Modelling of a battery system and design of a battery balancing algorithm

Internship Report: Modelling of a Battery System and Design of a Battery Balancing Algorithm

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Summary

In this report the development of a battery-system model, and a battery balancing algorithm that is used for the system at hand are discussed. Both these topics are discussed in the context of a modular battery system, consisting of Lithium-Ion battery cells, used to supply both a vehicle drive train, and the vehicle auxiliary systems. This battery-system model has been developed with the aim of aiding the judgement of the performance of the battery system, and be able to develop the balancing algorithm.

This battery balancing algorithm utilises an active balancing approach, with which energy is taken from the battery pack to equalise the State-of-Charge levels, while at the same time supplying power to the auxiliary systems in the vehicle. This has been implemented in such a way that an optimal trade-off is made between the regulation of this auxiliary power supply, and the balancing of the battery cells.

After creating the battery-system model, and implementing the balancing algorithm in this model, simulations have been done in order to prove the functioning of both. From this it can be seen that the battery balancing algorithm has been implemented successfully, as well as that a functional system-level battery-system model has been created successfully.

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1 Introduction

With the increasing electrification of vehicles, battery technology becomes more and more important. While the chemistry of Lithium-Ion type batteries is still being improved, the way these batteries are used can also be further improved. This is the case as even with more and more sophisticated battery management systems, the battery packs still cannot be used to their fullest potential. One such limit is that not all of the energy can always be extracted from the battery pack, as differences between the cells, such as a difference in capacity and internal resistance, lead to imbalance in State-of-Charge level. Due to this imbalance some cells reach the lower terminal voltage cut-off bound at an earlier point compared to other cells in the battery pack, at which point energy can no longer be extracted from the battery pack. When this occurs the energy left in the battery pack cannot be extracted anymore, thus negatively impacting the driving range. During charging the same holds, as some cells may reach the upper terminal-voltage cut-off bound before the other cells, meaning that not all cells are completely full. Unless balancing is done after the charging, this also results in a lower driving range, however this would increase the time the charging process takes.

Three main options by which the driving range of a battery pack can be increased exist. The first option would be to switch to a different battery cell chemistry, with a higher energy density for instance. However, such a switch results in many unknowns, and might not benefit the pack performance on the short term. A second option would be to build a battery pack with a higher capacity, however, that would increase the weight of the vehicle. For both of these options, the differences between cells would still be present, and thus the problem identified above would not be remedied. A better option would be is to further optimise the way the existing battery pack is used, in order to increase the driving range. This can be achieved by improving the way in which the State-of-Charge imbalance is dealt with. By properly dealing with this State-of-Charge imbalance, all cells can be made to reach the lower terminal-voltage cut-off bound at the same time, thus meaning all energy is extracted. This can be done by balancing the State-of-Charge levels of the battery cells, which is a process in which actions are undertaken to equalise these levels. There are multiple approaches to balancing. On the one hand there are the passive balancing methods, which can only be used during charging. These methods work by dissipating the excess energy over resistors, such as to equalise the terminal voltage levels. Another is the active balancing methods, which can be used during charging and discharging. These methods re-purpose or redistribute the excess energy cells in order to equalise the cell terminal voltage levels [1], and thus lead to more efficient usage of the battery pack, and hence will be the area of focus in this report.

Two main issues regarding the balancing of batteries will be focussed on in this report. Firstly, the report will focus on the development of a battery-system model that captures the behaviour of the battery pack designed by the UTEV research group, in order to aid the development of a balancing algorithm for this battery pack, and allow for a new simulation platform for research. The second topic of focus in this report is the development of a balancing algorithm, for use with the same battery pack. This balancing algorithm has been simulated using the battery-system model, in order to prove and tune the balancing algorithm. As the balancing hardware in the battery pack deals with balancing of the battery cells, and the supply of power to the auxiliary systems in the vehicle, both of these need to be controlled by the algorithm.

The bi-focal nature of this project is reflected in the parts of this report, by focussing separately on the aspects of each part within a chapter if needed. This report starts off with the context of the project, followed by a definition of the research problem. After this the methodology, including the solutions that were found using this methodology, is presented, followed by the results obtained using these solutions. The report is concluded with conclusions and recommendations.

A major part of the work in this report has been created to support a submission [2] to the IPEC 2018 ECCE Asia conference in Niigata. This submission has been accepted to the conference, and will be published in due time.

2 Project Context

This project can be seen as part of a bigger project within the UTEV (University of Toronto Electrical Vehicle) research centre, which is a cooperation between the University of Toronto and automotive start-up Havelaar. The focus of this research centre lies on electric vehicles, with the intention of using the found novelties in Havelaar vehicles. To implement and test these findings, UTEV also develops prototypes that can be used in Havelaar vehicles. As such, a part of UTEV focusses on battery research, more specifically on the development of a modular battery system, which allows for use under extreme conditions and has an advanced battery management system. This battery system is intended for a Havelaar concept vehicle, the Havelaar Bison, an electric pick-up truck which can be seen in Figure 1. And as part of this battery system, the balancing algorithm developed in this project is proposed.

Figure 1: Havelaar Bison, a prototype of a fully electric pick-up truck

To be able to develop this battery balancing algorithm, first a battery system model needs to be developed, as such a model was not yet present. As the battery system has a scalable structure, the simulation model should also be able to deal with this. Next to this, the new balancing algorithm has to be an improvement over the previously developed balancing algorithm, which was not achieving the performance required from it. Both of these topics are solved in this project, as the development of a battery-system model is of great aid to the development of a balancing algorithm. Besides this the battery-system model is also very useful for many new research trajectories, for instance for observing the effects of differences between cells on the behaviour of the battery pack.

2.1 Battery Models

As a way to identify the state-of-the-art of battery models, a literature review has been conducted. For this review multiple pieces of literature covering different types of battery models have been reviewed. Besides this, pieces of literature on higher level battery-system models have also been reviewed, as these correspond more to the overal goal of the simulation model in this project. From this literature review, two different classes of battery cell models have been found:

1. Equivalent Circuit Models
2. Electro-Chemical Models

Within the first class of models, an equivalent circuit of the battery is used to model the non-linear behaviour of the battery, as can be found in [3] and [4]. This model consists out of an equivalent circuit from electrical components, an example of which can be seen in Figure 2. In this figure, it can be seen that this circuit consists of a voltage source, a resistor and RC circuits, two in the case of Figure 2, making it a second-order model. The voltage source, is controlled such that it supplies the open-circuit voltage of the battery cell to the circuit, corresponding to the current State-of-Charge value of the battery cell. While the resistor and RC circuit respectively model the internal resistance and dynamics of the battery cell. Together the components of the equivalent circuit model result in the terminal voltage of the modelled battery cell, including the dynamics of this terminal voltage related to the State-of-Charge level and the current applied on the cell. To further capture these dynamics, more RC circuits can be included, which means the dynamics can be modelled more closely, at the cost of additional computing power being required.

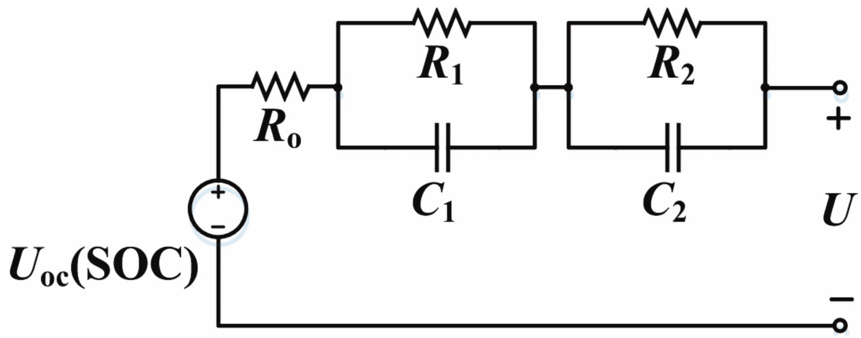

Figure 2: The equivalent circuit model that can be used to model the dynamics of battery cells. Diagram taken from [3].

One of the benefits of this class of models is that this is the most commonly used battery model, and thus has been proven to work in numerous papers. Another benefit is that the model can be build in such a way to trade-off some accuracy for faster computation, by reducing the amount of RC circuits. Next to this, another benefit of this class of models is that the evolution of the terminal voltage can be directly related to the different components within the model, thus making tuning and analysis easier. A downside of this basic variant of the equivalent circuit model, however, is that the model is not temperature dependent. This temperature dependence is important, as the ambient temperature, as well as self heating of the battery cell under the application of current, cause the impedance and capacity of the battery to change. One possibility to implement this temperature dependence, is by replacing the electrical components by temperature-dependent components, as suggested in [4]. This be implemented with the use of look-up tables, filled with parameters for the equivalent circuit relating to different cell temperatures. These look-up tables will then require an input from a thermal model, which gives a cell temperature based on both the ambient temperature and self heating. Additionally, the open-circuit voltage can also be made temperature dependent, capturing the influence of operating temperature on the open-circuit voltage of the cell.

The second class of models are the electrochemical models, which describe the dynamics of the chemical processes that occur within the battery during charge and discharge processes, as is done in [5] and [6]. An example of this is a pseudo-two-dimensional (P2D) model, which models the electrode potential in each individual electrode of the battery, as well as Butler-Volmer kinetics between these electrodes. A graphical representation of the battery cell, as is used to derive the partial differential equations of the P2D model, can be seen in Figure 3. Solving these partial differential equations yields the terminal voltage of the battery cell. Multiple variants of the P2D model exist, among which the Doyle-Fuller-Newman model, and the simplified Single-Particle model. The benefit of the latter when compared to the former is that it reduces the necessary computation time, while only losing a small amount of accuracy. The overal benefit of this class of models, is that they capture a high accuracy, however this comes at the cost of a high computational effort and high complexity. This complexity mainly arises when formulating the model, thus requiring knowledge of chemistry. These chemical models can also be extended, in order to include temperature effects, for which a thermal model similarly as for the equivalent circuit model can be used.

The different classes of models identified from the literature research form the base for the development of a model. To this end, the observation can be made that the equivalent circuit model is a very powerful model, which provides a decent level of detail, while being acceptable on the front of computing power. From the literature review it is also concluded that including thermal effects into the battery-system model is required to achieve a higher level of accuracy.

2.2 Balancing Methods

To be able to identify existing balancing schemes, a literature review has been done on the state-of-the-art of battery balancing. To this end, literature covering different battery balancing methods have been reviewed. Besides that, also literature explaining algorithms used in balancing methods was reviewed. This section only focusses on the balancing of cells connected in series, as [6] shows that battery cells connected in parallel balance automatically. This will occur by a current that will run between the cells, which flows from the highest State-of-Charge cell to the lower State-of-Charge cells, caused by the difference in terminal voltage between the parallel connected battery cells.

During this literature review, three categories of balancing methods have been found:

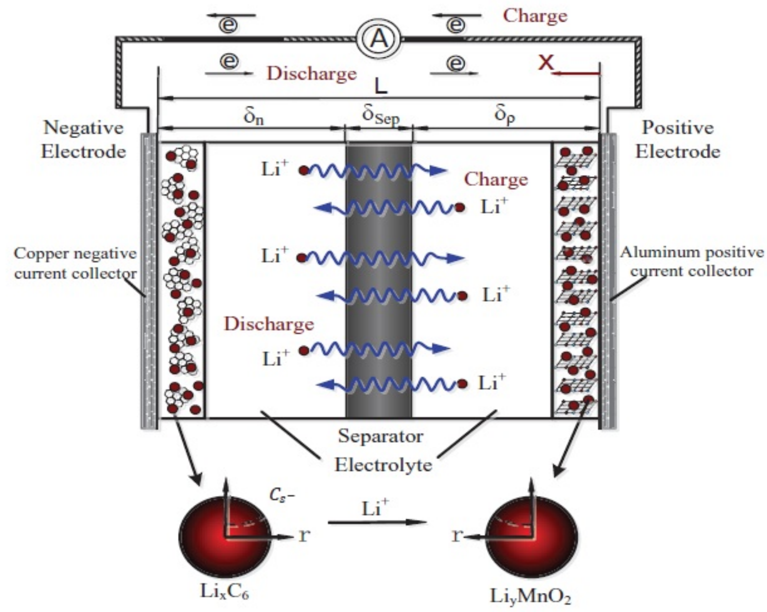

Figure 3: The graphical representation used to derive the pseudo-two-dimensional model for a battery cell. Diagram taken from [5].

1. **Shunting Passive Balancing** can be used during charging, to remove excess energy from battery cells with the highest voltage in the string of cells. In this way, these cells will not reach the upper terminal-voltage cut-off bound before the rest of the cells. There are multiple methods to achieve this, the least complicated of which uses resistors placed in parallel to the cells, as is shown in Figure 4. Another ways to achieve this same charging behaviour, is by controlling the currents the individual cells receive during charging. This lowers the current flow into the higher voltage cells, and thus equalises the terminal voltage. For this multiple methods are presented in [7]. The benefits of Shunting Passive Balancing methods, are that they are cheap to apply, as no extensive hardware is needed for a simple version of this method. This however becomes less true when for the more complicated versions presented in [7]. A downside of this method, is that it can only be used during charging, meaning that the problem caused by the difference between the cells is not managed during discharge. Another downside is that the energy dissipated is lost to heat, thus lowering the efficiency of the battery pack.

2. **Shuttling Active Balancing** makes use of energy-storage devices, such as capacitors, inductors or additional batteries, to temporarily store energy from higher-voltage battery cells. This energy can later be transferred to other cells in the pack. An example of this method is Switched-Capacitor balancing [7], which uses capacitors that can be connected in parallel to a cell, as well as to the neighbouring cell, as can be seen in Figure 5. When connecting the capacitor to a battery cell, the voltages

of both equalise, due to a current flowing between the two. In case the capacitor has been equalised to a lower-voltage cell, and is then connected to a higher-voltage cell, a current will flow from the higher-voltage cell into the capacitor until both have the same voltage. When the capacitor is then connected to the lower-voltage cell, this current will be reversed, and will thus charge the lower-voltage cell. By repeating this process for all cells, with a certain periodicity, a balance in cell voltage can be achieved. However, this balance in cell voltage does not necessarily have to correspond to a balance in State-of-Charge, as the cells can be different, which is a downside. A benefit of this method is that it can be used during both charging and discharging, meaning it can help the cells in the battery pack reach both the lower- and upper-voltage thresholds at the same time. Another benefit is that the energy is not lost, and thus the battery pack efficiency is not impacted by balancing. A downside of this method is that it has to be active continuously, in order to keep the cells equal, meaning not much freedom for control is present.

3. **Energy-Converter Active Balancing** makes use of isolated converters to balance the battery cells in a pack, as discussed in [7] and [8]. These methods are able to transport energy from one cell to a string of cells, or from the string of cells to one cell. Multiple variants for this exist, one of which is called the Switched-Transformer balancing in [7], which can be seen in Figure 6. This variant allows energy transfer energy to be supplied by the full string of batteries to the lowest State-of-Charge cell, by selecting a cell using switches. By connecting the converter to the string of batteries, the input of the converter is powered. The output of this converter is connected to the cell, and activating it thus brings the selected cell closer to the rest of the pack in terms of State-of-Charge level. This can then be repeated for the other cells, leading to a balanced pack. Alternative configurations also are presented in [7], in which for instance a Step-up converter is used to connect the individual cells to the cells in the pack, thus achieving the opposite functionality, with the same result. A benefit of Energy-Converter Active Balancing methods is that most of the configurations for this work for both charging and discharging, and thus have the same benefits at Shuttling Active Balancing Methods, however at higher costs. These higher costs, however, also give more flexibility in terms of control. A downside is the high cost associated with the converter, increases depending on how long the string of cells is chosen.

Balancing Algorithms

Multiple possible balancing algorithms exist to control the balancing methods presented above. The first distinction that can be made between the different balancing algorithms, is the measure that is used to judge the need for balancing, as is discussed in [9]. It is possible to measure the terminal voltage of the battery cells, and balance based on the difference between these terminal voltages. The main benefit of this is that it does not require any observer, and thus is not dependent on a model. However, a downside of this is that the

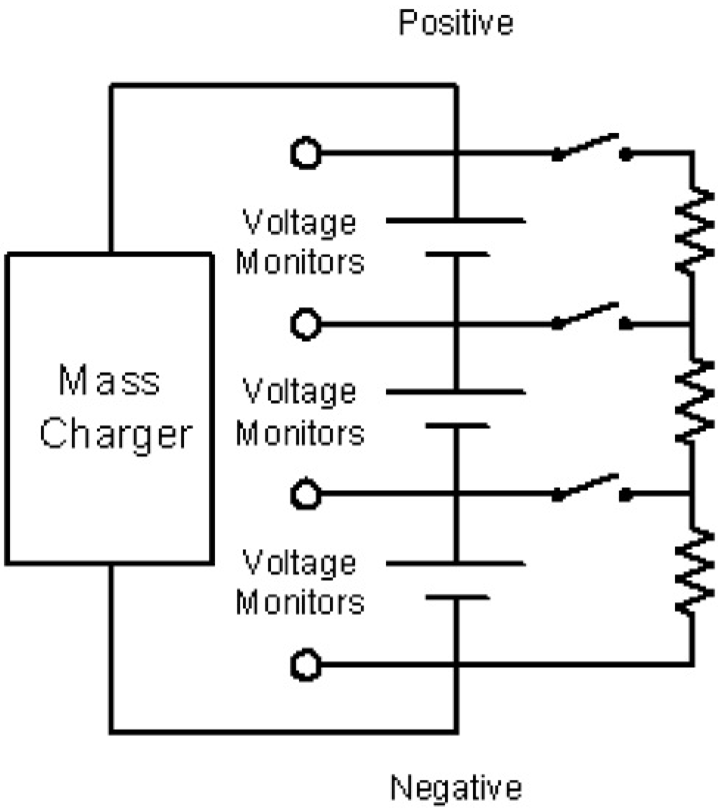

Figure 4: An example of a Shunting Passive Balancing method, in this case using a Dissipative Shunting-Resistor circuit. Diagram taken from [7].

terminal voltage depends on the cell characteristics, and can thus differ between the cells, leading to a different response when current is applied. Another measure that can be used is the State-of-Charge of the battery cells. This allows for a better indication of the amount of charge that remains in the cells, and thus for more accurate balancing. The downside of this, is however, that a state observer is needed to arrive at these State-of-Charge values. Besides this, also the amount of energy that has been inserted or extracted from the cell can be used. This, however, requires a coulomb counter and thus leads to extra complexity. On the other hand, this does have the benefit of having a high accuracy. Finally, the amount Charge in the battery can be used as a balancing measrue. When balancing in this way, the charge left in the cell can be equalised, which leads to the discharge process of the cells being synchronised, meaning constant balancing is not needed. A downside is that this gives difficulty when estimating.

Another distinction that can be made between balancing algorithms is the way in which the control part of the balancing algorithm is executed. For this multiple options exist, of which a selection is presented here. One option is to use a rule-based approach, as is done in [2]. The benefit of this is that the controller is very simple, however a downside of this is that the controller is far from optimal. Another option is to use a more advanced

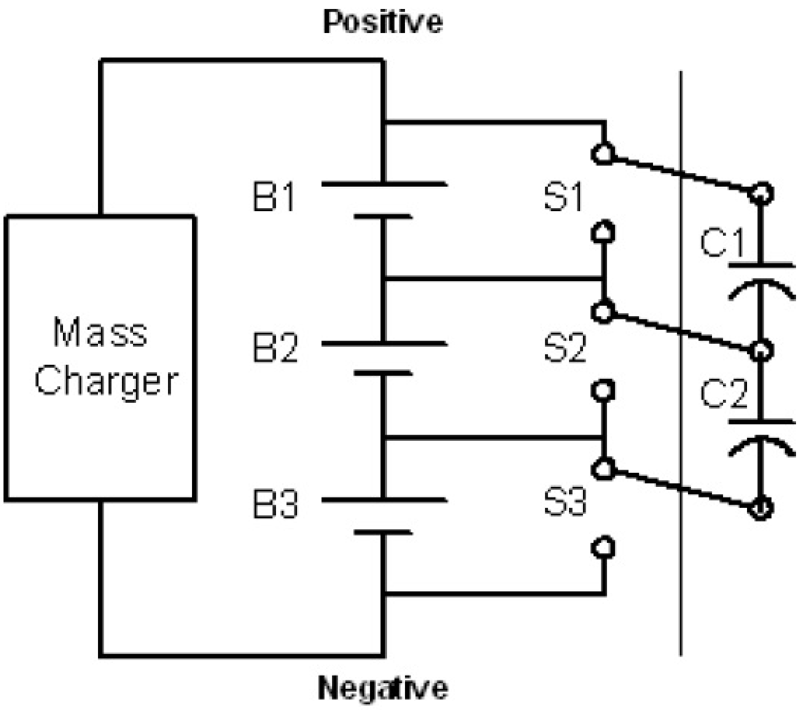

Figure 5: An example of a Shuttling Active Balancing method, in this case using a Switched-Capacitor circuit. Diagram taken from [7].

controller, that decides based upon what is best for action, in order to optimise a certain measure. This can be done either using a feedback or a feedforward controller, depending if the required action can directly be derived from the measure.

From the reviewed literature on balancing methods and balancing algorithms, it has been found that several different balancing methods exist, however that a balancing method that re-uses the energy, such as the one present in the UTEV battery system, is most efficient, as it does not waste the energy. Also it has been found that these balancing methods can be used with different balancing algorithms. The choice for the balancing algorithms is relatively unconstrained, however a controller that optimises a measure is preferred.

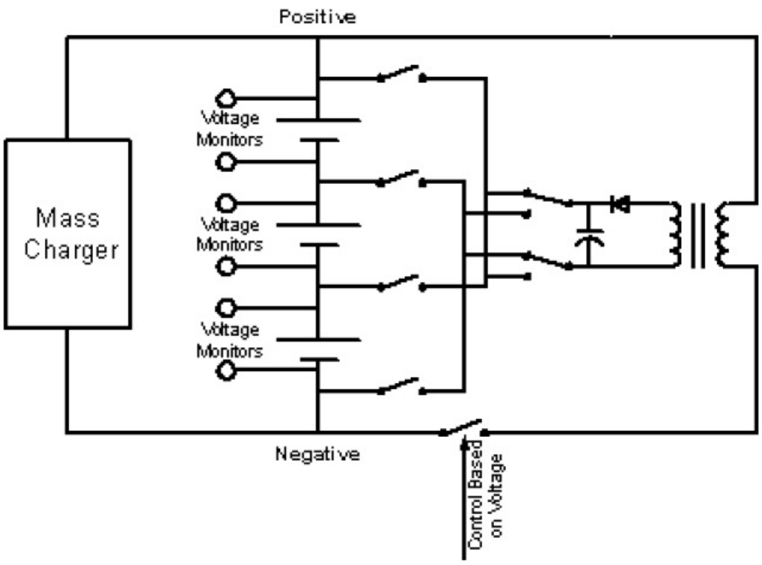

Figure 6: An example of Energy-Converter Active Balancing, in this case using a Switched-Transformer circuit. Diagram taken from [7].

3 Problem Definition

In this section the two main problems that this report deals with will be introduced and elaborated. First, there is the problem of creating a battery system model, which has to satisfy a certain standard. Next to this, there is the problem of designing a balancing algorithm that can achieve State-of-Charge balance between the battery cells in the battery pack using the available balancing hardware.

3.1 Battery-System Model

To specify the functioning expected from the battery-system model, five requirements have been defined. These requirements have been used to aid the development of the module.

1. **Scalability** of the battery pack size to adapt to different topologies.
2. **Electro-Thermal interactions** to better model the behaviour.
3. **Behaviour and Structure** of the system must be identical to measurements.
4. **Easy to use**.
5. **Short run-time**.

Battery Pack Hardware Description

The UTEV battery pack can be separated into 18 modules. This is done with the purpose of scalability and second-life applications, such as powerwalls, in mind. Each of these 18 modules is identical and can be separated into 3 main components. Firstly, there are the battery cells, connected to each other through bus bars soldered between the cell tabs. Besides this there is the enclosure of the battery cells, which doubles as a cooling structure. Finally, each module has a Battery Management System (BMS), which contains a switch matrix and a Ćuk converter that are used by this module for balancing. All module-level battery management systems are connected in parallel to the auxiliary bus. This auxiliary bus connects the modules in the high-voltage battery pack to the auxiliary battery, which is a component that can be identified on the pack level. Another component on the pack level, is the supervisory battery management system, which is connected to all of the module-level battery management systems, and enforces the pack thresholds and controls the balancing using information from these module-level battery management systems. A schematic of the complete system can be seen in Figure 7.

When focussing on the module level, it can be seen that each module is made up of 24 cells, which are arranged as 4 parallel cells over 6 sub-modules in series. The 4 parallel cells enable the pack to run at higher currents, and give the pack a higher capacity. In case of difference between the terminal voltages of these parallel cells a current will run from the cell with the higher voltage to those with the lower voltages, in order to equalise the voltage over this sub-module, as explained in Chapter 2.2. The 6 sub-modules are

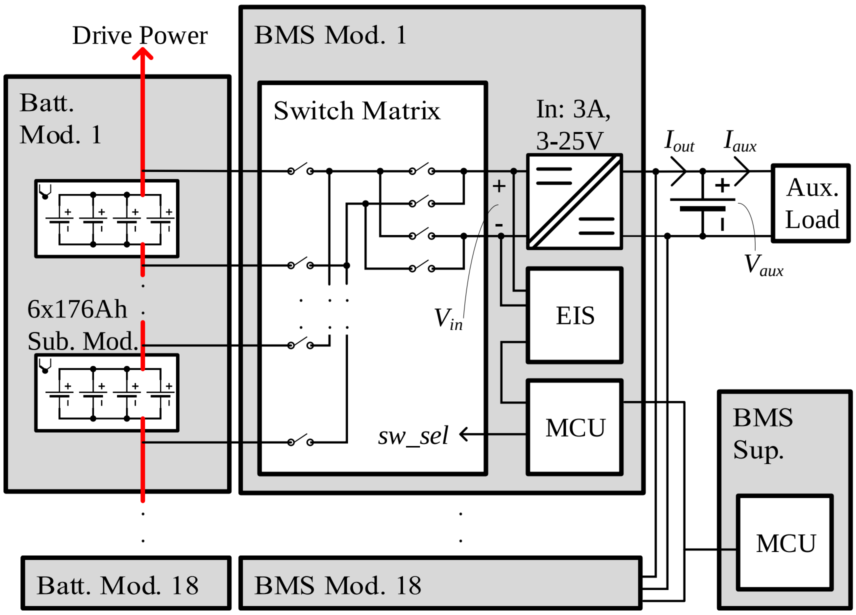

Figure 7: A schematic overview of the hardware present in the battery system, including the balancing hardware.

connected in series, in order to reach the wanted voltage level for the module of between 18 and 25 Volt, depending on the State-of-Charge. Lithium-Ion type cells are used in the pack, which have a Nickel-Manganese-Cobalt ($LiNiMnCo$) cathode and a Graphite (C_6) anode. These cells have a capacity of $44Ah$, leading to a sub-module capacity of $176Ah$. As the sub-modules are connected in series, the module has the same capacity, at a higher voltage level.

The battery cells are mounted in a metal frame, which has two functions. The first function is that it holds the cells in the sub-module together mechanically, making the sub-module a separate unit, that can be used independently without any additional support. Secondly, and most importantly, the metal frame is used for cooling the battery cells. This is done by circulating coolant from the vehicle cooling system through the hollow tubes that make up the metal frame. By using the frame for this, each cell is directly in contact with a cooling channel, which allows the heat generated in the battery cells to be transferred directly to the cooling system. This enables accurate temperature regulation within the battery module, and thus within the battery pack.

The third and final physical component of the module is the module-level BMS. The module BMS has two main roles, the first of which is to monitor the individual sub-modules. This is done by measuring the terminal voltages and sub-module temperatures. These measurements can be used by the supervisory BMS for instance for state estimation, but also to ensure the operating limits of the battery cells are not exceeded. Next to this, the module BMS executes the balancing of the sub-modules within the module. This is done by using the switch matrix that can be seen in Figure 7. By selecting switch positions either a single sub-module, or the complete module can be selected for balancing, as can be seen from the switch matrix in Figure 7. When a module or sub-module is selected for balancing, a current is drawn out of it, as the Ćuk converter located on each of the module-level BMS boards is unidirectional. This thus means that during balancing the module or sub-module can only be discharged. More on how the choice of the switch position is made will follow in Chapter 3.2.

The output current from the converters flows into the final main component of the battery pack, the auxiliary battery. This auxiliary battery is a 12-volt Lead-Acid battery, which is used to supply the auxiliary systems in the vehicle through the auxiliary bus. This battery acts as a buffer between the high-voltage pack, and the auxiliary systems, and is topped op using energy from the balancing process. In this way, energy from the balancing process can temporarily be stored, or can directly be used by the auxiliary systems, depending on the power requested by these systems.

From the information in this section the first problem can be defined as: A system-level simulation model of the battery system has to be created that has a sufficient level of detail and models the hardware present in the system, according to Figure 7.

3.2 Balancing Algorithm

Battery balancing can be used to improve the way the capacity of the batteries is utilised, through maximising the extracted energy at the time when a cell reaches the lower terminal voltage cut-off. Within this project an active balancing approach has been chosen, as this a more efficient balancing approach. This allows for the energy that has been extracted during the balancing to be reused, for instance to power auxiliary loads in the vehicle. To operate this a balancing scheme a balancing algorithm is needed, designed to achieves the balancing objectives. In this case two objectives need to be achieved. The first objective is decreasing the difference in the State-of-Charge levels between the different sub-modules and modules, in order to optimise the use of energy. The second objective is to supply the requested amount of power to the auxiliary loads in the vehicle, in order to make sure that the systems in the vehicle are able to operate. The contradiction between these objectives is that supplying power to the auxiliary loads can negatively impact the State-of-Charge balance within the pack, especially when this requested power is high, while on the other hand balancing might negatively impact the amount of power supplied to the auxiliary loads. The main goal of the balancing algorithm is thus to achieve a trade-off between these goals.

As the balancing process makes use of a hardware implementation which was previously decided on, the implementation of the balancing algorithm is constrained. This hardware implementation is discussed below, after after which it is used to identify which variables are free to be controlled. Finally, the rule-based balancing algorithm that is currently present in the system will be explained.

Balancing Hardware

As explained in Chapter 2.2, each module-level BMS has a switch matrix and a Ćuk converter, which is used for balancing. The switch matrix is used by the module BMS to connect either one sub-module, or the complete module to the converter for balancing, as can be seen from the switches in Figure 7. This thus means that seven distinct switch combinations are present for each module, with six options corresponding to the sub-modules, and one option to the module. The position of these switches is decided upon by the balancing algorithm in the supervisory BMS, and is actuated by the module BMS. The reasoning behind these decisions for the rule-based algorithm will further be explained in the next Section 3.2.

After the switch matrix, a Ćuk converter is used to convert the voltage level the input side to the voltage level of the auxiliary bus. This converter has to be able to do this over a wide range, as for an almost-empty sub-module the voltage is around 3 volts, whereas it is around 25 volts for a fully charged module. Besides this another hardware component that plays a role in the balancing is the auxiliary battery, more specifically the voltage level of this battery. This voltage level will decrease over time, as the auxiliary loads will discharge the auxiliary battery. In order to prevent the auxiliary bus voltage from dropping below safe bounds, this auxiliary battery will need to be charged using energy from the main battery pack, which will increase the voltage level again. As both the input current and the output voltage of this converter are fixed, setting the duty ratio of the converter allows for control over the output current of the controller. This output current will be higher when a module is selected instead of a sub-module, as the input voltage has changed.

From this hardware description, it follows which variables in the system need to be controlled by the balancing algorithm for each module. The first variable is to select either a sub-module within the module, or the full module, which determines the position of the switches. This selection is done using eight discrete options ranging from 0 to 7, for which 0 corresponds to the module being turned off, 1-6 correspond to one of the 6 sub-modules, and the number 7 corresponds to the complete module being selected. The second variable is the current setpoint at which the Ćuk converter is running, in order to determine the power flowing from the main battery into the auxiliary battery. The duty ratio of the converter is a variable that is free between 0 and 1. As the converters are connected to the auxiliary bus in parallel, both these variables can be chosen independently for each module.

Rule-based Balancing Algorithm

In order to control the variables found in the previous subsection, a balancing algorithm is needed. This algorithm has the task of achieving both the posed objectives, and thus balancing the State-of-Charge of the battery cells, while at the same time regulating the voltage level of the auxiliary battery. As a starting point for this, a rule-based balancing algorithm [2] specific to the balancing method used within the UTEV project had been created before the start of this project. This rule-based balancing algorithm consists out

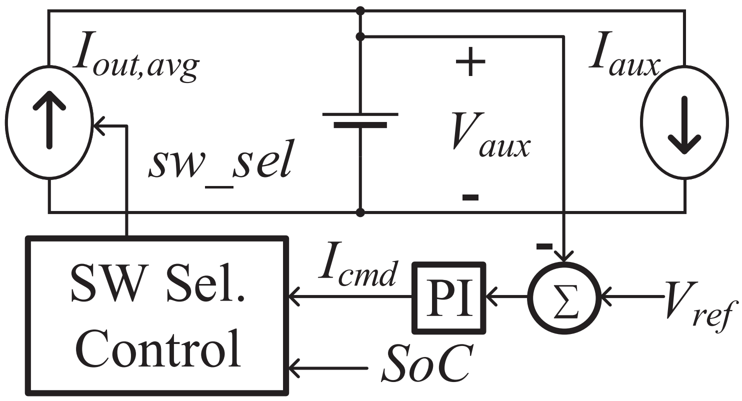

Figure 8: The control loop used for the rule-based balancing algorithm.

of two control loops, which can be seen in Figure 8. The outer control loop regulates the voltage level of the auxiliary bus, while the inner control loop regulates the State-of-Charge balancing of the cells.

The outer loop is made up of a PI controller, which determines the required output current of the converter to reduce the voltage error of the auxiliary battery, with regard to a voltage reference. This current is calculated in the form of the on-time for the converter, which is operating in burst mode, meaning the output current of the converter is kept at a constant for an amount of time, controlled through the duty-ratio D. Besides this, the actual output current is influenced by the selection of either a sub-module or the complete module, due to the difference in voltage levels. The average value of this output current, $I_{out,avg}$, can be calculated using

$$I_{out,avg} = D(n_{mod} I_{input} \frac{V_{mod}}{V_{aux}} + n_{submod} I_{input} \frac{V_{submod}}{V_{aux}}), \tag{1}$$

in which n_{mod} is the number of selected modules, n_{submod} is the number of selected sub-modules, I_{input} is the fixed input current, and V_{aux} is the auxiliary bus voltage.

Within the inner loop, which takes place in the *SW Sel. Control* block, the difference in State-of-Charge between the different sub-modules in a module, and between the modules is managed. This is done by selecting which sub-modules or modules to draw the command current I_{cmd} from, according to a set of rules. Using these rules, a selection of either the full module (module mode), or a sub-module (sub-module mode), is made for each module. This means that for each module either a module or sub-module is connected to the converter belonging to that module. These rules have the goal of improving the State-of-Charge balance, while supplying power to the auxiliary bus. These rules are as follows:

1. Set the on-time t_{on} to the maximal value, making $D = 1$.
2. Find the suitable combination of sub-modules and modules over all modules to meet or just exceed the current command I_{cmd}, using Equation 1, by fixing $I_{out,avg}$ to I_{cmd} and varying n_{mod} and n_{submod}. This while preferring the use of sub-modules, with the goal of improving the SoC balance.
3. Calculate the on-time t_on that matches the current command I_{cmd}, using Equation 1 with the combination of sub-modules and modules found at step 2.
4. Choose the n_{mod} number of modules with the highest minimum SoC to operate as a module.
5. Choose the highest SoC sub-module in the remaining modules to operate in sub-module mode.
6. Send out the switch positions and converter setpoints using sw_{sel}, and start converter operation.
7. Upon receiving of new current command I_{cmd}, return to 1.

By using these rules, the difference in State-of-Charge between the different sub-modules is indeed reduced, while supplying power to the auxiliary bus. This can be seen in Chapter 5.1, where simulations and measurements using the rule-based balancing algorithm are shown. From these results it became apparent that improvements to the balancing algorithm are needed.

The problem for this part of the project thus can be defined as: A balancing algorithm that is able to achieve a trade-off between the objectives of the balancing problem, auxiliary bus regulation and State-of-Charge balancing, utilising the hardware at hand.

4 Methodology

Several steps have been taken in this project in order to solve the problems identified in the previous chapter. These steps are described in this chapter, along with the solutions that were found for the problems through these steps. First, the methodology and chosen solution of the battery-system model will be discussed, after which the methodology and development of the balancing algorithm is discussed.

4.1 Development of the Battery-System Model

For the development of the battery-system model a four part methodology was used. This methodology consisted of an analysis of the battery system, to find the specifications the system and the identification of the state-of-the-art in battery models. This can be found in the Chapter 2, and has been done to find models to base the battery-system model on. Besides this, also research has been done into the documentation of MATLAB Simulink, in order to find out how to implement these found models in a scalable way, such that they are suitable for the goals at hand. After these steps the model has been implemented in MATLAB Simulink.

From the analysis of the battery system, a schematic illustrating the systems in and surrounding the battery pack has been made, as can be seen in Figure 9. Each of these systems shown in this figure corresponds to part of the model. For added clarity the parts of the model have been divided over two domains, the physical domain, which models the physical behaviour of the battery pack, and the management domain, which corresponds to the actions taking place in the software of the battery management system.

Within the physical domain the most important part is the *Electrical Battery Simulation*, which models the electrical behaviour of the battery cells. Besides this part there is the *Thermal Battery Simulation*, which models the thermal behaviour of the battery. Next to this, there is the *Converter Model*, which contains a model of the converter that is used to move energy from the cells to the auxiliary battery during the balancing process. Finally, the physical domain also contains an *Auxiliary Battery and Bus Model*, which contains a model of the Lead-Acid battery that is connected to the auxiliary bus, and thus models the reaction of the auxiliary bus to loads from the vehicle systems.

In the management domain, the first part of the model is the *Estimation Algorithm*. This part takes measurable signals from the battery system, and estimates unobservable battery states using an observer. Using this observer the *Battery Management System* can operate based on internal states of the batteries that are not known through measurement alone, in order to enforced electrical and thermal limits, as well as managing the balance of the battery cells, through the balancing algorithm.

Physical Domain

After identifying the main parts of the battery system, the models corresponding to these parts had to be designed and implemented in MATLAB Simulink. To do this the knowledge

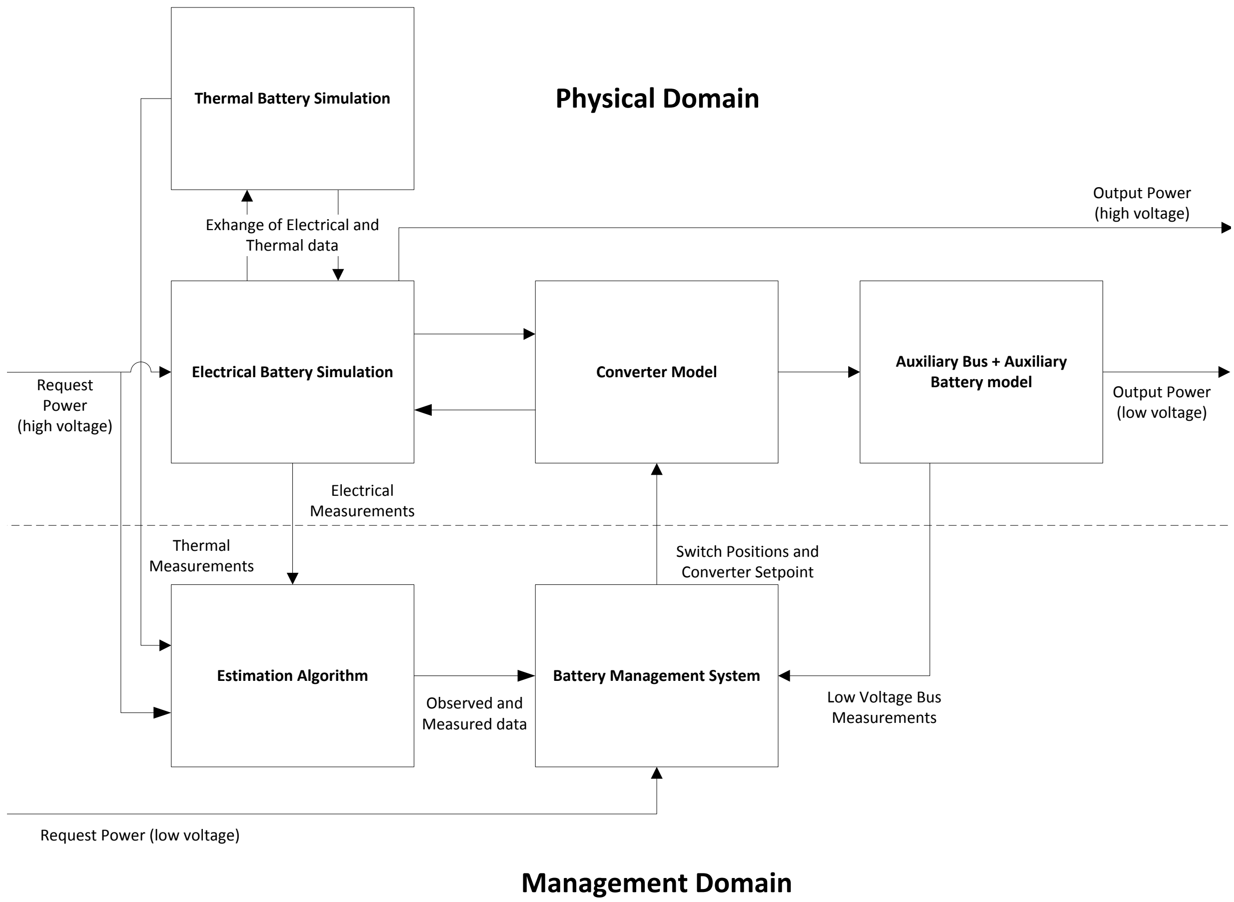

Figure 9: A schematic representation of the System-Level battery-system model.

gained during the literature study, and during the research of the Simulink documentation has been used. Firstly, the *Electrical Battery Simulation* has been implemented, as schematic of which can be seen in Figure 10. This model consists of three main parts, a coulomb counting loop, a look-up table used to find the open-circuit voltage, and an equivalent circuit model (ECM) with two RC circuits, as can be seen in Figure 2, to model the overpotential of the battery cell. This equivalent circuit model currently uses fixed parameter values, due to an unavailability of battery data, it can, however, be easily adapted to work with parameters that vary with the State-of-Charge and cell temperature, such as to make it a Linear-Parameter-Varying model. All of the parts of this electrical battery simulation are implemented such that they are executed separately for each cell. This is done by supplying the model with a matrix for inputs and parameters. To do this, a structure around the model was created, which allows the battery pack topology to be easily scalable. This structure consists of two parts, the first of which distributes the current that is being drawn from the pack into a matrix, in which the entries correspond to the currents being drawn from the individual cells. This matrix is structured in such a way that the horizontal dimension corresponds to the amount of parallel cells, and that the vertical dimension corresponds to the amount of series cells. This matrix input is then manipulated in the model by using element wise operations, and nested for loops when necessary, to separately treat all cells. The second part of the structure takes care of the interaction between the cells, and computes the terminal voltage of each module and that of the complete pack.

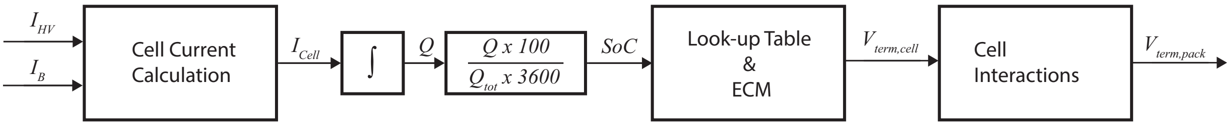

Figure 10: A schematic representation of the Electrical Battery Simulation.

The *Thermal Battery Simulation* is done in parallel to the electrical battery simulation. This thermal battery simulation takes the heat generation that results from the currents being drawn from the cells in the electrical battery simulation, and computes the temperature evolution of the cells based on this heat generation and the cooling supplied by the cooling system. The found cell temperatures are then fed back into the electrical battery simulation, where the changing temperature can be used to adapt the impedance values and open-circuit voltage curve of the cells, in case temperature sensitive models are implemented for these. This model has been implemented as a black box, as it will be supplied by another student working on the project at a later point.

Further in the physical domain, the *Converter Model* has been implemented. This has been done in a straight forward way, by using an assumed fixed efficiency for the Ćuk converter. However, as this is not the case in reality, a more detailed model is recommended for a later version of the model. The *Auxiliary Battery and Bus Model*, finally, makes use of a exponential battery model [10] to describe the open-circuit voltage, and overpotential of the Lead-Acid battery. This is calculated through

$$V_{aux} = E_0 - K\frac{Q}{Q - Q_{out}} + A \exp -BQ_{out} - R_i I_{load}, \quad (2)$$

where E_0, K, A and B are parameters used to fit the model to the open-circuit voltage curve of the Lead-Acid battery, Q is the capacity of the battery, Q_{out} is the extracted charge, R_i is the internal resistance and I_{load} is the current over the auxiliary battery. Using this, the load current imposed on the auxiliary bus changes the voltage level of the auxiliary battery as would happen in the real system, to warrant a response by the balancing algorithm similar to the response a real Lead-Acid battery would have.

Management Domain

The *Estimation Algorithm* block has been implemented using a state observer. This is a Luenberger observer, which has been chosen for the relative simplicity compared to an Extended Kalman Filter. From comparisons done within the UTEV group, it was found that the Extended Kalman Filter has only a small performance benefit over the Luenberger observer, while requiring more computation. As the observer is executed on a low performance chip, a choice was made to use the Luenberger observer, for the simplicity. To this end the same observer has also been used for the simulation model, in order to keep the simulation and experiment setup as identical as possible. To use the observer for each of the individual sub-modules, the same matrix structure as used for the electrical battery simulation is used. As a first step, this observer looks for the State-of-Charge value to which the corresponding open-circuit voltage matches the measured terminal voltage, using a lookup table of the open-circuit voltage. This State-of-Charge is then used to estimate the terminal voltage of the system, based on the previous states of the system and the measured current, using

$$\hat{V}_{term,k-1} = C\hat{x}_{k-1} + DI_{bat}, \tag{3}$$

in which C relates to the gradient of the State-of-Charge against the open-circuit voltage, and D is the internal resistance of the battery. After this the current states are estimated through an equivalent circuit battery model with 2 RC components, similar to the one used in the electrical battery simulation. This is done using the previous state $\hat{x}_{k-1}$, the measured current I_{bat}, as well as both the measured terminal voltage V_{term} and estimated terminal voltage $\hat{V}_{term}$. These last two terms are used to correct for errors from the equivalent circuit model, and the error in the State-of-Charge estimation, through a gain L, using

$$\hat{x}_k = A\hat{x}_{k-1} + BI_{bat,k-1} - L(V_{term,k-1} - \hat{V}_{term,k-1}), \tag{4}$$

in which A and B are matrices representing the equivalent circuit model. This thus leads to an estimate of the State-of-Charge value, as a value for this can be taken from $\hat{x}_k$.

The final part of the battery-system model is the *Battery Management System*. This part of the model uses the measurements done on the cells and the values found by the estimation algorithm as inputs. Within the BMS one part manages the electrical and thermal limits of the battery pack, while the other part of the system manages the balancing of the State-of-Charge levels. The way the balancing is implemented through the use of an algorithm will be discussed in the next section. Due to the hardware implementation used in the experimental setup, only an execution frequency of $0.1Hz$ is achievable for both the Estimation Algoritm and the Battery Management Algorithm, this thus means estimations and balancing decisions can only be made once every 10 seconds.

4.2 Balancing Algorithm Development

To improve upon the current balancing algorithm, a new balancing algorithm has been developed. This has been done to better achieve the objectives of the balancing algorithm, namely the State-of-Charge balancing of the sub-modules and modules in the battery pack, and the regulation of the auxiliary bus voltage, which were introduced in Chapter 3.2. For State-of-Charge balancing, the goal is for all the sub-modules within a module to be at the same State-of-Charge level, as well as for all modules to be at the same State-of-Charge level. As perfect balance is not possible due to the fact that the balancing algorithm is only executed every 10 seconds, balance is said to be achieved when all the cells are within a certain bound. It is shown in 5 that the current rule-based balancing algorithm does not achieve these objectives, as the modules do not converge to the same State-of-Charge level.

In the new balancing algorithm, the control loop for the auxiliary bus regulation and State-of-Charge balancing is split. An optimal compromise between these actions can be found by applying a form of optimal control to this, which should thus lead to both good bus regulation and good State-of-Charge balancing. This approach has been chosen as this option allows for freedom in the tuning of the algorithm after implementation, through implementing different cost functions, and the fact that optimality can be proven by doing mathematical analysis on the chosen parameters. Next to that, this algorithm also allows for control based on future states, through model predictive control. The downsides of this solution are the need to do mathematical analysis in order to prove the algorithm is functioning optimally, however this only needs to be done when changing the parameters.

The control loop for the new balancing algorithm can be seen in Figure 11, in which the split between the auxiliary bus regulation and State-of-Charge balancing can be seen. The auxiliary bus regulation control loop is strongly related to the original control loop from Figure 8. However, this reference current is now inserted in a calculation block. This calculation block uses both the required current I_{cmd} and another balancing parameter in the calculation of the cost function. This balancing parameter is free to be chosen, with a possible choice being the State-of-Charge of the battery cells, however also the cell terminal voltage or cell temperature could be used as an input. In the scope of this project, however, the State-of-Charge of the battery cells has been selected as this parameter, although the algorithm is implemented in such a way that this can be easily changed.

Within the calculation block two calculations are done. First, the State-of-Charge error e_{SoC} and balancing speed $\dot{e}_{SoC}$ are calculated, as a measure to judge the bus balancing at all times. The State-of-Charge error defines the difference in State-of-Charge between a sub-module and the sub-module with the lowest State-of-Charge within the same module:

$$e_{SoC}(i,j) = SoC(i,j) - min(SoC(j)), \tag{5}$$

in which i is the sub-module, and j is the number of the module to which it belongs. This calculation is then repeated for all of the sub-modules, in each module. In order to obtain convergence between the modules, also a module e_{SoC} is calculated through

$$e_{SoC}(7,j) = min(SoC(j)) - min(SoC), \tag{6}$$

by subtracting the minimum State-of-Charge of the pack from the minimum State-of-Charge of the module. Using the found State-of-Charge error values, the balancing speed can be calculated for all the sub-modules and modules in the pack, in order to show the speed at which an option can balance, for different currents. This is done using

$$\dot{e}_{SoC} = \frac{e_{SoC} * I_{bal}}{3600 * Q_{nom}}, \tag{7}$$

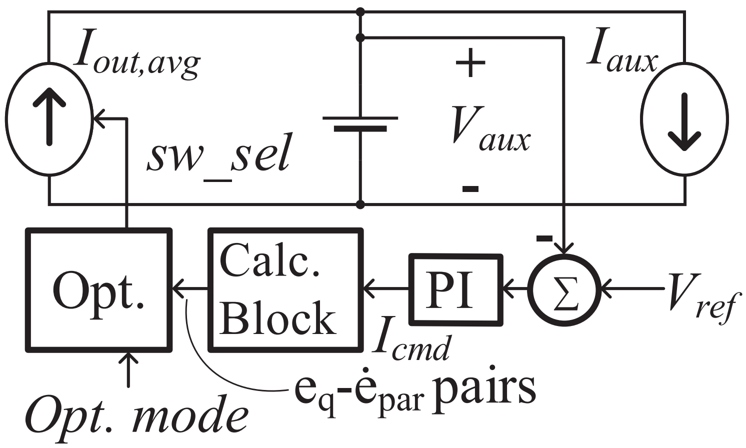

Figure 11: The control loop used for the optimal balancing algorithm.

for a range of 100 different balancing currents. This is done to offer a large range of options for which to calculate a cost.

Besides the State-of-Charge balancing, the algorithm also needs to control the auxiliary bus voltage, and thus also needs a variable to predict the impact of this. As the auxiliary systems demand current from the auxiliary bus, the State-of-Charge of the auxiliary battery decreases under this demand, especially when more current is taken from the auxiliary bus, than is supplied to it. This results in the auxiliary bus voltage dropping, which needs to be prevented in order to guarantee optimal operation conditions for the systems connected to this bus. In order to keep this voltage drop to a minimum, the State-of-Charge of the auxiliary battery needs to be kept steady. This can be achieved by supplied to the auxiliary battery from the balancing hardware. To be able to find an optimal trade-off between the current that needs to be supplied to the auxiliary bus, and the balancing of the State-of-Charge levels within the battery pack, also a quantitative figure needs to be found for the impact each balancing option has on the auxiliary bus regulation, this can be done in the form of $e_{Q,predicted}$. Using the calculated command current I_{cmd}, and the total output current onto the auxiliary bus $I_{out,total}$, from the last step, the actual charge error on the auxiliary bus, $e_{Q,real}$, is calculated. This charge error is arrived at by

$$\dot{e}_{Q,real} = \int_{0}^{k} I_{cmd}(k) - I_{out,total}(k-1), \tag{8}$$

in which I_{out} corresponds to the current that has been put onto the auxiliary bus, summed over the outputs of the converters. Next to this, a predicted charge error increase, e_{dQ} for the next time step can be calculated. This is done for each of the balancing options, as this charge error increase depends on the amount of current the converter puts out. This predicted charge error increase is calculated by

$$\dot{e}_{dQ} = \int_{k}^{k+1} I_{out} - n * I_{average}, \tag{9}$$

where I_{out} is the amount of current that each option outputs on the auxiliary bus. $I_{average}$ is the average current required by the auxiliary bus up to the current point in time, thus giving an amount of current that can be expected to be required. This average current is multiplied by a factor n, as to distribute the current required over the different modules. This factor n is calculated in such a way that it corresponds to the balance between the average State-of-Charge levels of the modules, thus giving a fair distribution.

Using the actual charge error found in Equation 8, together with the found error increase from Equation 9, a predicted auxiliary bus error caused by each of the options for each of the modules is found. This is calculated by

$$e_{Q,predicted} = e_{Q,real} * n - e_{dQ}, \tag{10}$$

where n again is a scaling factor. And thus shows the impact of a balancing option on the regulation of the auxiliary bus.

After these calculations, each balancing option thus has two values associated with it, which correspond to the two objectives, namely State-of-Charge balancing and auxiliary bus regulation. These values can then be used to find the optimal choice, which is done by implementing the cost function

$$J = x^\top Q x + u^\top R u, \tag{11}$$

In which Q and R are cost matrices, that have been tuned such to arrive at the wished trade-off between the two objective. This tuning has been done based on the results found from experiment, and was repeated until improvement was observable. In the tuning, incremental changes to the entries in Q and R have been made, such as to either favour the State-of-Charge balancing or the auxiliary bus regulation more. The final values have been used for the simulations in Chapter **??**, and are presented there. Next to that, x and u are the states and inputs defined as

$$x = \begin{bmatrix} \frac{1}{\dot{e}_{SoC}} \\ |e_{Q,predicted}| \end{bmatrix}, \quad u = D, \tag{12}$$

where D is the duty cycle of the Ćuk converter. Using these states and inputs in a cost function that is minimized, the predicted auxiliary bus error $e_{Q,predicted}$ will be minimised, the balancing speed $\dot{e}_{SoC}$ will be maximized, and the input current will be minimized, such as to achieve the balancing objectives, and minimise the converter losses. In this the absolute value of the predicted charge error $e_{Q,predicted}$ is taken in order to ensure convergence toward zero. Without this, the continued usage of high currents might bring the cost below zero, which would negatively impact the State-of-Charge balance. This is important, as the minimal value of the cost is selected as the optimal operation point, this minimal value is thus always positive or zero. These operations are conducted in parallel for all the different modules present in the battery pack.

The results found using this new balancing algorithm can be found in Chapter 5.2, together with the cost matrices that were arrived at by tuning. This tuning was done by small increments to the entries of the const matrices, depending on the results seen after running a test simulation.

5 Results and Discussions

In this chapter the results for simulations of the simulation model, and balancing algorithm, as proposed in the previous chapter are shown and discussed. First, the results that verify the functioning of the simulation model are discussed, after which the results for simulations of the developed balancing algorithm are discussed.

5.1 Battery-System Model

In order to test and verify the battery-system model, a comparison between outputs of the simulation model and measurement results from an experiment that has been done with the same system setup. This experiment was also a verification of the rule-based balancing algorithm. A setup consisting of two modules with 6 series and 2 parallel cells was used, to which 2 module battery management systems, and a supervisory battery management system were connected, as well as a Lead-Acid battery. During the experiment this auxiliary battery was being discharged by a load, as to emulate an auxiliary load profile. This profile consists of a start-up phase in which a high current is drawn, similar to what is experienced when starting the systems in the vehicle, a medium-load phase, corresponding to driving the vehicle, and finally a low-load phase, corresponding to the vehicle being parked. As cooling was not available on this experimental setup, no driving cycle was imposed on the cells, in order to prevent damage to the battery pack. In Figure 12 to 14 the results of these measurements can be seen. The control signal in Figure 14 represent the selection of the sub-modules and module mode for each of the modules. In this figure, 0 corresponds to no option being selected, 1 to 6 corresponding to each of the sub-modules being selected, and 7 corresponds to the module being selected.

The battery-system model has been initialised for the same State-of-Charge conditions as were introduced into the battery pack in the experiment, and has been executed using the same auxiliary load profile. Simulating this yields the results shown in Figure 15 to 17. On a high-level comparison of the State-of-Charge, the simulation results in Figure 15 look very similar to those from the experiment in Figure 12. In both cases, it shows both modules converging to a different State-of-Charge, as can be seen in the top plot of the figures. In Figure 13 and 16 it can be seen that the auxiliary bus voltage level for both the measurement and simulation is regulated to the reference value of 12.5 V.

When comparing the results more closely, it can be seen that during the experiment the State-of-Charge balance within the separate modules is reached at an earlier time compared to simulation results. It can also be seen that the way the State-of-Charge evolves is slightly different between the simulation and experiment. These differences are mainly due to a difference between the parameters used to describe the battery cells in the battery model, and the real battery cells used in the experiment. Next to this, the battery-system model assumes all cells to be equal, while that is very unlikely to be the case in the real battery pack, due to production inaccuracies. The difference between the battery cells can cause the terminal voltage to develop differently in reality than in the model, leading to different State-of-Charge values being estimated by the estimation

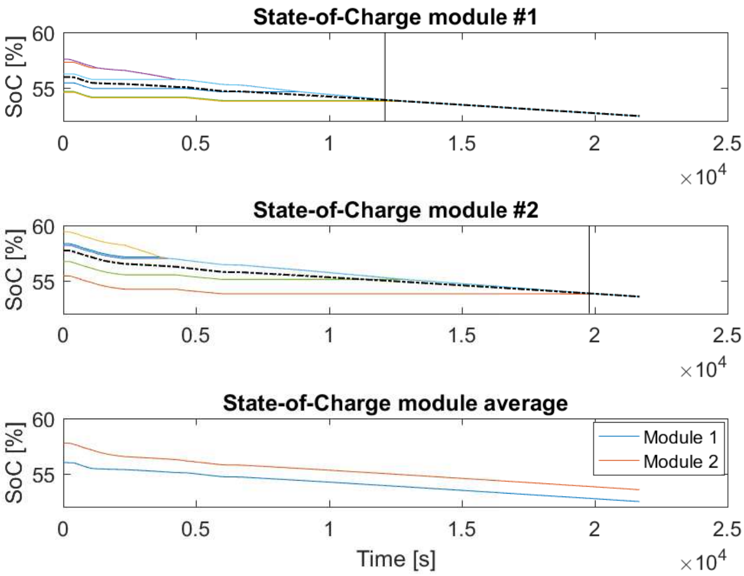

Figure 12: Measured State-of-Charge values from each of the modules during an experiment using the rule-based balancing algorithm.

algorithm in both cases. These differences in turn cause different actions from the control algorithm, which leads to a different balancing process in reality, compared to what can be seen from simulations. However, this is not a big issue, as the model does allow for the use of different parameters for each cell, so more realistic simulations in which the difference between cells are taken into account can be conducted. Such a simulation could for instance use different parameters for each cell, based on a normal distribution of expected variations in impedance and capacity between the cells. Another alternative would be to implement an LPV battery model, making the battery parameters State-of-Charge and temperature dependent. Besides the assumption that the cells are the same, another problem is that the parameters that were used in the simulation model and observer are not precise enough, which also adds to the deviation. This is the result of the parameters being based on inaccurate battery tests, which were conducted without a clear repeatable method.

From both the measurement and simulation results it can be seen that an improved algorithm is a necessary development. This mainly is apparent from the lack of convergence in the State-of-Charge levels of the different modules, as Figures 12 and 15 show. This is mainly due to how the auxiliary bus voltage regulation has been implemented, as this takes priority over balancing in the algorithm. This causes both modules to operate in module mode in the early phases of the experiment, which causes a difference in State-of-Charge between the modules that cannot be overcome.

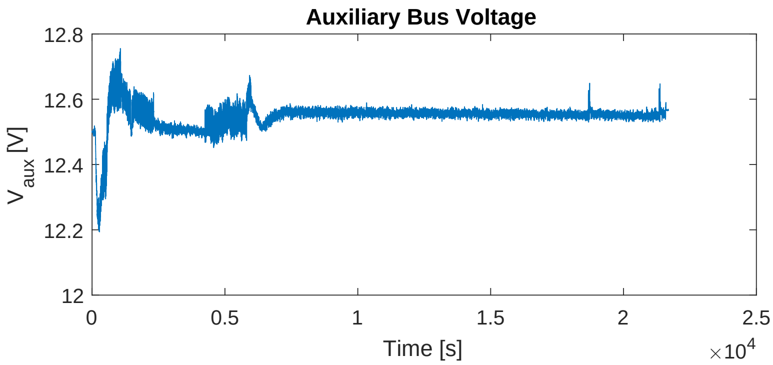

Figure 13: Measured auxiliary bus voltage levels during an experiment using the rule-based balancing algorithm.

5.2 Balancing Algorithm

To inspect the functioning of the newly developed balancing algorithm, simulations have been done using the battery-system model. Multiple scenarios have been simulated, in order to verify the functioning of the balancing algorithm over different scenarios. In order to place the new optimal balancing algorithm into the context of the old rule-based balancing algorithm, first a simulation has been done using the same scenario as was used for the verification of the battery-system model in the previous section, as this allows for easy comparison between the two algorithms. After this, additional simulations have been done for the new balancing algorithm, in which the amount of modules were increased, in order to show behaviour closer to the actual situation in a vehicle. Next to this simulations with different auxiliary load profiles have also been done.

For all of the simulations with the new algorithm, the following cost matrices have been used

$$Q = \begin{bmatrix} \frac{1}{100} & 0 \\ 0 & 10 \end{bmatrix}, \quad R = 5. \tag{13}$$

The values in these matrices have been found by tuning the entries incrementally, until satisfactory results were obtained.

In Figures 18 until 20 the simulation results for the optimal balancing algorithm can be seen. The scenario used for this is the same as that used to verify the simulation model, and thus allows for comparison to the rule-based balancing algorithm. When comparison the results in Figure 18 to those in Figure 15, the first thing that can be noticed is that for the optimal balancing algorithm all State-of-Charge values converge to the same value at 16000 seconds, which is an improvement over the rule-based balancing algorithm. At the same time auxiliary bus regulation is also achieved, as seen in Figure 19, however, it is achieved to a lesser extent than it is for the rule-based controller in Figure 16. This is, however, part of the trade-off between the two objectives that are present in the balancing algorithm, and is an acceptable occurrence, as long as convergence to 12.5 Volts is achieved. To guarantee this, bounds can be implemented, to which the controller must adhere, for instance 10

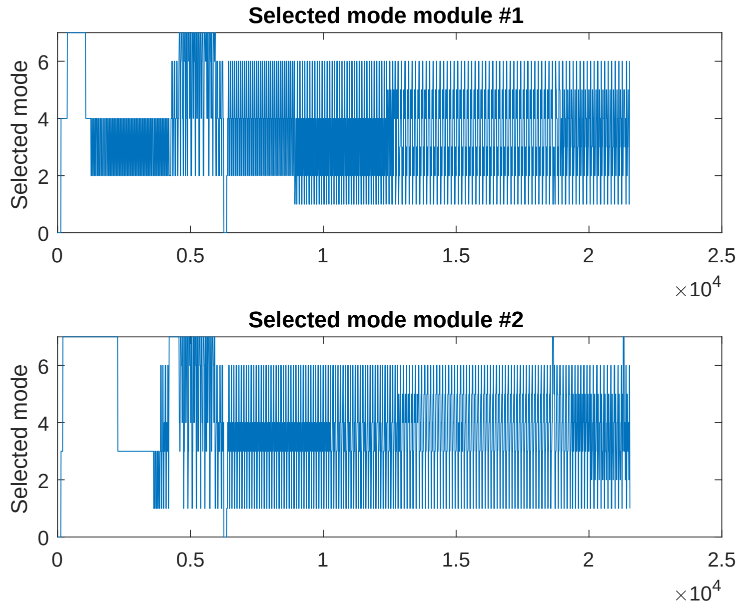

Figure 14: Mode selection for each of the modules during an experiment using the rule-based balancing algorithm.

and 14 Volts. Within these bounds the optimal balancing algorithm can operate without restrictions, however, outside these bounds the bias between the states in the Q matrix can be altered, in order to make sure the voltage returns to a level within the bounds. Another remark that can be made about the voltage is that it contains many spikes, this is due to the Equivalent Series Resistance (ESR) of the Lead-Acid battery. When a current is inserted into the auxiliary battery this causes a voltage increase related to the magnitude of the current and the ESR. As the currents current from the balancing algorithm can be relatively large, especially when operating in module mode this leads to a large voltage increase.

Several further observations can be made when going deeper into the control actions of the optimal balancing algorithm, which are displayed in Figure 20. Firstly, it can be seen that only module number 2 operates in module mode in the first stage, as this module has a sub-module with a higher minimum State-of-Charge when compared to module number 1, as can be seen in the bottom plot of Figure 18. This thus means that the optimal control algorithm is trying to decrease the difference in State-of-Charge between the two modules, by drawing a high current from the module with the highest minimum State-of-Charge, while drawing a lower current from the other module by operating it in sub-module mode, which means that it is still delivering a current to the auxiliary bus, in order to aid bus regulation. Next to this, it can also be seen that from around 8000 seconds onwards, module 2 is switching between module and sub-module mode, as this module has not reached internal balance yet, but also needs to reduce the minimum State-of-Charge level closer to that of module 1. These two goals result in the switching between the two modes,

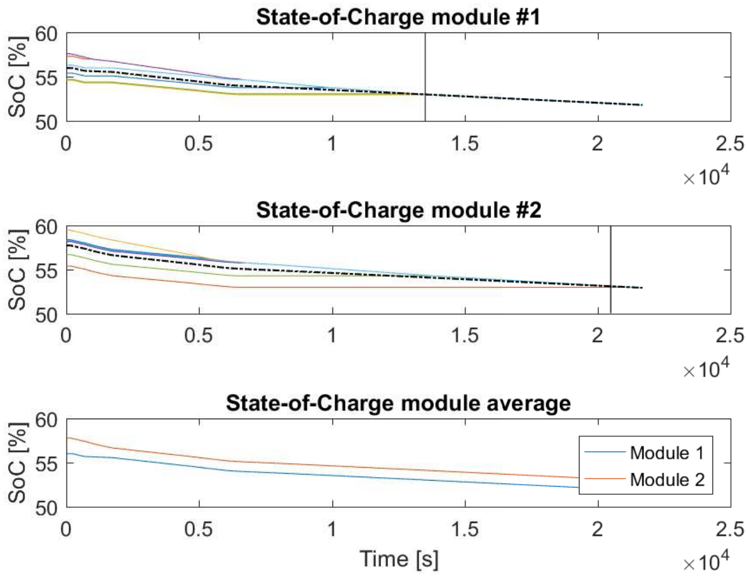

Figure 15: State-of-Charge values from each of the modules for a simulation using the rule-based balancing algorithm.

as to both improve the State-of-Charge balance within the module, and the State-of-Charge balance within the pack. Module one, on the other hand, is switching between being turned off and balancing all cells, in order to maintain the balance in this module. After around 16000 seconds both modules start switching between all the modes, as both modules are balanced, and the most effective option in terms of auxiliary bus regulation now becomes the optimal choice.

When comparing the control actions of the rule-based and the optimal controller, respectively in Figure 15 until 17 and Figure 18 until 20, it can be seen that the control actuation is different between the two. The rule-based controller mainly focusses on the regulation of the bus voltage during the first phase up to around 6000 seconds, which results in only little convergence in terms of State-of-Charge. On the other hand, the optimal controller is actually focussing on decreasing the difference in State-of-Charge during this phase, in order to bring the sub-module State-of-Charge levels closer together. This means that once the rule-based controller starts focussing of the balancing, the optimal controller has already partially balanced the cells.

To further verify the designed optimal balancing algorithm, additional simulations have been done. For these simulations the amount of modules has been increased from 2 to 4 modules, as to evaluate if the functioning of the algorithm scales as intended. The results for this can be seen in Figures 21 to 23. To support the scaling in the battery pack size, the current required by the auxiliary systems has also been increased by a factor 2. The results that can be seen in these figures show similar behaviour to the scenario with 2 modules discussed above, thus proving that the functioning of the algorithm scales as intended with

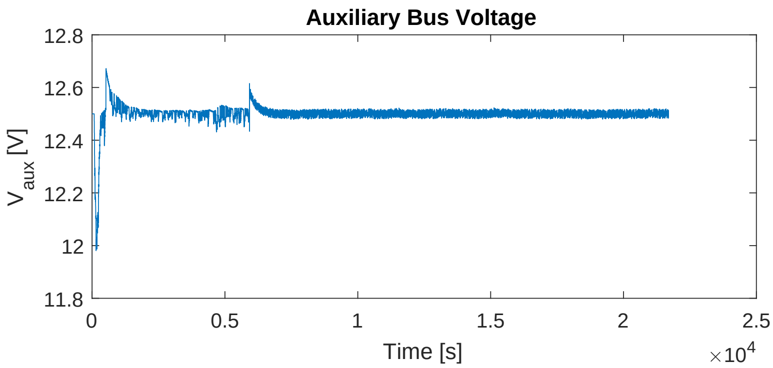

Figure 16: Auxiliary bus voltage levels for a simulation using the rule-based balancing algorithm.

the amount of modules. Even the time at which all the sub-modules are balanced remains around the point of 16000 seconds.

Looking at these results, several observations regarding the control actions can be made. Firstly, it can be seen that the conclusion from the optimal balancing algorithm for two modules still applies, meaning that the cell balancing still is prioritized over bus regulation when the State-of-Charge differences are large, and the auxiliary bus voltage error is small. However, now these observations are supported more clearly, as there are higher load currents on the auxiliary bus, meaning that it requires module 2 and module 4 to run in module-mode in the early phases of the load cycle, in order to limit the voltage error on the auxiliary bus. These two modules have the highest minimum State-of-Charge, as can be seen in Figure 21. In this way these modules are brought closer in State-of-Charge to the other modules, while also satisfying part of the energy demand of the auxiliary bus. After this, it can be seen in Figure 23 that between around 5000 seconds and around 15000 seconds all of the modules are operating in sub-module mode for the majority of the time, in order to achieve better internal pack and module balance. The small portion of time spent in module mode during this time, is to prevent the charge error from becoming extremely large, and thus decreasing the auxiliary bus voltage too much.

Since the balancing algorithm has to function in each possible scenario, it is also important to simulate for different conditions, such as different load cycles. One such different load cycle has been simulated for the simulation with 4 modules. This load cycle corresponds to the vehicle being parked first, after which it is activated. This scenario is more in accordance with the real functioning of a vehicle that has been parked with a State-of-Charge imbalance, however also still does not correspond to the actual driving, as no driving cycle is imposed, to retain comparability to the experiments.

When simulating the optimal balancing algorithm for this load cycle, this yields the results from Figures 24 to 26. When looking at these results, it can be seen that the algorithm still functions as intended even during this different load profile. It can however be seen in Figure 24 that while the cell balancing performance within the modules is only slightly worse to that what was observed for previous scenarios, the overal balancing

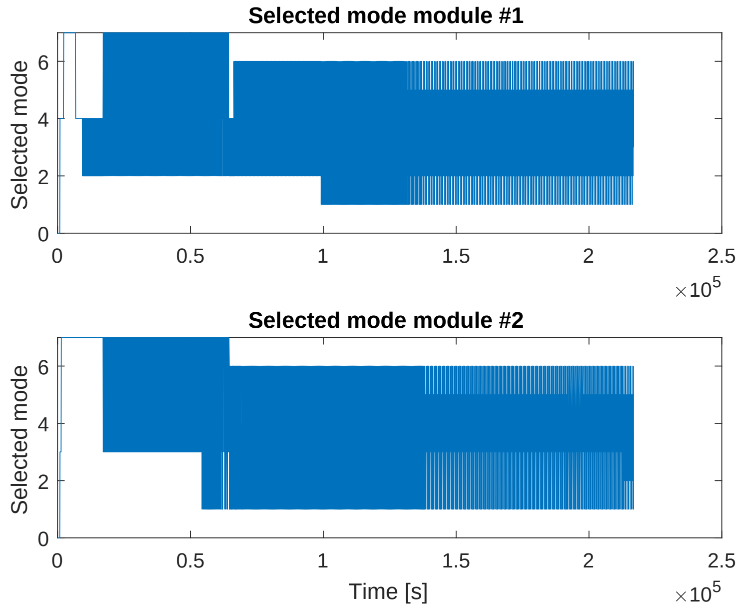

Figure 17: Mode selection for each of the modules for a simulation using the rule-based balancing algorithm.

between the modules is slower, only achieving full convergence around 22000 seconds. This can mainly be attributed to the error on the auxiliary bus not becoming large enough for an error to build up on the auxiliary bus, hence causing all modules to mainly operate in sub-module mode during this phase, as can be seen in Figure 26. Thiss causes a decrease in balancing performance, as operation in module mode is needed to bring the modules with a higher minimum State-of-Charge closer to the other modules. This can possibly be solved by changing the tuning parameters of the balancing algorithm, however that would possibly impact other scenarios. Another solution could be to implement several different tuning parameters for different conditions.

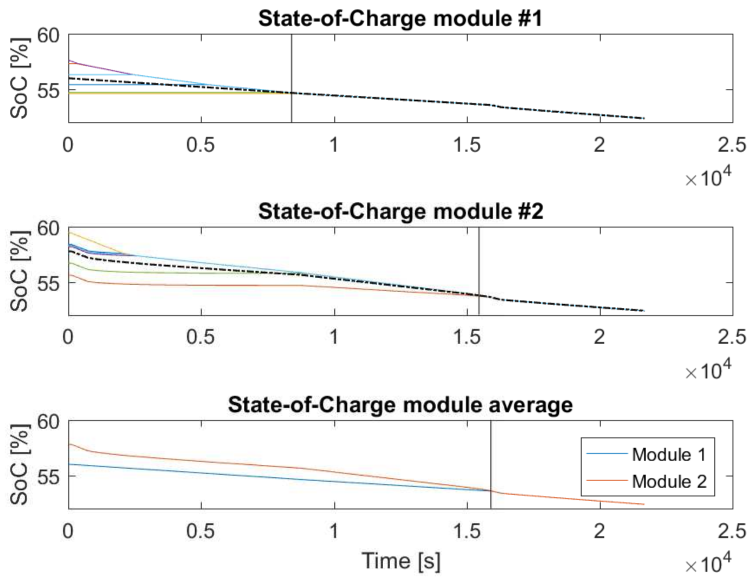

Figure 18: State-of-Charge values from each of the modules for a simulation using the optimal balancing algorithm.

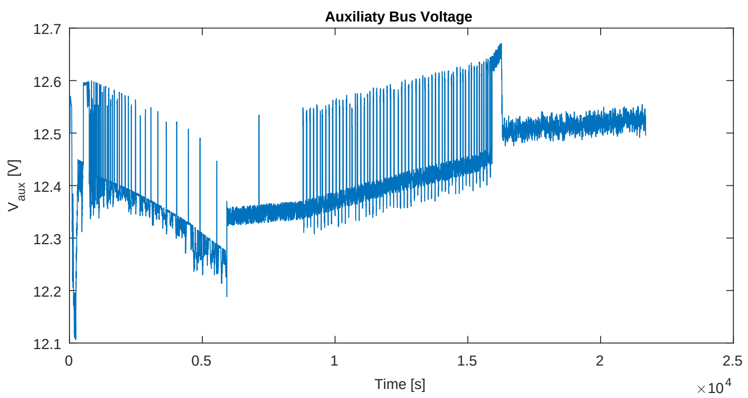

Figure 19: Auxiliary bus voltage levels for a simulation using the optimal balancing algorithm.

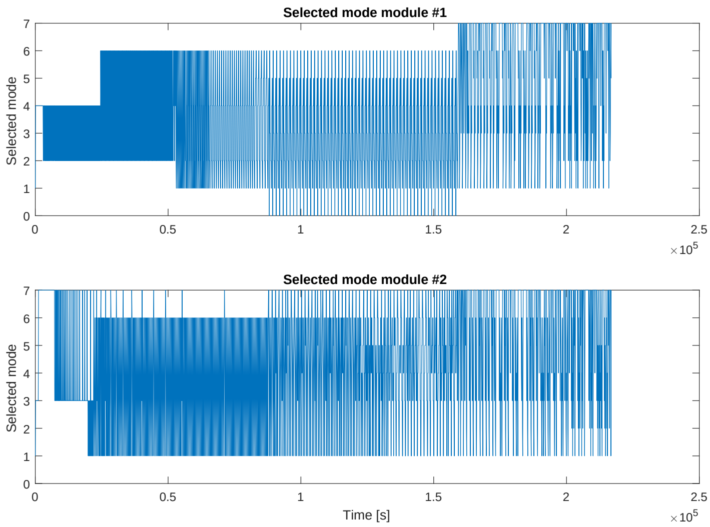

Figure 20: Mode selection for each of the modules for a simulation using the optimal balancing algorithm.

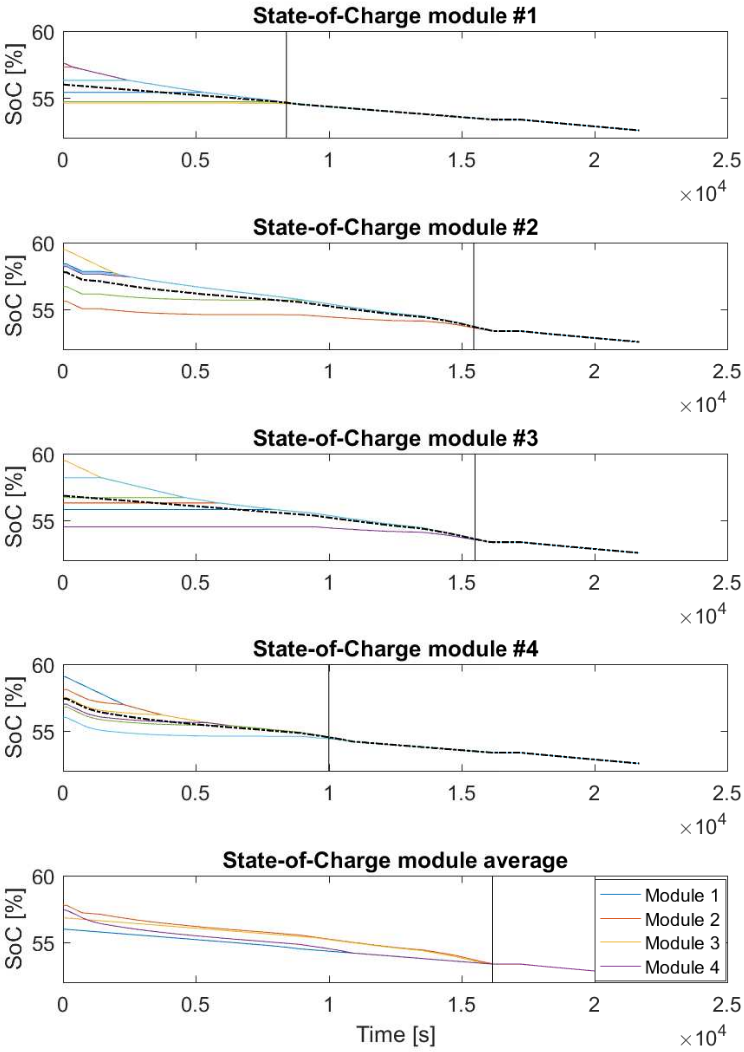

Figure 21: State-of-Charge values from all of the modules for a simulation using four modules on the optimal balancing algorithm.

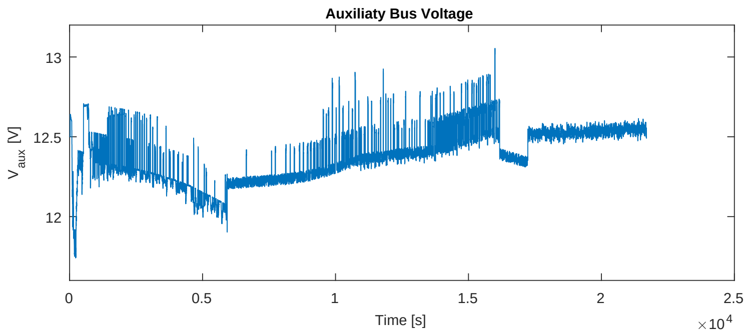

Figure 22: Auxiliary bus voltage levels for a simulation using four modules on the optimal balancing algorithm.

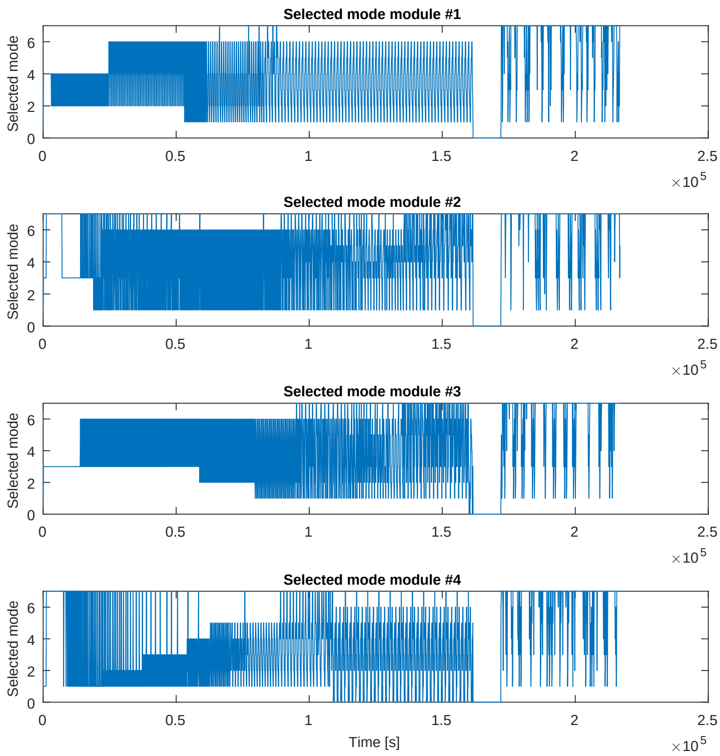

Figure 23: Mode selection for each of the modules for a simulation using four modules the optimal balancing algorithm.

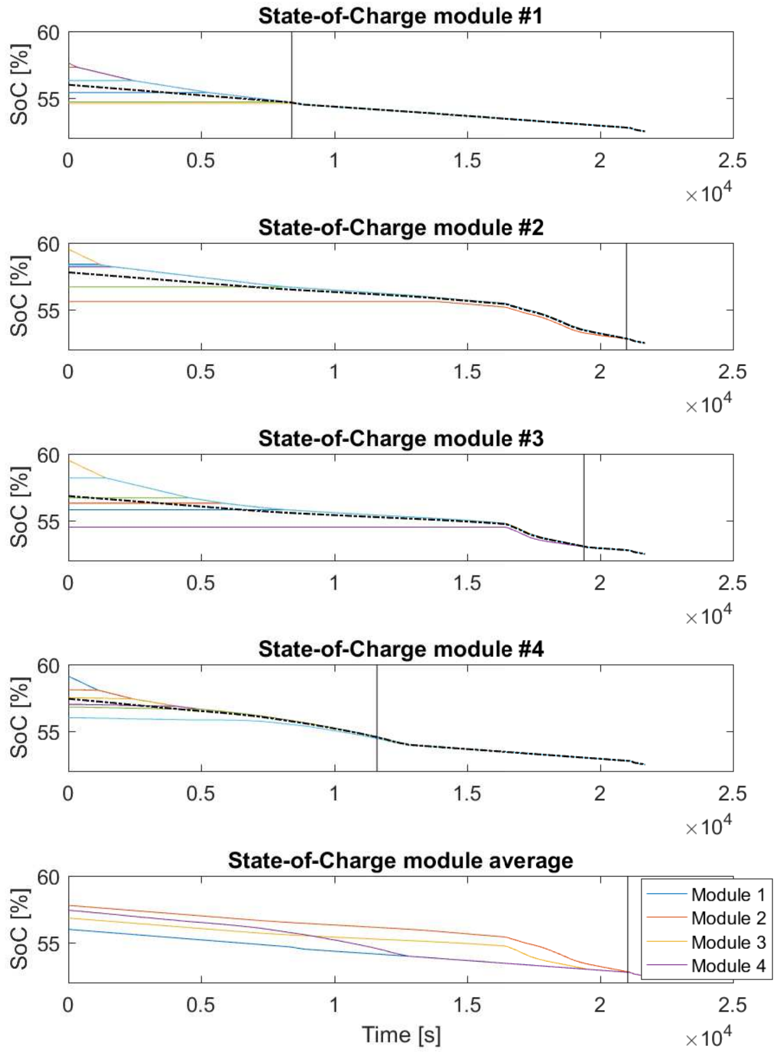

Figure 24: State-of-Charge values from all of the modules for a simulation using four modules on the optimal balancing algorithm, using a different auxiliary load profile.

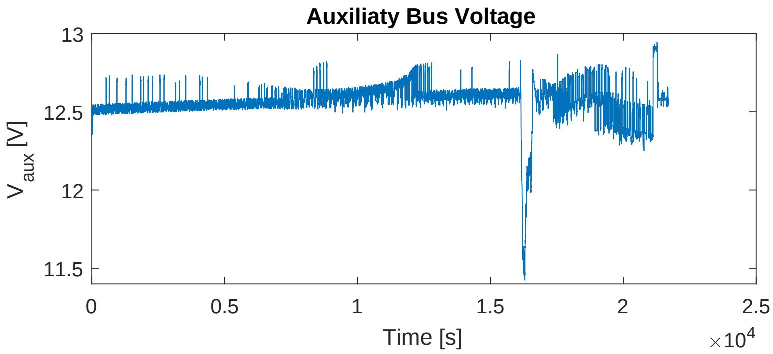

Figure 25: Auxiliary bus voltage levels for a simulation using four modules on the optimal balancing algorithm, using a different auxiliary load profile.

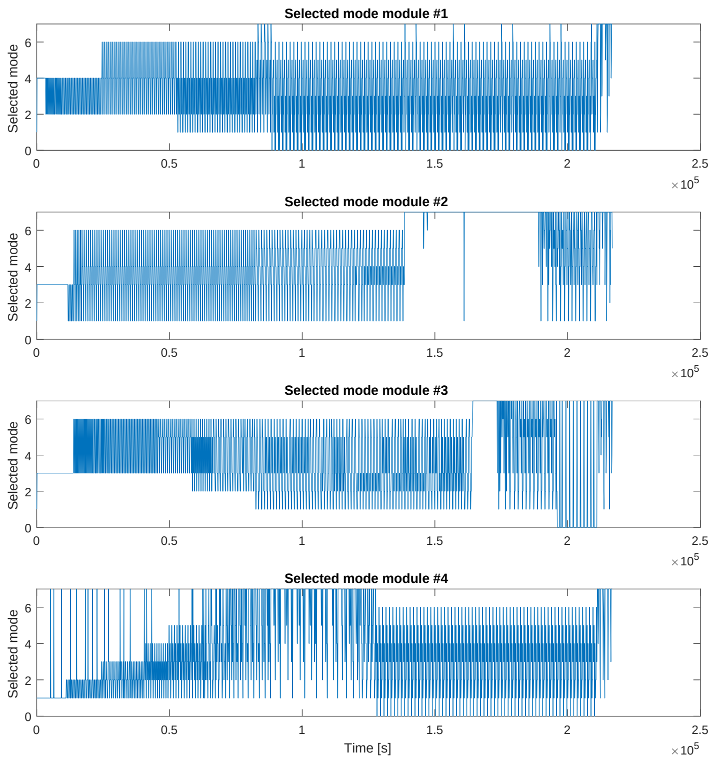

Figure 26: Mode selection for each of the modules for a simulation using four modules the optimal balancing algorithm, using a different auxiliary load profile.

6 Conclusions and Recommendations

From Chapter 5, it can be concluded that the two main goals of the project have been achieved successfully. The first goal, implementing a battery-system model which satisfies the requests that have been posed at the outset of this project, has been achieved. With this model simulations can be done for any battery pack topology within the design space of the UTEV battery project. Next to this, also new research paths can be pursued, such as research on the impact of internal difference between battery cells. Next to this, the battery-system model can also be used to quickly develop and test balancing algorithms. The second goal, of implementing an improved balancing algorithm, has also been achieved. This has been done in the form of the optimal balancing algorithm, which shows improved State-of-Charge balancing performance over the rule-based balancing algorithm that was previously in use. The improvement in performance can be seen in Chapter 5, where it is shown that the new algorithm allows for quicker balancing than was the case for the original rule-based balancing algorithm, while at the same time allowing for more flexility in the regulation of the auxiliary bus voltage.

While the current version of the simulation model is functional, several recommendations for improvements to it can be made. Firstly, the implementation of the thermal model needs to be improved, as this is currently not fully modular, nor fully characterised, making it hard to be used. A way to improve on this, would be to step away from implementing the full vehicle cooling system, and to move towards implementing a more basic cooling system, such as the one used during experiments. This is recommended, as too many unknowns exist for the vehicle-level cooling system to successfully model it, while the setup that is used during experiments has less unknowns. Once implemented, this more-detailed implementation of the cooling system will aid the realism of the simulations, especially under high current profiles where temperature becomes an important factor in the behaviour of the battery cells. Another recommendation for the battery-system model, is to implement the effects of ageing of the battery cells, such that meaningful simulations over longer usage cycles can be done, with the goal of finding out how rapidly the battery pack would age under assumed conditions. A final recommendation is that more characterisation of the battery cells should be done, as the values currently used to describe the battery cells in the model are not accurate enough for the simulations to fully match experimental outcomes. In this characterisation the focus should especially lie on the relation of the battery parameters with temperature and State-of-Charge levels.

Besides these recommendations on the battery-system model, also recommendations can be made for the optimal balancing algorithm. A first recommendation is that the balancing algorithm can be further tuned, this in order to obtain better performance. This is recommended, as it is currently not fully clear if total optimality is being achieved. A way to guarantee that this algorithm indeed gives the optimal outcome is to do an extensive analysis on the mathematical theory behind the balancing algorithm. Another way to prove that the outcome is indeed optimal would be to find the absolute optimal outcome through calculation, and to compare this to the outcome of the algorithm. However, while this is helpful for a specific case, it is not guaranteed that this extrapolates to every possible scenario, hence it is never possible to guarantee overal optimality using this method. A final recommendation for the balancing algorithm, is that more simulations need to be executed, in order to find out how the algorithm behaves over a range of possible scenarios. Doing thorough analysis on the outcomes of these simulations, will lead to a better understanding of the decision-making process of the balancing algorithm, and the impact the different scenarios have on this.

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