Simulation Analysis of Potential Lifetime Extension Through Dynamic Battery Reconfiguration

Albert Škegro, Torsten Wik, *Member, IEEE*, Changfu Zou, *Senior Member, IEEE*

***Abstract*—Reconfigurable battery packs (RBPs) are emerging as a promising solution to mitigate the performance limitations of conventional battery packs (CBPs), particularly due to cell-to-cell variation and premature degradation. This research presents a simulation-based study assessing the potential lifetime extension of RBPs compared to CBPs. Using aging data for lithium iron phosphate (LFP) and nickel-manganese-cobalt (NMC) cells, we quantify lifetime gains in terms of equivalent full cycles (EFC). Results indicate that RBP architectures can yield significant lifetime benefits, particularly in series configurations with large cell count and scenarios with high variability in initial cell capacity or resistance. These findings establish a foundation for aging-aware RBP control strategies and inform future RBP hardware designs.**

***Index Terms*—Batteries, Battery management systems (BMS), Modular reconfigurable batteries, Lifetime, Switching cells.**

I. Introduction

Contemporary transportation systems rely significantly on fossil fuels, whose consumption and associated tailpipe emissions not only damage ecosystems but are also main contributors to climate change and are unsustainable in the long run.

Electrification based on lithium-ion (Li-ion) batteries presents a promising way to mitigate this dependency. In order to attain their voltage and capacity specifications, battery packs for electric vehicles (EVs) and stationary energy storage systems (ESSs) are often comprised of hundreds, or even thousands, Li-ion cells arranged in complex series and parallel topologies.

In spite of this, large battery packs tend to be used inefficiently. As a result of variations in the manufacturing process and different local conditions in the pack, the cells do not age uniformly. A consequent large spread in cell capacities, or cell internal resistances, results in significant performance degradation for the CBP with regard to capacity utilization and power output. Furthermore, the inability to disconnect cells implies that failure of a single cell not only presents a safety hazard but also renders the remaining healthy cells in the CBP unusable.

Dynamic battery reconfiguration is a promising concept in this regard [1]. Essentially, battery packs allowing for dynamic reconfiguration, i.e., RBPs, enable greater flexibility during the battery pack operation than FBPs. The reconfiguration is achieved by employing additional power electronics, e.g., by placing a certain number of switches around each cell, or group of cells, thus allowing for finer cell-level control and a range of potential benefits such as enhanced fault tolerance, prolonged battery pack lifetime, customized output voltage, and mixing of cells having different properties. An illustrative implementation is presented at Fig. 1.

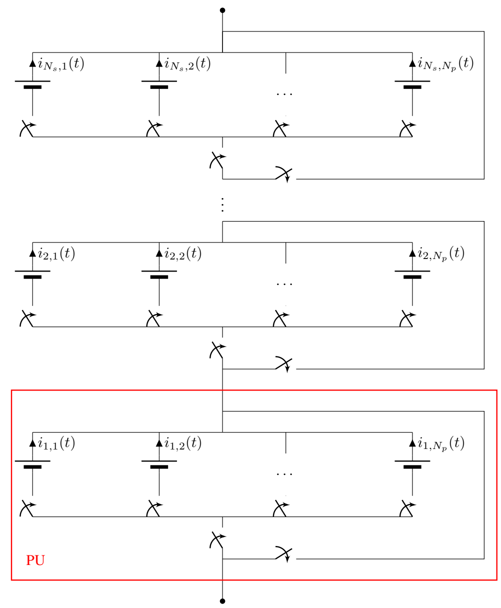

Fig. 1: The reconfigurable battery pack (RBP) with one of the reconfigurable battery units (RBU) enclosed in red, where N denotes the number of series-connected RBUs in the RBP.

Despite promising applications in battery packs for EVs (e.g., [2]) and ESSs (e.g., DC charging and microgrids [3]), the quantitative impact of dynamic reconfiguration on battery pack lifetime extension remains underexplored. To address this, this research introduces a simulation framework that investigates the lifetime extension of using RBPs in place of CBPs. The approach incorporates stochastic initial conditions, realistic aging models (calendar and cycle-based), different temperatures and the dynamic load profile. Two battery chemistries are analyzed: LFP and NMC. The results provide insight into when and how reconfiguration is most beneficial, and inform future design choices for future RBP hardware designs and related control algorithm.

This work was funded by Mistra Innovation 23 under the BattVolt project.
Authors are with the Department of Electrical Engineering, Chalmers University of Technology, 41296 Gothenburg, Sweden (e-mail: skegro@chalmers.se; tw@chalmers.se; changfu.zou@chalmers.se)

II. Current Results

A. Simulation Framework

In the RBP architecture, each cell is equipped with a switch, enabling dynamic operation (see Fig. 1. Cell degradation is modeled as the superposition of calendar aging (a function of time, SOC, and temperature) and cycle aging (dependent on depth of discharge, C-rate, and EFCs). Initial capacity and resistance values are drawn from normal distributions based on experimental data [4].

The simulation assumes well-managed pack temperatures [5] and negligible switching losses in RBP architecture [3]. The end-of-life (EOL) is defined when the cell capacity of the first cell in the pack drops to 80% of the nominal cell capacity. Each configuration is simulated for 1000 Monte Carlo runs using `MATLAB` on a Linux-based high-performance computer cluster.

To quantify these improvements, the gain in extracted EFCs is defined as:

$$\chi_\epsilon^k = \left(\frac{\epsilon_{RBP}}{\epsilon_{CBP}} - 1\right) \cdot 100\,[\%]\,, \tag{1}$$

where ϵ_{RBP} and ϵ_{CBP} are the EFC of RBP and CBP at their EOL, respectfully. A representative depiction of the approach is given in Fig. 2.

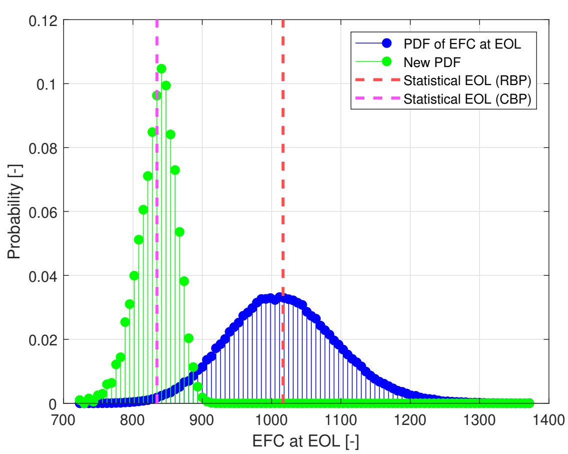

Fig. 2: Illustration of statistical EOL for an RBP and a CBP, each with 100 cells in series.

To summarize the overall performance across multiple experiments, sample mean and sample variance across Monte Carlo runs are given as:

$$\bar{\chi}\epsilon = \frac{1}{N_{exp}} \sum_{k=1}^{N_{exp}} \chi_\epsilon^k \tag{2a}$$

$$s_{\chi_\epsilon}^2 = \frac{1}{N_{exp}-1} \sum_{k=1}^{N_{exp}} \left(\chi_\epsilon^k - \bar{\chi}_\epsilon\right)^2 \tag{2b}$$

B. Key Findings

In the first study [6], the lifetime extension with respect to a more limited set of parameters and simplifying assumptions was analyzed and discussed for a publicly available dataset from cell aging experiments on NMC cells and cycle-aging dominated use cases. It has been shown that the lifetime extension for the 800 V battery system can be as high as 71%.

Further work shows that, for LFP cells, reconfiguration gains in LFP case improvements exceeded 20% in high-variability, large-pack configurations. While both LFP and NMC cells benefit from reconfiguration, NMC cells exhibit higher sensitivity to aging variability and thus achieve larger lifetime improvements.

Larger spreads in capacity and resistance resulted in more significant benefits. An increase in the initial spread of capacity (CV_Q) and resistance (CV_R) values leads to greater lifetime extension. A larger initial spread increases the likelihood that one cell will perform significantly worse than the others from the beginning of life, which can accelerate the onset of the pack's end of life (EOL). Reconfiguration mitigates this effect by allowing the system to isolate or redistribute load away from the weakest cells, thereby extending the overall lifetime.

The probability of having weak or failing cells increases with pack size. RBPs mitigate this issue by bypassing or redistributing load, leading to smoother degradation and longer overall pack life. Gains are particularly notable in configurations used in 400V and 800V systems.

Cycle-aging-dominated use cases (short rest between discharges) show greater benefit from reconfiguration than calendar-aging-dominated ones. This is because reconfiguration can actively manage cycling stress across the cell population.

References

[1] W. Han, et al., Next-generation battery management systems: Dynamic reconfiguration, IEEE Ind. Electron. Mag. 14 (4) (2020).

[2] N. Bouchhima, M. Schnierle, S. Schulte, K. P. Birke, Optimal energy management strategy for self-reconfigurable batteries, Energy 122 (2017) 560–569.

[3] J. Engelhardt, J. M. Zepter, T. Gabderakhmanova, G. Rohde, M. Marinelli, Double-string battery system with reconfigurable cell topology operated as a fast charging station for electric vehicles, Energies 14 (9) (2021).

[4] K. Rumpf, M. Naumann, A. Jossen, Experimental investigation of parametric cell-to-cell variation and correlation based on 1100 commercial lithium-ion cells, J. Energy Storage 14 (2017) 224–243.

[5] S. Wang, et al., Chapter 9 - Battery system active control strategies, in: Battery System Modeling, Elsevier, 2021, pp. 313–340.

[6] A. Škegro, C. Zou, T. Wik, Analysis of potential lifetime extension through dynamic battery reconfiguration, in: 2023 25th European Conference on Power Electronics and Applications (EPE'23 ECCE Europe), IEEE, 2023, pp. 1–11.