Charging time estimation and study of charging behavior for automotive Li-ion battery cells using a Matlab/Simulink model

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Abstract

An accurate estimation of the charging time of an automotive traction battery is possible only with the knowledge of different parameters of the battery and the vehicle. If this information is not available to the driver, the full time needed for charging of the battery may have to be assessed only from experience. A long route planning and estimation of required service life of the vehicle are therefore only roughly possible. Furthermore, with a better knowledge of estimated charging time, better management of public charging stations and better utilization of charging equipment can be achieved.

An algorithm based on Matlab/Simulink model is made in the present thesis to estimate the charging time of a Li-ion battery pack which consists of 32 cells with 40 Ah each, as well as to investigate the impact of different cell balancing methods and different charging strategies on charging process. The theoretical background of the battery and charging modelling is investigated and different battery models are compared to get the best trade-off between the model accuracy and computation complexity. In the end, an electrical equivalent circuit model from reference [1], consists of a series resistor and two ZARC elements, is chosen to represent the battery cell. The parameters of the equivalent circuit are updated according to the SOC, current and temperature changes during the charging process. The whole simulation model of the algorithm consists of a charging controller (implementing the charging strategy), cell balancing logic controller, and cell balancing hardware simulation circuit and battery cell models. Different balancing criteria: based on SOC (with PWM drive) and based on terminal voltage (with/without advance) are implemented in the cell balancing logic controller, as well as different balancing windows, to investigate their impact on charging time. As for charging strategy, traditional CCCV is investigated, further investigation is conducted into improved CCCV method. The impact of initial SOC, charging rate and aging factor on charging behavior are investigated as well. Experiment results are validated by the comparison of the results with the ones got from a Hardware-in-the-loop simulation system.

Key words: Charging time estimation, HIL, Li-ion battery, Passive balancing
Sammanfattning

En noggrann estimering av laddtiden hos batterier avsedda för traktionsapplikationer kräver kunskap kring batteriets och dess tillhörande laddsystems parametervärden. Utan tillgång till denna information kan laddtiden endast uppskattas från fordonsägarens tidigare erfarenheter vilket försvårar t.ex. ruttplanering. En estimering av laddtiden med tillräcklig noggrannhet kan även möjliggöra bättre utnyttjade ut av laddutrustning inklusive nytjandes av publika laddstationer.


Nyckelord: Hardware-in-the-loop, laddtid, litiumjonbatteri, passiv balansering
I would like to thank my examiner associate professor Oskar Wallmark at KTH and industry supervisor Dr. Christian Fleischer at NEVS. Without their guidance, it is simply not possible to finish this thesis. The advice from my colleagues at NEVS, Shivaram Rajput, Yizhou Zhang and Kaixiang Dai., helps a lot to overcome the obstacles in the process. Colleagues in advanced battery technology group at NEVS really give an enjoyable atmosphere in office. Last but not least, I would like to thank my family members, who always support me at any time. Thank you all.
# Content table

Abstract ........................................................................................................................... i
Sammanfattning............................................................................................................... iii
Acknowledgements ......................................................................................................... v
Content table .................................................................................................................. vi

## Chapter 1 Introduction
1.1. Motivation .................................................................................................................. 1
1.2. Project target .............................................................................................................. 2
1.3. Thesis Outline .......................................................................................................... 2

## Chapter 2 Literature review and theoretical background .............................................. 3
2.1. Battery cell models ................................................................................................. 3
  2.1.1. RC models ......................................................................................................... 3
  2.1.2. ZARC element model .................................................................................... 4
  2.1.3. Electrochemical models .................................................................................. 6
2.2. Main variables in battery charging ....................................................................... 7
  2.2.1. SOC.................................................................................................................. 7
  2.2.2. OCV ............................................................................................................... 8
  2.2.3. Polarization voltage ....................................................................................... 8
  2.2.4. Initial SOC .................................................................................................... 10
  2.2.5. Aging factor .................................................................................................. 11
2.3. Charging theories ................................................................................................. 12
  2.3.1. CCCV charging method ............................................................................... 12
  2.3.2. Multistage current charging method ............................................................ 14
2.4. Balancing methods ............................................................................................... 15

## Chapter 3 Matlab model implementation .................................................................. 17
3.1. Overview of the Matlab model for charging simulation ........................................ 17
3.2. Charging controller ............................................................................................... 18
  3.2.1. CCCV charging controller ......................................................................... 18
  3.2.2. Improved CCCV charging controller ......................................................... 22
3.3. Balancing logic block ............................................................................................ 24
  3.3.1. Balancing based on terminal voltage without advance .................................. 24
  3.3.2. Balancing based on terminal voltage with advance ...................................... 28
  3.3.3. Balancing based on SOC (OCV) ................................................................. 29
  3.3.4. Balancing based on SOC (OCV) with PWM Driving................................. 31
3.4. Balancing circuit block .......................................................................................... 31
  3.4.1. Balancing circuit for normal drive .............................................................. 31
3.4.2. Balancing circuit for PWM drive .......................................................... 32
3.5. Battery pack block .................................................................................. 33
  3.5.1. General layout ..................................................................................... 33
  3.5.2. Aging factor ....................................................................................... 35
  3.5.3. Updating SOC and OCV .................................................................... 35
  3.5.4. Updating ohmic resistance .................................................................. 37
  3.5.5. ZARC related blocks ........................................................................... 38
  3.5.6. Thermal model .................................................................................... 39
3.6. Auxiliary blocks ....................................................................................... 40

Chapter 4 Simulation scenarios and the simulation results .................................. 41
  4.1. CCCV charging and balancing based on terminal voltage without advance .... 43
    4.1.1. Simulation with new battery cell and zero initial SOC ....................... 43
    4.1.2. Simulation with different aging status of battery cells and zero initial SOC 45
  4.2. CCCV charging and balancing based on terminal voltage with advance ...... 48
    4.2.1. Simulation with new battery cell and zero initial SOC ....................... 48
    4.2.2. Simulation with different aging status of battery cells and zero initial SOC 50
  4.3. CCCV charging and balancing based on SOC (OCV) .................................. 52
    4.3.1. Simulation with new battery cell and zero initial SOC ....................... 52
    4.3.2. Simulation with different aging status of battery cells and zero initial SOC 54
  4.4. CCCV charging and balancing based on SOC (OCV) with PWM driving ...... 56
    4.4.1. Simulation with new battery cell and zero initial SOC ....................... 56
    4.4.2. Simulation with different aging status of battery cells and zero initial SOC 57
  4.5. Improved CCCV charging and balancing based on SOC (OCV) ................. 58
  4.6. Impact of different initial SOCs on charging behavior ............................. 60
  4.7. Impact of different charging currents on charging behavior ..................... 62
  4.8. Conclusion ............................................................................................... 63

Chapter 5 Hardware-in-the-loop validation of the simulation results ...................... 64
  5.1. HIL system ............................................................................................. 64
  5.2. HIL validation results .............................................................................. 65
    5.2.1. HIL simulation for CCCV charging and balancing based on terminal voltage without advance ...................................................... 65
    5.2.2. HIL simulation for CCCV charging and balancing based on terminal voltage with advance .......................................................... 67
    5.2.3. HIL simulation for CCCV charging and balancing based on SOC (OCV) 68
    5.2.4. HIL simulation for CCCV charging and balancing based on SOC (OCV)
with PWM drive........................................................................................................69

5.3. Conclusion...........................................................................................................71

Chapter 6 Discussion.................................................................................................................. 72

Chapter 7 Appendix.............................................................................................................. 74

7.1. Figures for Section 4.4.1....................................................................................... 74

7.2. Figures for Section 4.4.2....................................................................................... 76

7.3. Figures for Section 4.5.......................................................................................... 78

7.4. Figures for Section 4.6.......................................................................................... 79

7.5. Figures for Section 4.7.......................................................................................... 84

Reference................................................................................................................................. 87
Chapter 1 Introduction

1.1. Motivation

As the concern of global warming becomes greater and more international, greener ways to live, especially green mobility which can ameliorate the situation a lot, attracts more and more attention. This leads to a hot trend of new electric vehicle (EV) manufacturer coming up as well as the transform of old vehicle manufacturers into solution providers for greener transport. A rapid growth in both the EV sales and charging equipment is observed worldwide. Figure 1.1 and figure 1.2 give the growth of EV and EV supplying equipment.

![Global EV sales 2010-2014](image1)

*Figure 1.1 Global EV sales 2010-2014 [2]*

![Global EVSE stock](image2)

*Figure 1.2 Global EVSE (Electric Vehicle Supplying Equipment) stock [2]*

EVSE stock more than doubled for slow charging points between the end of 2012 and 2014, and increased eightfold for fast charging point [2].

However, up to date, EVs still face enormous challenges to replace conventional vehicles. In addition to the relatively high price of EVs, where cost of battery pack plays an important role, the lack of experience with the new technology certainly causes a slowly growing willingness to change the drive mode. Therefore, it is important to come up with new production methods and to raise
higher quantities to reduce the price of electric cars. Also, the inexperienced user has the uncertainty in dealing with the novel technique. The decisive aspect, here, is the limited range in combination with a slow recharging of vehicle. The estimated download time of the traction battery of an electric car is rarely known to the driver. An accurate estimation of the charging time is possible only with the knowledge of different parameters of the battery and the vehicle. If the information is not available to the driver, full time needed for charging of the battery is usually assessed by experience. A long route planning and estimation of required service life of the vehicle are therefore only roughly possible. Furthermore, with the knowledge of estimated charging time, better management of public charging stations and better utilization of charging equipment can be achieved.

1.2. Project target

The present thesis aims to develop an algorithm based on Matlab/Simulink model to estimate the charging time of the Li-ion batteries in electric vehicles, further experiments to investigate in the impact of different balancing methods and different charging strategies on charging time are also conducted.

To validate the simulation, theoretically we have to do a charging test on real battery pack under the same circumstance with the simulation. However, this leads to too high time and economic cost, especially when the aging phenomena of the battery is considered, which almost make the test impossible. A hardware-in-the loop (HIL) simulation system solve this problem quite decently. The HIL simulator emulates the voltage behavior of the battery pack with rather high efficiency, which make it acceptable to treat it as a real battery pack. Therefore, the accuracy of the algorithm is tested via a Hardware-in-loop simulation system.

1.3. Thesis Outline

The outline of the thesis is given as follows. Chap 1 gives brief introduction to the purpose of the thesis as well as the structure of the report. Chap 2 talks about literature review on batteries theory and other theoretical background for this thesis. Chap 3 introduces implementation of the Matlab model for charging simulation. Chap 4 introduces the simulation scenarios and results. Chap 5 shows the simulation validation with the HIL simulator. Chap 6 concludes the thesis and discusses about possible further work.
Chapter 2 Literature review and theoretical background

2.1. Battery cell models

The behavior of a battery cell can be described via an electrical equivalent circuit which can emulate certain operating cases exactly. Therefore to choose a proper model for battery cell is a key part of the algorithm to estimate the charging time. Reference [3] and [4] introduce several equivalent circuit models for Li-ion battery. This section introduces different electrical equivalent circuits of battery cell and compares their advantages and disadvantages.

2.1.1. RC models

2.1.1.1. Zero order model

The simplest electrical equivalent circuit is the zero-order R circuit, as illustrated in the figure 2.1.

\[ U_{cell} = OCV + I \cdot R_1 \] (2.1)

The model includes one voltage source Open-Circuit Voltage (OCV) and a resistor. The OCV and the resistor both depends on State of Charge (SOC), current and temperature. The model is simple and therefore it is easy to implement and operate, which keeps the computational power of the simulation at a rather low level. However, this model doesn’t reflect the transient behavior of battery cell, in many cases, the model can’t meet the accuracy requirement of the simulation.

2.1.1.2. First order RC model

The first order RC model of battery cell is shown in figure 2.2.

![Figure 2.1 Zero-order electrical model for battery cell](image-url)
Figure 2.2 First-order electrical model for battery cell

The model has an additional RC component compared to the zero order equivalent circuit. The RC component consists of one resistor and one capacitor which are connected in parallel and the parameters still depend on SOC, current and temperature. This part is used to reflect the transient behavior of the battery cell. The first order RC model is widely applied due to its balance between the complexity and accuracy.

2.1.1.3. Second order RC model

The second order RC model of battery cell can be found in the figure 2.3.

Figure 2.3 Second-order electrical model for battery cell

Obviously, second order RC model has one extra RC component compared to the first order RC model. Again, all the parameters in the model depend on SOC, current and temperature. With the additional RC component, the second order RC model can achieve better accuracy in terms of describing the transient behavior of the cell but the computing power increases at the same time.

According to the requirement of accuracy of the model, the number of RC components added into the model can be increased even to infinity. However, as indicated above, the complexity of the model increases with the number of RC components. The model is always chosen based on the trade-off between accuracy and computing power.

2.1.2. ZARC element model

The figure 2.4 gives an illustration of ZARC (defined by reference [5], named after the fact that it is a circuit element representing depressed arcs in Z plane/impedance plane) element model.
Figure 2.4 Second-order electrical model for battery cell

![Diagram of a second-order electrical model for battery cell]

Figure 2.5 Nyquist plot of the complex impedance of a Kokam 40 Ah NMC cathode cell [1]

![Nyquist plot of the complex impedance of a Kokam 40 Ah NMC cathode cell]

ZARC element is a parallel circuit which consists of a resistor and a constant-phase-element (CPE), to describe a depressed semicircle. A CPE is characterized by a generalized capacity $A$ and depression factor $\xi$. The depression factor $\xi$ can be any value between 0 and 1, when it equals 0, the CPE is a pure resistor, while if it is 1, and the CPE is a pure capacitor. The formula 2.2 describes the characteristics of the CPE:
\[ Z_{FPE} = A \cdot (j\omega)^{-\xi} \]  

While the impedance of the ZARC element can be

\[ Z_{ZARC} = \frac{R \cdot A(j\omega)^{-\xi}}{R + A(j\omega)^{-\xi}} \quad \text{with} \quad 0 < \xi \leq 1 \]  

According to reference [1], figure 2.5 shows the impedance spectrum of the Kokam 40 Ah NM cathode battery cell and the equivalent model. While figure 2.7 from reference [6] shows the complex plane representation of a ZARC element with different CPE exponents. All impedances are normalized to the resistance R. As we can see, the depressed semicircle of the impedance spectra can be described by a ZARC element accurately. A linear line with a slope of 45°, which is related to the diffusion process, can be approximated by another ZARC element. Therefore, the ZARC element model is shown as in figure 2.5. According to reference [1], the impact of the inductance in figure 2.5, is really at a limited value on battery behavior, therefore, it can be neglected in the battery cell model.

Figure 2.7 Complex-plane representation of a ZARC element [6]

However, it is impossible to transfer the ZARC parameters without approximation from frequency domain to time domain. One commonly used way is to approximate ZARC with several numbers of RC element, as shown in figure 2.6. Theoretically, infinite numbers of RC elements are needed to reproduce ZARC element exactly. A tradeoff between accuracy and computation cost has to be made. According to the comparison made in reference [6], the error for 5 RC elements approximation is low enough to be acceptable.

In this thesis, since the focus is to simulate the charging process for the whole battery pack with cell balancing operations. The AC characteristics of the cells need to be taken into consideration to make an accurate simulation. Therefore the ZARC element model with 5 RC elements approximation from reference [1] is chosen to implement the cell characteristics.

2.1.3. Electrochemical models

Electrochemical model can work as an alternative to the electrical models introduced in the previous sections. It inherently include the dependency of battery performance on SOC and temperature. However, it is much more complex and cannot be easily implemented on-line.
2.2. Main variables in battery charging

2.2.1. SOC

2.2.1.1. SOC definition

SOC is short for state of charge, which is defined as the ratio between the remaining charge in the battery cell (or battery pack/module) and the nominal capacity of the battery cell (or battery pack/module).

\[
SOC = \frac{\text{current charge}}{\text{Nominal capacity}} \times 100\% \tag{2.4}
\]

In HEV/EV applications, the SOC serves as the fuel gauge, directly affecting the range of the vehicle and energy management strategy. However, unlike the fossil fuel for combustion engines, the SOC of battery cell cannot be measured directly by physical equipment. Instead, SOC is always estimated in variant ways, which differ in accuracy, computation cost and being adaptive or not. An accurate SOC estimation is obviously necessary, almost all the other main parameters of battery cell are the function of SOC, which will be explained in the coming sections. According to reference [7], from the simplest ampere-hour counting, methods with filter observer, such as Kalman filter (including extended Kalman filter), particle filter (including unscented particle filter) to complex algorithms like neutral network algorithm, numerous ways of estimating SOC are brought up.

2.2.1.2. Ampere-hour counting SOC estimation

The most simple way to estimate SOC of battery cell is ampere-hour counting. Ampere-hour counting calculates the time integration of current as the charge increase and updates the SOC based on this, as shown in formula 2.5.

\[
SOC = \frac{\text{initial SOC} + \int \text{current} \, dt}{\text{battery capacity}} \times 100\% \tag{2.5}
\]

An accurate ampere-hour counting estimation of SOC needs accurate and fast measurement of current and the knowledge of initial SOC and the battery capacity. This method is simple which lower the computation cost and can work quite accurately with Li-ion battery if the conditions of current measurement are met, since there are no significant side reactions during normal operations. However, after a long run, the measurement error will be accumulated to a significant level, which leads to inaccuracy. Therefore, additional calibration is required. In practice, ampere-hour counting method is only used in combination with OCV (open circuit voltage) based SOC estimation, which will be explained in Section 2.2.2.

In a word, ampere-hour counting method is a good way to estimate the SOC of Li-ion in EVs with the advantage of low computing cost. Therefore, in this thesis, only this method is utilized to estimate the SOC.
2.2.2. OCV

OCV is short for open circuit voltage. In practice, the OCV of the battery is often used to approximate the electromotive force of the battery, which represents the electric field force of the battery and describes the inner driving force when the battery is outputting electric energy. If the battery is rested for long enough time to wait for the balancing or polarization to finish, the OCV of the battery cell can be measured directly. With the knowledge of terminal voltage of the cell, the OCV can also be calculated from the equivalent circuit model, as explained in Section 2.1.

The OCV of a Li-ion battery, especially ones with manganese oxide cathode, has an almost linear relationship with SOC, and the relationship is independent of battery running conditions. The relationship of a new Kokam 40 Ah NMC Li-ion battery cell can be shown in figure 2.8. Therefore,

\[ U_p = U_{out} - U_R - OCV \]  

where \( U_{out} \) is the terminal voltage of battery cell, \( U_R \) is the voltage drop across the ohmic resistance. And \( R_1 \) is the charge transfer resistance, \( C_1 \) is the electric double-layer capacitance of the electrode interface, \( R_2 \) is the diffusion resistance of charge in the electrodes and the electrolyte and \( C_2 \) is the concentration diffusion capacitance. The values of polarization voltage during charging and discharging are more or less the same with little difference, but opposite signs at steady state. According to reference [8], figure 2.9 shows the change of ohmic resistance with SOC.

![Figure 2.8 OCV-SOC relationship of Kokam 40 Ah NMC Li-ion battery cell (new)](image-url)
As is shown, the ohmic resistance is rather small and the impact of its change with SOC on voltage is negligible. In addition, the OCV can be found according to SOC-OCV relationship when SOC is known. Therefore, the polarization voltage can be obtained when the terminal voltage is measured and the SOC is estimated. Experimental investigation on polarization voltage and the factors that can influence it can be conducted.

According to the time domain analysis of charging polarization conducted in reference [8], using the N-order RC model, the polarization voltage can be derived as

\[ U_p = U_p(0) + K_{SOC} \times K_I \times I \times (A_1 + A_2 + A_3 + \cdots + A_N) + B_{p0-} + B_{SOH} \] (2.7)

where \( U_p(0) \) is the initial polarization voltage in the beginning of the charging, \( K_{SOC} \) is the distortion factor of the initial SOC, \( K_I \) is the distortion factor of the charging current, \( I \) is the charging current, \( A_1, A_2, A_3 \ldots A_N \) are the polarization RC coefficients, i.e. \( R_1(1 - \exp(-t/R_1C_1)) \sim R_N(1 - \exp(-t/R_NC_N)) \), \( N \) is the order of RC models to approximate the polarization voltage, \( t \) is the time of charging, \( B_{p0-} \) is the distortion factor of the initial polarization state, \( B_{SOH} \) is the distortion factor of initial SOH (state of health, aging). As is shown in formula 2.7, the polarization voltage is influenced by many factors, such as current rate, initial battery state (aging, initial SOC, initial polarization), SOC, which makes the polarization voltage highly non-linear.

The impact of SOC and initial SOC on polarization voltage is investigated through the analysis in SOC domain, conducted in reference [8]. Figure 2.11 shows the SOC gradient characteristics of polarization voltage.
As is shown in figure 2.11, the SOC gradient of polarization voltage is significantly higher when SOC is low (< 3%), and it increases with the current rates. Based on the SOC gradient characteristics, using different current to charge battery till 3% of SOC, where the SOC gradient reaches the inflection point, the relationship between current rate and the amplitude of polarization voltage at inflection point is found in reference [8]. The relationship can be described with a linear function, with larger current, larger polarization voltage becomes.

The relationship of established polarization voltage with SOC is also found with different SOC state but same current rate in reference [8], shown in figure 2.12.

The polarization voltage is high when SOC is smaller than 10% or larger than 80%, it is at a much lower level when the SOC is in the range of 10% ~ 70%.

In order to avoid overvoltage and to fully charge all the battery cells in the pack, the charging current should be kept to a low level in the beginning and at the end of the charging process, while in the middle stage, the current should be as high as possible to shorten the charging time.

### 2.2.4. Initial SOC

Initial SOC is also one of the major parameters that affect the charging process. Obviously, different initial SOC lead to difference in remaining charging capacity. Besides, another main impact of initial SOC on charging is due to the impact on polarization voltage. Figure 2.13 from reference [8] shows the impact of different initial SOC on polarization voltage’s SOC gradient.
Significant difference occurs to the SOC gradient of polarization voltage due to different initial SOCs.

2.2.5. Aging factor

Aging will affect a lot in charging process. Reference [9] investigates in the capacity degradation and battery pack capacity deviation caused by aging. The investigation in reference [9] is based on 48 Sanyo/Pana-sonic UR18650E cylindrical cells with an average capacity of 1.85 Ah and 2.05 Ah of an A graded cell. Figure 2.14 shows the trend of impact from aging factor.

As is shown in figure 2.14, the maximum available capacity of the battery cell decreases dramatically with the increase of charging/discharging cycles. The deviation of the battery cells in the same battery pack increases as well.

Moreover, aging will also increase the internal impedance of the battery cell, which will affect the internal voltage drop. Figure 2.15 from reference [9] shows the impact of aging on polarization voltage.
The polarization voltage becomes bigger in a 100 cycle usage battery cell than that in a new battery with only 1 cycle of usage.

2.3. Charging theories

Charging profiles of current and other parameters have strong influence on battery performance and its life cycle. Many charging methods are brought up in reference [10] and [8], they vary in charging efficiency, charging time, impact on battery health as well as economic and computational cost. They range from simplest CCCV charging all the way to complex methods like multistage charging with ant colony algorithm.

2.3.1. CCCV charging method

CCCV is the most widely adopted method in practice, due to its simplicity and easy to implement. A constant current is applied to the battery in the first stage, when the voltage of the battery reaches a pre-set maximum voltage, the voltage will be kept as constant and the current will decrease exponentially, till the pre-set charging complete criteria is met. Figure 2.16 from reference [10] shows a typical current and voltage profile during CCCV charging.

The CCCV charging process is a combination of constant current charging and constant voltage charging. Therefore, it guarantees fast charging process when the battery can accept high current rate and limited battery polarization at the end of charging, which prevents damaging the battery cell.

A typical flow chart for CCCV charging method is shown in figure 2.17. It is critical to choose the right constant current and constant voltage value.
Figure 2.17 Typical flow chart of CCCV charging

If the voltage in the beginning of charging is smaller than a cutoff voltage, the battery will be charged in trickle charging mode, with a small current such as 0.1C, until the voltage reaches the
cutoff value. The constant current charging mode ends when voltage hits the preset value. The whole charging process is completed if the charging time reaches the maximum time or and current reduces to a preset level. In general, the lower constant current is, the longer the charging becomes, but also the better charging efficiency and life cycle it will achieve.

Further improvements can be done to CCCV charging method to prolong the lifecycle and the charging efficiency. According to reference [8], the criteria can be as follows.

a. Make the constant current value adaptable, according to the actual capacity and ambient temperature.

b. Add an adaptive pre-advancing transition into the constant voltage phase and reduce the constant voltage value. The pre-advancing is adaptive, according to the start conditions in the CV phase (polarization voltage and battery voltage).

2.3.2. Multistage current charging method

Multistage current charging (MSCC) method is an enhanced way of constant current charging. Instead of using one constant charging current like in CCCV, multistage current charging tries to find out the optimal charging current in each charging stage, to make the perfect balance between charging speed and charging efficiency. Figure 2.18 from reference [10] shows the typical charging current and voltage profiles of MSCC.

Figure 2.18 Current and voltage profiles of MSCC [10]

Obviously, the criteria to assign different charging stages and to set the current value for a corresponding stage are vital parts of MSCC. The charging stages can be divided according to voltages levels. While the appropriate current value for each stage can be found with many techniques like fuzzy logic controller. With different voltage stages, we can keep the charging currents as large as possible while not damaging the battery life span by adjusting the currents according to voltages stages.

Reference [11] gives a possible way to set the current values according to the polarization voltage in each stage, and set the largest acceptable current value as the charging current. Figure 2.19 shows the experimental current and voltage profiles.
In reference [11], the polarization acceptable charging current (PACC) is proposed on the basis of the polarization time factor: the CC charging time length is equal to the larger polarization time factor at a specified SOC point. If the external battery voltage exactly gets the preset cutoff voltage at the end of charging, then the charging current is the acceptable charging current value at this SOC point.

And the experiment in reference [11] shows the average charging rate of this method is between 0.5C CCCV charging and 1C CCCV charging, but with a benefit of lowest average polarization voltage.

2.4. Balancing methods

Battery pack of EVs has more than only one cell connected in parallel, in series or even in a mixed way to meet the voltage and power requirement of the high power electrical machines. However, due to manufacture processing variation and different working conditions, like temperature and voltage, the battery cells in a same battery pack are of different characteristics, which may cause problems during battery usage. To make matters worse, the inconsistency of battery cells will lead to difference in temperature and voltage among all the cells, which in turn will enlarge the inconsistency of characteristics.

The typical impact of battery cell inconsistency on charging can be explained with the simple example. A battery pack consists of 80 cells connected in series, which have inconsistency of characteristics, most importantly difference in capacity. If we charge the battery pack, the charging will stop when the cell with smallest capacity is fully charged. However, the rest cells are not fully charged. This leads to inefficient usage of battery pack capacity and damage to cells in a long run. Therefore, cell balancing method needs to be taken no matter the battery pack is being charged or discharged.

Reference [12] and [13] propose many balancing technologies for Li-ion battery cell. Depends on different ways to deal with the excess energy, the balancing topologies can be divided into three categories: releasing redundant energy, transferring energy between cells and controlling charging/discharging energy of individual cell.

Releasing redundant energy is to dissipate the energy of fuller cells to balance the energy in different cells. An auxiliary circuit consisting of a resistor and a switch connected in parallel to the
battery cell, as shown in figure 2.20. It is a simple but reliable way. However, its disadvantages are as obvious as the benefits: inefficient and can be only used for charging balancing.

![Diagram of battery cells and switches](image)

**Figure 2.20 Releasing redundant energy balancing topology**

There are two modes to operate the switches. The first way is to turn on all the switches during charging, therefore cell with higher voltage gets higher bleeding current through the shunt resistor and vice versa. In this way, with a proper resistance value, the slower cells can catch up with the faster cells after some time. The second mode needs voltage sensing and more complicated control of switches. As the switches are controlled according to preset voltage level. The faster cells dissipate more energy, so that the balancing can be done when slower cells catch up.

In this thesis, due to the implementation cost and equipment available, only the shunt resistor with controlled switch topology is implemented in the simulation.
Chapter 3 Matlab model implementation

3.1. Overview of the Matlab model for charging simulation

To estimate the charging time, the core part is to implement simulation of the whole charging process, with acceptable accuracy and computation cost. In this thesis, the battery pack being investigated consists of 32 series connected Kokam NMC Li-ion battery cells with a nominal capacity of 40Ah for each cell. A battery cell model, which is based on the ZARC equivalent circuit model introduced in Section 2.1.2, is brought up in reference [1] for this battery pack. Based on this battery cell model and system layout with most of the functionalities and parameters for base case (CCCV charging, voltage based balancing without advance) in Matlab/Simulink used for reference [1], the charging simulation models for several scenarios are implemented in this thesis. The simulation model consists of 4 major parts: charging controller, balancing logic, balancing circuit simulation and battery cell model. The layout of the simulation model is shown in Figure 3.1.

Figure 3.1 Simulation model layout [1]

The charging controller is the block which implements the charging algorithm and sets the current and voltage profiles during the charging process. It takes in the setting parameters like rated charging current and maximum cell voltage during charging process as well as the feedback signals like cell voltage from the battery cell model and the control signal from the balancing logic block. The charging controller outputs the charging current value along with other information such as number of cells, voltage limits and charging enable that the coming blocks need.

The balancing logic block comes after the charging controller. It is the block which defines the control logic for the switches in balancing circuits. The balancing logic block takes in the output signals from the controller as well as feedback signals from the battery pack model, such as information like cell voltage, SOC percentage and current cell capacity. The balancing logic block outputs the control signals for all the 32 switches connected in parallel to each cell, along with the information that the downstream blocks need such as charging current. The logic inside the block is designed using flow chart in Simulink.

The switch control signals are sent to balancing circuit block. The balancing circuit block uses a power electronic simulation toolbox for Simulink called PLECS to implement the shunt resistor.
and controlled switches in physical signal and circuits. The block takes in the controls signals of switches from the balancing logic block and the cell voltages from the battery pack block. It outputs the balancing current (bleeding) of each cell to the battery pack model for calculating the actual cell currents.

The last but the most important major block is the battery pack block from reference [1], where the calculation of equivalent circuit of the battery model and the relevant parameters are implemented. This block takes in the charging current value, balancing current values, and initial battery cell status information such as initial SOC, initial temperature and aging factor. It updates and outputs the cell voltages, SOC status, equivalent circuit parameters and power consumption of each cell.

Auxiliary blocks such as data storage and simulation stop are also implemented. The data storage block stores the parameters that characterize the charging process, such as SOC and voltage in the format of array into Matlab data files, which will be further needed when plotting the curves. The simulation stop is the block which defines the criteria of the end of charging, when the conditions are met, it stops the charging simulation.

### 3.2. Charging controller

The inputs and outputs of the charging controller block are explained in Section 3.1. However, the internal structure of the charging controller depends on the charging algorithm implemented.

#### 3.2.1. CCCV charging controller

CCCV charging is the most widely adopted method of charging. This thesis investigates the CCCV charging in the first place. Based on a PI controller, the CCCV charging controller can be implemented. The internal structure then is shown in Figure 3.2.

![Figure 3.2 CCCV charge controller](image)

The set value for constant voltage comes in No. 2 input port. While the feedback signal of cells voltages comes in No. 6 input port. The cell with the maximum voltage is picked out to control the charging process. The difference of these two voltages becomes the input of the discrete PI controller. The PI controller tries to find the current value according to the voltage difference. Due to the saturator followed, the maximum value of the current is limited to the set current value incoming through input port No. 1. In addition, a hysteresis controller is inserted to define the zero value zone.
of the current to prevent too frequent zero crossing. The switch is controlled by the stop signal coming from the balancing logic controller through No.7 input port. Only when the charging is not stopped, the current value can get through the switch then become the output.

3.2.1.1. PI controller parameterization for CCCV charging

The PI parameters of this thesis are chosen using a try and error approach. The criteria is as follows:

a. The charging current should rise to the set value as soon as possible in the beginning of charging;
b. The charging current should decrease at a proper speed when the voltage reaches the preset limit.

The following cases shows the impact of different PI settings on charging behavior. The first case is with proportional and integral parameter as 50 and 1 respectively. And the second one is with proportional and integral parameter as 1 and 10 respectively. And they are all charged with the scenario in Section 4.1.2, the cell voltages’ and cell currents’ behavior in the charging process are shown in figures below.

Figure 3.3 Voltage with time for charging with first PI settings
Figure 3.4 Voltage with time for charging with second PI settings

Figure 3.5 Cell current with time for charging with first PI settings
As it can be seen in the comparison of figure 3.3 to figure 3.6, for the first PI settings, the charging current is still at a high value when the largest cell voltage hits the target voltage, therefore it triggers stop charging criteria. However, when the charging current is set to 0, the cell voltage drops dramatically due to the lack of internal impedance involvement. Thus, the criteria for resuming charging is triggered after. This behavior happens in repeat, therefore it causes oscillation in cell voltage and cell current during charging process, as shown in figure 3.3 and figure 3.5 respectively. This may lead to damage to battery cells and has to be avoided. In the charging process in the second PI setting, the charging current is reduced at a proper speed when the largest cell voltage hits the target. Therefore the voltage overshot is limited, the charging stop criteria is not triggered. The cell voltage and cell current profiles become smooth. Additionally, due to the charging process is not interrupted, it takes less time to fully charge the battery pack, improved from 5.1 hour to 4.9 hour. Therefore, the second PI setting is adopted in this thesis.

### 3.2.1.2. Magnitude limiter and Hysteresis zero-crossing

As shown in Figure 3.2, the saturation dynamic block has three inputs. The first input and the third input set the upper and lower limit for the second input value respectively. As shown in the figure, the current value comes out of the PI controller is set in the range of 0 to the constant current value set by the No.1 input port.

![Figure 3.7 Implementation of hysteresis zero-crossing](image)

Figure 3.7 shows the implementation of the hysteresis zero-crossing. The current comes in and goes to the first port of the signal switch and to the block which gets the absolute value of the current. The absolute value of the current is sent to the hysteresis relay, whose parameters can be shown in
Figure 3.8

The signal switch outputs the signal coming to its first input port only when the condition of its second input is met, otherwise the output follows the signal coming to the third input port. Therefore the signal switch only outputs the current value when the hysteresis outputs 1 (when it is on). As a consequence, when the current changes from zero to positive value, the relay will turn on only when the absolute value of the current is larger than 0.05. Meanwhile, when the current falls from positive value to zero, the relay will turn off only after the current falls below 0.005, which leads to the output of the signal switch zero. In this way, we avoid the unnecessary oscillation and calculation when the current value is near zero but has a certain degree of fluctuation, and the model becomes more stable.

The voltage limits, total number of cells and charging enable signal are output along with the current value, since they may be needed in the control of the downstream blocks.

3.2.2. Improved CCCV charging controller

As explained in Section 2.2.3, the polarization voltage is relatively high in low end SOC and high end SOC. Therefore, the charging current should be kept at a relatively low level to limit the overvoltage to prevent the damage to the battery cell. Therefore, we have to introduce a pre charge stage in CCCV charging. Figure 3.9 shows the polarization voltage of all the cells in Kokam 40 Ah battery pack when they are charged with the charging scenario used in Section 4.3.1.
Figure 3.9 Polarization voltages in simulation result of Section 4.3.1

Figure 3.10 Polarization voltages against SOC in simulation result of Section 4.3.1

Figure 3.10 shows the polarization voltage against the SOC. As we can see in figure 3.10, when SOC is lower than 20%, the polarization voltage is significantly higher than the later charging stage. A preset voltage value needs to be chosen according to figure 2.8, which shows the relationship between SOC and OCV. This value can be 3.6 V, if the voltage is smaller than this value, the charging current is kept at 0.1C. The implementation is shown in figure 3.11.
Figure 3.11 Implementation of improved CCCV charging

Compared to the one introduced in Section 3.2.1, an additional switch is added after the charging stop switch. The second input of the switch is given by the comparison between the minimum cell voltage and the preset threshold 3.6 V. If the minimum cell voltage is lower than 3.6 V, the switch will output the pre-charging current, which is defined as 0.1C. The simulation result is shown and discussed in Section 4.5.

3.3. Balancing logic block

As it is explained in Section 3.1, the balancing logic block takes in the charging current, voltage and SOC of all the cells, while output the control signals for switches in balancing circuits, according to the balancing logic implemented via flow chart.

The balancing topology used in this thesis is the shunt resistor circuit with controlled switches to dissipate the energy in fuller cells. As is explained in Section 3.1, there are two modes to operate this topology: one is to turn on all the switches during charging, and the other is to control the switch according to preset conditions. However, in this thesis application, the bleeding current is only of an amplitude around 0.9A while the charging current can be as high as 40A. Therefore, turning on all the switches is not an effective approach to implement the balancing. Instead, in this thesis balancing switches are controlled according to certain conditions.

However, the conditions for the switch control, can be classified into several categories according to the control parameter and control time. In this thesis, the mainly investigated conditions are balancing based on terminal voltage, balancing based on SOC, balancing when the maximum voltage (SOC) is reached and balancing in advance to the moment of reach maximum voltage (SOC). Different combinations of these conditions make different balancing control logic.

3.3.1. Balancing based on terminal voltage without advance

Terminal voltage can be measured directly in practice, therefore this method is easy to implement. However, terminal voltage contains the polarization voltage and ohmic voltage drop, and doesn’t necessarily reflect the actual SOC status. Moreover, the terminal voltage changes significantly with the current.

The control logic of this method mainly depends on the balancing window, which is shown in Figure 3.12.
As shown in figure 3.12, the balancing window is defined as the voltage region lines in between the maximum allowed overshot voltage and the lower limit voltage. The balancing logic can be described as the following scenarios:

a. When the cell voltage hits the lower limit, the control switch of that cell is turned on to start its bleeding.

b. When the cell with largest voltage hits the maximum allowed overshot voltage, the charging will be stopped while let the bleeding process go on.

c. When the cell with largest voltage falls below the target voltage, charging is resumed.

d. When the voltages of all the cells are within the balancing window, the charging is done. All the switches are turned off and stop the charging.

The balancing logic is implemented via flow chart in Simulink, which is shown in figure 3.13.

3.13 Flow chart for balancing logic based on voltage

Table 3.1 shows the data type of all the parameters, including input variables, output variables and local variables.

<table>
<thead>
<tr>
<th>Name</th>
<th>Scope</th>
<th>Port</th>
<th>Datatype</th>
<th>Size</th>
<th>Initial value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Input</td>
<td>1</td>
<td>-1 (inherited)</td>
<td>Inherited from input</td>
<td>NA</td>
</tr>
<tr>
<td>Charging_enable</td>
<td>Input</td>
<td>2</td>
<td>-1 (inherited)</td>
<td>Inherited from input</td>
<td>NA</td>
</tr>
<tr>
<td>U_max_OCV</td>
<td>Input</td>
<td>3</td>
<td>-1 (inherited)</td>
<td>Inherited from input</td>
<td>NA</td>
</tr>
<tr>
<td>switch</td>
<td>Output</td>
<td>1</td>
<td>double</td>
<td>32</td>
<td>zero vector</td>
</tr>
<tr>
<td>i</td>
<td>Local</td>
<td>NA</td>
<td>double</td>
<td>1</td>
<td>NA</td>
</tr>
</tbody>
</table>
### Table 3.1 Variables of balancing logic flow chart

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Index_voltage_max</td>
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<td>NA</td>
</tr>
<tr>
<td>Local</td>
<td>Input</td>
<td>5</td>
</tr>
<tr>
<td>double</td>
<td></td>
<td>-1</td>
</tr>
<tr>
<td>Inherited from input</td>
<td></td>
<td>NA</td>
</tr>
<tr>
<td>Charging_stop</td>
<td>Output</td>
<td>2</td>
</tr>
<tr>
<td>double</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>NA</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Charging_stop</td>
<td>Output</td>
<td>NA</td>
</tr>
<tr>
<td>double</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>1</td>
</tr>
<tr>
<td>4.175</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overshot_allowed</td>
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<td>NA</td>
</tr>
<tr>
<td>double</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>4.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Index_voltage_min</td>
<td>Local</td>
<td>NA</td>
</tr>
<tr>
<td>double</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>Output</td>
<td>NA</td>
</tr>
<tr>
<td>double</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>Output</td>
<td>NA</td>
</tr>
<tr>
<td>double</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>NA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The algorithm flow is shown in figure 3.14.

**Figure 3.14 Algorithm flow for balancing logic based on terminal voltage without advance**

The algorithm first check if the charging is enabled or not, only when the charging is enabled.
the algorithm will go on. Then two functions are called to find the indexes for the cell with the largest and lowest voltage respectively. The flow chart of these two functions can be shown in figure 3.15 and figure 3.16 respectively.

Figure 3.15 Flow for finding the index of cell with largest voltage

If all the cell voltages are within the balancing window, that is, the largest cell voltage is smaller than the maximum allowed overshoot voltage and the lowest cell voltage is larger than the lower limit voltage, the charging stop will be triggered and the switches are turned off. If the charging is not done yet, the balancing function is called to control the switches of all the cells. The algorithm flow of balancing function can be shown in figure 3.17.

Figure 3.16 Flow for finding the index of cell with lowest voltage

Figure 3.17 Flow for balancing function
Then the algorithm will check if the charging is stopped. However, the charging can be stopped in two different conditions. One is when all the cell voltages are within the balancing window, while the other is when the largest cell voltage hits the maximum allowed overshoot voltage but not all the cell voltages are within the balancing window. If it is the first case, charging can’t be resumed, the algorithm will end. If it is the second case, the algorithm further checks if the largest cell voltage falls below the target voltage because of bleeding or not. Charging will only be resumed if the condition is met.

However, if the charging is not stopped, the algorithm will check if the largest cell voltage hits the maximum allowed voltage or not. If it hits the limit, charging will be stopped and the algorithm goes to end. Otherwise the algorithm goes to end directly.

The flow chart outputs the vector with 32 elements for the switch control signals and a one digit signal to stop the charging when the set conditions are met. Some of the input information may be needed in the control of downstream blocks, therefore, they are also output.

### 3.3.2. Balancing based on terminal voltage with advance

The main structure of the state flow chart in this method will be the same with the one introduced in Section 3.3.1, since the balancing window is still valid here to work as the criteria to define the end of charging. The changes will happen in the balance function. The algorithm flow of the balancing function is shown in figure 3.18.

![Figure 3.18 Flow for balancing function with advance](image)

As shown in the figure, the difference of the balancing function with the one introduced in Section 3.3.1, is that, the balancing switch is turned on when the voltage of the cell is larger than the minimum voltage of all the cells by a certain value (delta). And the switch is turned off when the condition is not met any more. Therefore, instead of starting the balancing when the maximum voltage of all cells enters the balancing window, the balancing is started whenever the voltage difference between the cell and the cell with minimum voltage becomes larger than a preset value.
In this way, the balancing starts much earlier than the case in 3.3.1. Of course, the parameters used in this algorithm is almost the same with the ones shown in table 3.1, with one more variable named voltage_delta, which defines the allowed difference between the cell voltage and the minimum cell voltage. Therefore the balancing may start in advance compared with the balancing logic in Section 3.3.1, especially when the aging status of all the cells differ a lot. Thus the charging behavior will be improved.

3.3.3. Balancing based on SOC (OCV)

Figure 3.19 shows the implementation of the balancing logic block based on SOC.

![Figure 3.19 Flow chart for balancing logic based on SOC](image)

Compared with figure 3.13, two additional inputs are added: capacities of cells and SOC of cells.

Table 3.2 shows the data type of all the parameters, including input variables, output variables and local variables.

<table>
<thead>
<tr>
<th>Name</th>
<th>Scope</th>
<th>Port</th>
<th>Datatype</th>
<th>Size</th>
<th>Initial value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Input</td>
<td>1</td>
<td>-1 (inherited)</td>
<td>Inherited from input</td>
<td>NA</td>
</tr>
<tr>
<td>Charging_enable</td>
<td>Input</td>
<td>2</td>
<td>-1 (inherited)</td>
<td>Inherited from input</td>
<td>NA</td>
</tr>
<tr>
<td>U_max_OCV</td>
<td>Input</td>
<td>3</td>
<td>-1 (inherited)</td>
<td>Inherited from input</td>
<td>NA</td>
</tr>
<tr>
<td>switch</td>
<td>Output</td>
<td>1</td>
<td>double</td>
<td>32</td>
<td>zero vector</td>
</tr>
<tr>
<td>i</td>
<td>Local</td>
<td>NA</td>
<td>double</td>
<td>1</td>
<td>NA</td>
</tr>
<tr>
<td>Capacity_Bat</td>
<td>Input</td>
<td>4</td>
<td>-1 (inherited)</td>
<td>Inherited from input</td>
<td>NA</td>
</tr>
<tr>
<td>Remaining_charge</td>
<td>Output</td>
<td>NA</td>
<td>double</td>
<td>32</td>
<td>NA</td>
</tr>
<tr>
<td>index_remainingcharge_max</td>
<td>Local</td>
<td>NA</td>
<td>double</td>
<td>1</td>
<td>NA</td>
</tr>
</tbody>
</table>
### Table 3.2 Variables of balancing logic based on SOC flow chart

Compared with variables in table 3.1, several extra variables are added:

a. Inputs: Capacity_Bat and SOC, which are the vector for cell capacity and cell SOC respectively

b. Function output: Remaining_charge, which is the vector for remaining charge of cells; m and n, which are the index for maximum remaining charge and minimum remaining charge respectively

c. Local variables: index_remainingcharge_min, index_remainingcharge_max which are the local variable for the index for minimum remaining charge and maximum remaining charge respectively; remaining_charge, which is the local vector for remaining charge of cells

The algorithm flow is similar with the one introduced in 3.3.1, since the balancing window is still valid here to work as the criteria to define the end of charging. Since the capacity and the SOC of all the cells are known, the remaining charge of each cell can be known from the formula 3.1:

\[
\text{remaining charge} = \text{Capacity} \cdot (1 - \frac{\text{SOC}}{100})
\]  

and this is implemented in function RemainingCharge. Two functions, index_remainingcharge_max and index_remainingcharge_min, are added to find the index of the cell with most remaining charge and the least remaining charge. These two function of course have similar structure with the function in figure 3.15 and figure 3.16. The balancing function will be different, since the balancing criteria is based on the remaining charge of each cell. The algorithm flow of the balancing function is shown in figure 3.20.

![Table 3.2 Variables of balancing logic based on SOC flow chart](image-url)
As shown in the figure, the balancing switch is turned on when the difference of remaining charge between one cell and the slowest charged cell is larger than a preset value. The switch is turned off when the condition is not met. Since all the cells are connected in series, they share the same charging current if the balancing is not activated. Thus, cells with same remaining charge will reach full capacity at the same time. Therefore, this method has a better accuracy than the previous introduced ones.

3.3.4. Balancing based on SOC (OCV) with PWM Driving

As it can be seen in the result for the switching behavior of SOC based balancing logic in Section 4.3, the bleeding switch of the fastest charging cell is turned on very early, which leads to a very long time of heat generation in the shunt resistor. This will increase the temperature stress of the resistor and the cell, causing damage or enlarging the aging status inconsistency. To alleviate the heat stress, a PWM signal can be applied to the switch when it is necessary, instead of a constant high state. The balancing logic block of the method will stay the same with the one introduced in Section 3.3.3, but the balancing circuit will be different. The difference is explained in Section 3.4.2. The PWM makes the average balancing current smaller, which leads to longer charging time, but with the benefit of lower heat stress.

3.4. Balancing circuit block

3.4.1. Balancing circuit for normal drive

The balancing circuit block is implemented with a power electronics simulation toolbox called PLECS. The PLECS circuit takes in the cell voltages from the battery pack block and the switch
control signals from the balancing logic block. The other input signals from the balancing logic block bypass the PLECS circuit for the usage in the downstream block. One of the 32 cell balancing circuits can be shown in figure 3.21. The PLECS circuit convert the voltage signals to physical voltage via a controlled voltage source, whose voltage goes through the MOSFET (drain to source). While the switch control signal goes to the gate of the MOSFET. The shunt resistor is connected in series with MOSFET and a current sensor. The current sensor converts the physical balancing current into balancing current signals. These balancing currents are the outputs of the PLECS circuit. A heat sink is also modeled to represent the behavior of the cooling pad used under MOSFET in practice. The heat sink is connected to a constant heat source, which makes the temperature stable at 25℃. D1 is the representation of the parasitic diode of the MOSFET, connected in parallel but opposite to the MOSFET.

![Figure 3.21 Cell balancing circuit example](image)

The value of the resistor is set to 50Ω, to make the maximum bleeding current as 0.9A. While the MOSFET has almost zero conducting impedance.

### 3.4.2. Balancing circuit for PWM drive

As explained in Section 3.3.4, for some balancing logic, PWM drive circuit is needed to alleviate the heat stress on shunt resistor and the cell. The implementation is shown in figure 3.22.

![Figure 3.22 Cell balancing circuit for PWM driving logic](image)

Compared with figure 3.21, the main circuit components and parameters are the same in figure 3.22. However, the drive circuit for MOSFET is much different as shown in the figure 3.22. When the balancing logic block decides to start balancing and set the input ‘switch’ signal high. The switch is triggered, and outputs the PWM driving signal from the pulse generator to the gate of the MOSFET. The PWM has a frequency of 8 Hz and 80% duty cycle, which makes each positive pulse 100 ms. Figure 3.23 shows part of the PWM driving signal of cell 16 in the charging scenario in Section 4.4.1.
3.5. Battery pack block

3.5.1. General layout

The battery pack model is based on the Simulink model of Kokam 40 Ah battery brought up in reference [1]. As explained in Section 2.1.2, this thesis utilizes the equivalent circuit model of an ohmic resistor and two ZARC elements, and each of the ZARC elements is approximated with 5 RC circuits. In practice, the battery pack of EVs consists of a lot of battery cells, and normally several battery cells are manufactured in one battery module, and a few battery modules make up a battery pack. Here in this thesis, the 32 battery cells are grouped into 4 battery modules, with 8 cells in each of the battery module. Figure 3.24 shows one of the 4 battery modules implemented in Simulink.

![Figure 3.24 Module 1 of the battery pack](image)

As is shown in figure 3.1, the model for the battery module takes in the current signals, including charging current and balancing current, from the upstream block. In addition, the module takes in the initial status, including initial SOC, aging factor, ambient temperature and initial cell
temperature. The input information is used to update the SOC first, and then update the OCV according to SOC-OCV relationship explained in Section 2.2.2. The equivalent circuit parameters: ohmic resistance, the resistance in the ZARC, the generalized capacity $A$ and the depression factor $\xi$. The voltage of the battery cell can be obtained by adding up the OCV, ohmic resistor voltage drop and the voltage across the ZARC element. Similarly, the power consumption of the battery cell can be obtained as well. Figure 3.25 shows the initial SOC block.

![Figure 3.25 Initial SOC block](image)

As is shown in figure 3.25, the initial SOC for 8 cells in the module is defined in 8 constant blocks, which get values from the initial.m file. The structure of the aging factor block and the initial temperature block is similar, with the difference that the temperature block has 16 constant blocks (8 for initial cell temperature and 8 for ambient temperature). The aging factor is defined as a value lying between 0 and 1, while 0 stands for brand new battery cell with a capacity of 42 Ah and 1 stands for totally aged battery cell with the capacity degrades down to 38 Ah.

![Figure 3.26 Part of the battery module (2 cells) [1]](image)

As shown in figure 3.26, the balancing current is added up with the charging current, due to the direction of the current sensor in PLECS circuit introduced in Section 3.4. The sum of the currents is the actual charging current of each cell, and it is sent to the cell model along with the initial status information to update the cell status.

Figure 3.27 shows the inside layout of the battery cell model from the Simulink model for reference [1].
As shown in Figure 3.27, the cell model consists of several look up tables and calculation blocks, including SOC/OCV updating block, ohmic resistance updating blocks, ZARC parameters updating blocks and thermal model block.

### 3.5.2. Aging factor

As explained in Section 3.5.1, the aging factors of battery cells are defined in constant blocks. While the battery cell has two sets of parameters, including capacity, look-up table for ohmic resistance, ZARC element parameter look-up tables, one set for new battery and one set for aged battery. As the change of the parameters with regard to aging process is assumed to be linear, the aging factor works as a weighing average factor for these two sets of parameters. For example, to calculate the capacity of the battery cell with certain aging factor, the formula can be:

\[
\text{capacity} = (1 - \text{aging factor}) \times \text{capacity}_{\text{new}} + \text{aging factor} \times \text{capacity}_{\text{aged}}
\]  

(3.2)

Similar formula can be applied to ohmic resistance and ZARC element parameters in the following form:

\[
\text{parameter} = (1 - \text{aging factor}) \times \text{parameter}_{\text{new}} + \text{aging factor} \times \text{parameter}_{\text{aged}}
\]

(3.3)

Therefore, when the aging factor is 0, the parameter equals the respective value in the new set, while when the aging factor is 1, the parameter equals the respective value in the old set.

### 3.5.3. Updating SOC and OCV

#### 3.5.3.1. SOC update

This thesis uses ampere hour counting method to update the SOC. The formula can be shown as follows.

\[
\text{SOC} = \frac{\int \text{I} \, dt}{\text{capacity}} + \text{Initial SOC}
\]

(3.4)

While capacity with the current aging status can be calculated from formula 3.2.
A block called CalcCapacity calculates the capacity under the current aging status with the method explained in Section 3.5.2. The current is divided by the capacity value and the ratio is converted into a percentage. The percentage value is sent to a discrete integrator with the second input port as the external initial condition source. And the gain of the integrator is set to one. Therefore, the output of the integrator is the updated SOC according to formula 3.4. The updated SOC is output to No.2 output port as well as the input of the pre-look-up table for OCV calculation.

3.5.3.2. OCV update

The updated SOC in percentage value is sent to the pre-look-up table, which output the position and interval that contains the input value. The pre-look-up table divide the axis for SOC into many intervals by inserting break points. All the integers between -10 to 100 are the break points involved in the pre-look-up table. In this way, the SOC value is converted to an integral value ranging from -10 to 100.

Then the integral SOC value is sent to two look-up tables, one stores the SOC-OCV relationship for new battery and the other stores the relationship for old battery. The two relationship can be shown in figure 3.28 and figure 3.29 respectively.

![Figure 3.28 SOC-OCV for new battery cell](image-url)
As is shown in the figures above, the OCV of the aged cell is slightly larger than the one of the new cell under same SOC condition. Again, the OCV of the battery cell is calculated according to formula 3.3 to reflect the impact of the aging process, which is implemented in CalcNewAged block. The final OCV value is output to No.1 output port.

3.5.4. Updating ohmic resistance

A block called PrelookUp_SOC_T in figure 3.27 works in a similar way with the pre-look-up table explained in Section 3.5.3.2. The block consists of two pre-look-up tables, one for SOC and the other for temperature. However, the break points in these look up tables are much less than the one used in pre-look-up table for SOC-OCV relationship, due to the fact that the equivalent circuit parameters are less sensitive to SOC and temperature. The SOC pre-look-up table has 7 break points: 10, 20, 30, 50, 70, 90 and 100. Therefore all the SOC values can only fall in 6 intervals. And the temperature pre-look-up table has 5 break points: -10, 0, 10, 25 and 40. Therefore, all the temperature values can only falls in 4 intervals. The interval where the input signal falls and its relative position in the table are the two outputs of the pre-look-up table. The outputs of the two pre-look-up tables are sent to one bus and the bus signal (look up data) is output to the output port of the block.

The look up data is sent to Calc_V_R0 block in figure 3.27, where the ohmic resistance, the voltage drop across it and the power consumption of it are updated.

The look-up data is used as the input of the two look-up tables for updating ohmic resistance. One of the two tables is for a new battery and the other is for an aged battery. Like in the blocks explained before, the two output of the tables are used to calculate the average resistance according to the aging factor. The updated resistance is then multiplied with current and the square of the current to update the voltage across the resistor and the power consumption respectively. The updated resistance, voltage and power consumption are the three outputs of the block.
3.5.5. ZARC related blocks

As shown in figure 3.27, the look-up data from PrelookUp_SOC_T block is also sent to two ZARC element blocks: Calc_V_R1 and Calc_V_R2. These two blocks update the parameters related to the two ZARC elements, including the resistance in the ZARC, the generalized capacity $A$, the depression factor $\xi$, the voltage across the ZARC and the power consumption of ZARC element. As the two blocks have exact the same structure, only Calc_V_R1 is explained in this section.

The look up data and aging factor are sent to blocks called calcR1, calcA1 and calcPhi1, which update the ZARC resistance, the generalized capacity $A$ and the depression factor $\xi$ respectively. These three blocks mainly consist of look up tables.

The calcR1 block follows the formula:

$$R = K_I(temperature, current) \cdot R(SOC, temperature)$$

(3.5)

where $K_I$ is the current factor for the resistance, which is the function of the temperature and current. The two look-up tables, calc_pnew_R1 and calc_paged_R1, are outputting the resistance according to SOC the temperature value. As explained before, the two blocks are for new and aged battery respectively, and then their output are sent to the block called calcNewAged to calculate the average value of $R(SOC, temperature)$ to reflect the aging impact. While the lower two look-up tables together with the pre-look-up table output the current factor $K_I$ according to temperature and current value. Again, the blocks called calc_pnew_KI and calc_paged_KI are for new and aged battery respectively, and then their output are sent to the block calcNewAged to calculate the average value of $KI(temperature, current)$. The outputs of the lower part and the upper part multiply with each other to find the final resistance $R$.

The structure of calcA1 and calcPhi1 are similar. In each of them there are two look-up tables output the parameter according to SOC and temperature value. Like in block calcR1, the two tables are for new and aged battery respectively, and then their output are sent to the block calcNewAged to calculate the average value of the parameter.

As is explained in Section 2.2.2, the ZARC element is approximated by a circuit consists of 5RC elements (denoted as A, B, C, D and E). According to reference [6], the parameters can be calculated with following formulas:

$$\omega_{ZARC} = \left( \frac{1}{R_A} \right)^{\frac{1}{2}}$$

(3.6)

$$R_C = f_1(\xi) \cdot R \cdot \frac{\sin \frac{\pi \xi}{2}}{1+\cos \frac{\pi \xi}{2}}$$

(3.7)

$$C_C = \frac{1}{\omega_{ZARC} R_C}$$

(3.8)

$$R_B = R_D = f_2(\xi) \cdot \left( \frac{R-R_C}{2} \right)$$

(3.9)

$$C_B = \frac{1}{\omega_{ZARC} f_3(\xi) R_B}$$

(3.10)

$$C_D = \frac{1}{\omega_{ZARC} f_3(\xi) R_D}$$

(3.11)

$$R_A = R_E = \frac{R-R_C-R_B-R_D}{2}$$

(3.12)
\[
C_A = \frac{1}{\omega_{ZARC}(f_2(\xi))^2 R_A}
\]
\[
C_E = \frac{1}{\omega_{ZARC}(f_2(\xi))^2 R_E}
\]

where R is the ZARC resistance, A is the generalized capacity and \(\xi\) is the depression factor; \(R_A\), \(R_B\), \(R_C\), \(R_D\) and \(R_E\) are the resistances in 5 RC components; \(C_A\), \(C_B\), \(C_C\), \(C_D\) and \(C_E\) are the capacities in the RC components; \(f_1(\xi)\), \(f_2(\xi)\) and \(f_3(\xi)\) are the optimization factors, which can be found in the table below according to reference [6].

<table>
<thead>
<tr>
<th>(\xi)</th>
<th>0.45</th>
<th>0.5</th>
<th>0.55</th>
<th>0.6</th>
<th>0.65</th>
<th>0.7</th>
<th>0.75</th>
<th>0.8</th>
<th>0.85</th>
<th>0.9</th>
<th>0.95</th>
<th>0.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_1(\xi))</td>
<td>0.939</td>
<td>0.906</td>
<td>0.891</td>
<td>0.869</td>
<td>0.850</td>
<td>0.837</td>
<td>0.831</td>
<td>0.833</td>
<td>0.847</td>
<td>0.876</td>
<td>0.923</td>
<td>0.998</td>
</tr>
<tr>
<td>(f_2(\xi))</td>
<td>0.641</td>
<td>0.670</td>
<td>0.708</td>
<td>0.733</td>
<td>0.754</td>
<td>0.772</td>
<td>0.788</td>
<td>0.804</td>
<td>0.819</td>
<td>0.835</td>
<td>0.850</td>
<td>0.863</td>
</tr>
</tbody>
</table>

Table 3.3 Optimization factors \(f_1(\xi)\), \(f_2(\xi)\) and \(f_3(\xi)\) for 5 RC circuit approximation [6]

For the approximation with five RC circuits, the characteristic frequency of the third semicircle (index C) is chosen the same as the characteristic frequency of the ZARC element. And the resistances are symmetrical (B equals D, A equals E), and the boundary condition

\[
R = R_A + R_B + R_C + R_D + R_E
\]

is met.

A block called calcRC_param, implements these formulas and look-up tables to convert the ZARC into 5 RC (A… E) circuits.

The block outputs the parameters: \(R_A\), \(R_B\), \(R_C\), \(R_D\), \(R_E\) and \(C_A\), \(C_B\), \(C_C\), \(C_D\), \(C_E\).

Blocks named RC1 to RC5, calculate the voltage across the RC components, the power consumption and the current flows through the resistor. The governing equations are

\[
U = \frac{\int I_C dt}{C}
\]
\[
P = I_R^2 \cdot R
\]
\[
I_R = I_R - I_C
\]

Pay attention that a lower limit for capacity is set as \(4 \cdot \frac{\text{SimDT}/10}{R}\) when calculating the voltage across the RC components. This is to make sure that the time constant of the RC component is at least 4 times larger than the simulation sampling time \(\frac{\text{SimDT}}{10}\).

### 3.5.6. Thermal model

The thermal model of the battery cell follows the following equation

\[
\text{cell temperature} = \text{Initial temperature} + \frac{1}{C} \int \left(\frac{dQ}{dt} \text{ heat dissipation rate}\right) dt
\]

where C is the heat capacitance of the battery pack, Q is the heat generated in the battery cell. The heat dissipation rate can be obtained from the difference between cell temperature and the ambient temperature.
3.6. Auxiliary blocks

The main auxiliary blocks in figure 3.1 are the data storage block and the simulation stop block. The data storage block stores the SOC, current and voltage of each cell into .m files to save RAM when the simulation is running. While, the simulation stop block defines the criteria to stop the charging simulation. The criteria are different for different balancing logics. For terminal voltage based balancing method, the criteria is as follows:

a. The charging current is zero;
b. All the switches in balancing circuits are off;
c. The minimum terminal voltage of all the cells are larger than 4.175 V.

While for SOC (OCV) based balancing logic, the criteria is as follows:

a. The charging current is zero;
b. All the switches in balancing circuits are off;
c. The minimum SOC of all the cells are larger than 99.5%.

The simulation stops when all these three conditions are met.
Chapter 4 Simulation scenarios and the simulation results

As is explained in chapter 3, combinations of different charging methods and balancing logic make different charging simulation scenarios. This chapter talks about the simulation results and the analysis of them for all the simulation scenarios.

Each scenario is simulated with several different settings, varying with aging factor and initial SOC. As explained in Section 2.2.4 and 2.2.5, the initial SOC has impact on equivalent circuit parameters as well as the charging process. The impact is investigated in the simulation with different settings.

Reference [9] investigates the production caused capacity deviation of battery pack. According to reference [9], a brand new battery with 48 cells, whose average capacity per cell is 1.8 Ah, has a maximum capacity deviation of 0.03 Ah from the average capacity, which takes up 1.67% of the average capacity. In this thesis, we assume that the brand new Kokam 40 Ah battery pack has the same ratio of production-caused capacity deviation with the one in reference [9], which is 1.67% of the average capacity. Therefore the aging factor setting table is shown as in table 4.1.

<table>
<thead>
<tr>
<th>No. of cell</th>
<th>Aging factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.333</td>
</tr>
<tr>
<td>2</td>
<td>0.341</td>
</tr>
<tr>
<td>3</td>
<td>0.353</td>
</tr>
<tr>
<td>4</td>
<td>0.362</td>
</tr>
<tr>
<td>5</td>
<td>0.372</td>
</tr>
<tr>
<td>6</td>
<td>0.383</td>
</tr>
<tr>
<td>7</td>
<td>0.391</td>
</tr>
<tr>
<td>8</td>
<td>0.401</td>
</tr>
<tr>
<td>9</td>
<td>0.413</td>
</tr>
<tr>
<td>10</td>
<td>0.422</td>
</tr>
<tr>
<td>11</td>
<td>0.430</td>
</tr>
<tr>
<td>12</td>
<td>0.443</td>
</tr>
<tr>
<td>13</td>
<td>0.455</td>
</tr>
<tr>
<td>14</td>
<td>0.467</td>
</tr>
<tr>
<td>15</td>
<td>0.472</td>
</tr>
<tr>
<td>16</td>
<td>0.513</td>
</tr>
<tr>
<td>17</td>
<td>0.501</td>
</tr>
<tr>
<td>18</td>
<td>0.511</td>
</tr>
<tr>
<td>19</td>
<td>0.522</td>
</tr>
<tr>
<td>20</td>
<td>0.535</td>
</tr>
<tr>
<td>21</td>
<td>0.540</td>
</tr>
<tr>
<td>22</td>
<td>0.553</td>
</tr>
<tr>
<td>23</td>
<td>0.531</td>
</tr>
<tr>
<td>24</td>
<td>0.562</td>
</tr>
<tr>
<td>25</td>
<td>0.571</td>
</tr>
<tr>
<td>26</td>
<td>0.583</td>
</tr>
</tbody>
</table>
For a fully aged battery pack, the maximum capacity deviation from the average capacity is 2 Ah (5%), according to the definition of end of life for the Kokam 40 Ah NMC battery. To investigate the impact of aging on battery cell behavior, the 32 cells are set to different aging status, ranging from brand new to totally aged. Therefore the aging factors of the 32 cells are set as a 32 digit vector starts with 0 and ends with 1. Table 4.2 shows the aging factor settings.

<table>
<thead>
<tr>
<th>No. of cell</th>
<th>Aging factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.01</td>
</tr>
<tr>
<td>3</td>
<td>0.08</td>
</tr>
<tr>
<td>4</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>0.13</td>
</tr>
<tr>
<td>6</td>
<td>0.18</td>
</tr>
<tr>
<td>7</td>
<td>0.21</td>
</tr>
<tr>
<td>8</td>
<td>0.34</td>
</tr>
<tr>
<td>9</td>
<td>0.26</td>
</tr>
<tr>
<td>10</td>
<td>0.31</td>
</tr>
<tr>
<td>11</td>
<td>0.359</td>
</tr>
<tr>
<td>12</td>
<td>0.41</td>
</tr>
<tr>
<td>13</td>
<td>0.425</td>
</tr>
<tr>
<td>14</td>
<td>0.467</td>
</tr>
<tr>
<td>15</td>
<td>0.47</td>
</tr>
<tr>
<td>16</td>
<td>0.51</td>
</tr>
<tr>
<td>17</td>
<td>0.50</td>
</tr>
<tr>
<td>18</td>
<td>0.52</td>
</tr>
<tr>
<td>19</td>
<td>0.53</td>
</tr>
<tr>
<td>20</td>
<td>0.54</td>
</tr>
<tr>
<td>21</td>
<td>0.61</td>
</tr>
<tr>
<td>22</td>
<td>0.68</td>
</tr>
<tr>
<td>23</td>
<td>0.69</td>
</tr>
<tr>
<td>24</td>
<td>0.78</td>
</tr>
<tr>
<td>25</td>
<td>0.75</td>
</tr>
<tr>
<td>26</td>
<td>0.82</td>
</tr>
<tr>
<td>27</td>
<td>0.88</td>
</tr>
<tr>
<td>28</td>
<td>0.91</td>
</tr>
<tr>
<td>29</td>
<td>0.84</td>
</tr>
<tr>
<td>30</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Table 4.2 Aging factors for different aging status of battery cells to investigate impact of aging

The charging current, if not specified, is set to 1C, that is 40 A. Only in Section 4.7 where the impact of charging current on charging behavior is investigated, the applied currents are different.

4.1. CCCV charging and balancing based on terminal voltage without advance

4.1.1. Simulation with new battery cell and zero initial SOC

The charging uses 1C current rate to a new battery pack, whose capacity aging factors are displayed in table 4.1. All the cells are with 0 initial SOC. The balancing method is based on terminal voltage, which is described in 3.3.1. Figure 4.1 to figure 4.4 show the charging behavior of this scenario.

Figure 4.1 SOC with time for charging scenario in Section 4.1.1
Figure 4.2 Voltage with time for charging scenario in Section 4.1.1

Figure 4.3 Cell currents with time for charging scenario in Section 4.1.1
As is shown in the figures above, most part of the SOC is charged within one hour. However, as the highest cell voltage approaches the target value, the charging current drops very fast as shown in figure 4.3. The balancing starts after around 0.7h when the highest cell voltage hits the target value. The inconsistency of SOC and cell voltage among all the cells are improved in the rest part of charging. The whole charging is done in 2.1h. Table 4.3 shows part of the parameters when the charging is done.

### 4.1.2. Simulation with different aging status of battery cells and zero initial SOC

The charging uses 1C current rate to an old battery pack, whose capacity aging factors are displayed in table 4.2. All the cells are with 0 initial SOC. The balancing method is based on terminal voltage, which is described in 3.3.1. Figure 4.5 to figure 4.8 show the charging behavior of this scenario.
Figure 4.5 SOC with time for charging scenario in Section 4.1.2

Figure 4.6 Voltage with time for charging scenario in Section 4.1.2
Compared to 2.1h of charging time in scenario 4.1.1, the charging of aged battery takes much longer than the new one, ending up with 5.22h. This is because the capacity deviation between the cells is much larger. When the fastest cell reaches the target voltage around 0.7h, the slowest cell still has a relatively low SOC, as is shown in figure 4.5. This part can only be charged with small current value and the balancing process also takes longer, with larger capacity deviation among cells. The balancing is also starting from 0.7h, after when the inconsistency of cells becomes smaller.

Table 4.4 shows part of the parameters in the end of charging. As is shown in the table, the SOC
deviation in this scenario is larger than the one in 4.1.1.

4.2. CCCV charging and balancing based on terminal voltage with advance

4.2.1. Simulation with new battery cell and zero initial SOC

The charging uses 1C current rate to a new battery pack, whose capacity aging factors are displayed in table 4.1. All the cells are with 0 initial SOC. The balancing method is also based on terminal voltage but with advance compared to the one used in 4.1, which is described in 3.3.2. Figure 4.9 to figure 4.12 show the charging behavior of this scenario.

![Figure 4.9 SOC with time for charging scenario in Section 4.2.1](image1)

![Figure 4.10 Voltage with time for charging scenario in Section 4.2.1](image2)
Compared with results in 4.1.1, the balancing process starts in the right beginning of charging in this scenario, while the balancing starts at 0.7h in scenario 4.1.1. However, as the battery is new, the capacity deviation is small, the balancing in both 4.1.1 scenario and this scenario are completed quite well. As is shown in figure 4.12, the balancing is completed at 1.5 h, about 0.7h in advance compared with the scenario 4.1.1. Therefore, the charging time of this scenario doesn’t improve compared with the result in 4.1.1. Table 4.5 shows part of the data in the end of charging.
4.2.2. Simulation with different aging status of battery cells and zero initial SOC

The charging uses 1C current rate to an old battery pack, whose capacity aging factors are displayed in Table 4.2. All the cells are with 0 initial SOC. The balancing method is based on terminal voltage, which is described in 3.3.2. Figure 4.13 to figure 4.16 show the charging behavior of this scenario.

Figure 4.13 SOC with time for charging scenario in Section 4.2.2

Figure 4.14 Voltage with time for charging scenario in Section 4.2.2
Like in scenario 4.2.1, the balancing in this scenario starts also from the right beginning of the charging process. However, since the capacity deviation is much larger in old battery pack, the charging time is improved a lot compared to scenario 4.1.2, from 5.22 h to 4.82 h. Table 4.6 shows part of the parameters in the end of the charging. As is shown, the SOC inconsistency is smaller than the one in scenario 4.1.2.

<table>
<thead>
<tr>
<th></th>
<th>Fullest cell</th>
<th>Slowest cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC</td>
<td>100.3%</td>
<td>99.51%</td>
</tr>
<tr>
<td>Voltage</td>
<td>4.19</td>
<td>4.175</td>
</tr>
<tr>
<td>Charging time</td>
<td>4.82h</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6 Simulation data at the end of charging for charging scenario in Section 4.2.2
4.3 CCCV charging and balancing based on SOC (OCV)

4.3.1 Simulation with new battery cell and zero initial SOC

The charging uses 1C current rate to a new battery pack, whose capacity aging factors are displayed in table 4.1. All the cells are with 0 initial SOC. The balancing method is based on SOC, which is described in 3.3.3. Figure 4.17 to figure 4.20 show the charging behavior of this scenario.

![Figure 4.17 SOC with time for charging scenario in Section 4.3.1](image)

![Figure 4.18 Voltage with time for charging scenario in Section 4.3.1](image)
As is shown in figures above, the charging time is improved to 1.825 h. As the same with the scenario in 4.2, the balancing starts in the beginning of charging. However, with the accurate knowledge of cell SOC, the decision of balancing time can be more accurate without the influence of current compared to the balancing method based on terminal voltage. Therefore, the charging time is further improved. Part of the data in the end of charging is shown in table 4.7, the inconsistency of cell SOC is smaller than the ones in scenario 4.1 and 4.2.
4.3.2. Simulation with different aging status of battery cells and zero initial SOC

The charging uses 1C current rate to an old battery pack, whose capacity aging factors are displayed in table 4.2. All the cells are with 0 initial SOC. The balancing method is based on SOC, which is described in 3.3.3. Figure 4.21 to figure 4.24 show the charging behavior of this scenario.
Figure 4.23 Cell current with time for charging scenario in Section 4.3.2

Figure 4.24 Switches behavior with time for charging scenario in Section 4.3.2

<table>
<thead>
<tr>
<th></th>
<th>Fullest cell</th>
<th>Slowest cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC</td>
<td>100.1%</td>
<td>99.5%</td>
</tr>
<tr>
<td>Voltage</td>
<td>4.19</td>
<td>4.177</td>
</tr>
<tr>
<td>Charging time</td>
<td>4.535h</td>
<td></td>
</tr>
<tr>
<td>Maximum heat generated</td>
<td>55.9 kJ</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.8 Simulation data at the end of charging for charging scenario in Section 4.3.2

The charging time is further improved to 4.535 h, compared to 4.82 h in scenario 4.2.2. The balancing starts also in the beginning of charging. Table 4.8 shows part of the data in the end of charging. The inconsistency of cell SOCs is smaller than the case in scenario 4.2.2.
4.4. CCCV charging and balancing based on SOC (OCV) with PWM driving

4.4.1. Simulation with new battery cell and zero initial SOC

The charging uses 1C current rate to a new battery pack, whose capacity aging factors are displayed in table 4.1. All the cells are with 0 initial SOC. The balancing method is based on SOC, which is described in 3.3.4. The purpose of this method is to reduce the heat stress on the shunt resistor of the balancing circuit in scenario 4.3. Figure 7.1 to figure 7.4 in the Appendix show the charging behavior of this scenario.

<table>
<thead>
<tr>
<th></th>
<th>Fullest cell</th>
<th>Slowest cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC</td>
<td>99.7%</td>
<td>99.5%</td>
</tr>
<tr>
<td>Voltage</td>
<td>4.19</td>
<td>4.183</td>
</tr>
<tr>
<td>Charging time</td>
<td>1.93h</td>
<td>1.93h</td>
</tr>
<tr>
<td>Maximum heat generated</td>
<td>18.25kJ</td>
<td>18.25kJ</td>
</tr>
</tbody>
</table>
Table 4.9 Simulation data at the end of charging for the scenario in Section 4.4.1

The balancing logic in this scenario is the same as the one in scenario 4.3. As explained in Section 3.4.2, the balancing switch of this scenario is driven by a PWM (80% duty cycle) signal instead of a constant high level signal in other scenarios to reduce the heat stress on the shunt resistors in the balancing circuits. Figure 4.26 shows the heat generated by the shunt resistors in scenario 4.3.1. Compare figure 4.25 with figure 4.26, the maximum heat generated from all the shunt resistors is reduced from 18.8 kJ to 18.25kJ. However, with a lower average balancing current, the instant power of the heat generation on the shunt resistor is 64% of the one in scenario 4.3.1, which may make the cooling for the balancing circuit easier and cheaper to implement. However, the cost for this improvement is a longer charging time. Table 4.9 shows part of the simulation data at the end of charging.

4.4.2. Simulation with different aging status of battery cells and zero initial SOC

The charging uses 1C current rate to an old battery pack, whose capacity aging factors are displayed in table 4.2. All the cells are with 0 initial SOC. The balancing method is based on SOC, which is described in 3.3.4. The purpose of this method is to reduce the heat stress on the shunt resistor of the balancing circuit in scenario 4.3. Figure 7.5 to figure 7.8 show the charging behavior of this scenario.

Figure 4.27 Heat generated by balancing resistor for the scenario in Section 4.4.2
As explained in 4.4.1, the balancing method is the same with the one in 4.3 and 4.4.1. Compared to the charging time of about 4.5h in Section 4.3.2, the charging time increases to 5.532h. However, as explained in 4.4.1, the power stress of heat generation on the shunt resistors is reduced. Figure 4.27 shows the heat generated by the shunt resistors in the current scenario while figure 4.28 shows the heat generated in Section 4.3.2. Table 4.10 shows part of the simulation data at the end of charging.

### Table 4.10 Simulation data at the end of charging for the scenario in Section 4.3.2

<table>
<thead>
<tr>
<th>SOC</th>
<th>Fullest cell</th>
<th>Slowest cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>100.3%</td>
<td>99.5%</td>
</tr>
<tr>
<td>Charging time</td>
<td>4.19</td>
<td>4.176</td>
</tr>
<tr>
<td>Maximum heat generated</td>
<td>54kJ</td>
<td></td>
</tr>
</tbody>
</table>

**4.5. Improved CCCV charging and balancing based on SOC (OCV)**

As explained in 2.2.3, the polarization of Li-ion battery is of significantly amplitude in the beginning (low SOC) and the end (high SOC) of charging. Therefore, a large charging current in the beginning of charging when the battery is charged from zero initial SOC, may cause very high polarization voltage, which will lead damage to battery cell. Figure 4.29 shows the polarization voltage over time in the simulation of Section 4.3.1. Figure 4.30 shows the polarization voltage over SOC in the simulation of Section 4.3.1. As is shown in the figures, the polarization voltage has two peaks, which appear at the time of 0.1 h (10% SOC) and 0.8 h (80% SOC) respectively. A pre-charge state described in Section 3.2.2 is introduced to CCCV charging to reduce the polarization in the beginning of charging. The rest charging condition is kept the same with the simulation of Section 4.3.1. Figure 7.9 to figure 7.11 in the appendix show the results of this scenario.
Figure 4.29 Polarization voltage with time for scenario in Section 4.3.1

Figure 4.30 Polarization voltage with SOC for scenario in Section 4.3.1
Figure 31 Polarization voltage with time for scenario in Section 4.5

Figure 4.32 Polarization voltage with SOC for scenario in Section 4.5

The charging time increases to 3.6 h compared to 1.825 h in the scenario of Section 4.3.1, due to the small charging rate (0.1C) in the pre charge state. However, as shown in figure 4.31 and figure 4.32, the polarization in the beginning of charging is significantly reduced compared to the profile in figure 4.29 and figure 4.30. There is still a peak of polarization voltage at the end of charging (80% SOC), which can be reduced by entering the constant voltage phase in advance. This charging method can be used when the time for charging is abundant to prolong the battery life.

4.6. Impact of different initial SOCs on charging behavior

Most of the charging conditions including balancing logic are kept the same with the simulation in Section 4.1.1. Only different initial SOCs (10%, 40% and 80%) values are applied. Figure 7.12 to figure 7.20 in the appendix show the results of SOC, voltage and cell current of the simulations.

Figure 4.33 Polarization voltage with time of 10% initial SOC for scenario in Section 4.6
Special attention should be paid to the polarization voltage. Compared to the scenario in 4.1.1, the charging with 40% and 80% of initial SOC only have one peak for polarization voltage. The reason for this is explained in Section 2.2.3. The charging with 10% initial SOC still has two peaks for polarization voltage, however, the peak value is significantly smaller than the one in Section 4.1.1. The peak values for polarization voltage in the scenarios with 40% and 80% initial SOC are also smaller than the relevant value in 4.1.1. A conclusion can be drew that the higher the initial
SOC is, the smaller of the peak polarization voltage will become. Table 4.11 shows part of the data at the end of charging for each scenario. The charging time decreases with initial SOC value. However, the battery cells becomes less fully charged as the initial SOC becomes higher. This is most likely because the time for balancing becomes shorter.

4.7. Impact of different charging currents on charging behavior

Most of the charging conditions including balancing logic are kept the same with the simulation in Section 4.1.1. Only different charging rates (0.5C and 2C) are applied. Figure 7.21 to figure 7.26 in the appendix show the results of SOC, voltage and cell current of the simulations.

<table>
<thead>
<tr>
<th></th>
<th>0.5C</th>
<th>2C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fullest cell</td>
<td>Slowest cell</td>
<td>Fullest cell</td>
</tr>
</tbody>
</table>

Figure 4.36 Polarization voltage when charging with 2C for the scenario in Section 4.7

Figure 4.37 Polarization voltage when charging with 0.5C for the scenario in Section 4.7
Table 4.12 Simulation data at the end of charging for the scenario in Section 4.7

Compared to the scenario in 4.1.1, the polarization voltage peak values are much higher in the scenario with 2C charging current, and are much less in the scenario with 0.5C. Table 4.12 shows the data at the end of charging for each scenario. The charging time of 2C (1.62 h) is slightly shorter than the one in Section 4.1.1 (2.1 h), however, the time of 0.5C becomes much longer. The cells are less fully charged and of bigger voltage and SOC deviation as the charging rate becomes higher. This is due to higher polarization in the scenario of high charging rate.

<table>
<thead>
<tr>
<th>SOC</th>
<th>99.96%</th>
<th>99%</th>
<th>99.84%</th>
<th>98.87%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>4.188</td>
<td>4.175</td>
<td>4.192</td>
<td>4.176</td>
</tr>
<tr>
<td>Charging time</td>
<td>2.995h</td>
<td></td>
<td></td>
<td>1.62h</td>
</tr>
</tbody>
</table>

4.8. Conclusion

In this thesis, three balancing logic, voltage based balancing (without advance), advanced voltage based balancing and SOC based balancing, are investigated. SOC based balancing has the advantage of shorter charging time and smaller deviation after charging, compared to voltage based balancing logic. Advanced voltage balancing has a shorter charging time than regular voltage balancing logic. However, attention should be paid that the accurate knowledge of SOC is difficult to acquire, complex algorithms need to be implemented, which will increase the economic and computational cost. Improvements of the standard SOC based balancing charging method, SOC balancing with PWM drive and improved CCCV charging controller, are investigated. The magnitude of improvement and the cost of charging time is obtained from the simulation, which might be useful to weigh the gain and loss of these improvements. Furthermore, the impact of initial SOC, charging rate and aging factor on charging behavior are investigated. Higher initial SOC leads to lower polarization, while higher charging rate does the opposite. The aging factor has huge impact on charging behavior. The larger the cell characteristics deviation, the longer the charging time and higher balancing loss. The more aged cell has smaller capacity, thus smaller charging time, but with higher polarization and longer balancing time. In addition, due to shorter charging time of aged cell, the charging controller has to reduce the charging rate very early to fully charge the relatively newer cells, which leads to a much longer total charging time.
Chapter 5 Hardware-in-the-loop validation of the simulation results

5.1. HIL system

The simulation needs to be validated in real case. However, since real battery test has relatively high economic and time expense, especially when aging process of the battery is involved, a real-time hardware-in-the-loop simulation is conducted instead. Moreover, compared to real battery test, HIL simulation can have more detailed control of parameters due to the fact that some parameters can’t be measured in real case. Therefore the simulation results in chapter 4 is validated in HIL simulation. The used HIL simulator is brought up in reference [1]. Figure 5.1 shows the layout of the HIL simulation system.

Figure 5.1 HIL simulator system layout [14]

According to reference [14], the system consists of 3 blocks: the host PC, HIL simulator and the commercial BMS. The host PC builds the offline Matlab/Simulink model and uses the code generation function of Matlab and download the code into the DSP in HIL simulator. The DSP runs the online battery simulation and behaves the core of the HIL simulator. The HIL simulator also has 8 hardware boards which emulates the voltage behavior of the battery cells with each board emulating 4 cells. The commercial BMS is a master-slave system. The slaves are the local monitoring units (LMU) which get the measurement data from the boards in HIL simulator and communicate with the master BMCU (battery management control unit). The accuracy of the HIL system is validated in reference [14], which shows that the system is highly reliable and accurate. Figure 5.2 and figure 5.3 show the validation of the HIL system in reference [14]. Therefore the HIL system can be relied on to validate simulation results in chapter 4. In this thesis, only the host PC and HIL simulator is used in the validation of the simulations in chapter 4, while the BMCU and LMUs are not connected. The Matlab/Simulink model, which contains the same charging controller and balancing logic controller with the relevant ones used in chapter 4, is built in the host PC. However, the balancing circuit block in the model is not implemented in PLECS anymore. Instead, the balancing current is calculated based on the knowledge of balancing switch signal and cell terminal voltage. The charging current of the cells are deducted by the value of the relevant balancing current. In this way, the balancing behavior is numerically the same with the ones in
chapter 4. The Matlab/Simulink model is then generated into C code by Matlab code generation function. The code is downloaded into the DSP in the HIL simulator, which runs the simulation for validating the scenarios in chapter 4.

Part of the validation results are given in Section 5.2. The charging condition for these scenarios is that the 32 cells are of different aging factor and are charged with 1C from zero initial SOC.

![Electro-thermal battery model validation between measurement data and model simulation](image1)

**Figure 5.2** Electro-thermal battery model validation between measurement data and model simulation [14]

![HIL battery cell emulation using dynamic driving cycle](image2)

**Figure 5.3** HIL battery cell emulation using dynamic driving cycle [14]

5.2. HIL validation results

5.2.1. HIL simulation for CCCV charging and balancing based on terminal voltage without advance

Figure 5.4 to figure 5.6 show the HIL simulation results for the charging condition in Section 4.1.2. Compared to the charging time of 5.22 h in Section 4.1.2, the charging time of the HIL simulation is slightly longer and of 5.614 h. As explained in 5.1, the result from HIL simulation has really high accuracy and can be regarded as real value. The relative error of charging time estimation can be defined as

$$\text{Relative error} = \frac{\text{Charging time in HIL} - \text{Simulated charging time}}{\text{Charging time in HIL}} \times 100\% \quad (5.1)$$

The relative error of the charging time estimation in this scenario is 7.02%, which shows the charging time estimation is of relatively high accuracy. Figure 5.6 shows the temperature profiles of the first 16 cells. The profiles share the same shape with the polarization voltage in figure 4.29, which indicates that the heat generation of the battery cell is related to the polarization and the more aged cell, the more heat generated during charging.
Figure 5.4 SOC with time of the validation for simulation in Section 4.1.2

Figure 5.5 Voltage with time of the validation for simulation in Section 4.1.2
5.2.2. HIL simulation for CCCV charging and balancing based on terminal voltage with advance

Figure 5.7 to figure 5.9 show the HIL simulation results for the charging condition in Section 4.2.2. Compared to the charging time of 4.82 h in Section 4.2.2, the charging time of the HIL simulation is slightly longer and of 5.11 h. Therefore the relative error for the charging time estimation is 5.68%, which shows the charging time estimation is of relatively high accuracy. Figure 5.9 shows the temperature profiles of the first 16 cells.
5.2.3. HIL simulation for CCCV charging and balancing based on SOC (OCV)

Figure 5.10 to figure 5.12 show the HIL simulation results for the charging condition in Section 4.3.2. Compared to the charging time of 4.535 h in Section 4.3.2, the charging time of the HIL simulation is slightly longer and of 4.895 h. Therefore the relative error for the charging time estimation is 7.35%, which shows the charging time estimation is of relatively high accuracy. Figure 5.12 shows the temperature profiles of the first 16 cells.
5.2.4. HIL simulation for CCCV charging and balancing based on SOC (OCV) with PWM drive.

Figure 5.13 to figure 5.15 show the HIL simulation results for the charging condition in Section 4.4.2. Compared to the charging time of 5.532 h in Section 4.4.2, the charging time of the HIL simulation is slightly longer and of 5.625 h. Therefore the relative error for the charging time estimation is 1.65%, which shows the charging time estimation is of relatively high accuracy. Figure 5.15 shows the temperature profiles of the first 16 cells.
Figure 5.13 SOC with time of the validation for simulation in Section 4.4.2

Figure 5.14 Voltage with time of the validation for simulation in Section 4.3.2
5.3. Conclusion

The charging simulation for scenarios in Section 4.1.2, 4.2.2, 4.3.2 and 4.4.2 are validated via the real time simulation in HIL system. The charging behavior in the HIL simulation is the same with relevant ones in Chapter 4. The accuracy of the charging time estimation is represented by the relative error of charging time estimation, which is defined in formula 5.1. As is shown above, all the simulation scenarios tested in the HIL system end with rather small relative error (less than 10%), which proves that the charging simulation model is quite accurate.
Chapter 6 Discussion

Based on the Li-ion battery cell model brought up in reference [1], this thesis developed a Matlab/Simulink model for charging simulation to estimate the charging time and investigate different charging strategy, balancing logic and the impact of several important parameters. As described in Section 2.1.2, the battery cell model in reference [1] utilizes ZARC elements to emulate the impedance spectrum of Li-ion battery cell with very high accuracy. CCCV charging algorithm is implemented via a PI controller in the charging control module of the model, which is introduced in Section 3.2. Discussion about the impact of PI parameters on the charging behavior is given in Section 3.2.1.1, inappropriate PI settings may lead to oscillation in cell voltages which will damage the battery cell. The criteria of choosing PI parameters is given in the same section. As shown in Section 4.5, a pre charging state can be introduced to CCCV charging to alleviate the polarization when SOC is at low level, the implementation of this improvement is described in Section 3.2.2. The thesis looks into different balancing logics: voltage based balancing without advance, voltage based balancing with advance, SOC based balancing and SOC based balancing with PWM drive. The implementation and algorithm flow of all the logics are introduced in Section 3.3.1, 3.3.2, 3.3.3 and 3.3.4 respectively. The charging simulation results for all these balancing logics can be found in Section 4.1, 4.2, 4.3 and 4.4 respectively. The balancing hardware block in the model is implemented with a toolbox called PLECS in Simulink, which is described in Section 3.4. Voltage based balancing (with/without advance) and SOC based balancing use the same balancing circuit in Section 3.4.1. While SOC based balancing with PWM drive uses a different balancing circuit where the MOSFETs are driven by PWM signals instead of a constant high signal. The circuit can be found in Section 3.4.2. From the comparison of simulation results in Section 4.1, 4.2, 4.3 and 4.4, the conclusion can be that SOC based balancing has the advantage of shorter charging time and smaller deviation after charging, compared to voltage based balancing logic, while advanced voltage balancing has a shorter charging time than regular voltage balancing logic. However, attention should also be paid that the accurate knowledge of SOC is difficult to acquire, complex algorithms need to be implemented, which will increase the economic and computational cost. SOC based balancing with PWM drive can reduce the heat stress on the shunt resistors of the balancing circuits, but with the cost of longer charging time. The impact of different parameters: aging factor, initial SOC and charging rate and on charging behavior are investigated as well. The simulation results of different initial SOC and charging rate can be found in Section 4.6 and 4.7 respectively. With higher initial SOCs, the polarization becomes less significant, while with higher charging current the polarization becomes more severe, which leads to larger deviation of SOC and voltage between cells and longer the balancing time. As shown in Section 4.7, the charging time of 2C charging rate is only slightly shorter than the one of 1C charging in Section 4.3. Aging factor has the most significant impact on charging behavior. Each of the charging scenario has two result sections in chapter 4, one for a new battery with little capacity deviation between cells and the other one for cells with the largest capacity deviation. Much longer charging time, larger deviation of SOC and more severe polarization are observed for the situation of old cells. The simulations for scenarios in Section 4.1, 4.2, 4.3 and 4.4 with old battery cells aging factors are validated with HIL simulator introduced in Section 5.1. The profile for SOC, voltage and cell temperature of each scenario are given in Section 5.2. The accuracy of the charging time estimation from the model is measured with relative error define in formula 5.1. All scenarios show quite good accuracy (within 10%).
As charging of Li-ion battery is rather complex and lots of sophisticated theories are brought up on this topic, future work of this thesis can have a really wide choice. Possible directions can be from one of the following.

a. Investigate in more complex charging algorithm, including impact on charging behavior, computational cost.

b. Investigate in active balancing methods.

c. Investigate in the SOC estimation algorithm. In this thesis, the SOC is assumed to be known exactly without measurement error, however, in real case, this would lead to difference in SOC based balancing logic.

d. Introduce more realistic thermal model to investigate the thermal behavior.

e. Set up the experiment surroundings for real test to validate the estimation.

f. Develop a charging control system in EV, with a dash board for the customer to choose charging method, balancing method and other charging settings according to the need and time allowed.
Chapter 7 Appendix

7.1. Figures for Section 4.4.1

Figure 7.1 SOC with time for the scenario in Section 4.4.1

Figure 7.2 Voltage with time for the scenario in Section 4.4.1
Figure 7.3 Cell current with time for the scenario in Section 4.4.1

Figure 7.4 Switches behavior with time for the scenario in Section 4.4.1
7.2. Figures for Section 4.4.2

**Figure 7.5** SOC with time for the scenario in Section 4.4.2

**Figure 7.6** Voltage with time for the scenario in Section 4.4.2
Figure 7.7 Cell current with time for the scenario in Section 4.4.2

Figure 7.8 Switches behavior with time for the scenario in Section 4.4.2
7.3. Figures for Section 4.5

Figure 7.9 SOC with time for scenario in Section 4.5

Figure 7.10 Voltage with time for scenario in Section 4.5
7.4. Figures for Section 4.6

![Figure 7.11 Cell current with time for scenario in Section 4.5](image1)

![Figure 7.12 SOC with time of 10% initial SOC for scenario in Section 4.6](image2)
Figure 7.13 SOC with time of 40% initial SOC for scenario in Section 4.6

Figure 7.14 SOC with time of 80% initial SOC for scenario in Section 4.6
Figure 7.15 Voltage with time of 10% initial SOC for scenario in Section 4.6

Figure 7.16 Voltage with time of 40% initial SOC for scenario in Section 4.6
Figure 7.17 Voltage with time of 80% initial SOC for scenario in Section 4.6

Figure 7.18 Cell currents with time of 10% initial SOC for scenario in Section 4.6
Figure 7.19 Cell currents with time of 40% initial SOC for scenario in Section 4.6

Figure 7.20 Cell currents with time of 80% initial SOC for scenario in Section 4.6
7.5. Figures for Section 4.7

Figure 7.21 SOC with time when charging with 2C for scenario in Section 4.7

Figure 7.22 SOC with time when charging with 0.5C for scenario in Section 4.7
Figure 7.23 Voltage with time when charging with 2C for scenario in Section 4.7

Figure 7.24 Voltage with time when charging with 0.5C for scenario in Section 4.7
Figure 7.25 Cell current when charging with 2C for scenario in Section 4.7

Figure 7.26 Cell current when charging with 0.5C for scenario in Section 4.7
Reference


