Journal of Energy Storage 18 (2018) 175–184

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Assessing the potential of an electric vehicle hybrid battery system comprising solid-state lithium metal polymer high energy and lithium-ion high power batteries

Raphael Wegmann[a,*], Volker Döge[a], Dirk Uwe Sauer[b,c,d]

[a] Corporate Sector Research and Advance Engineering, Robert Bosch GmbH, 71272 Renningen, Germany
[b] Electrochemical Energy Conversion and Storage Systems Group, Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, 52066 Aachen, Germany
[c] Jülich Aachen Research Alliance, JARA-Energy, Germany
[d] Institute for Power Generation and Storage Systems (PGS), E.ON ERC, RWTH Aachen University, 52074 Aachen, Germany

ARTICLE INFO

Keywords:
Hybrid battery system
Solid-state lithium metal polymer battery
Electric vehicle

ABSTRACT

In this work the characterization and application of a prototype solid-state lithium metal battery for an electric vehicle application is addressed. This mid-temperature battery is operated at a temperature of 80 °C. In an innovative approach, this high energy technology is integrated into a hybrid battery system, where it is supported by a highest power lithium-titanate technology. Three hybrid battery system configurations are systematically derived for a high class vehicle with different performance requirements. On the basis of an overall vehicle simulation model, comprising a thermal model of the lithium metal polymer battery pack, the performance of the system is evaluated under regular and extreme driving conditions. The results indicate that battery hybridization makes a reasonable utilization of the lithium metal polymer battery in an electric vehicle possible. The power capability of the overall battery system in discharge as well as charge direction is significantly increased. Moreover, the system allows for a wider utilization of overall battery system's energy, resulting in an increase of drivable distance. Furthermore, additional functionalities of the hybrid battery system are discussed, such as warm-up procedure, low temperature performance enhancement and redundancy.

1. Introduction

The integration of battery systems into a vehicle's electrical drivetrain plays an important role for today's carmakers. But there remain challenges in battery system operation and integration. Battery system costs still outweigh those of other drivetrain components [1–5]. Moreover, the adequate dimensioning of battery systems with respect to electrical power and energy for different vehicle types as well as the achievement of a good lifetime performance [6–10] remain challenging. In order to improve the cell's power and energy performance, cost and safety, researchers work on the development of advanced battery cell materials [11].

In today's electric vehicles the most prominent battery type is the lithium-ion battery technology. Most vehicles' battery cells comprise a carbon based anode and a metal oxide material cathode [12,13]. In order to achieve higher battery energy densities major effort is put on the development of further battery technologies. One promising technology is the utilization of lithium metal anodes, since lithium metal offers superior specific capacity in comparison to graphite [14–16].

To avoid growth of lithium dendrites as well as to allow for an electrochemically stable lithium metal anode operation the use of polymer as well as inorganic solid-state electrolytes is discussed in literature [14–16].

The use of a solid-state polymer electrolyte may also lead to advantages in processing by supporting simpler and less production steps. Moreover, due to the solid-state of the electrolyte versatile geometric shapes are possible. Due to the comparably low ionic conductivity of most polymer based solid electrolytes the battery operating temperature has to be increased [14].

This paper focuses on the integration of a lithium metal polymer high energy battery in an electric vehicle. The investigated lithium metal polymer battery is operated at a temperature of 80 °C. In order to allow for advanced functionalities and an increased power capability the lithium metal polymer battery is integrated into a hybrid battery system topology.

The hybrid battery system combines two battery parts on system

* Corresponding author.
E-mail address: Raphael.Wegmann@de.bosch.com (R. Wegmann).

https://doi.org/10.1016/j.est.2018.05.001
Received 10 March 2018; Received in revised form 30 April 2018; Accepted 1 May 2018

Nomenclature

Symbols

A	surface
C_{th}	heat capacity
E	energy
F	force
I	current
L	inductance
N	number of time steps
P	power
Q, $\dot{Q}$	heat, heat current
R_{th}	thermal resistance
T	temperature
U	voltage
c_r, c_w	rolling friction and drag coefficient
h	heat transfer coefficient
k	time step
l	length, thickness
s	distance
t, τ	time
λ	thermal conductivity

Acronyms

BMS	battery management system
D	diode
EB	high energy battery part
HBS	hybrid battery system
LFP	lithium iron phosphate
Li	lithium
LTO	lithium-titanate oxide
NCA	nickel cobalt aluminium oxide
PB	high power battery part
S	semiconductor switch
SoC	state of charge
SoE	state of energy
act	actual
amb	ambient parameter
bat	battery
batsys	battery system
ch	charge
cond	conduction
conv	convection
des	desired
dch	discharge
dem	demand
eb	high energy battery part
em	electrical machine
hbs	hybrid battery system
in	inside the Li/LFP battery system
iso	insulation
nom	nominal
pb	high power battery part
rms	root mean square
th	thermal parameter

level, where a battery part itself is an interconnection of multiple battery cells of one cell type. Several topologies of hybrid battery systems are reviewed and suggested in [17,18]. Furthermore, the scaling of the system is discussed e.g. in [19,20,4]. Here one battery part consists of high energy density lithium polymer battery cells and the other battery part consists of high power density lithium-ion cells. The cell types are introduced in Section 2. The aim is to evaluate how much the energy optimized mid-temperature battery part can be supported in specific operating conditions.

Moreover, for further information about the dimensioning as well as operation strategies of such a system the reader is referred to previous work of the authors [10,19,21]. This paper consequently extends our previous work, since focus has been given to battery hybridization based on lithium-ion batteries in the previous work exclusively. In the following, new results are presented, analysing battery hybridization based on lithium metal polymer mid-temperature batteries.

The remainder of the paper is structured as follows. In Section 2 the battery cells investigated here are introduced and characterized. Then the integration of the lithium metal solid-state cell is discussed. In Section 2.3 the hybrid battery system (HBS) and its functionalities on system level are debated. The modelling environment as well as the thermal model of the lithium metal polymer battery are presented in Section 3. Details about how to ensure an operating temperature of 80 °C are given. Then, in Section 4 case studies are derived for a high class vehicle in order to compare a single-cell reference battery system and different hybrid battery system topologies. Subsequently results are discussed in Section 5. Finally, a conclusion is given in Section 6.

2. Combining high energy lithium metal polymer and high power lithium-ion batteries in electric vehicles

In Section 2.1 high energy density lithium secondary batteries are compared to each other in terms of performance characteristics. Section 2.2 discusses two types of high power density energy storages. The lithium-titanate battery used in this work is presented. Finally Section 2.3 introduces the innovative approach of battery hybridization taking into account the combination of a lithium metal polymer high energy battery and a lithium-titanate high power battery on system level.

2.1. High energy density secondary lithium batteries

The anode of today's lithium-ion batteries usually consists of graphite. By using a lithium metal anode instead of such a graphite anode, the battery's energy density can be increased significantly. This is due to the considerably larger specific capacity and lower electric potential of lithium metal in comparison to graphite [14,22]. Therefore, a lithium metal polymer battery shall be examined in this work, with respect to its usage as a high energy density battery in an electric vehicle.

The specific battery presented in this work is a prototype version of a lithium metal polymer battery (Li/LFP). It comprises a lithium iron phosphate (LFP) cathode and is operated at 80 °C. The basic characteristics of this cell are shown in Table 1. The open circuit voltage, derived from a measurement in the laboratory, is shown in Fig. 1 (black curve). The flat potential profile of the LFP cathode in combination with the lithium metal anode can be clearly seen [23]. Furthermore, the open circuit voltage curve of a state of the art lithium-ion high energy cell (Panasonic NCR 18650 BD) is shown in the figure for comparison. For this reference cell, the basic characteristics are also given in Table 1. It comprises a graphite anode and a nickel cobalt aluminium oxide (NCA) cathode and has been characterized in a previous publication of the authors [10].

Moreover, the 10 s discharge and charge peak power capabilities over state of charge (SoC) are shown in Fig. 2a and b respectively for the two high energy lithium secondary battery cells. Actually the power capability is normalized by the cell's nominal energy for better comparison. The peak power capability takes into account the respective battery's SoC dependent open circuit voltage, the temperature and SoC dependent inner resistance as well as the mostly temperature dependent