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Module design and fault diagnosis in electric vehicle batteries

Gregory J. Offer*, Vladimir Yufit, David A. Howey[1], Billy Wu, Nigel P. Brandon

Department of Earth Science Engineering, Imperial College London, London SW7 2AZ, United Kingdom

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ABSTRACT

Systems integration issues, such as electrical and thermal design and management of full battery packs – often containing hundreds of cells – have been rarely explored in the academic literature. In this paper we discuss the design and construction of a 9 kWh battery pack for a motorsports application. The pack contained 504 lithium cells arranged into 2 sidepods, each containing 3 modules, with each module in a 12P7S configuration. This paper focuses particularly on testing the full battery pack and diagnosing subsequent problems related to cells being connected in parallel. We demonstrate how a full vehicle test can be used to identify malfunctioning strings of cells for further investigation. After individual cell testing it was concluded that a single high inter-cell contact resistance was causing currents to flow unevenly within the pack, leading to cells being unequally worked. This is supported by a Matlab/Simulink model of one battery module, including contact resistances. Over time the unequal current flowing through cells can lead to significant differences in cells' state of charge and open circuit voltages, large currents flowing between cells even when the load is disconnected, cells discharging and aging more quickly than others, and jeopardise capacity and lifetime of the pack.

1. Introduction

Electric and hybrid vehicles depend on electrochemical battery systems, with lithium-ion chemistries widely accepted as the current state of the art in terms of energy density and performance. Research and development into new electrode and electrolyte materials and chemistries continues apace. However, the electrical, mechanical and thermal integration of cells into packs and packs into electrical vehicles is paramount in order to ensure long and safe operation. Such integration issues have been relatively poorly researched in the literature to date. Whilst there are papers exploring the electrical and thermal behaviour of individual cells under a variety of conditions [1–5], the monitoring and testing of individual cells in battery packs [6,7], and the thermal management of battery packs [4,8–10], there are few which look at the electrical issues associated with the design and testing of complete modules, and those that do are for much lower power applications [11].

A number of factors are important in this regard. Mechanical integrity is crucial, and the challenge here given the relatively low energy densities of batteries is to minimise weight and the use of additional support materials, whilst providing adequate support and protection particularly in crash scenarios. Certain chemistries (notably $LiCoO_2$ cathodes) are prone to dangerous 'thermal runaway' if cells are overheated, overcharged, short circuited, crushed or punctured [12], and therefore various safety mechanisms are typically incorporated at cell level, such as for example vents or deliberate delamination of the layers due to internal release of gases in an unsafe scenario [13].

In addition to ensuring the safety of vehicle occupants, the lifetime of the batteries must be maximised through the module design and battery management approach. Operating current, depth and rate of charge/discharge, and temperature all strongly affect lifetime. Batteries are particularly intolerant to temperature extremes, with high temperatures being encountered during high current loading conditions such as fast charging or acceleration transients which cause large specific internal heat generation [2]. This is primarily due to resistive heating in the contacts, electrodes and electrolyte [8]. The temperatures reached within a cell depend on the level of heat generation, the thermal properties and the heat transfer around the cell, i.e. the cooling system.

High power lithium-ion cells tend to have very low internal resistances, of the order of mΩ, and the contact resistances between cells are normally measured in μΩ assuming connections have been made correctly. However, faulty contacts which lead to much higher contact resistances (e.g. of the order of mΩ) will adversely affect pack performance, often in unexpected ways, and this can be detected by current pulse techniques combined with individual cell testing, as described later in this paper. In parallel-connected

* Corresponding author. Tel.: +44 020 75945018.
E-mail addresses: gregory.offer@imperial.ac.uk (G.J. Offer), v.yufit@imperial.ac.uk (V. Yufit), d.howey@imperial.ac.uk, david.howey@eng.ox.ac.uk (D.A. Howey), billy.wu06@imperial.ac.uk (B. Wu), n.brandon@imperial.ac.uk (N.P. Brandon).
[1] Present address: Department of Engineering Science, University of Oxford, Oxford OX1 3PJ, United Kingdom.

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cells, it is normally assumed that 'self balancing' will occur due to all cells being forced to the same potential [11]. However, as we later discuss, large differences in interconnection resistances in this configuration can lead to differences in the currents flowing through individual cells, which means that cells may not be well balanced under load and over time this could lead to unequal performance of individual cells. Clearly it is important to avoid this. In addition if unequal current pathways are introduced through poor design cells may become unbalanced under load.

This is conceptually a similar problem to that experienced within cells at high charge and discharge rates. One-dimensional models perpendicular to the plane of the separator/electrolyte predict that the reactions occur at the electrode/electrolyte interfaces regardless the position of current collection tabs [8]. Under high currents however, a 1D model is not sufficient because there are spatial variations in the orthogonal directions. Indeed, 2D [5] and 3D [4] models predict that reactions preferentially occur in proximity of the current collection tabs in planar cells in the plane parallel to the separator due to noticeable ohmic drop along the current collector [4,5]. Hence under high charge or discharge rates, large spatial variations in lithium concentration, reaction current density and overpotential might occur within a cell, and upon removal of the load large internal currents could flow as lithium redistribution occurs [3]. This is further compounded by thermal gradients within a cell which can also cause changes to internal resistances and lead to even greater internal spatial variations [3,9,10].

The electrical behaviour of a battery can be represented by an electrical circuit model comprising of interconnected resistors, capacitors and inductors. Varying degrees of complexity are possible depending on the level of fidelity required, but the simplest modelling usually includes a series inductor, resistance R_i and then one or two RC time constant pairs (e.g. C_{dl} the double layer capacitance and R_{ct} the charge transfer resistance as shown) representing various dynamic effects. However, for the typical sampling rates at which battery management systems operate (1–10 Hz maximum), the relevant dynamics are the instantaneous change caused by the voltage drop across the internal resistance, diffusion – with time constants of minutes to hours – and change in open circuit potential according to state of charge.

Previous authors have shown that short current pulses can be used to estimate the series resistance and other parameters of a battery system, and that the resulting current and voltage behaviour of the full pack in a real vehicle follows the model predictions reasonably accurately [14]. Indeed, in addition to traditional frequency response measurement techniques [7], pulse techniques have been used to estimate the internal resistance of lithium cells in a hybrid vehicle, and this can be used to provide a measure of battery degradation (capacity fade) over time [6].

In this paper we discuss issues associated with the design and testing of complete battery packs for electric vehicles. Secondly we explore a methodology for detecting and analysing faults in complete battery modules at the pack and vehicle testing stage, by using a current pulse (or 'current interrupt') method for pack level, and electrochemical impedance spectroscopy for cell level tests.

2. Battery pack construction

The battery pack used for experimental testing consisted of 504 4.8 Ah (at a 0.5 C discharge rate) Kokam Lithium-polymer pouch cells with a maximum and minimum operating voltage limit of 4.2 V and 2.7 V respectively. The cells have a rated capacity of 17.8 Wh each and continuous discharge current of 96 A with a peak current of 192 A.

These were divided into two sidepods containing 252 cells each, for use in a prototype electric racing vehicle. Each sidepod was further subdivided into three modules containing 84 cells each. The cells in each module were arranged in a 12P7S configuration, giving each module an operating voltage range of 18.9–29.4 V. The three modules were connected in series giving a sidepod operating voltage range of 56.7–88.2 V. The two battery sidepods were connected in parallel to two PM72601B Kelly Motor controllers powering two Agni 95R brushed DC motors each rated at 77 V maximum. The main battery specifications are shown in Table 1.

Table 1
Battery pack specifications.

Maximum voltage	88.2 V
Minimum voltage	56.7 V
Nominal voltage	77.7 V
Capacity	115.2 Ah
Watt hours	8950 Wh
Continuous discharge current	2208 A
Peak discharge current	4704 A
Maximum power	415 kW
Nominal power	195 kW

A battery management system (BMS) produced by REAP systems Ltd., monitored the voltages and temperatures of each parallel strip of cells with a sampling rate of 1 Hz. Each BMS board has the capability to measure 14 voltages and 7 temperatures. Voltage measurements were made at the outer point on one side of each parallel strip and temperature measurements were made in the centre of a strip where the temperature is assumed to be highest. All sensor wires were routed to the top of the module through 2 × 10-pin Harwin connectors and then to the BMS boards, with appropriate fusing. The BMS then communicated with a National Instruments compactRIO supervisory controller via CANbus.

The main components of the battery modules are shown in Fig. 1. Two gridded polypropylene plates provided the cell support for each battery module at the centre of the cells. The mid-plates are the most structurally important part of the modules, supporting the bulk weight of the cells and provide the fundamental support structure that other elements are fixed to. Two end plates sat around the cell tabs. Aluminium bars provided the electrical connections between the individual cells.

Polypropylene T-pieces and L-pieces were used to clamp the aluminium bars as well electrically isolate them. Tie rods ran through the span of these blocks, from one T-piece to another ensuring the cell tabs were securely fastened. Along the length of the cells, pins were inserted from both sides of the module through the T-pieces, end plate and mid plates. These were held in place by threaded inserts and plastics spacers that set the distance between the plates and electrically insulated the metal pins.

The T-pieces and L-pieces secured and aligned the aluminium connection blocks to transfer the load from the endplate to the pins and vice versa, and secure the blocks, the endplates and the pins together. The T-design allowed the blocks to be tightened together using tie rods and secured all parts adequately without restricting or inducing additional stresses. Fig. 2 shows this arrangement.

The three modules were connected in series in each sidepod with electrical connections being made at the diagonal corners of the modules with bolted aluminium bars, as shown in Fig. 3. Copper connectors were considered however it was shown that large contact pressures would be required for an aluminium–copper interface to be effective.

Due to the connection configuration, the positive and negative terminals of the pack are at opposite ends. For the vehicle design, it was desirable to have the positive and negative terminals on the same side. Therefore, an aluminium bus bar was used to return the negative terminal to the same position as the positive terminal.

Two Gigavac GX200 contactors were also located within each sidepod. These were rated to a continuous discharge current of