Journal of Energy Storage 14 (2017) 22–38

Contents lists available at ScienceDirect

Journal of Energy Storage

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

Optimized operation of hybrid battery systems for electric vehicles using deterministic and stochastic dynamic programming

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ARTICLE INFO

Article history:
Received 17 May 2017
Received in revised form 6 September 2017
Accepted 11 September 2017
Available online xxx

Keywords:
Hybrid battery system
Lithium-ion battery
Operation strategy
Electric vehicle
Dynamic programming
Equivalent energy consumption minimization strategy

ABSTRACT

The utilization, dimensioning and operation of hybrid battery systems in all-electric vehicles is addressed in this work. These hybrid battery systems consist of one high power and one high energy lithium-ion battery each. Besides a discussion of the advantages of such a hybridization on battery system level, an insight is given into the dimensioning of the system and related aspects. Moreover, major focus of this paper is dedicated to the energy optimal operation of the hybrid battery system. Therefore, two optimization methods are investigated and applied to the given system and control problem. First the global optimal control solution is derived via dynamic programming. Then a causal controller, which allows for a real-time applicable control of the system, is discussed. A stochastic model of a vehicle's drive missions is introduced and implemented within a stochastic dynamic programming framework. The obtained control laws are applied to vehicle simulations, which include a model of the drivetrain and vehicle chassis. The performance of the controllers is then compared to each other using three driving cycles and two vehicle classes. Finally the causal controller is validated in a hardware-in-the-loop test bench.

1. Introduction

To further lower the dependence on crude oil and to preserve the environment, legislation in the United States of America and Europe prescribes car manufacturers to constantly reduce the CO_2 and other pollutant emissions of their car fleets [1–3].

The development of battery electric vehicles represents an essential element in reaching this target. Zero emissions while driving, high drivetrain efficiency and the possibility to integrate renewable energies into the energy market emphasize the usefullness of this vehicle domain. But still, there are challenges especially in battery system operation and design.

On the one hand the battery system remains the cost-dominating element within the drivetrain [4–6]. This requires the battery not to be oversized in terms of electrical energy or power. On the other hand technical aspects while operating the battery, such as degradation, remain challenging [7,8]. Furthermore, difficulties arise due to a lack of power capability of different lithium-ion batteries especially in operating points at low temperatures, aged state and/or extreme states of charge.

To overcome the mentioned problems different concepts of energy storage hybridization are discussed in literature. Hybrid energy storage systems combine two or even more energy storage technologies. Often the combination of a high power density storage with a high energy density storage technology is discussed in order to meet the requirements of the respective application. Hybridization on battery cell level is being discussed in [9]. The author mainly presents concepts where two electrodes are connected serially. One electrode stores charge in a faradaic reaction and another electrode stores charge in an electrochemical double layer. This concept is also known as asymmetric capacitor and widely discussed in literature [10]. Another, less investigated approach combines the two latter materials in a parallel connection at one electrode. Thus a bi-material electrode architecture is achieved [9].

Besides the hybridization on electrode level one can find the external combination of two storage technologies on system level. For instance in [11–13] direct-parallel connections of battery cells with double layer as well as asymmetric capacitors are discussed.

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https://doi.org/10.1016/j.est.2017.09.008
2352-152X/

Nomenclature

Symbols

d	control variable SDP, P_{2d}
$\boldsymbol{f}(\cdot)$	differential system state equation
$g(\cdot)$	instantaneous cost function optimal control problem and DDP
i	iteration count SDP
$l(\cdot)$	instantaneous cost function SDP and EECMS
$\boldsymbol{q}$	Markov state vector
$\boldsymbol{s}$, Δs	state vector SDP, driven distance
t, Δt	time, discrete time step
u	control variable, I_1
v	vehicle velocity
$\boldsymbol{w}$	disturbance, here driving cycle
$\boldsymbol{x}$	state vector of optimal control problem and in DDP
z	state variable EECMS, SoC_1
$\mathcal{D}$	control space SDP
E	electric energy
F	force
$G(\cdot)$	Lagrange cost term
$H(\cdot)$	Hamiltonian EECMS
I	current
$J(\cdot)$	cost functional
N	number of discrete time steps
P	electric power
Q	electric charge
R	resistance
$\mathcal{S}$	state space SDP
U	voltage
$\mathcal{U}$	control space optimal control problem, DDP and EECMS
$\mathcal{X}$	state space optimal control problem and DDP

Greek symbols

ε	convergence limit SDP, EECMS
γ	discount factor SDP
λ	multiplier EECMS
π	control policy optimal control problem, EECMS and DDP
$\phi(\cdot)$	penalty term
σ	control policy SDP

Subscripts, superscripts

1	battery part 1 of hybrid battery system
2	battery part 2 of hybrid battery system
2d	power or current of battery part 2 at dc-link
accel	acceleration
bat, batsys	battery part, overall battery system
ch	charging
dc	direct current
dch	discharging
dem	demand
eb	high energy battery part
el	electrical
k	time step index
loss	electric losses
net	net
nom	nominal value
oc	open circuit
p	peak
pb	high power battery part
PT	powertrain
trac	traction
veh	vehicle
*	optimal value

Acronyms

DDP	deterministic dynamic programming
EECMS	equivalent energy consumption minimization strategy
LTO	lithium titanate
NCA	nickel cobalt aluminium oxide
SDP	stochastic dynamic programming
SoC	state of charge

The authors demonstrate possibilities of the hybrid energy storage system to minimize the energy throughput and temperature rise on the battery, the reduction of voltage drop on the battery as well as the increase in power capability of the whole storage system. However, direct-parallel connection involves drawbacks such as an uncontrollable current distribution between the storage parts and the need to carefully match the operational voltage, temperature and current limits of the particular storage part. In addition, inhomogeneous development of battery parameters over service life has to be taken into account, with available capacity and resistance being especially relevant.

Another approach of external hybridization is the coupling of two storage technologies via power electronics. It is also referred to as an active hybrid energy storage system [14]. This approach offers flexibility with respect to the battery systems technical design. An adequate scaling of power capability and energy can be achieved [15,5,14,16].

In order to meet requirements on power capability, different storage technologies exist that can be utilized. Electrochemical double-layer capacitors (also called super-capacitors) show a high gravimetric and volumetric power density that outperforms batteries [17]. Furthermore, they also provide very good zub-zero temperature power performance, a high efficiency and cycle life as well as an excellent cost-per-power ratio [18,17,19,9]. However, several drawbacks exist that make a careful evaluation for a specific application necessary, whether the utilization of a double-layer capacitor is reasonable. On the one hand the gravimetric and volumetric energy density is much lower than that of lithium-ion batteries; on the other hand also the cost-per-energy is considerably higher than that of lithium-ion batteries [18,17]. Additionally, for an implementation on system level it may occur that only a fraction of the double-layer capacitor's energy can be used in order to fulfil the voltage boundary requirement, e.g. the minimum voltage limits of an inverter or a dc-to-dc-converter. The coupling of batteries and double-layer capacitors is discussed e.g. in [20,15,21,22].

Besides, lithium-ion batteries that are designed towards high power exist on the market. One can find batteries that comprise a lithium-titanate anode combined with a metal-oxide cathode (LTO battery) [23]. A lithium-titanate anode offers the advantage that it, in contrast to a graphite anode, does not build a passivating solid electrolyte interface layer since the lithium-titanate potential is >1.5 V vs. Li/Li^+. In comparison to lithium-ion high energy batteries comprising a graphite anode, LTO batteries offer higher cycle life [17]. Another advantage of LTO is that current control on system level does not have to be as elaborated as it has to be for lithium-ion batteries comprising a graphite anode. However, when it comes to choosing an adequate high power storage technology, depending on the application's requirements it has to be evaluated what is the best and necessary trade-off between cycle life, safety, power, energy, cost, volume and weight. In this work a high power LTO battery cell is chosen, further discussion and a characterization is found in Section 2.