Chapter 1

Introduction

1.1 Motivation

Battery electrical vehicles (BEVs) are widely regarded as a promising solution for the future as they are a great way to improve mobility and reduce pollution. The increased awareness of the environmental impact of conventional internal combustion engine (ICE) vehicles and climate change consequences makes BEVs increasingly more attractive and popular. The main power sources of these vehicles are energy storage systems made up of Lithium-ion technology. The chief features that make this technology attractive nowadays are its high voltage, high energy density, high efficiency, and long cycle. To satisfy the system requirements on operating voltage, power, and driving range, the battery consists of a large number of single cells, which are connected in series and parallel. While connecting cells in parallel leads to an increase in capacity, the battery output voltage increases when cells are connected in series. Due to its chemistry, a Lithium-ion cell has a defined operating window. If it is operated outside this window, it will be permanently damaged or destroyed. For this reason, all cells are monitored by a battery management system that ensures a safe operation. Unfortunately, the battery cells are not identical in terms of electric characteristics such as capacity and internal resistance. This cell-to-cell variation arises due to manufacturing process tolerances. Despite the end of the production classification of battery cells, the capacity spread remains by 1% to 3% at the beginning of life [1]. In addition, the cell disparity is exacerbated over battery life due to operation conditions, among which temperature gradients [2]. Since the useful capacity is limited by the lowest capacity cell, its efficiency depends on the capacity spread. Figure 1.1 shows how the cell with the lowest capacity limits the electrical energy extracted from the storage system.

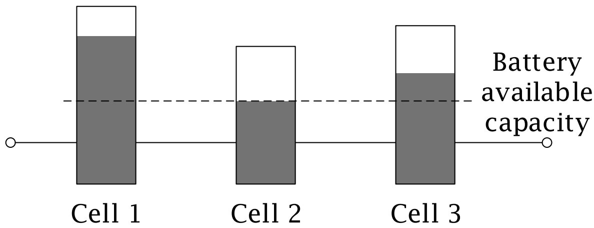

Figure 1.1: Schematic representation of interconnected battery cells with different capacities and states of charge. The available battery capacity is limited by the weakest cell.

Due to the limited operating range of the cells, cell 2 with the lowest charge limits the entire battery pack. If this cell is completely discharged, no further energy shall be taken from the battery pack, as otherwise deep discharging and thus damage to this cell will occur. The remaining load in the other cells remains unused. Accordingly, the cell with the largest state of charge limits the battery pack during the charging process. To increase BEV competitiveness, the current research focuses on improving the efficiency of electric driving and energy storage. To this end, various approaches for equalizing imbalance battery cells use either resistors to dissipate excess load in the form of heat or components to transfer energy from one cell to the other. The amount of energy shift between cells is limited through the used electronic components, such as capacitors and transformers [3].

In this work, a new approach to balance cells is examined. This approach is based on a modular battery system consisting of cell modules connected in series, denoted reconfigurable battery. Thanks to semiconductor switches, these modules can be connected and disconnected during the operation in order to equalize the state of charge of the cells. For example, cell 2, shown in figure 1.1, is excluded from the discharging process once it is bypassed. As a result, the states of charge of the other cells are approaching the charge level of cell 2. The new degree of freedom available in reconfigurable battery, namely the terminal voltage of the battery that can be controlled by bypassing battery cells, should be exploited to achieve the best possible system efficiency. This is even more important because the performance of reconfigurable batteries in terms of efficiency and lifetime not only depends on the cell interconnection topology but rather on the energy management strategy, which controls the cell state and decides when and which cell should be bypassed. Despite this, these reconfigurable battery systems are widely discussed in the literature from a hardware realization point of view. Energy management strategies for reconfigurable batteries are often developed using rule-based controls [4]. On the other hand, a lot of research has been carried out in the field of energy management strategies for electric hybrid vehicles in the last few years. These strategies are typically divided into rule-based strategies and into optimization-based controls, including instantaneous optimization and dynamic programming optimization [5] and [6]. Rule-based controls are widely applied in real-time applications, particularly due to their low computation and memory resources required. Authors in [7] and [8] presented rule-based controls using fuzzy logic. As the rules were not model-based developed, the control strategies are thus not scalable. Furthermore, the performance of the control strategy regarding optimization depends on the rule design. The optimization-based strategies are characterized by the fact that control decisions are calculated using optimization models. A further classification can be done based on the optimization method. Some approaches treat the energy management strategy as an optimal control problem. In this case, the optimization is considered as a whole and needs future information about the requested battery power. Due to the necessity of a priori knowledge of the entire driving profile, this approach is limited to offline applications. In fact, the results of this approach establish a benchmark for evaluating the performance of causal strategies. Furthermore, these results can be used to develop near-optimal energy management strategy suitable for real implementations. Namely, the authors in [9] developed a rule-based strategy representing a trade-off between high accuracy and manageable computing time. It consists in using the results obtained from the optimization model to design the control rule. Other approaches treat the energy management strategy as a static optimization problem that is solved based on the actual information only [10].

With the above survey, it is of great interest to develop the energy management strategy for a reconfigurable battery from the point of view of optimization theory. This would ensure an optimal battery system operation and maximize the profits such as efficiency and lifetime.

1.2 Goals and Contributions of the work

This work aims to develop energy management strategies for reconfigurable batteries using the optimization-based approach to balance the battery cells optimally. First, two mathematical models are established. The extracted energy model describes the interrelationship between the number of active cells and each cell's depth of discharge. The balancing energy model describes the interrelationship between the number of active cells and the battery's balancing level. In a second step, different optimization problems are provided using the developed mathematical models. Since the cells are either active or bypassed, the developed optimization models belong to the class of mixed-integer programming, which required specific search algorithms. Therefore, methods of mixed-integer optimization were examined as part of this work. As a result, three energy management strategies are established, namely a noncausal strategy that ensures the global optimum and two causal strategies for local optimizing well-suited for real-time operation. The validation of the developed strategies is done by means of simulations of realistic scenarios using a battery model experimentally validated.

1.3 Structure of the work

Chapter 1 introduces the field of work. Chapter 2 describes a Lithium-ion storage system from a chemistry point of view as well as electrical modeling. Chapter 3 provides the mathematical models of the reconfigurable architecture. An overview of optimization methods is given in Chapter 4, focusing on dynamic optimization, especially the dynamic programming method. Chapter 5 describes the noncausal optimization strategy. Simulation results illustrated in Chapter 6 show how this strategy maximizes the battery's efficiency. Thereafter, the same work is done for the causal strategies described in Chapter 7. The results of these strategies are shown and then compared with the result of the noncausal strategy in Chapter 8 to prove the feasibility of these real-time strategies. Chapter 9 concludes this work.

Chapter 2

Lithium-ion storage system

2.1 Lithium-ion cell

Lithium-ion cell is a known electrochemical energy storage unit since the second half of the 20th century: first, as non-rechargeable primary cell developed, and then after exhaustive research and development, it has become the most used rechargeable battery.

2.1.1 Cell structure

An electrochemical process takes place in the Lithium-ion cell transforming the chemically stored energy into electrical energy and vice versa. A schematic structure of a Lithium-ion cell is illustrated in figure 2.1. During the charging process, i.e., the electrical energy is converted into chemical energy, the Lithium ions migrate through the separator and intercalate into the graphite. While the loss of electrons oxidizes the active material of the positive electrode, the negative electrode's active material is reduced by the gain of these electrons. During the discharging process, it will come to the revision of the charging process. Lithium atoms release electrons and leave the graphite. The resulting ions move to the positive electrode diffusing through the separator. To establish a charge balance, electrons are released into the

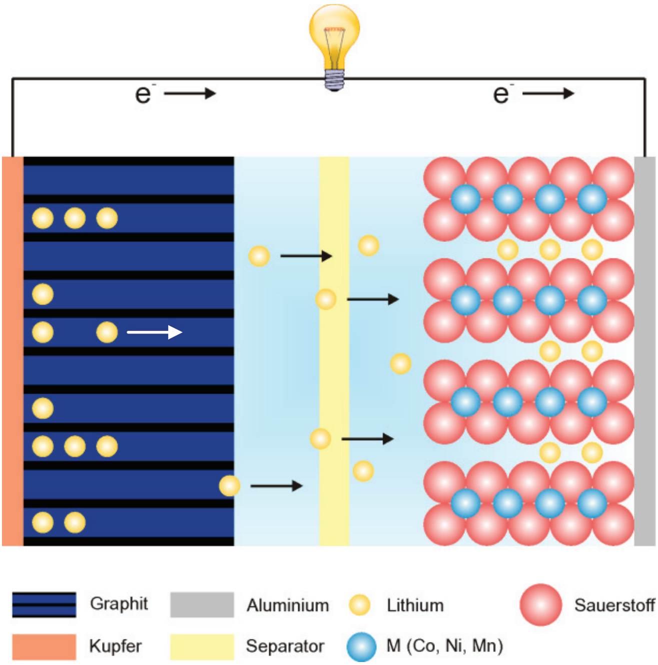

Figure 2.1: Schematic illustration of a Lithium-ion cell during discharging [11] [12].

electric load circuit.

The electrodes of a Lithium-ion cell can be made of different active materials or different additives. The electrochemical potential between both electrodes shall be maximized. The separator separates the two electrodes from each other in order to prevent an intern short circuit.

Various chemical compositions of the cathode have been proposed in the literature, such as Nickel Manganese Cobalt Oxide, Manganese Oxide, and Iron Phosphate. However, an exhaustive investigation of overall factors affecting the safety and the performance of the new material when used in a large-scale battery should occur before its adaption in electric vehicles. For more information about this filed the readers may refer to [13], [12], [14] and [11]. Some of the most common Lithium-ion cell used in electric-vehicle batteries are the Lithium Nickel Manganese Cobalt Oxide and Lithium Iron Phosphate. Each technology has slightly different chemical and electric characteristics [15] [16].

The advantage of a Lithium-ion cell over other storage systems is that the charge and discharge processes are completely reversible and thus are not subject to the memory effect. The redox reaction inside the cell over the discharge and charging process can be divided into an anode and cathode reaction. While the anode reaction is given by

$$\mathrm{Li^+} + x\ \mathrm{e^-} + \mathrm{C_6} \rightleftharpoons \mathrm{Li}_x\mathrm{C_6},$$

a general reaction equation for the charging or discharge process at the cathode can be described as follows [11]

$$\mathrm{Li}_{x+y}\mathrm{MO_2} \rightleftharpoons x\ \mathrm{Li^+} + x\ \mathrm{e^-} + \mathrm{Li}_y\mathrm{MO_2}.$$

The chemical reactions inside the cell can be generally described as the diffusion of Lithium ions between anode and cathode through the electrolyte. This chemical reaction involves the transfer of electrons as chemical bonds are formed: Lithium always binds to the negative electrode's graphite layers and the oxidized metals at the positive electrode. The exact number of electrons, Lithium ions, and carbon atoms involved in the reaction depends on the cell's chemical composition.

2.1.2 Cell modeling

Modeling the behavior of a Lithium-ion cell is complex due to non-linear effects and transient during operation. Different models such as electrochemical, analytic, stochastic, and electric models are reported in the literature. These different approaches arise from a variety of application fields. In addition to the improvement of cell performance, the use of an accurate cell model plays an important role in the optimization of the whole battery system. The choice of the convenient model depends on the cell characteristics that need to be modeled and the available computing hardware.

Black-box model

This model describes the electrical behavior of a cell without reproducing the underlying physical processes. The model parameters that do not have physical significance are identified using measurement data describing the cell behavior [17]. This modeling approach is mainly used in the analysis of stationary load use cases. A black-box model has high accuracy in the measured operating points domain, but interpolation or extrapolation can occur in a limited way [18]. An example of a black-box model is the neural network model.

Electrochemical model

The purpose of the physical-chemical model is to describe the cell's internal state in its very detail. Electrochemical and thermodynamic laws are used for the development of the model [19]. In order to model the overall characteristics of the cell, each effect is represented individually by a partial differential equation. These effects are superimposed afterward. Such an approach is known for its high accuracy and the ability to model the cell's dynamic behavior. On the other hand, the computational complexity and parameterization effort are high. This approach is therefore mainly used in the development and optimization of the electrochemical cell.

Equivalent circuit model

This modeling approach is based on the dynamic electrical characteristics of a cell. Such a model uses electrical circuit elements in order to describe the electrical transfer function of a cell in a wide frequency band. Diverse equivalent circuit models are developed, varying from simple model to more detailed model that features the self-discharge rate and the electrochemical overpotentials [20]. The simplest model consists of an ideal voltage source and a resistance connected in series, as shown in figure 2.2. Thus, this equivalent circuit only models the instantaneous cell response to a change in its current.

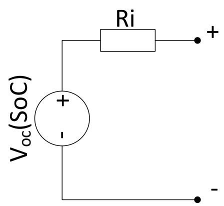

Figure 2.2: Static equivalent circuit model: the cell is modeled as an ideal voltage source with a series resistor.

However, this model does not deal with the dynamics of electrochemistry such as activation and concentration polarization [21] [22]. Thus, the equivalent circuit should be extended by adding one or more RC elements; each is a parallel connection of resistance and capacitor.

Several equivalent circuit models are introduced, which differ in the structure and parameterization effort. The simplest variant is the combination of an ideal voltage