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A Study of Cell-to-Cell Interactions and Degradation in Parallel Strings: Implications for the Battery Management System

C. Pastor-Fernández [a, *], T. Bruen [a], W.D. Widanage [a], M.A. Gama-Valdez [b], J. Marco [a]

[a] WMG, University of Warwick, Coventry, CV4 7AL, UK
[b] Jaguar Land Rover, Banbury Road, Warwick, CV35 0XJ, UK

HIGHLIGHTS

- Experimental evaluation of SoH within parallel connected cells aged differently.
- Current, SoC and cell temperature drive SoH cell-to-cell convergence.
- An initial 45% difference in cell-to-cell SoH (resistance) converges to 30%.
- An initial 40% difference in cell-to-cell SoH (capacity) converges to 10%.
- A linear correlation between capacity fade and resistance increase is observed.

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ABSTRACT

Vehicle battery systems are usually designed with a high number of cells connected in parallel to meet the stringent requirements of power and energy. The self-balancing characteristic of parallel cells allows a battery management system (BMS) to approximate the cells as one equivalent cell with a single state of health (SoH) value, estimated either as capacity fade (SoH_E) or resistance increase (SoH_P). A single SoH value is however not applicable if the initial SoH of each cell is different, which can occur when cell properties change due to inconsistent manufacturing processes or in-homogeneous operating environments. As such this work quantifies the convergence of SoH_E and SoH_P due to initial differences in cell SoH and examines the convergence factors. Four 3 Ah 18650 cells connected in parallel at 25 °C are aged by charging and discharging for 500 cycles. For an initial SoH_E difference of 40% and SoH_P difference of 45%, SoH_E converge to 10% and SoH_P to 30% by the end of the experiment. From this, a strong linear correlation between ΔSoH_E and ΔSoH_P is also observed. The results therefore imply that a BMS should consider a calibration strategy to accurately estimate the SoH of parallel cells until convergence is reached.

1. Introduction

In recent years lithium-ion (Li-ion) cells in a battery pack have become the favourable choice for electric power transportation systems. In order to increase the pack capacity and meet requirements for power and energy, cells in a battery module are often electrically connected in parallel [1]. For instance, each unit of the BMW E-Mini 35 kWh battery pack is composed of 53 cells connected in parallel and 2 in series. Two units constitutes a module and the whole battery is composed of 48 modules connected in series [2]. Another example is the Tesla Model S 85 kWh battery pack. This battery pack includes 16 modules of 6S74P configuration (6 cells connected in series and 74 cells connected in parallel) summing to 7104 cells within the complete battery assembly [3].

Battery health diagnosis is essential to develop a control strategy in order to ensure safe and lifetime efficient operation of electric and hybrid vehicles. State of Health (SoH) is the parameter used by the Battery Management System (BMS) to monitor battery ageing. SoH is often calculated based on two metrics: capacity fade and power fade [4]. These metrics are directly related to vehicle level attributes that limit driving range and vehicle power, respectively. For the case where cells are connected in parallel, the BMS typically does not monitor the SoH of each individual cell because the BMS does not have access to individual cell currents

* Corresponding author.
E-mail address: c.pastor-fernandez@warwick.ac.uk (C. Pastor-Fernández).

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and temperatures. Thus, the BMS cannot determine the capacity fade and power fade at cell level. For this case the BMS approximates the SoH as that of an equivalent single value for the whole battery stack. This approximation is based on the assumption that the SoH of cells connected in parallel are the same since they have identical terminal voltages. This assumption is however no longer valid when cell properties change due to manufacturing tolerances and usage conditions. For instance, the presence of temperature gradients or the existence of different resistance paths that will underpin an uneven current distribution within the system represent typical scenarios where cell-to-cell SoH may be different. Such an imbalanced scenario has been previously examined in Refs. [5–8]. Another potential application of this study is second life grid storage modules connected in parallel as suggested in Refs. [9,10].

In a recent study, Gogoana et al. [5] cycled two cylindrical lithium-iron phosphate (LFP) cells connected in parallel to evaluate the degradation of each cell over time. They identified that an initial 20% discrepancy in internal resistance between cells in a parallel string results in a 40% reduction of the total cycle life. They attributed this result to the uneven high currents experienced by each cell.

Gong et al. [6] cycled four groups of Li-ion cells. Each group of cells was composed of two cells with different degradation levels. They showed that when two cells with a 20% impedance difference were connected in parallel, the peak current experienced was 40% higher than if the cells had the same impedance.

Zhang et al. [7] cycled two 26650 LFP cells connected in parallel, with each cell at a different temperature (5 °C and 25 °C). Based on a simplified thermal-electrochemical model, it was shown that temperature differences between the cells makes self-balancing difficult, which consequently accelerates battery degradation.

Shi et al. [8] cycled two groups of LFP batteries (each one composed of two cells) for cycle life and basic performance analysis. The first group was tested at 25 °C, whereas the second group was tested at 25 °C and 50 °C to evaluate the effect of high temperature. They concluded that imbalanced currents can directly affect the capacity fade rate of cells connected in parallel.

These studies highlight that cells connected in parallel will age differently when the SoH of each individual cell is not the same. These results raise the question as to whether the BMS will estimate the SoH correctly under this situation. The contribution of this work is to find an answer for this question quantifying the cell-to-cell SoH for a scenario when each initial cell SoH is different. To understand the reasons behind the cell-to-cell SoH variation, SoC, current and temperature distribution in the short-term, and charge-throughput and thermal energy in the long-term are examined. A simple SoH diagnosis and prognosis approach is also presented, where capacity and resistance, and the change in SoH_E (based on a measure of the cell capacity) and the change in SoH_P (based on a measure of the cell resistance) are approximated by a linear relationship. The overall output of this work is expected to improve the accuracy of SoH diagnosis and prognosis functions within the BMS when cells are connected in parallel.

The structure of this work is divided as follows: Section 2 explains the most common definitions used in the literature for SoH capacity fade (SoH_E) and power fade (SoH_P). Section 3 summarises the experiment where four commercially available 3 Ah 18650 lithium-ion cells connected in parallel were aged by 500 cycles. The results are given in Section 4, where the factors which drive the SoH convergence are evaluated. Based on the results for capacity and resistance fade, Section 5 proposes a simple approach for SoH diagnosis and prognosis based on a linear correlation between capacity and resistance, and between the change in SoH_E (ΔSoH_E) and the change in SoH_P (ΔSoH_P). Finally, the limitations of this study and further work are stated in Section 6 and conclusions are presented in Section 7.

2. SoH definition

SoH diagnosis and prognosis is essential to ensure effective control and management of Li-ion Batteries (LIBs). The SoH will evolve differently depending on the battery state: cycling or storage [11]. The SoH depends also on different parameters which can be controlled by the BMS. For automotive applications these parameters are typically battery temperature, Depth of Discharge (DoD), discharging and charging current rates for cycling, and the SoC employed for storage conditions [4]. Since the SoH depends on different parameters it is difficult to estimate the contribution of each parameter. The SoH has an upper and a lower limit: Begin of Life (BoL) and End of Life (EoL). BoL (SoH = 100%) represents the state when the battery is new, and EoL (SoH = 0%) is defined as the condition when the battery cannot meet the performance specification for the particular application for which it was designed [13]. In essence, EoL corresponds to the battery End of Warranty (EoW) period, adopted in some automotive standards [14,15]. In relation to capacity and resistance, the EoL values are commonly defined as [4,11–13]:

$$C_{\mathrm{EoL}} = 0.8 \cdot C_{\mathrm{BoL}} \quad (1)$$

$$R_{\mathrm{EoL}} = 2 \cdot R_{\mathrm{BoL}} \quad (2)$$

According to [4] and [11–13], SoH_E and SoH_P are often calculated as a percentage with respect to the difference between BoL and EoL in either capacity (Equation (3)) or resistance (Equation (4)).

$$SoH_E = \frac{C_{now} - C_{EoL}}{C_{BoL} - C_{EoL}} \cdot 100 = \frac{C_{now} - 0.8 \cdot C_{BoL}}{C_{BoL} - 0.8 \cdot C_{BoL}} \cdot 100 = \frac{C_{now} - 0.8 \cdot C_{BoL}}{0.2 \cdot C_{BoL}} \cdot 100 \quad (3)$$

$$SoH_P = \frac{R_{now} - R_{EoL}}{R_{BoL} - R_{EoL}} \cdot 100 = \frac{R_{now} - 2 \cdot R_{BoL}}{R_{BoL} - 2 \cdot R_{BoL}} \cdot 100 = \left(2 - \frac{R_{now}}{R_{BoL}}\right) \cdot 100 \quad (4)$$

The decision as to which measure of battery health to use, SoH_E, SoH_P or both, depends on the application. In the case of the automotive industry SoH_E is commonly employed in high-energy applications such as BEVs (specific energy >150 Wh/kg) [16], SoH_P is used for high-power applications such as Hybrid Electric Vehicles (HEVs) (specific power > 1500 W/kg) [16] and both metrics can be combined for Plug-in-HEV (PHEV) applications.

3. Experimental procedure

This study extends the experiment performed in [1], where four 3 Ah 18650 Li-ion cells were aged by 0, 50, 100 and 150 cycles individually to ensure an initial SoH_E difference of 40% and SoH_P difference of 45% between the least and the most aged cells. These values correspond to a difference of capacity and impedance of circa 8% and 30% respectively. Research published highlights that differences in cell properties from initial manufacture and integration may be circa 25% for impedance [5] and 9% for capacity [17], which is in agreement with the initial differences considered in this study. The four cells are then connected in parallel and cycled for a total of 500 cycles, where 500 cycles represents the EoL state according to the manufacturer's specifications. Thus, all the cells were loaded at least for 500 cycles. The experimental procedure is