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# Physics based modeling of a series parallel battery pack for asymmetry analysis, predictive control and life extension

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## HIGHLIGHTS

- Development of a physics based series parallel pack model.
- Contributions of cathode degradation towards capacity fade.
- Design and operation based asymmetry analysis.
- Predictive control algorithm for temperature management.
- Life extension using reconfigurable battery pack.

## ARTICLE INFO

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## ABSTRACT

Lithium-Ion batteries used for electric vehicle applications are subject to large currents and various operation conditions, making battery pack design and life extension a challenging problem. With increase in complexity, modeling and simulation can lead to insights that ensure optimal performance and life extension. In this manuscript, an electrochemical-thermal (ECT) coupled model for a 6 series × 5 parallel pack is developed for Li ion cells with NCA/C electrodes and validated against experimental data. Contribution of the cathode to overall degradation at various operating conditions is assessed. Pack asymmetry is analyzed from a design and an operational perspective. Design based asymmetry leads to a new approach of obtaining the individual cell responses of the pack from an average ECT output. Operational asymmetry is demonstrated in terms of effects of thermal gradients on cycle life, and an efficient model predictive control technique is developed. Concept of reconfigurable battery pack is studied using detailed simulations that can be used for effective monitoring and extension of battery pack life.

## 1. Introduction

The increasing demand for environmental friendly technology and advances in hybrid electric vehicles, have brought tremendous changes to an era where automobiles were perennially powered by gasoline. Lithium Ion batteries with its high energy/power density, light weight and smaller size is a key player in this rapidly expanding automobile market. With more stringent environmental regulations on vehicular emissions and greater demand for better fuel economy the demand for electric vehicles is expected to increase. In such large scale applications where there is a requirement of high power, a single lithium Ion cell does not suffice and a battery pack composed of several cells connected together is needed. Battery packs can be configured in various ways depending on the applications they are used for. Temperature and C rate form a crucial factor in determining the performance of a battery pack [1,2]. Configuration, and modes of usage introduce unique research challenges in battery pack design. When battery packs are operated at high temperature and current the capacity loss that occurs is significantly high [3–5].

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Pack models can have various configurations with batteries consisting of serial only cells or a mix of series and parallel cells. Pack asymmetry arises due to variations that occur between the cells that constitute the pack. Asymmetry can arise due to design parameters like loading or porosity, or operating parameters like temperature and C rate. Thus asymmetry is invariable in any pack design and can greatly influence the performance. Most reported studies however, use representative packs to study pack behavior and do not take into account pack asymmetry. A simulation of a series/parallel pack taking into account the asymmetry is crucial to delineate the negative effects that variations between cells of the pack can have on the overall pack performance. Gogoana et al. [6] study the effect of mismatching internal resistances of parallel connected LFP ($LiFePO_4$) cells cycled at a high rate. Chiu et al. [7] use a series only LFP battery pack to study the effects of temperature variations within such a pack.

Various design level models have been developed in order to study the thermal behavior of battery packs. Martin et al. [8] design a thermal management system for a cylindrical Lithium Ion battery pack. Jarrett and Kim [9] design a parametric cooling plate model for a battery pack by assessing the sensitivity of optimum design to the cooling plate boundary conditions. Sun et al. [10] design a decoupled three-dimensional (3D) battery pack thermal model to estimate temperature variation across a pack and temperature contours of individual cells in a pack. Hartridge [11] design cell and pack level thermal models for high power pouch cells. Although such simulation models aid designers to develop efficient battery packs and cooling concepts, these complex simulations are time consuming and not amenable for SOC estimation directly.

Zhong et al. [12] develop a relation between the pack SOC and the parameters of the cells in the pack to design a balance control strategy for SOC estimation. Baronti et al. [13] study a series connected battery pack to develop an analytical active balancing model to transfer charge between cells of the pack. Li et al. [14] developed a framework for multi-cell state estimation taking into account the variations between the SOC and resistances of different cells using a recursive least squares algorithm. Xiong et al. [15] use an equivalent circuit model with lumped parameters to develop a series connected battery pack by grouping cells with similar capacities and resistances together thereby reducing the computational times. Sun and Xiong [16] develop a series connected battery pack for SOC estimation where a bias correction for single cells based on the average cell model is proposed to improve upon the representative battery pack model.

The capacity fade that occurs in a battery pack is characterized by a loss of cyclable power of the pack. Regardless of whether the battery pack is cycled natural loss of derivable energy stored within the battery would occur. The lifetime of the battery associated to this is referred to as the ”calender life”. Cycle life is defined as the life time related to cyclic charge and discharge of the battery. This can be related to changes that occur in the electrodes (phase change, volume change) [17–19]. Impedance rise also effects the performance of the battery and the rise in impedance within the cell can be experimentally measured using electrochemical impedance spectroscopy [20,21]. Capacity fade and impedance rise is of major concern in automotive applications as it determines the life time of the pack. Various internal mechanisms such as the SEI formation on the anode-electrolyte interface also cause capacity loss due to the low equilibrium potential of lithiated graphite [17,18]. Once the protective layer is formed it continues to grow with cycling and reduce the amount of active material available for cycling. While SEI formation at the anode has a significant contribution in the total capacity fade, batteries using nickel based cathodes have additional degradation occurring at the cathode as well. A nickel oxide layer formation at the cathode due to electrolyte decompositions results in increase of charge transfer impedance and subsequently increased capacity fade of the cell [22]. Although cells with nickel based cathodes are generating much research attention, a systematic study that apportions the total degradation to individual electrodes is still wanting.

Given that temperature plays a significant role in the performance of a pack, efficient thermal protection systems form one of the most essential components of battery packs [23,24]. Every degree rise in temperature during operation in a range of 30–40 °C reduces the life of a Lithium ion battery pack by about 2 months [25]. Low temperature operation on the other hand, not only decreases the lifespan of the pack but also causes significant increase in the internal resistance of the pack [26]. Hence, improving the cooling system within the battery pack is given high priority in most studies.Choi and Kang [27] use internal resistance depending on temperature and SOC to predict heat generated by the system. Bandhauer et al. [28] simulate both air and liquid cooling surfaces using a dynamic power profile, to observe that although liquid cooling reduces the peak cell temperature it causes temperature difference across the cell. Liquid flow and air flow thermal management systems are also considered by Jarett and Kim [29] and Giuliano et al. [30] respectively where cooling strategies are designed to improve battery temperature uniformity. Thermal control systems based on phase change materials (PCM) are considered by Kizilel et al. [31] and Sabbah et al. [1]. Most thermal management systems use a feedback control based design. Due to inherent dependence of the battery electrochemical processes on temperature, the conventional feedback control results in higher heat dissipation and inefficient operation, hence a more efficient thermal control is needed.

In many state of the art applications, the battery pack configuration is fixed and cannot be changed during operation or faulty behavior. When certain cells in the battery pack are defective, the operating time and lifespan of the battery pack drastically reduces. In the event of a single cell failure during operation, the entire battery pack system fails, making it highly unreliable. A novel way to mitigate this issue is by using a reconfigurable pack, wherein when a certain number of cells fail or go faulty during operation they can be replaced with new cells and the pack can continue to be used. Adany et al. [32] and Kim and Shin [33] used switching algorithms where select cells of the pack are used at different demand conditions by controlling the current flowing through each of these groups of cells. Hamidi [34] propose a hardware level solution to develop a reconfigurable battery pack.

Addressing the open research areas discussed above and aiming to provide key insights for efficient pack design, in this work a battery pack model is developed based on the electrochemical thermal model (ECT) for Li ion cells. The configuration studied is a 30 cell series parallel (6S5P) system, with NCA/C electrodes. Each electrode has signature degradation behavior, and the first part of the work studies the individual contributions of anode and cathode degradation on the pack capacity fade. Furthermore pack asymmetry is studied using multiple instances of representative cells. Asymmetry induced by design variables as well as operating conditions are analyzed. Based on the former, a novel method to obtain the complete pack response without tedious simulations for the entire array of cells is introduced. The latter gives the effect of temperature variation on life of the battery pack. Subsequently, a predictive thermal model control is proposed to overcome the over-cooling and over heating issues associated with traditional thermal management systems. In addition to the performance analysis of a traditional battery pack, concept of a reconfigurable battery pack is discussed in the last section. A pack configuration where fresh cells are connected with aged cells is simulated and the performance of such a battery pack is analyzed. The simulation