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Assessing the potential of a hybrid battery system to reduce battery aging in an electric vehicle by studying the cycle life of a graphite|NCA high energy and a LTO|metal oxide high power battery cell considering realistic test profiles

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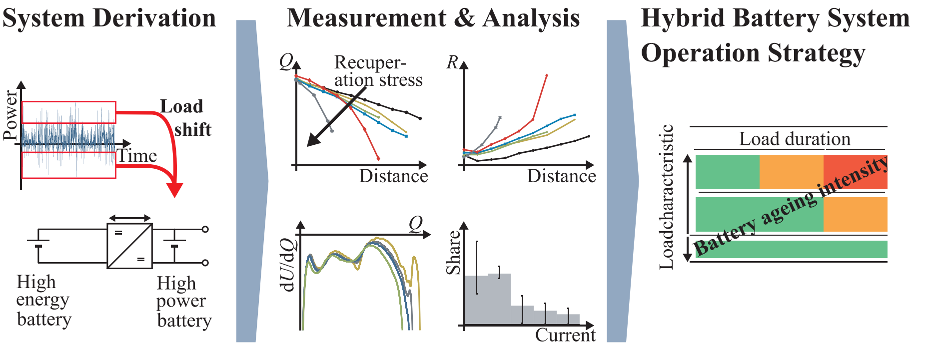
HIGHLIGHTS

- Lithium-ion battery cell ageing in a hybridized BEV battery system is addressed.
- Up to date NCA (240 Wh kg^{-1}) and LTO (2400 W kg^{-1}) technologies investigated.
- Increase in recuperation pulse time is main energy cell ageing driver.
- Ageing per trip distance is independent from micro cycling for graphite-NCA cell.
- HE/HP load splits enable battery lifetime improvement at long recuperation phases.

GRAPHICAL ABSTRACT



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ABSTRACT

The utilization of a hybrid battery system (combination of different battery packs via dc/dc converter) in an electric vehicle application is discussed. It is investigated whether battery aging in an electric vehicle can be reduced by using a hybrid battery system. Cycle aging measurements of lithium-ion battery cells were performed at 23 °C against the background of the latter application. Recommendations for hybrid battery system electric vehicle operation are given. For Panasonic NCR 18650 BD cylindrical high energy cells (graphite anode, Li(NiCoAl) O_2 cathode), three cycle aging campaigns were conducted systematically, evaluating the impact of charging as well as discharging loads with different time scales and microcycling per driving distance. A significant impact of recuperation pulse duration on aging per driving distance could be observed, whereas varied discharge load characteristics did not vary the aging characteristics. On the basis of differential open circuit voltage analysis, possible degradation mechanisms are discussed. The main driver of capacity loss and resistance increase in cycle aging campaigns with real world driving cycles appears to be the loss of cyclable lithium. Within the operating conditions investigated here, anode aging is intensified with increasing recuperation pulse duration. Another cycle aging campaign with symmetric current rate of 10 C for a prismatic high power battery cell ($Li_4Ti_5O_{12}$ anode, metal oxide cathode) yielded excellent cycle performance of this cell.

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Nomenclature

Symbols

E	energy
P	power
Q	charge
Q_o	characteristic DVA minima (cathode)
Q_m	characteristic DVA minima (anode, cathode)
Q_u	characteristic DVA minima (anode)
$Q_{o,m}$	distance between Q_o, Q_m
$Q_{m,u}$	distance between Q_m, Q_u
$Q_{lss,ess}$	charge between maximum charging voltage and cut-off voltage
R	resistance
t,Δt	time, duration of pulse
v	velocity

Acronyms

BEV	battery electric vehicle
BoL	begin of life
BoT	begin of test
CADC	common artemis driving cycle
CC, CV	constant current, constant voltage
DCR	direct current resistance
DoD	depth of discharge
DoDE	depth of discharged energy
DP	discharging pulse
DVA	differential voltage analysis curve
EMS	energy management strategy
EoL	end of life
FCE	full cycle equivalents
HBS	hybrid battery system
HE	high energy
HE-NCA	investigated high energy cell
HP	high power
HP-LTO	investigated high power cell
LTO	lithium-titanate oxide
NCA	nickel cobalt aluminium oxide
NCM	nickel cobalt manganese oxide
OCV	open circuit voltage
RP	recuperation pulse
SEI	solid electrolyte interface
SoC	state of charge
STDC	stuttgart driving cycle
act	actual
batsys	overall battery system
dem	demand
eb	high energy battery part
pb	high power battery part

1. Introduction

1.1. Motivation

The development of full battery electric vehicles (BEV) has been strengthened by car manufacturers in recent years. Battery systems consisting of a single cell type are typically used in today's conventional BEV. These systems are called mono battery systems here.

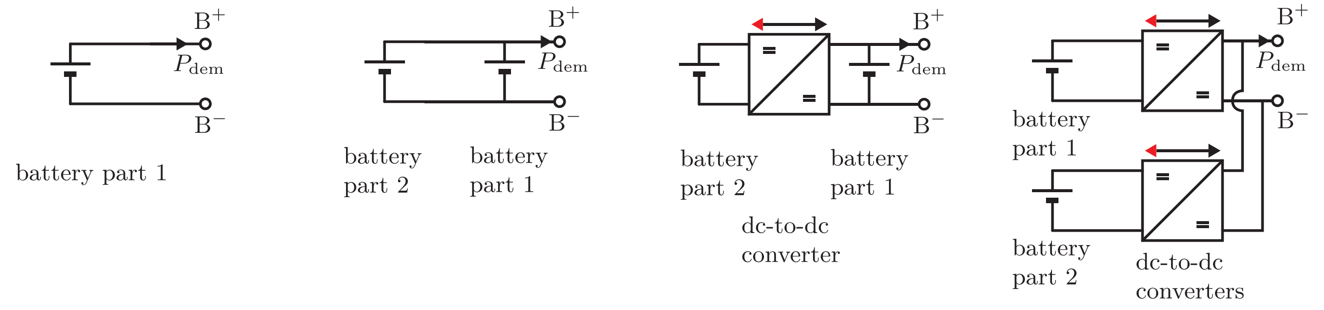
Moreover, in the research community the hybridization of automotive battery systems has been introduced in order to potentially overcome drawbacks of mono battery systems, such as high cost [1–3] and low power performance, e. g. at low temperatures [4,5].

Hybrid battery systems (HBS) are defined as a combination of a battery part based on a high energy (HE) cell and a battery part based on a high power (HP) cell. The battery parts themselves consist of multiple interconnected HE and HP battery cells respectively. In general, multiple types of secondary batteries can be considered. The connection of the battery parts on system level can be a direct parallel connection or a connection via dc-to-dc converter. The latter system will be evaluated in the context of battery aging hereafter.

1.2. Literature review

Different HBS topologies are reviewed and suggested in literature. Zimmermann et al. discuss several hybrid storage concepts comprising HP and HE storage units [6]. A division into active, passive and discrete concepts is carried out, depending on the connection principle of the hybrid storage system. A similar separation can be found in [7]. In [8] it is concluded that improved vehicle performance in next-generation BEVs could be achieved by battery hybridization comprising advanced power electronics.

Essential battery system topologies are shown in Fig. 1. The power contacts B^+ and B^- represent the battery system's interface to the drive unit. In a BEV it is the dc-to-ac inverter and the electrical machine. Fig. 1a shows the mono battery system. Finally, typical hybrid battery system topologies are shown in the Fig. 1b–d. Passive parallel



(a) Mono battery system. (b) Passive HBS. (c) Active HBS with one dc-to-dc converter. (d) Active HBS with two dc-to-dc converters.

Fig. 1. Discussed battery system concepts comprising one (mono) and two battery parts (hybrid battery system, HBS). Power contacts B^+ and B^- indicate the interface to the electric drive unit. P_{dem} is the overall battery system power demand. The red arrowhead indicates an optional direction of power flow that can be realized depending on the dc-to-dc converter topology. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)