Applied Energy xxx (2013) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Design of a lithium-ion battery pack for PHEV using a hybrid optimization method

Nansi Xue [a,*], Wenbo Du [a], Thomas A. Greszler [c], Wei Shyy [b], Joaquim R.R.A. Martins [a]

[a] Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI, USA
[b] Department of Mechanical Engineering, Hong Kong University of Science and Technology, Hong Kong
[c] Saft America Inc., Cockeysville, MD, USA

HIGHLIGHTS

- We propose an optimization method for hybrid vehicle battery pack design.
- A hybrid gradient-free and gradient-based optimization method is used.
- Balance between active material and electrolyte determines battery optimality.
- Optimized battery pack satisfies energy and power requirements exactly.
- Optimized batteries show 14–18% improvement in properties over initial designs.

ARTICLE INFO

Article history:
Received 12 August 2013
Received in revised form 10 October 2013
Accepted 27 October 2013
Available online xxxx

Keywords:
Lithium-ion
Optimization
Hybrid vehicle
Battery pack design

ABSTRACT

This paper outlines a method for optimizing the design of a lithium-ion battery pack for hybrid vehicle applications using a hybrid numerical optimization method that combines multiple individual optimizers. A gradient-free optimizer (ALPSO) is coupled with a gradient-based optimizer (SNOPT) to solve a mixed-integer nonlinear battery pack design problem. This method enables maximizing the properties of a battery pack subjected to multiple safety and performance constraints. The optimization framework is applied to minimize the mass, volume and material costs. The optimized pack design satisfies the energy and power constraints exactly and shows 13.9–18% improvement in battery pack properties over initial designs. The optimal pack designs also performed better in driving cycle tests, resulting in 23.1–32.8% increase in distance covered per unit of battery performance metric, where the metric is either mass, volume or material cost.

1. Introduction

Hybrid vehicles are becoming increasingly common as automakers make use of alternative energy storage systems to improve vehicle performance and efficiency [1,2], and to reduce their environmental impact [3]. Among the alternative energy storage systems, lithium-ion batteries are a popular choice due to their high energy densities and cycling durability [4]. Plug-in hybrid electric vehicles (PHEVs) incorporate these batteries to provide all-electric driving range for daily commuting. The main problem with lithium-ion batteries is that their energy density is orders of magnitude lower than that of gasoline. As such, the lithium-ion battery packs on PHEVs tend to be heavy, bulky and expensive. This limits the all-electric driving range the PHEV can sustain, and hence reduces the advantages of the hybrid drivetrain. Therefore, an optimally designed battery system is essential to maximize the potential benefits of PHEV.

Lithium-ion electrochemical modeling has been well studied in the past 20 years, with models of varying degrees of fidelity being introduced. Doyle and Newman [5] introduced a continuum formulation to model the ion transport and kinetics within an electrochemical cell. Equivalent circuit models simplify cell mechanisms and reduce a battery to a few parameters identified by simplified circuits [6,7]. These models have been subsequently applied to analyze battery performance in electric vehicle operations [8,9]. Ramadesigan et al. [10] provided a comprehensive overview of various model and simulation techniques of lithium-ion batteries from a system engineering perspective. A number of authors have examined the development and modeling of electrochemical energy storage systems for vehicle applications as well. Cooper [11] has examined the use of lead-acid battery for hybrid electric vehicles. Liaw and Dubarry [12] proposed a methodology to understand battery performance and life cycle through driving cycle and duty cycle analyses. This enables transfer between the laboratory

* Corresponding author. Tel.: +1 7347644319.
E-mail address: courtrun@umich.edu (N. Xue).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.10.044

List of Symbols

Electrochemistry variables

a	interfacial surface area
A	cross-section area of an electrochemical cell
b	material unit cost
c	salt concentration in electrolyte
c_s	salt concentration in solid matrix
D	diffusion coefficient of electrolyte
D_s	diffusion coefficient of solid matrix
$f_\pm$	mean molar activity coefficient of electrolyte
F	Faraday's constant
i_n	transfer current density at the surface of active material
i_o	exchange current density
i_2	current density in electrolyte
l	thickness
m	number of electrochemical cell in parallel
n	number of electrochemical cell in series
Q	charge capacity
R	universal gas constant
T	temperature
U	surface overpotential
$\alpha_a,\ \alpha_c$	anodic and cathodic transfer quotient
ϵ	volume fraction
κ	ionic conductivity in electrolyte
σ	ionic conductivity in solid matrix
Φ_1	potential in solid matrix
Φ_2	potential in electrolyte
ρ	material density

Subscripts

o	initial state value
s	value in solid matrix
$+$	positive electrode
$-$	negative electrode

Optimization variables

A	Jacobian of constraints w.r.t. design variables
c_j	inequality constraints
$\hat{c}_k$	equality constraints
g	gradient vector of objective w.r.t. design variables
p^i	best position of the ith particle
p^g	global best position
r_1, r_2	random numbers between 0 and 1
s	solution to the quadratic subproblem in SQP
V	velocity of particle in design space
w_0	inertia weight in ALPSO
w_1, w_2	confidence parameters in ALPSO
W	estimate of second-order derivatives in SQP
$\boldsymbol{x}$	position of particle in design space
Δt	time step value in ALPSO, normally taken to be 1

and real-life battery testing by providing a realistic model to simulate battery performance using real-life test data [13].

While numerical models provide an understanding of the physics of battery operation, optimization algorithms provide the means to maximize the battery properties and performance in hybrid vehicle operations. Shahi et al. [14] applied a multi-objective optimization approach for the hybridization of a PHEV subject to Urban Dynamometer Driving Schedule (UDDS) and Winnipeg Weekday Duty Cycle (WWDC) drive cycle requirements. Wu et al. [15] described a methodology to minimize the drivetrain cost of a parallel PHEV by optimizing its component sizes. Hung and Wu [16] developed an integrated optimization strategy in which both the component sizing and control strategies are taken into consideration to maximize the energy capacity stored while minimizing the energy consumed for a given driving cycle. Optimization of combined component sizing and control strategies have been explored by Zou et al. [17] to study the hybridization of a tracked vehicle, and by Kim and Peng [18] for the design of fuel cell/battery hybrid vehicles. Darcovich et al. [19] extended lithium ion battery use to improve residential energy storage with micro-cogeneration by examining high-capacity cathode materials.

While power management, control strategies and component sizing all play key roles in achieving greater overall vehicle efficiency, a detailed optimization of PHEV battery packs has not been considered. Most of the earlier battery optimization researches have focused on single-cell optimization, where the battery is optimized for maximum energy density [20–24]. More recent efforts have optimized the energy capacity of battery cells with respect to different power capacities by varying the applied current [25,26]. Most optimization studies, however, have ignored the multitude of requirements due to hybrid vehicle operations. Specifically, the battery pack has to satisfy: (1) voltage and current constraints for both safety reasons and to minimize power electronic cost, and (2) energy and power requirements for performance. To address these issues, we present a numerical framework to optimize the mass, volume and material costs of the battery pack, while satisfying all relevant requirements. By combining efficient numerical methods with existing battery models, waste attributed to sub-optimal pack design can be reduced. This type of analysis is especially important as electric vehicles become more mainstream and higher volume where small variation from the optimal solution, which may only result in slight overdesign (in terms of cost or volume), results in large penalties when compounded over a large quantity of vehicles. This type of analysis also provides a quick, cost effective design tool in the early phases of vehicle development – giving realistic guidelines on what is possible in terms of cost, size, and weight for a given battery chemistry.

In the following sections we explain the details of the numerical framework followed by the optimization results for a representative PHEV battery pack design. Using the optimization results we aim to demonstrate that the resulting battery pack is able to fulfill the various PHEV operation requirements most efficiently, hence maximizing the potential gains of PHEV operation. Finally, three federal test drive cycles are used to evaluate the performance of the battery designs by comparing the all-electric driving ranges.

2. Methodology

This section presents an overview of the optimization framework and the details of the individual components. An optimization problem has the general form:

$$\begin{aligned} &\text{minimize} \quad f(\boldsymbol{x}), \qquad f:\mathbb{R}^n \to \mathbb{R} \\ &\text{subject to} \quad \begin{cases} \boldsymbol{x}_{min} \leqslant \boldsymbol{x} \leqslant \boldsymbol{x}_{max} & \\ c_j(\boldsymbol{x}) \leqslant 0 & j = 1,\ldots,m \\ \hat{c}_k(\boldsymbol{x}) = 0, & k = 1,\ldots,\hat{m} \end{cases} \end{aligned} \tag{1}$$

where $f(\boldsymbol{x})$ is the objective function to be optimized with respect to the bounded variables $\boldsymbol{x}$, and subject to inequality constraints $c(\boldsymbol{x})$ and equality constraints $\hat{c}(\boldsymbol{x})$.

The optimization process is an iterative one that repeatedly samples the design space to locate the optimal design point, as

Please cite this article in press as: Xue N et al. Design of a lithium-ion battery pack for PHEV using a hybrid optimization method. Appl Energy (2013), http://dx.doi.org/10.1016/j.apenergy.2013.10.044