside the autonomous operation of a trolleybus away from overhead line, the energy storage system can be used for the voltage drop compensations in distribution system. The stored energy is used for the start of the trolleybus when operates with overhead line. The power needed for the start is not provided by distribution network, but is provided by the energy storage system. This reduces the voltage drops in distribution grid and minimizes the losses which increase efficiency of the whole transportation system. At the same time, this reduces the needs of large investments in transformer substations.

---

[1] SAM is Super Accumulator Module: integration of batteries, supercapacitors (supercaps) and its management by the Center of Competence IIEE Lucerne University of Applied Sciences and Arts

[2] Source: www.tbus.org.uk

Fig. 1: HESS Swisstrolley3 in operation in Zurich

The exact distance that the trolleybus can operate without an overhead line depends on many factors. First of all is the capacity and loading of the energy storage device, then the route topology, the route profile (maximum speed, acceleration of the vehicle, braking phase, number of stops, etc.). It must be considered that when stopping on an overhead line free section, the energy storage will be partly recharged by the braking process. Trolley vehicles have always had the possibility to regenerate braking energy back into the overhead lines. Recuperative energy can be used in different ways with different properties and operate with different efficiency. The average energy consumption including recuperation of the Swisstrolley3 from Carrosserie HESS AG is shown in Fig.2.

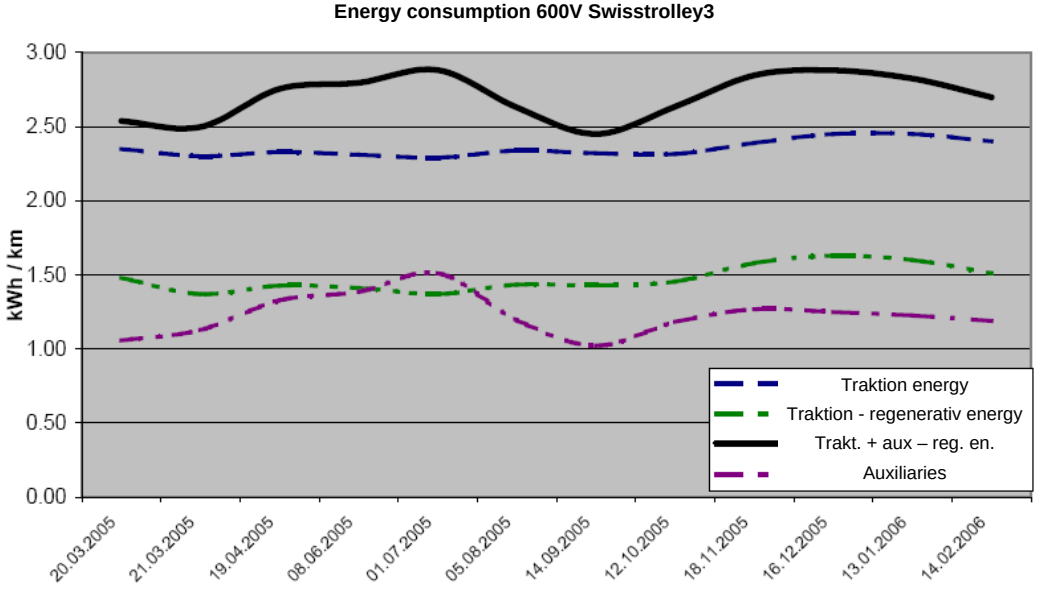

Fig. 2: Swisstrolley3 average energy consumption (final report for Swiss Federal Office of Energy SFOE - Hans-Jörg Gisler 2006)

It can be seen that about 25% of the energy consumed can be regenerated and returned to the DC overhead line. Use of on-board energy storage (so called "Energy Pack") increases this percentage up to 35%. Almost all braking energy can be stored in the vehicle's "Energy Pack" thereby eliminating virtually all losses in the overhead line. Existing systems require a second trolley vehicle(s) in the same electrical section of the overhead line as the vehicle which is regenerating braking energy, to use the available energy. If there is no second vehicle, almost all regenerated braking energy is dissipated as heat in the braking resistors, which represents the worst case. There are two main methods for energy saving with recuperation: energy transfer back into the power distribution network, i.e. overhead line, or storage of the braking energy. The former is explained above; the latter will be discussed below.

Materials and Methods

There are a number of possibilities for energy storage, including flywheels, batteries, supercapacitors (ultracap, double-layer capacitors, etc.), fuel cells or a combination of some of these options. Flywheels can be considered as inappropriate due to the space limitations and safety aspects on board a moving vehicle. Fuel cells are popular in today's hybrid vehicles however due to the automatic recharging possibilities offered by a trolleybus system, fuel cells do not offer an optimal solution. Batteries and supercapacitors are electrochemical devices. However, the working principles vary, making their characteristics very different. Batteries have a relatively high energy density according to the chemistry used but low power density, whereas supercapacitors have a much lower energy density, but a significantly higher power density. The weight of supercapacitors is twice less than that of a battery with the same energy storage capacity. Supercapacitors provide a fast access to the stored energy and allow a total discharge (100 %) while batteries only allow a discharge of 80 %. Charging of supercapacitors is much faster than charging a battery and can be done with less danger (no danger for overcharging, no major charging circuits required, no danger when there is a reverse polarisation whilst charging). On the other hand, the life of the latest supercapacitors exceeds one million cycles, this is 500 times more than a battery. There is no loss of storage capacity for an increasing number of charging/discharging cycles. One major disadvantage is that the energy storage capacity of supercapacitors is much smaller than the one of a battery with the same physical dimensions. The characteristics of the two allow their combination to achieve a much better overall performance.

Energy Pack

This new idea is the product of a long cooperation between Carrosserie HESS AG[3], a Swiss company which is a key global player in the field of trolleybus design and production, and the Integral Intelligent and Efficient Energy Systems Competence Centre of the Lucerne University of Applied Sciences and Arts[4], headed by Prof. Vinzenz Härri.

The "Energy Pack" comprises:

1) an energy storage system (batteries and supercapacitors) known as the "Super Accumulator Module" (SAM)

2) a power electronics module

3) an energy management system which interfaces with the trolleybus' management system

A conceptual schematic of the proposed 'Energy Pack' system is shown in Fig. 3. The system is constructed using a modular based approach to enable integration of more primary sub-systems. As shown in Fig. 3, these primary sub-systems are: the Energy Pack storage system, the drive system, the distribution grid (overvoltage lines), board main supply, the power electronic system and the energy management system. Red arrows in Fig. 3 represent the direction of energy flow while blue arrows depict the communication between sub-systems. Both

[3] Carrosserie Hess AG: www.hess-ag.ch
[4] Centre of Competence Integral Intelligent & Efficient Energy Systems; http://www.hslu.ch/iiee

amount and direction of power exchange amongst the sub-systems are controlled via a power interface module by an efficient energy management unit in accordance with the system variables.

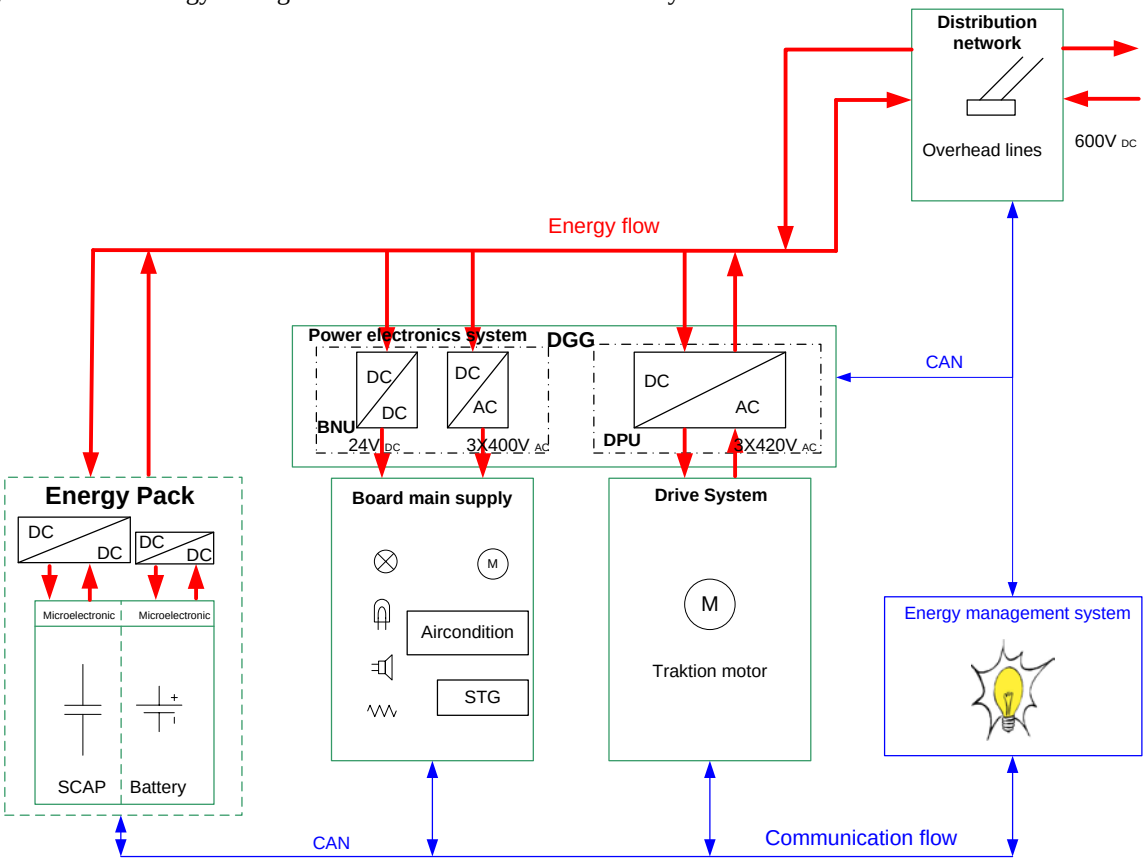

Fig. 3: Basic diagram Trolleybus "Energy Pack" for Trolleybus

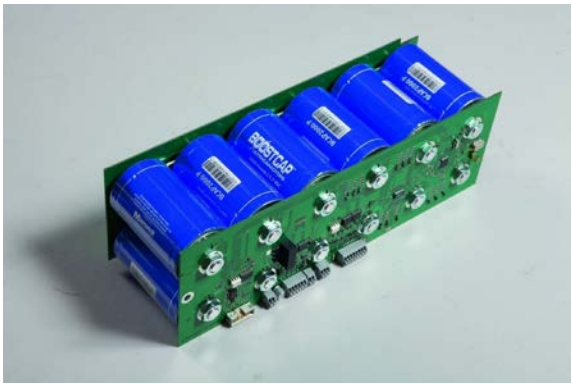

Fig. 4: (a) Battery pack for the SAM (b) SCAP pack for the SAM

Lithium iron phosphate ($LiFePO_4$) batteries are proposed as the primary energy source. The supercapacitors are seen as a complementary storage device that can accommodate the fluctuating power requirements of the trolleybus, minimizing constraints of the main energy source. The supercapacitors absorb and supply the large

current pulses, and the battery provides the average power demand. This allows the size of the battery pack to be reduced, and dimensioned for the energy requirement of the cycle, rather than the power requirement. Charging of the "Energy Pack" (during braking or during running beneath overhead lines) and discharging (accelerating or running without overhead lines) is controlled by a bi-directional DC/DC pulse converter and an energy management system. The energy management system should be able to control and optimize the whole process, as well as to make the interface between the trolleybus as a system and an "Energy Pack" as a storage system. In order to obtain high efficiency in an energy system, high voltage and small currents are required. In order to provide this by means of batteries and supercapacitors, they must be connected in series. The process of balancing the batteries and supercapacitors is controlled by the energy management system. The data flow in the system is made with a CAN communication system.

The main objectives of the "Energy Pack" are:

- Autonomous operation – travelling a part of the route without power supply from the overhead power lines, e.g. along prospective route extensions, where the route passes an historical building, manoeuvring in a depot area, running past temporary road works or along diversions,
- Reduced energy consumption – reduction of the power taken from the traction power supply (overhead line) by taking energy for acceleration from the "Energy Pack" and storing the trolleybus braking energy (regeneration).
- Stabilizing the line voltage – the line voltage drop is reduced as an effect of the vehicle's lower power demand.

Acknowledgements

The Energy Pack as on-board energy storage system with batteries and supercapacitors for the new generation of trolleybuses has been described. The proposed system is versatile, and can also be regarded as an ideal platform for energy related future research within on-board storage system concept.
Thanks to our main partners Carrosserie HESS AG and vbl AG[5] we are able to start and successfully run the "Energy Pack" project.
The advantages of the "Energy Pack" have encouraged the "*Verkehrsverbund Luzern*[6]" (Lucerne Transport Authority) together with the Lucerne University of Applied Sciences and Arts, Centre of Competence Efficient Energy Systems, to start a new project. The project's main task is to analyse the possibilities for using the "Energy Pack" in Lucerne's public transport. One of the possibilities is the extension of existing trolleybus routes in the Lucerne network. Another could be the partial or complete replacement of diesel bus routes in central Lucerne with trolleybus routes.
The "Energy Pack" project is financially supported by the CTI[7] ("Federal Office for Professional Education and Technology OPET / Innovation Promotion Agency CTI"). The CTI considers the "Energy Pack" as the ideal alternative to a diesel-powered APU[8] in the new generation of trolleybuses.
Consideration of all the features of the new vehicle equipped with an "Energy Pack" as an on-board energy storage system should lead to an extremely attractive system, which is also promising in respect of operating economics.

[5] vbl AG: Verkehrsbetrieb Luzern: www.vbl.ch
[6] Verkehrsverbund Luzern: http://www.verkehrsverbund-luzern.ch/
[7] Federal Office for Professional Education and Technology OPET / Innovation Promotion Agency CTI: www.kti-cti.ch
[8] APU means Auxiliary Power Unit, electrical generator with a combustion engine

References

[1] *"Supercapacitor Module SAM for Hybrid Drives: 3rd Generation Specification including energy management"*, V.V. Haerri, Lucerne University of Applied Sciences and Arts, Center of Competence Efficient Energy Systems, Symposium IAMF, March 2008, Genève Switzerland

[2] *"Electricity for Mobility: Technological Aspects of the Total Hybrid-Electric Concept (TOHYCO)-Rider Hybrid Supercapacitor Bus Project"*, V. V. Haerri, Lucerne University of Applied Sciences and Arts, Center of Competence Efficient Energy Systems, SEREC Institute ETH Zurich, February 2008

[3] *"Kleinbus TOHYCO-Rider mit SAM-Superkapazitätenspeicher"*, V.V. Haerri, P.Schweizer, HJ. Riesen, D. Carriero, P. Collins, Lucerne University of Applied Sciences and Arts, Center of Competence Efficient Energy Systems, BFE Schlussbericht, October 2008

[4] *"Super-Accumulator Module (SAM)"*, V. V. Haerri, S. Egger, S. Eigen, Lucerne University of Applied Sciences and Arts, Center of Competence Efficient Energy Systems, BFE Jahresbericht 2002, December 2002

[5] *"Supercapacitor circuitry concept SAM for public transport vehicles and other applications"*, Lucerne University of Applied Sciences and Arts, Center of Competence Efficient Energy Systems, proceeding EVS-18 (el. Vehicle Symposium), 2001

[6] "Swisstrolley 3 Gelenktrolleybus", HJ. Gisler, Carrosserie HESS AG, BFE Schlussbericht, April 2006

[7] *"The use of supercapacitors for energy storage in traction systems"*, P. Barrade, A. Rufer, Laboratory of Industrial Electronics, Swiss Federal Institute of Technology Lausanne Switzerland, IEEE Vehicle Power and Propulsion, 2004

[8] *"Power-Electronic Interface for a Supercapacitor-Based Energy-Storage Substation in DC-Transportation Networks"*, A. Rufer, Laboratory of Industrial Electronics, Swiss Federal Institute of Technology Lausanne Switzerland

[9] *"A Supercapacitor-Based Energy Storage Substation for Voltage Compensation in Weak Transportation Networks"*, A. Rufer, P. Barrade, Laboratory of Industrial Electronics, Swiss Federal Institute of Technology Lausanne Switzerland, IEEE Transactions on power delivery, Vol. 19, No.2, April 2004

[10] *"The Energy storage System for Public Transport Vehicles"*, P. Drabek, L. Streit, Department of electromechanics and power electronics, West Bohemia University in Pilsen, Czech Republic, IEEE Transactions on power, 2004

[11] *"A New Battery/Ultra-Capacitor Hybrid Energy Storage System for Electric, Hybrid and Plug-in Hybrid Electric Vehicles"*, J. Cao, A. Emadi, Electric Power and power Electronics Center, Electrical and Computer Engineering Department Illinois institute of Technology, USA

[12] *"Intelligent Power management of a Supercapacitor based Hybrid power Train for Light-rail Vehicles and City Buses"*, A. Lohner, W. Evers, Vossloh-Kiepe GmbH, Düsseldorf, Germany

[13] *"Kiepe Power Hybrid / HESS-Doppelgelenk-Bus mit Vossloh Kiepe Hybridantrieb"*, Vossloh Kiepe GmbH, Düsseldorf, Germany

[14] *"A Plug-In Hybrid "Blue-Angel III" for Vehicle to Grid System with a Wireless Grid Interface"*, Vinzenz V. Haerri, Udaya K. Madawala, Duleepa J. Thrimawithana, Rinaldo Arnold, Aleksandar Maksimovic: in Proc. 2010 IEEE Vehicle Power and Propulsion Conference VPPC, Lille, 1-3 Sept. 2010

[15] *"Sizing of a hybrid locomotive based on accumulators and ultracapacitors"*, A. Jaafar, B. Sareni, X. Roboam, M. Thiounn-Guermeur: in Proc. 2010 IEEE Vehicle Power and Propulsion Conference VPPC, Lille, 1-3 Sept. 2010

[16] *"Evaluation of the benefits of using dual-source energy storage in hybrid electric vehicles"*, A. Lajunen: in Proc. 2010 IEEE Vehicle Power and Propulsion Conference VPPC, Lille, 1-3 Sept. 2010

[17] *"Different energy managements of Hybrid Energy Storage System using batteries and supercapacitors"*, A.L. Allegre, R.A. Bouscayrol,: in Proc. 2010 IEEE Vehicle Power and Propulsion Conference VPPC, Lille, 1-3 Sept. 2010

[18] *"The use of supercapacitors in EV: modeling, sizing and control"*, M.Y. Ayad, M. Becherif, S. Aitcheikh, M. Wack: in Proc. 2010 IEEE Vehicle Power and Propulsion Conference VPPC, Lille, 1-3 Sept. 2010

[19] *"On braking efficiency of urban electric transportation systems based on power electronics"*, P.M. Nicolae, I.D. Nicolae: in Proc. 2010 IEEE Vehicle Power and Propulsion Conference VPPC, Lille, 1-3 Sept. 2010