Journal of Power Sources 267 (2014) 288–299

Contents lists available at ScienceDirect

Journal of Power Sources

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

# Multi-objective optimal design of lithium-ion battery packs based on evolutionary algorithms

Bernardo Severino [d], Felipe Gana [d], Rodrigo Palma-Behnke [b, d, *], Pablo A. Estévez [b, d], Williams R. Calderón-Muñoz [a], Marcos E. Orchard [b], Jorge Reyes [d], Marcelo Cortés [c, d]

[a] *Department of Mechanical Engineering, Universidad de Chile, Beauchef 850, Santiago, Chile*
[b] *Department of Electrical Engineering, Universidad de Chile, Av. Tupper 2007, Santiago, Chile*
[c] *Department of Electrical Engineering, Universidad de Antofagasta, Av. Angamos 601, Antofagasta, Chile*
[d] *Energy Center, Universidad de Chile, Av. Tupper 2007, Santiago, Chile*

## HIGHLIGHTS

- An optimization methodology for the battery thermal management design is proposed.
- The methodology is based on multi-objective PSO and multi-physics simulations.
- A theoretical case shows the trade-off between temperature operation and area.
- A real battery pack based on pouch cells for a solar car was designed.
- A novel battery packaging design framework is able to find better solutions.

## ARTICLE INFO

*Article history:*
Received 17 October 2013
Received in revised form
13 May 2014
Accepted 17 May 2014
Available online 28 May 2014

*Keywords:*
Lithium-battery energy storage systems
Battery thermal management system
Battery cell arrangement
Optimal design
Multiphysics simulation
Multi-objective particle swarm optimization

## ABSTRACT

Lithium-battery energy storage systems (LiBESS) are increasingly being used on electric mobility and stationary applications. Despite its increasing use and improvements of the technology there are still challenges associated with cost reduction, increasing lifetime and capacity, and higher safety. A correct battery thermal management system (BTMS) design is critical to achieve these goals. In this paper, a general framework for obtaining optimal BTMS designs is proposed. Due to the trade-off between the BTMS's design goals and the complex modeling of thermal response inside the battery pack, this paper proposes to solve this problem using a novel Multi-Objective Particle Swarm Optimization (MOPSO) approach. A theoretical case of a module with 6 cells and a real case of a pack used in a Solar Race Car are presented. The results show the capabilities of the proposal methodology, in which improved designs for battery packs are obtained.

## 1. Introduction

Lithium-ion cells have become one of the most used technologies for energy storage in electric mobility applications, due to its specific energy, energy density, and specific power [1,2]. They are also considered an alternative for stationary storage systems in power systems becoming the key to a high penetration of distributed renewable energy and second-timescale grid power services [3].

Despite the increasing use of LiBESS, there are still challenges to overcome in order to achieve a competitive technology that allows the full development of the aforementioned applications. Among these challenges are [1]: reducing costs, increasing life and capacity, and improving safety. To achieve these objectives not only better cells are needed, but also a better integration of them must be done, where the thermal operation is a critical issue [4,5]. Hence, a good LiBESS design must consider that each cell of the battery pack should operate at temperatures between 25 °C and mm, and the temperature difference between them should be less than 5 °C. This is in order to achieve a good balance between performance and lifetime [6]. To prevent a significant capacity fade and thermal runaway the temperature must be under 60 °C and 80 °C respectively [7]. Additionally, both energy and power of the Li-ion

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* Corresponding author. Department of Electrical Engineering, Universidad de Antofagasta, Av. Angamos 601, Antofagasta, Chile. Tel.: +56 2 2978 4201.
*E-mail address:* rodpalma@cec.uchile.cl (R. Palma-Behnke).

http://dx.doi.org/10.1016/j.jpowsour.2014.05.088

batteries are substantially reduced if the temperature falls below −10 °C [8].

A good design of the battery thermal management system (BTMS) should take into account these thermal operational constraints. The design of the BTMS includes the size of the cooling system together with the arrangement of the cells in the delimited space. In general [9], the BTMS should satisfy the following requirements: (i) Optimum operating temperature range for every cell and battery module, rejecting heat in hot climates/adding heat in cold climates; (ii) Small temperature variations within a cell and module; (iii) Small temperature variations among modules; (iv) Compact and lightweight, easily packaged, reliable, low-cost and easy for service; (v) Provision for ventilation if the battery generates potentially hazardous gases. Clearly, some of these goals are competing and it is difficult to express all of them in a single mathematical expression. In addition, some goals could become more relevant depending on the specific application [1] and/or more difficult to achieve depending on the electrothermal cell characteristics and the local application environment. Then, a multi-objective analysis is proposed to solve this design problem.

There have been several studies on the design of the BTMS for lithium-ion batteries. In literature two basic approaches can be identified: explicit optimization schemes and simulation based approaches. On the first approach, in Ref. [10] an optimum cooling plate for an electric vehicle pack obtained using average temperature of the cells, temperature uniformity and coolant pressure drop as objective functions. In Ref. [11], different alternatives for thermal management of a battery pack are evaluated using six sigma process optimization, with maximum temperature, pressure drop and temperature difference between cells as objectives. In Ref. [12], the parameters of an air cooling system for a Li-ion battery pack for an electric vehicle are optimized using a genetic algorithm.

On the second approach, [13] develops a numerical heat generation simulation model for a battery pack with cylindrical cells in order to compare the performance between an air and liquid cooling system, considering the BTMS power consumption as a critical objective. In Ref. [14], the design of an air cooling battery system is investigated and modeled, in order to satisfy required thermal specifications. In Ref. [15] a simulation model is developed in order to analyze the effect of thermal management and different ambient conditions on battery life. [16] performs three dimensional analyses of an air-cooled battery using Computational Fluid Dynamics (CFD). With the simulations, the best configurations for the pack are obtained. It is interesting to note how tailored numerical simulation models compete with the integration of Computer-Aided Engineering (CAE) as part of a simulation cycle.

The literature survey shows that despite using an optimization or a simulation approach, the general problem of designing a BTMS is necessarily divided into many pieces or sub-problems [17]. Recent efforts in the area of integrated design platforms are reported in Refs. [18,19]. Due to the huge variety of applications and the increasingly large lithium-ion cells market, the battery pack developers have focused in giving an ad-hoc solution for a specific problem [18]. In the process, a significant amount of R&D is pursued in order to achieve good results. However, the solutions are not very flexible, making it difficult addressing new requirements for new applications.

Consequently, there is a need for the development of a computational tool to improve the battery pack design process, including the designing of thermal management system. The main objective is to achieve a high degree of automation of the process and to ensure optimal design solutions. This can result in an improvement of the design periods, a reduction in the design costs, and the calculation of new/better design solutions, which are the main motivation for our research work.

The paper is organized in six sections. Section 2 shows the general framework where the proposed optimization methodology is embedded. Section 3 describes in detail the multi-objective optimization approach using an evolutionary algorithm and a CAE software as a simulation tool. In Section 4 a theoretical example is solved in order to illustrate the trade-off between space, temperature, and BTMS power consumption. Section 5 shows a real case of study with a comprehensive analysis of the results. Finally, Section 6 presents the conclusions and final remarks.

## 2. Proposed BTMS design framework

Although the scope of this paper is concentrated in the optimization approach for BTMS design, in this section we shortly describe the general framework under which our study is placed.

The proposed computational framework receives the application requirements as inputs: technical constraints, electrical use patterns, and environmental conditions, as shown in Fig. 1. The LiBESS design framework is composed of the following four steps:

- The first step consists of selecting the cell from a database and deciding the number of them to be used in the battery pack. Here, the goal is to minimize the present value of costs that depends on the investment cost, the number of times that the battery pack is replaced and the remaining cost.
- In the second step, both a cooling system type and a cell arrangement pattern are selected from a library of pre-defined alternatives. Hence, a multi-objective problem is defined; i.e., optimization goals, variables, constraints, and parameters.
- In the third step, the multi-objective problem is solved using evolutionary algorithms (EAs). The goal is to obtain the Pareto front of the design variables defined in the previous step. Here, the application requirements are considered in detail in order to achieve the design goals of the BTMS.
- Finally, in step four, a long-term evaluation of the battery pack is done considering results of the previous steps and a more detailed model of both the State of Charge (SoC) and the State of Health (SoH).

In this paper, we focus on the third step of the proposed framework. A multi-objective particle swarm (MOPSO) [20] algorithm is developed in Matlab® and is set in order to solve the optimal design of the battery thermal management system. COMSOL Multiphysics® is a multi-physics simulator used to simulate and evaluate the thermal response of each cell into the battery pack. An interface in Matlab is developed to connect the data generated from the simulation and the optimization modules. The scope of this study does not include a systematic experimental evaluation of the simulation software.

## 3. LiBESS optimization methodology

In light of the evident trade-off between the design goals of BTMS and the complex modeling of thermal response inside a battery pack, the optimal design problem is solved using a novel Multi-Objective Evolutionary Algorithm (MOEA) approach.

A general MO problem is defined as the minimization of the objective vector $\overrightarrow{F}(x) = [f_1(x), \ldots, f_k(x)]^T$ subject to a $n$-dimensional decision variable vector $\overrightarrow{x} = [x_1, \ldots, x_n]^T$, that is in the universe $\Omega$ that contains all possible $\overrightarrow{x}$ that can be used to satisfy an evaluation of $\overrightarrow{F}(x)$. In addition there are inequality and equality constraints, $g_i(x) \leq 0$, $i = \{1,\ldots,m\}$, and $h_j(x) = 0$, $j = \{1,\ldots,p\}$, respectively [21].

The use of EAs to solve MO problems has been motivated mainly because of the population-based nature of EAs which allows obtaining multiple elements of the Pareto optimal set in a single