Battery Pack Balancing Systems
For Underground Mine
Electric Vehicles

Xiudong Cui
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Abstract

Due to the massive usage of fossil fuels in petrol and diesel vehicles and their huge emissions of exhaust gas, electric vehicles (EVs) have gained intensive attention in recent years as an alternative. In underground mines, diesel vehicles are typically used, and expensive exhaust filters are compulsory to comply with occupational health and safety rules. Underground mine electric vehicles (UMEVs) are a clean alternative to diesel vehicles and have zero emissions. In order to replace diesel vehicles, fast charging is required to charge the battery pack to meet the operational needs of UMEVs for underground mines, and each battery pack consists of hundreds of battery cells connected in series or parallel. Non-uniformity among the cells in the battery pack is inevitable, and can significantly reduce the pack capacity, such that non-uniformity is the major constraint to the implementation of fast charging. A battery balancing system is pivotal to the alleviation of this problem by maximising the pack capacity. Many active balancing systems have been developed to transfer charges in imbalanced battery packs. In an active balancing system, there are three main parts: balancing circuits, balancing criteria, and control strategies for the balancing circuits. This thesis focuses on improving the performance of battery balancing systems from the balancing criteria and control aspects.

The battery state of charge (SOC) as the balancing criterion in the charging process is explored first. The target is to complete cell equalization in the charging process to charge more capacity into the battery pack. In the proposed approach, a battery equivalent circuit model (ECM) is used to model the battery. Based on the state space equation derived from the battery ECM, an adaptive extended Kalman filter is applied to dynamically estimate cell SOCs with robustness to model uncertainty. Only one
additional current sensor is required to detect the balancing current and calculate the current of each cell for the SOC estimation. Experimental results show that the proposed approach can charge more capacity to the battery pack than terminal voltage-based approaches.

Based on a multi-switched inductor (MSI) balancing circuit, a fuzzy logic (FL) controller for improving the balancing performances of lithium-ion battery packs is proposed to replace a proportional-integral (PI) controller. In the proposed FL controller, the cell’s open circuit voltage (OCV) and its OCV difference in the pack are used as the inputs, and the outputs of the controller are the inductor balancing currents. The FL controller has the advantage of maintaining high balancing currents over the PI controller in almost the entire balancing process, leading to high balancing speed. A prototype of a lithium-ion battery pack balancing system with FL and PI controllers was built to evaluate balancing performances. The experimental results show that the balancing system with the FL controller achieves much faster balancing speed and can recover more pack capacity than that with the PI controller.

Battery chargeable and discharge capacity as the balancing criterion is further proposed to overcome the non-uniformity of cells in the battery pack in both the charging and discharging processes, and particularly to deal with the non-uniformity of cell capacities in the pack. To determine the current of each cell in the balancing operation, only one extra current sensor is added in the selected flyback balancing circuit. The balancing simulation of a LiFePO4 battery pack was conducted in moderate and severe capacity imbalance scenarios. The simulation results show that the proposed battery balancing method has better performance than the other terminal voltage or SOC-based balancing methods in terms of charging more capacity into the battery pack in the charging process and discharging more capacity from the battery pack in the discharging process.
DECLARATION

This is to certify that:

1. This thesis contains no material which has been accepted for the award to the candidate of any other degree or diploma, except where due reference is made in the text of the examinable outcome.

2. To the best of the candidate’s knowledge, this thesis contains no material previously published or written by another person except where due reference is made in the text of the examinable outcome.

3. The work is based on the joint research and publications; the relative contributions of the respective authors are disclosed.

Xiudong Cui

June 2017
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To my dear wife, Yuping

To my loved daughter, Emily

And to my parents
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## Nomenclatures

<table>
<thead>
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<th>Abbreviation</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>EV</td>
<td>electric vehicle</td>
</tr>
<tr>
<td>UMEV</td>
<td>underground mine electric vehicles</td>
</tr>
<tr>
<td>SOC</td>
<td>state of charge</td>
</tr>
<tr>
<td>ECM</td>
<td>equivalent circuit model</td>
</tr>
<tr>
<td>MSI</td>
<td>multi-switched inductor</td>
</tr>
<tr>
<td>FL</td>
<td>fuzzy logic</td>
</tr>
<tr>
<td>OCV</td>
<td>open circuit voltage</td>
</tr>
<tr>
<td>MMT</td>
<td>million metric tons</td>
</tr>
<tr>
<td>LiCoO$_2$</td>
<td>lithium cobalt oxide</td>
</tr>
<tr>
<td>LiMnO$_4$</td>
<td>lithium manganese oxide</td>
</tr>
<tr>
<td>NCM</td>
<td>lithium nickel manganese cobalt oxide</td>
</tr>
<tr>
<td>NCA</td>
<td>lithium nickel cobalt aluminium oxide</td>
</tr>
<tr>
<td>LiFePO$_4$</td>
<td>lithium iron phosphate</td>
</tr>
<tr>
<td>LTO</td>
<td>lithium titanium oxide</td>
</tr>
<tr>
<td>CCCV</td>
<td>constant current and constant voltage method</td>
</tr>
<tr>
<td>DOD</td>
<td>depth of discharge</td>
</tr>
<tr>
<td>ASC</td>
<td>adjacent switched capacitor</td>
</tr>
<tr>
<td>DTSC</td>
<td>double tiered switched capacitor</td>
</tr>
<tr>
<td>SSC</td>
<td>single switched capacitor</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>CSSC</td>
<td>chain structured switched capacitor</td>
</tr>
<tr>
<td>MC</td>
<td>multiplier-capacitor</td>
</tr>
<tr>
<td>MWT</td>
<td>multiple-winding transformer</td>
</tr>
<tr>
<td>PWT</td>
<td>primary winding transformer</td>
</tr>
<tr>
<td>SRT</td>
<td>selective ramp transformer</td>
</tr>
<tr>
<td>MPT</td>
<td>multi-winding parallel transformer</td>
</tr>
<tr>
<td>SMWT</td>
<td>switched multiple winding transformer</td>
</tr>
<tr>
<td>BMWT</td>
<td>bidirectional multi-winding transformer</td>
</tr>
<tr>
<td>FTSM</td>
<td>flyback two-stage switching matrix</td>
</tr>
<tr>
<td>TCM</td>
<td>two-stage capsulated modularization</td>
</tr>
<tr>
<td>DSC</td>
<td>dynamic switch-changing</td>
</tr>
<tr>
<td>BCI</td>
<td>bidirectional coupled-inductor</td>
</tr>
<tr>
<td>BMT</td>
<td>bridged multi-winding transformer</td>
</tr>
<tr>
<td>BBC</td>
<td>buck-boost converter</td>
</tr>
<tr>
<td>IBBC</td>
<td>improved buck boost converter</td>
</tr>
<tr>
<td>IIC</td>
<td>integrated inductor and capacitor</td>
</tr>
<tr>
<td>RLBC</td>
<td>resonant LC and boost converter</td>
</tr>
<tr>
<td>CABC</td>
<td>capacitor-assisted boost converter</td>
</tr>
<tr>
<td>MIC</td>
<td>multiphase interleaved converter</td>
</tr>
<tr>
<td>AEKF</td>
<td>adaptive extended Kalman filter</td>
</tr>
<tr>
<td>PCC</td>
<td>pulse constant current</td>
</tr>
<tr>
<td>CTP</td>
<td>cell-to-pack mode</td>
</tr>
</tbody>
</table>
PTC pack-to-cell mode

CBCs capacitor-based balancing circuits

TBCs transformer-based balancing circuits

IBCs inductor-based balancing circuits

CukBCs Cuk converter-based BCs

Buck – BoostBCs buck-boost converter-based BCs

RMV ratio of mode-duration to cell-voltage

BBM battery balancing method

VB³M voltage based BBM

SOC stage of charge

SB³M SOC based BBM

OCV open circuit voltage

CC_i(t) chargeable capacity of cell i (Ah)

DC_i(t) dischargeable capacity of cell i (Ah)

Z_i(t) state of charge of cell i

C_i capacity of cell i

I_i(t) current of cell i

I_{b1} average balancing current in the primary side

I_{b2} average balancing current in the secondary side

N_1 number of turn in primary side

N_2 number of turn in secondary side
\( R_{ini} \) ohmic resistance (\( \Omega \))

\( R_{pei} \) electrochemical polarization resistance (\( \Omega \))

\( C_{pei} \) electrochemical polarization capacitance (F)

\( R_{pci} \) concentration polarization resistance (\( \Omega \))

\( C_{pci} \) concentration polarization capacitance (F)

\( V_{oci} \) open circuit voltage of cell i

\( \Delta V_{oci}, \Delta R_{ini}, \Delta R_{pei}, \Delta C_{pei}, \Delta R_{pci}, \Delta C_{pci} \) modelling parameter errors

\( w(t) \) process Gaussian noise

\( v_k \) measurement Gaussian noise

\( Q \) process Gaussian noises covariance

\( R \) measurement Gaussian noise covariance

\( y_k \) output vector in step k

\( H_k, M_k \) partial derivatives in step k

\( P \) covariance

\( K_k \) Kalman Gain in step k

\( Q_{i\alpha} \) capacity of cell i in time \( \alpha \)

\( Q_{i\beta} \) capacity of cell i in time \( \beta \)
Chapter 1

Introduction

1.1. Background

Global climate change is one of the main challenges in the twenty-first century. Human activities significantly influence this process. Since the Industrial Revolution, there has been increased use of fossil fuel. Carbon dioxide and other greenhouse gases are emitted and they accumulate in the atmosphere as a side-effect of fossil fuel consumption. The concentration of carbon dioxide in the atmosphere has increased by 42% since 1750 [1], when industrial civilization began. Carbon emissions from fossil fuels and cement production are climbing and the rate has been accelerating in the last fifty years, as shown in Figure 1-1, which is based on data compiled by the Carbon Dioxide Information Analysis Centre [2]. The emissions in 2010 amounted to 9167 million metric tons (MMTs), five times higher than those in 1950.
Figure 1-1. Annual carbon emissions from fossil fuels since 1750.

The increased carbon dioxide level in the atmosphere has caused environmental issues. The carbon dioxide level coincides with the temperature increase in the past century. Figure 1-2 shows the annual mean temperature change of global surface air since 1880 with the base of average temperature between 1951 and 1980 [3]. It is evident that the temperature has increased steadily and has the same pattern as the significant increase in carbon emission since the 1950s shown in Figure 1-1. If the use of fossil fuel keeps increasing, the temperature may rise more steeply in this century and the mean global temperature in 2100 will be 5.5 degrees higher than that in 2000 considering carbon feedback [4]. Higher temperatures will lead to sea level rise due to thermal expansion, triggering catastrophes, such as drought around the world, and affecting agricultural output [5].
To alleviate this trend, it is necessary to reduce the use of fossil fuel and increase the percentage of renewable energy such as wind and solar power [6]. Currently, Transportation accounts for 26 % of the overall greenhouse emissions and is one of the few industrial sectors that continues to increase [7].

Owing to breakthroughs in battery technology, such as the invention of lithium-ion batteries, increased attention has been paid to electric vehicles (EVs), which have theoretically zero exhaust emissions [8]. EVs can store renewable energy in the off-peak hours and release it back to the grid during peak hours to overcome the intermittent nature of renewable energy [9]. There are many EVs on the market around the world. Table 1-1 summarizes some of them.
Chapter 1 Introduction

**TABLE 1-1. CURRENT ELECTRIC VEHICLES.**

<table>
<thead>
<tr>
<th>EVs</th>
<th>Battery manufacturer</th>
<th>Battery type</th>
<th>Battery capacity (kWh)</th>
<th>Approx. driving range (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BYD-e6</td>
<td>BYD</td>
<td>LiFePO₄</td>
<td>57</td>
<td>400</td>
</tr>
<tr>
<td>Chevrolet Volt</td>
<td>A123</td>
<td>LiFePO₄</td>
<td>20</td>
<td>132</td>
</tr>
<tr>
<td>Ford Focus</td>
<td>LG-Chem</td>
<td>LiMnO₄</td>
<td>23</td>
<td>122</td>
</tr>
<tr>
<td>Nissan Leaf</td>
<td>Nissan AEC</td>
<td>LiMnO₄</td>
<td>24</td>
<td>169</td>
</tr>
<tr>
<td>Tesla Model S</td>
<td>Panasonic</td>
<td>NCA</td>
<td>60</td>
<td>334</td>
</tr>
<tr>
<td>Tesla Model X</td>
<td>Panasonic</td>
<td>NCA</td>
<td>75</td>
<td>413</td>
</tr>
<tr>
<td>BMW Mini E</td>
<td>LG-Chem</td>
<td>NCM</td>
<td>35</td>
<td>241</td>
</tr>
<tr>
<td>Mitsubishi MEV</td>
<td>Toshiba</td>
<td>NCM</td>
<td>20</td>
<td>161</td>
</tr>
</tbody>
</table>

In underground mines, diesel vehicles are used as passenger transport vehicles. Due to strict emission and safety requirements, expensive exhaust filters are compulsory and these filters must be replaced regularly. Underground mine electric vehicles (UMEVs) offer a clean alternative to diesel vehicles, as they have zero exhaust emissions. Several UMEVs are currently available, as listed in Table 1-2.
TABLE 1-2. UNDERGROUND MINE ELECTRIC PERSONNEL CARRIERS.

<table>
<thead>
<tr>
<th>Company</th>
<th>Electrical carriers</th>
<th>Battery type</th>
<th>Battery capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damascus</td>
<td>MAC-12 Electric transporter</td>
<td>Lead acid</td>
<td>7.2 kWh</td>
</tr>
<tr>
<td>Saskatoon</td>
<td>PapaBravo Innovations Gofer</td>
<td>LiFePO₄</td>
<td>48 kWh</td>
</tr>
<tr>
<td>Industrial Fabrication</td>
<td>Minecat UT150-eMV</td>
<td>Lithium ion</td>
<td>Up to 80kWh</td>
</tr>
<tr>
<td>Prairie Machine &amp; Parts</td>
<td>Marmot-EV</td>
<td>LiFePO₄</td>
<td>95 kWh</td>
</tr>
</tbody>
</table>

1.2. Battery pack charging

In the applications of EVs and UMEVs, charging the battery pack is one of the main bottlenecks. Charging performance is affected by many factors, including battery type, charger connection to power supply (charging connection interface), power of the charging station and battery pack non-uniformity. This thesis focuses on technologies to alleviate the consequences of the non-uniformity of battery packs which reduces the usable pack capacity. Therefore, the first three factors are briefly introduced in this section and the last factor, pack non-uniformity, is discussed in detail in the next section.
1.2.1. Battery types

Lithium-ion batteries are the most popular energy storage choice in EVs [10-12]. Most lithium-ion batteries use carbon as the anode material. Based on their cathode materials, there are at least five successful commercial batteries [11]: lithium cobalt oxide (LiCoO$_2$), lithium manganese oxide (LiMnO$_4$), lithium nickel manganese cobalt oxide (NCM), lithium nickel cobalt aluminium oxide (NCA), and lithium iron phosphate (LiFePO$_4$). Titanium can also be used as the anode material and the corresponding commercial product is the lithium titanium oxide (LTO) battery. The main parameters of these batteries are summarized in Table 1-3.

The LiCoO$_2$ battery is the first and most commercially successful lithium-ion battery. Its major limitations are its high cost, low thermal stability and fast capacity-fading rate with high current. An improved version of the LiCoO$_2$ battery is the NCA battery, which has less Co material to reduce the cost. The NCA battery is widely used in commercial EVs such as the Tesla series. However, the capacity-fading rate is high when the temperature is above 40°C, due to the growth of the solid electrolyte interface (SEI) [11].

The LiMnO$_4$ battery is promoted because Mn is cheaper and less toxic than Co. However, this battery type also has a high capacity-fading rate. The NCM battery was invented by adding Co to the LiMnO$_4$ battery to increase its stability. This NCM battery has similar specific capacity to the LiCoO$_2$ battery but a lower cost.

The LiFePO$_4$ battery has both a cheaper price and more stable performance compared with the batteries mentioned above. Because of its better stability, it has a long cycle life and fast charging rate. However, it has moderate specific capacity and volume capacity.
Finally, the LTO battery is very stable with a long cycle life. However, its cost is high due to the use of Titanium.

**Table 1-3. Basic Specifications of Lithium-Ion Batteries.**

<table>
<thead>
<tr>
<th></th>
<th>LiCoO₂</th>
<th>LiMnO₄</th>
<th>LiFePO₄</th>
<th>NCM</th>
<th>NCA</th>
<th>LTO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average voltage (V)</strong></td>
<td>3.8</td>
<td>4.1</td>
<td>3.4</td>
<td>3.7</td>
<td>3.7</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Operating voltage range (V)</strong></td>
<td>2.5~4.2</td>
<td>2.5~4.2</td>
<td>2~3.6</td>
<td>2.5~4.2</td>
<td>2.5~4.2</td>
<td>1.5~2.7</td>
</tr>
<tr>
<td><strong>Specific capacity (Ah/kg)</strong></td>
<td>274/148*</td>
<td>148/120*</td>
<td>170/165*</td>
<td>280/160*</td>
<td>279/199*</td>
<td>175</td>
</tr>
<tr>
<td><strong>Volumetric capacity (mAh/cm³)</strong></td>
<td>1363/550*</td>
<td>596</td>
<td>589</td>
<td>1333/600*</td>
<td>1284/700*</td>
<td>600</td>
</tr>
<tr>
<td><strong>Cycle life</strong></td>
<td>500+</td>
<td>500+</td>
<td>1000+</td>
<td>500+</td>
<td>500+</td>
<td>1000+</td>
</tr>
<tr>
<td><strong>Operating temperature in charge (°C)</strong></td>
<td>0~45</td>
<td>0~45</td>
<td>0~45</td>
<td>0~45</td>
<td>0~45</td>
<td>0~45</td>
</tr>
<tr>
<td><strong>Typical maximum charge rate</strong>*</td>
<td>1C</td>
<td>1C</td>
<td>4C</td>
<td>1C</td>
<td>1C</td>
<td>10C</td>
</tr>
</tbody>
</table>

Notes:
*These two values stand for theoretical value/typical value in commercial products, respectively.
**The cycle life is defined as the cycle number when the cell capacity drops to 80% of its nominal value.
***The charging rate stands for the charging current in C rate, where C represents nominal capacity.
Based on the characteristics of battery terminal voltage, commercial lithium-ion batteries are categorized into two groups. The first group has a flat voltage plateau most of the time during battery discharging. A typical type of this battery in this group is the LiFePO$_4$ battery. The second group has steeper voltage output during battery discharging. A typical example is the NCA battery. Figure 1-3 shows the potential voltages of these two battery types versus their specific capacities [11].

![Terminal voltage characteristics of LiFePO$_4$ battery and NCA battery.](image)

Figure 1-3. Terminal voltage characteristics of LiFePO$_4$ battery and NCA battery.

### 1.2.2. Charger connectors

There is an industrial standard for the connectors (connection interfaces) of EV chargers. They vary with the power levels of the charging infrastructures [13] and are divided into three levels: Level 1, Level 2, and Level 3, as summarized in Table 1-4 [14, 15].
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Level 1: The charging power is low, typically 1.4kW or 1.9 kW. The standard SAE J1772 is applied to this level of connectors. It connects the grid power directly to the on-board charger in EVs. The charging time is long and may be more than ten hours.

Level 2: The charging power is 7.2 kW with single phase or 23kW with three phase. The standard SAE J1772 is applied to the connector [15]. Usually it is used in on-board chargers. The time to fully charge a battery pack in the EV is about 2-6 hours.

Level 3: The charging power varies from 25kW to 120kW with different standards. There are two well-established standards: the Japanese CHAdeMO and SAE J1772 hybrid. The charging infrastructure with power level 3 supports fast charging and can charge the battery packs in EVs generally within one hour. The chargers with this power level are off-board.

Table 1-4. Standards for Different Power Levels.

<table>
<thead>
<tr>
<th>Power level</th>
<th>Charger location</th>
<th>Typical use</th>
<th>Connection standards</th>
<th>Expected power level (kW)</th>
<th>Charging time (h)</th>
<th>EV pack capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>On-board</td>
<td>Home</td>
<td>SAE J1772</td>
<td>1.4(12A)</td>
<td>11-36</td>
<td>16-50kWh</td>
</tr>
<tr>
<td>120Vac(US)</td>
<td>1-phase</td>
<td>Home</td>
<td>SAE J1772</td>
<td>1.9(20A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>230Vac(AU)</td>
<td></td>
<td>or office</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 2</td>
<td>On-board</td>
<td>Private</td>
<td>SAE J1772</td>
<td>8 (32A)</td>
<td>2-6</td>
<td>16-30kWh</td>
</tr>
<tr>
<td>240Vac(US)</td>
<td>1 or 3 phase</td>
<td>Or public outlets</td>
<td></td>
<td>19.2(80A)</td>
<td>2-3</td>
<td>16-50kWh</td>
</tr>
<tr>
<td>400Vac(AU)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 3</td>
<td>Off-board</td>
<td>Charging stations</td>
<td>CHAdeMO</td>
<td>50</td>
<td>0.4-1</td>
<td>20-50kWh</td>
</tr>
<tr>
<td>(Fast)</td>
<td>Vdc 3 phase</td>
<td>Charging stations</td>
<td>SAE J1772</td>
<td>100</td>
<td>0.2-0.5</td>
<td></td>
</tr>
</tbody>
</table>

Notes: EVSE stands for dedicated electric vehicle supply equipment.
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The CHAdeMO standard is the most popular candidate for a fast charger. This standard only defines a DC charging connector. EVs with this standard need separate AC and DC charging connection interfaces. The maximum charging power for this standard is 50kW. The SAE J1772 hybrid standard integrates the AC charge connector and the DC charge connector in one plug and the charging power can be up to 100kW. To date, there have been no commercial products on the market. Tesla has launched a supercharger for its EVs and its connection standard can support up to 120kW.

The specific connection standards change from one country to another. Figure 1-4 summaries the main standards used in the US, EU, China and Japan [16]. In Australia, the SAE J1772 standard is adopted for AC charging and DC CHAdeMO chargers are also in operation.

Figure 1-4. Global differences in connectivity [16].
1.2.3. Charging methods and fast chargers

The constant current and constant voltage method (CCCV) is the dominant charging method for lithium-ion batteries. This method is a trade-off between charging speed and charging safety. It is divided into two stages: a constant current (CC) stage and a constant voltage (CV) stage. In the CC stage, while the current is kept constant, the terminal voltage increases. When the terminal voltage achieves a pre-set clamp value, the charging enters the CV stage. In this stage, the charging current decreases to maintain the terminal voltage at a constant value. Figure 1-5 shows the current and voltage profile of the CCCV charging method.

![Figure 1-5. CCCV charging profile [17].](image)

For a battery pack in an EV, the power level of chargers decides the charging speed and therefore the time required. Table 1-5 summarizes the charging parameters of some commercial EVs. Due to high pack capacity, off-board chargers of Level 3 should be used for fast charging. There are various brands of off-board chargers on the market from companies such as Schneider, Aero Viroment, Nissan, and Fuji Electric. Figure 1-6 shows some examples. Most of the fast chargers on the market use the CHAdeMO connection standard.
<table>
<thead>
<tr>
<th>EVs</th>
<th>Battery capacity (Li-Ion)</th>
<th>Connection standard</th>
<th>Charging power (kW)</th>
<th>Charging time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chevrolet Volt PHEV</td>
<td>16kWh</td>
<td>SAE J1772</td>
<td>3.8</td>
<td>2-3 hours</td>
</tr>
<tr>
<td>Mitsubishi i-MiEV</td>
<td>16kWh</td>
<td>SAE J1772 CHAdeMO</td>
<td>3</td>
<td>14 hours AC 50 30 min DC</td>
</tr>
<tr>
<td>Nissan Leaf</td>
<td>24kWh</td>
<td>SAE J1772 CHAdeMO</td>
<td>3.3</td>
<td>6-8 hours AC 50 30 min DC</td>
</tr>
<tr>
<td>Tesla Roadster</td>
<td>53kWh</td>
<td>SAE J1772</td>
<td>9.6-16.8</td>
<td>4-12 hours</td>
</tr>
</tbody>
</table>

Figure 1-6. Fast chargers of different brands. (a) Schneider Electric[18]; (b) Aero Viroment[19]; (c) Nissan Nsqc-44[20]; (d) Efacec Qe50[21]; (e) Fuji Electric[22].
1.2.4. Pack charging for UMEVs

In this section, battery pack charging for UMEVs is discussed. To understand the charging strategy for UMEVs, the driving cycle in Australian coal mines is shown in Figure 1-7. It has a long and steep slope connecting the workshop on the ground and the underground coalmine working face. UMEVs consume up to one third of energy to climb this slope.

![Figure 1-7. Typical driving cycle for Australian underground coal mines.](image)

A. Battery selection

The LiFePO₄ battery is chosen for UMEVs because of its superior safety characteristics, long cycle life, fast charging speed and relatively low cost [12, 23]. Four LiFePO₄ batteries in the market were selected from three manufacturers: Guoxuan from China [24], EV Power from Australia [25] and A123 from the USA [26]. Their charging parameters are listed in Table 1-6. The maximum charging rates vary from 0.5 C to 4.3 C, which correspond to charging times from several hours to only 15 minutes.
It is expected that UMEVs should have the pack capacity to run at least two driving cycles (see Figure 1-7) without recharging [27]. To meet this requirement, a simulation based on the model of UMEVs was conducted for underground mine driving cycles [27, 28]. The results show that the capacity of the battery pack in the UMEVs should be set to 44kWh [27].

**B. Pack charging performance**

These four LiFePO₄ batteries form battery packs and their charging performances are evaluated in Table 1-7. The charger for the testing uses the CHAdeMO connection standard with 50kW maximum power output. The battery pack is expected to be fully charged within one hour in fast charging.

The GuoXuan battery pack was not suitable for this project because of its long charging time, a minimum of two hours. The battery pack with A123 2.3Ah battery cells can be charged in 15 minutes in theory, whilst the available power of the charger causes the minimum charging time to be around one hour. Because of the huge number of cells for this battery pack, this battery cell was not chosen for the project. Battery
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packs with EV power and A123 20Ah can both be charged in one hour. The A123 20Ah battery has a longer cycle life (3000 times) than the battery from EV Power. Therefore, the A123 20Ah battery was chosen [27].

TABLE 1-7. POWER DEMANDS FOR PROPOSED LIFEP04 44KWH BATTERY PACK IN UMEVS [24-26].

<table>
<thead>
<tr>
<th>Battery brand</th>
<th>Charging rate</th>
<th>Battery number</th>
<th>Maximum charger power</th>
<th>Estimated charging time</th>
</tr>
</thead>
<tbody>
<tr>
<td>GuoXuan</td>
<td>0.5C</td>
<td>1340</td>
<td>22kW</td>
<td>&gt;2h</td>
</tr>
<tr>
<td>EV Power</td>
<td>1C</td>
<td>350</td>
<td>44kW</td>
<td>Fast Charge: 1h</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Normal Charge: 4h</td>
</tr>
<tr>
<td>A123(2.3Ah)</td>
<td>1.3C (3A)</td>
<td>5800</td>
<td>55.9kW</td>
<td>45 min</td>
</tr>
<tr>
<td>(ANR266501)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A123(20Ah) (AMP20M1HD-A)</td>
<td>1C</td>
<td>670</td>
<td>44kW</td>
<td>1 h</td>
</tr>
</tbody>
</table>

C. Charging strategy for UMEVs

In underground mines such as coal mines, miners have always faced the threat of methane explosions [29], and explosion protection has been consistently developed in industrialized countries. The protection provides a high level of safety with strict regulations.

The battery pack and its charger are electrical equipment. They need to be connected and disconnected frequently. Sparking in such operations is a high-risk cause of explosions if methane exists in the area. Therefore, safety is one of the main concerns in the selection of charging systems and the establishment of the charging infrastructure.
for UMEVs. Field inspection is essential to decide special requirements such as the location of the charger for the charging system of UMEVs in a coal mine [30]. As shown in Figure. 1-6, the area at the bottom of the slope is safe for chargers with low capacity, because it is far from the workface. These chargers serve as slow chargers. In contrast fast chargers are installed near the workshop, where high-power points are provided. Based on the charger’s locations and driving modes, a charging strategy is proposed to maintain operations without interruption.

There are two main driving modes for passenger vehicles based on a survey conducted in major coal mining companies in Australia: shuttle bus mode and taxi mode. The shuttle bus mode is the main service type with a point-to-point driving cycle. In this mode, the UMEVs take the miners to the workface or bring them back. It is mainly used at the beginning and the end of the working time, each period taking less than two hours. The taxi mode takes passengers or tools to different underground locations during the daytime. The vehicle might wait from several minutes to several hours between undertaking different tasks in this mode.

For the shuttle bus mode, slow overnight charging is used to fully charge the UMEVs. Fast charging, which is supposed to fully charge the battery pack in one hour, is used in the daytime. It re-charges the battery pack within 30 minutes when the miners change shifts at the workshop.

For the taxi mode, slow charging is used to charge the UMEVs. A dispatch centre is proposed to control the slow chargers and the UMEVs. The UMEVs are charged when they are not being used. Careful coordination allows the UMEVs to perform their tasks as a team without significant interruption due to charging.
1.3. Battery pack balancing

In EVs, battery packs typically consist of hundreds of battery cells connected in series or in parallel to obtain a high power output. Non-uniformity of battery packs such as different capacities and internal resistances is inevitable, and it deteriorates with time. This significantly reduces the usable capacity of battery packs [31, 32]. UMEVs have some unique features besides the common features shared with the EVs from the battery aspect. First, the capacities of the battery packs in UMEVs are generally larger than those in EVs. This means more battery cells are required if the same battery cells are used in both cases. Second, the working environment of the battery packs in UMEVs is harsher than that of the EVs. For instance, the battery pack in UMEVs need to be contained in the explosion-proof enclosure which might lead to larger temperature difference and worse non-uniformity of the cells in the battery pack. Both features indicate there is a higher requirement for balancing systems in UMEVs than EVs.

A. Battery pack non-uniformity

Battery pack non-uniformity can be capacity non-uniformity, SOC non-uniformity or voltage non-uniformity. Capacity non-uniformity is the dominant form in aged battery packs. This non-uniformity mainly results from different cell ageing speeds. For single cells, the ageing speeds are determined by the charging and discharging current, the depth of discharge (DOD) and the ambient temperature [33, 34]. In a battery pack connected in series, the charging and discharging current are the same for each cell. The temperature difference and the DOD are the main reasons for capacity non-uniformity [35, 36]. Figure 1-8 shows the relationship between the temperature and the cycle life for batteries for the same charging and discharging current of 1C [37]. The cycle life is defined as the cycle number when the battery capacity declines to 80% of its nominal capacity [38]. The cycle life is longest around 25 °C and halves at 40 °C. In a battery pack, the temperatures among cells are significantly different, even when a cooling
system is applied, and this difference can be up to 5°C even for a new battery pack [35, 39].

![Figure 1-8. Evolution of cycle life versus working temperature [38].](image)

SOC non-uniformity is the reason for the imbalance in new battery packs where the capacity non-uniformity is insignificant. SOC non-uniformity is caused by different cell charging efficiencies and self-discharging rates. These differences are trivial in one cycle. However, after many charging and discharging cycles, the non-uniformity can accumulate to become severe if no intervention is undertaken [40]. Unlike capacity non-uniformity, which is permanent, SOC non-uniformity is recoverable. It can be handled with active balancing systems. Alternatively, passive balancing systems can be used to balance the pack in each cycle [40].

Finally, voltage non-uniformity is caused by other battery parameter variations except capacity such as different internal resistances. Such voltage non-uniformity cannot be handled when the terminal voltage is used as the balancing criterion. For battery types with a voltage plateau, voltage non-uniformity can lead to significant pack capacity loss when voltage is used as the balancing criterion. Therefore, SOC or other balancing criteria are preferred when voltage non-uniformity is a concern.
### B. Calculation of usable pack capacity

The usable capacity of the battery pack is severely affected by the non-uniformity of cells in the pack. Consider a battery pack with three cells in series with the assumption that three cells initially have the same capacities. After two years’ use, the different ageing speeds of these cells cause capacity non-uniformity. Suppose that the weakest cell drops to 80% of its nominal capacity, whilst the other two cells only drop to 95% of their nominal capacities. Without balancing, the usable pack capacity would be less than 80% of the nominal capacity. With an effective active balancing system, the usable pack capacity can reach 90% of the initial pack capacity in theory.

When SOC non-uniformity is also considered, the usable battery pack capacity can be calculated for different scenarios [40, 41]:

\[
C_{\text{Pack}}(t) = \begin{cases} 
\min(C_r(t)) + \min((1 - \text{SOC}(t)) \cdot C(t)) & \text{No Balancing} \\
\min(C(t)) & \text{Passive Balancing} \\
\operatorname{mean}(C(t)) & \text{Active Balancing}
\end{cases}
\]  

(1.1)

where, \(C_{\text{Pack}}(t)\) is pack capacity at time \(t\), \(C_r(t)\) is the remaining cell capacity, \(\text{SOC}(t)\) is the cell state of charge at time \(t\) and \(C(t)\) is cell capacity at time \(t\).

For a battery pack without balancing systems, the usable pack capacity is further explained in Figure 1-9. In the figure, the rectangle represents the overall cell capacity and the dashed line indicates the charged capacity. The green area is the usable pack capacity. It is evident that the usable pack capacity is much less than the overall pack capacity [42-44].
The passive balancing system can only be used in the charging process to help fully charge all the cells. The maximum usable pack capacity is the capacity of the weakest cell in the pack.

In the active balancing system, ideally all the existing pack cell capacities should be fully utilized, namely the usable pack capacity is the averaged cell capacity. To obtain this maximum usable pack capacity, the balancing operation should be completed before the end of the charging or discharging process. Due to the limitation of available balancing time and the balancing current, the usable pack capacity may be calculated as [41]:

\[
C_{pack} = \min \left\{ C_i + I_{i, \text{bat}} \cdot t \cdot \left( \frac{1}{t} - \frac{1}{n_i} \right) \right\}_{i=1...n_i}
\]

Active Balancing

(1.2)
Eq. (1.2) is derived from a flyback-based balancing circuit and only one cell can be balanced at one time, $t$ is the overall available balancing time, $t_i$ is the balancing time to cell $i$ and $I_{i,\text{bal}}$ is the balancing current. It is evident that the balancing time plays an important role in balancing performance. In the present study, in order to increase the balancing time, new balancing criteria are proposed.

C. Balancing systems

A balancing system includes a balancing circuit, balancing control and balancing criterion. The balancing circuit is hardware which uses electronic components to move charges. The balancing control implements a balancing algorithm in a balancing circuit. The balancing criterion describes the non-uniformity and decides when to start or stop the balancing process. The balancing circuits are briefly introduced in this section and the balancing criteria and control are explained in the next two sections.

In the literature, there are two kinds of balancing circuits, according to their operational principle: passive balancing circuits and active balancing circuits [45]. Passive balancing circuits can fully charge all the cells. During this process, the currents in cells with higher voltages are dissipated into heat through shunting resistors. The advantages of these balancing circuits are that they are cheap and easy to implement. However, their speed is very slow and the maximum usable pack capacity is the capacity of the weakest cell in the pack. Since passive balancing circuits have significant capacity loss when a severe capacity imbalance exists, they are not studied further in this thesis.

Active balancing circuits transfer charge in cell to cell or cell to pack or pack to cell method to achieve uniformity. They are more expensive than passive balancing circuits. However, active balancing circuits have higher efficiency and balancing current. In charging and discharging conditions with severe capacity imbalance, only active balancing circuits have the potential to obtain the maximum usable pack capacity within each cycle.
1.3.1. Battery pack balancing criterion

The active balancing system can be applied in maintenance conditions [46-50] or charging and discharging conditions [41, 51, 52].

In maintenance conditions, the available balancing time is generally long and the balancing speed is not critical. However, in the charging and discharging conditions, there are stricter requirements for the balancing systems. The balancing time is limited and the balancing operation is expected to be completed before cells reach their voltage or SOC limits. This section discusses the challenges faced in charging and discharging conditions for balancing systems from the balancing criterion aspect.

Firstly, the balancing time is restricted by the charging or discharging time. For instance, the charging time is expected to be less than one hour for a fast charger. Then, the balancing system can achieve the designed goal only if the balancing is completed within one hour. This demands high balancing speed and current as well as full utilization of all the charging time.

However, the charging or discharging time may not be effectively used for balancing operations. The terminal voltage is widely used as the balancing criterion [46-52]. The terminal voltage is the sum of the OCV, the polarization voltage and the voltage across internal resistance, and only the OCV has an explicit relationship to the SOC. The difference of the terminal voltage may not accurately reflect the SOC difference, due to voltage non-uniformity. This may lead to unnecessary balancing operation of the cells that have been balanced and the available balancing time is wasted.

Finally, the flat OCV output plateau of some lithium-ion batteries is a further challenge to the balancing criterion of terminal voltage. For example, the LiFePO4 battery has a flat voltage plateau between 20% and 90% of SOC. Using terminal voltage
as the balancing criterion, the imbalance is hard to be detected in the charging or discharging process due to the small voltage variation. The balancing operation will not occur and this reduces the available balancing time.

Therefore, if the balancing system is operated in the charging and discharging processes, alternative balancing criteria such as SOC should be used, which can better reflect battery non-uniformity. The challenge is that not every active balancing circuit can use SOC as the balancing criterion, due to the nature of the balancing components. The balancing circuits are reviewed to identify the availability of SOC as the balancing criterion in Chapter 2.

For the active balancing circuits that could apply SOC as the balancing criterion, the accuracy of the SOC is another issue that decides the final effect of the balancing operation. Because of the balancing current, the SOC estimation of the battery pack is challenging. SOC has been proposed as a balancing criterion [53], whilst the pack cell SOC estimation, especially during the voltage plateau range, is not addressed in detail. This challenge is covered in Chapter 3 of this thesis.

When the SOC is used as the balancing criterion, the absence of capacity information can also lead to sub-optimal use of the available balancing time. This is reflected in over-equalization and balancing delay. For example, a cell with high initial SOC and high capacity might be discharged first and then charged later by the balancing system in the charging. This phenomenon leads to low efficiency and slow balancing speed. Balancing delay happens when the SOCs or voltages are the same at the beginning of charging or discharging. The balancing operation does not start until SOC non-uniformity is developed and large enough to be detected. The solution is adding the capacity information to the balancing criterion and this is covered in Chapter 5 of this thesis.
1.3.2. Battery pack balancing control

Another aspect in improving the performance of balancing systems is the control of balancing circuits. Generally, the balancing system may provide the highest balancing current at the beginning of the balancing process due to the initial large differences of terminal voltages or SOCs of cells in the pack. With the decrease of these differences, the balancing current reduces. If the balancing circuits and their controllers are chosen carefully, high balancing currents can be maintained in the whole balancing process, which can increase balancing speed significantly, and these balancing circuits are also ones that can use the SOC as the balancing criterion and choose the cell to be balanced arbitrarily according to their controllers.

The existing control methods for the balancing circuits can be categorized into three groups. In the first group, the balancing circuits can realize balancing operations automatically and do not have controllability. They mainly include capacitor-based and transformer-based balancing circuits [45, 51, 54-56]. The main problem with these balancing circuits is that balancing currents are not controllable to improve balancing speed.

In the second group, an open loop controller is designed to control the balancing circuits, which will follow a pre-defined procedure to conduct balancing according to their terminal voltages or SOCs [45, 46, 57-59]. Most balancing circuits belong to the second group. The control parameters are set for the whole balancing process, which may not be optimal in the later stages of the balancing process. As a result, the potential of these balancing circuits system cannot be fully used.

In the third group, a closed-loop controller is designed to control the balancing circuits, which can regulate balancing currents in the whole balancing process to improve balancing speed. Existing controllers include the PI controller and the fuzzy logic (FL) controller.
The PI controller is applied for a multi-switch inductor (MSI) balancing circuit [50]. The durations of the switching time change based on the battery voltages to regulate the balancing current. This PI controller lacks adaptivity since the balancing current decreases proportionally with voltage difference, and the balancing speed will be slower in the later stages of the balancing process when the voltage difference becomes smaller.

This drawback can be solved by a FL controller. The FL controller is applied to a Cûk balancing circuit to control the balancing current by changing the balancing frequency [60-62]. However, the balancing frequency of the FL controller needs to be changed dynamically and the FL controller is applied to Cûk balancing circuits. In Chapter 4 of this thesis, a FL controller with constant frequency is proposed to overcome the difficulty of implementation compared with changing frequency. Furthermore, the proposed FL controller is applied to a MSI balancing circuit [63], which has the merit of lower cost than the Cûk balancing circuit. This proposed FL controller also provides high adaptivity to maintain the balancing current at a high level, improving balancing speed and reducing the balancing time.

1.4. Thesis objectives

The objectives of this thesis are to improve the performance of the balancing system from the aspects of balancing criterion and balancing control. The balancing criterion aims to increase the balancing time to maximise battery pack capacity during the charging and discharging processes. The balancing control method aims to increase the balancing current in the whole balancing process.

The major contributions of the thesis are as follows:

- Balancing circuits are categorized based on the availability of using SOC or terminal voltage as the balancing criterion.
- The SOC is implemented as the balancing criterion based on experiments on the charging process to deal with the voltage plateau.
- An adaptive extended Kalman filter (AEKF) with fading memory is applied to estimate the SOC robustly.
- A fuzzy logic controller with adaptivity is used to control the balancing circuit to increase the balancing current.
- The chargeable and dischargeable capacity is proposed as the new balancing criteria to increase the balancing time during the charging and discharging processes.

1.5. Structure of the Thesis

The structure of the thesis reflects the discussion about current research and research gaps, and has been organized as follows:

Chapter 2 gives a detailed literature review of balancing circuits. Balancing circuits are categorized based on the availability of using terminal voltage or SOC as the balancing criterion, which is closely related to the main balancing components. For balancing circuits that can apply the SOC as the balancing criterion, the implementation costs of the balancing circuits are further studied in terms of the number of components of the circuits. Balancing circuits that only need to add one balancing current sensor are identified in the literature review.

Chapter 3 proposes the battery state of charge (SOC) as the balancing criterion in the charging process. The aim is to complete cell equalization in the charging process to charge more capacity into the battery pack. In the proposed approach, a battery equivalent circuit model (ECM) is used to model the battery. Based on the state space equation derived from the battery ECM, an adaptive extended Kalman filter is applied to dynamically estimate cell SOCs with robustness to model uncertainty. Only one additional current sensor is required to detect the balancing current and calculate the
current of each cell for SOC estimation. Experimental results show that the proposed approach can charge more capacity into the battery pack than terminal voltage-based approaches.

Chapter 4 uses a fuzzy logic (FL) controller to improve the balancing performance of lithium-ion battery packs. It is implemented on a multi-switched inductor (MSI) balancing circuit to replace a proportional-integral (PI) controller. In the proposed FL controller, the cell’s open circuit voltage (OCV) and its OCV difference in the pack are used as the inputs and the outputs of the controller are the inductor balancing currents. The FL controller has the advantage of maintaining high balancing currents over the PI controller in almost the entire balancing process, leading to high balancing speed. A prototype of a lithium-ion battery pack balancing system with the FL and PI controllers is built to evaluate balancing performances. The experimental results show that the balancing system with the FL controller achieves much faster balancing speed and can recover more pack capacity than that with the PI controller.

Chapter 5 further explores battery chargeable and discharge capacity as the balancing criterion to tackle the non-uniformity of cells in the battery pack. The implementation background is both the charging and discharging processes, particularly to deal with the non-uniformity of cell capacities in the pack. To determine the current of each cell in the balancing operation, only one extra current sensor is added in the selected flyback balancing circuit. The balancing simulation of a LiFePO$_4$ battery pack is conducted in moderate and severe capacity imbalance scenarios. The simulation results show that the proposed battery balancing method has better performance than the other terminal voltage or SOC-based balancing methods in terms of charging more capacity into the battery pack in the charging process and discharging more capacity from the battery pack in the discharging process.

Chapter 6 provides the conclusions and recommendations for future work.
Chapter 2

Literature Review

This chapter provides a review of existing balancing systems, which include balancing circuits, balancing criteria and balancing control. In this review, the active balancing circuits will be categorized into two groups. One group can only use terminal voltage as a balancing criterion. The other group can use both battery state of charge (SOC) and terminal voltage as balancing criteria. In this group, balancing criteria and balancing control are explored to identify the potential balancing circuits to which the new balancing control and balancing criteria can be applied to improve the performance of balancing systems. The selected balancing circuits are used in the later chapters. Each group is further divided into sub-groups based on the main balancing component, as summarized in Figure 2-1.

The first group includes capacitor-based balancing circuits and some transformer-based balancing circuits. In these balancing circuits, the terminal voltage differences of the cells in the battery pack are the driving force during the balancing operation. The advantage of these circuits is that the terminal voltages of the cells can be easily measured to use as a balancing criterion and the battery pack can be balanced automatically. One of the drawbacks is that for a certain battery with a flat voltage platform the terminal voltage cannot represent the SOC. This leads to degraded balancing performance or even balancing in the wrong direction when the battery pack
is charging or discharging. Furthermore, the balancing speed is hard to control and very slow when the voltage difference is small.

Figure 2-1. Categories of main active balancing circuits based on balancing criterion.
The second group includes inductor-based balancing circuits, some transformer-based balancing circuits and switched controlled balancing circuits. In these balancing circuits, balancing current amplitude and direction can be controlled by the balancing criterion of the SOCs or the terminal voltages of the cells in the battery pack. However, the focus in the second group is the balancing criterion of the SOCs. Balancing circuits which are good candidates for implementation with the SOC as the balancing criterion are marked with thick green circles in Figure 2-1.

The speed of the balancing operation and the cost of the balancing system are the main concerns of this thesis, and the existing balancing systems are explored based on these two aspects [45, 64-68]. For the balancing operation in the battery charging or discharging process, the balancing speed is even more important than other factors in the application due to the limited charging or discharging time [62, 69-72]. In many balancing circuits, the number of components is reduced to save costs [46, 71, 73-75]. The review also covers other factors related to the performance of the balancing system, including balancing efficiency [59, 73, 76, 77], balancing controllability [60, 61, 78-81] and balancing modularization [82-86].

2.1 Balancing circuits with terminal voltage as balancing criterion

Terminal voltage is a widely-used balancing criterion in balancing systems [45, 87]. In this section, balancing circuits with terminal voltage as the balancing criterion are discussed. The general procedure of the balancing process with this criterion can be divided into three phases: measurement, calculation, and balancing.

In the measurement phase, the terminal voltages of all the cells in the battery pack are measured. In the second phase, non-uniformity is calculated in terms of voltage differences. The voltage differences can be obtained by the differences between cells or
the difference between the cell and the average voltage of the cells in the pack. These differences are then compared with a pre-set threshold. If any of these differences is higher than the threshold, the balancing system enters the balancing phase. In the balancing phase, many balancing methods are based on balancing circuits: moving charge from the cell with higher voltage to its adjacent cell with lower voltage, or moving charge from the cell with the highest voltage to the cell with the lowest voltage (cell to cell), moving charge from the cell with the highest voltage to the battery pack (cell to pack), and moving charge from the battery pack to the cell with the lowest voltage (pack to cell). The balancing operation continues until the voltage differences are less than the threshold.

### 2.1.1 Capacitor-based balancing circuits

All balancing circuits with the capacitor as the main energy transfer component can only use terminal voltage as the balancing criterion [54-56, 58, 69, 88-96]. Since the voltage difference is the driving force that moves the charge, the balancing speed is slow. Due to the low speed, capacitor-based balancing circuits are generally applied in maintenance for EVs or energy back-up stations where speed is not critical.

These balancing circuits have advantages, such as simple control, low implementation complexity and high efficiency [59]. The basic capacitor-based balancing circuit is the adjacent switched capacitor (ASC) balancing circuit [95], as shown in Figure 2-2(a). In this balancing circuit, each battery needs one capacitor and one pair of switches.
The balancing happens between the adjacent battery cells in two steps. In the first step, the capacitor is parallel with the battery cell with higher voltage and the charge is transferred from the cell to the capacitor. In the second step, the capacitor is parallel with the adjacent cell with lower voltage and the charge is transferred from the capacitor to the cell. This process continues until these two cells have the same voltage value. The balancing circuits that are an extension of the ASC balancing circuit follow the same procedure.

The balancing speed of this balancing circuit is slow due to the low balancing current. Furthermore, when the imbalanced cells are at the ends of a string, the charge must be moved in many steps through the adjacent cells and this reduces balancing speed and efficiency.

The balancing current with ASC balancing circuit follows

---

Figure 2-2(a). Adjacent switched capacitor ASC balancing circuit [95] (b) double tiered switched capacitor (DTSC) balancing circuit [56].
\[ I_{C_i} = C_i(V_{U_i} - V_{L_i})f_{sw} \]  \hspace{1cm} (2-2)

where, \( V_{U_i} \) is the higher cell voltage, \( V_{L_i} \) is the lower cell voltage and \( f_{sw} \) is the switching frequency.

When the on-resistance of the switch is considered, the total resistance of the \( i \)-capacitor is

\[ R_{sw_i} = \frac{1}{(f_{sw}C_i)} + 2R_{sw} / D \]  \hspace{1cm} (2-3)

where, \( D \) is the duty cycle and \( R_{sw} \) is the on-resistance of the switches.

The energy loss per step is

\[ \Delta \eta = \frac{(V_{U_i} - V_{L_i})^2}{R_{sw_i}} \]  \hspace{1cm} (2-4)

To improve the balancing speed, a double-tiered switched capacitor (DTSC) balancing circuit has been invented, based on the ASC balancing circuit [56] as shown in Figure 2-2 (b). In the DTSC balancing circuit, for every two battery pairs that are adjacent, one parallel capacitor (e.g. \( C_{13} \) or \( C_{24} \)) is added. This design significantly increases the balancing current and reduces the balancing time to one quarter of the ASC balancing circuit. However, the addition of capacitors increases the cost.

Another method to increase the balancing speed is to reduce the steps in charge transfer. For this purpose, a single-switched capacitor (SSC) balancing circuit has been designed to include only one central balancing capacitor. Each battery cell is connected to this capacitor through a switch matrix, as shown in Figure 2-3 (a) [54, 97]. The SSC balancing circuit can move charge among any two battery cells in two steps. Compared with the ASC balancing circuit, this SSC balancing circuit significantly reduces the number of steps when the imbalanced battery cells are not adjacent, increasing balancing speed and efficiency.
Another balancing circuit which reduces the steps in charge transfer is the chain-structured switched capacitor (CSSC) balancing circuit, as shown in Figure 2-3(b). This balancing circuit has the same structure as the ASC balancing circuit, except that it adds one more balancing capacitor to connect the ends of the battery string [69, 98]. The CSSC balancing circuit reduces the steps in charge transfer when the imbalanced cells are at the ends of the string. However, this balancing circuit needs to control the direction of the charge transfer instead of balancing automatically, such as in the ASC balancing circuit.

To improve balancing efficiency and reduce stress on the switches, a resonant inductor can be added in series with the capacitor in the ASC balancing circuit. Then, the switches can be turned on and off at zero current or voltage to reduce energy loss [76]. However, the implementation is complex.
The multiplier-capacitor (MC) balancing circuit based on a voltage multiplier has also been proposed to balance cells in the pack. The MC balancing circuit combines a voltage multiplier and a charger, as shown in Figure 2-4 [89, 99, 100]. It can charge the battery pack through the voltage multiplier while conducting balancing. In the balancing process, there are two steps. The main switch SW is turned on in the first step. Each cell is discharged through the even-numbered diodes (Di-2) and the charges are stored in their capacitors and the charges from the charger are stored in the inductor. In the second step, the SW is turned off. The charges from the inductor and the capacitors are redistributed to the cells through odd-numbered diodes (Di-1). The charge each cell can accept is decided by its terminal voltage. The cell with lower terminal voltage accepts more charge. In this way, the cells are balanced automatically. The efficiency of the MC balancing circuit is low and the balancing currents for the battery cells at the bottom of the pack are high. This balancing circuit is suitable for battery packs with small capacities.

Figure 2-4. MC balancing circuit [89, 99, 100].
The equivalent resistance of the capacitor voltage multiplier is

\[
R_{\text{eq}} = \frac{1}{C_i f_{\text{sw}} \left(1 - \exp\left(-\frac{-D}{f_{\text{sw}} C_i R_{C_i}}\right)\right)} + \frac{R_{C_i}}{1 - D}
\]  

(2-5)

where, \(C_i\) is the capacitor connecting with cell \(i\) and \(D\) is the duty cycle.

The power losses in the equivalent circuit follow:

\[
P_{\text{loss}} = \sum_{i=1}^{N} I_{\text{cell}_i}^2 R_{\text{eq}_i}
\]

(2-6)

### 2.1.2 Transformer-based balancing circuits

This section focuses on transformer-based balancing circuits, which can only use voltage as a balancing criterion, and the control of such balancing circuits has simple control requirements. These balancing circuits are generally designed for battery packs connected in series and can be divided into three groups: balancing circuits based on multiple-winding transformers, balancing circuits based on multi-winding transformers and balancing circuits based on shared-winding transformers. Figure 2-5(a) shows a balancing circuit in the first group [65, 101].
In this group, each cell needs a separate transformer. The balancing operation is controlled by a switch (SW) in two stages in each cycle. In the first stage, the SW is turned on and the charge goes from the pack to the transformer. In the second stage, the switch is turned off and the charge is sent to the cells. The charge that a cell accepts is decided by the cell’s terminal voltage. The cells with lower voltage accept more charge. The control of this balancing circuit is simple, but the cost is very high, due to the use of multiple-winding transformer. In the MWT balancing circuit, the average balancing current for the selected cell is

$$I_{cell} = \frac{1}{2} \frac{V_{cell} D^2}{L_i f_{sw}}$$

(2-7)

where, $D$ is the duty cycle, $f_{sw}$ is the switching frequency, $L_i$ is the inductor of the selected cell and the $I_{cell}$ is the average balancing current of the selected cell.
To reduce the cost, other balancing circuits have been proposed, such as the primary-winding transformer (PWT) balancing circuit shown in Figure 2-5(b) [45, 66, 86, 102]. It belongs to the second group. In this group, each cell has its own secondary winding but shares the same primary winding. The balancing procedure is similar to that of the MWT balancing circuit.

To further reduce the cost, the winding on the primary side can be eliminated if the windings on the secondary side are highly symmetrical, as shown in Figure 2-6 [51, 57, 71, 73, 103]. The balancing operation can happen automatically to equalize the terminal voltages of cells. Resonance is achieved when a resonant inductor and capacitor are added to the circuit [51].

![Transformer resonant balancing circuit without primary winding](image)

Figure 2-6. Transformer resonant balancing circuit without primary winding [51].

The third group is balancing circuits that share a winding between adjacent cells to reduce the number of secondary side windings. One example is the selective ramp transformer (SRT) balancing circuit shown in Figure 2-7(a) [104, 105]. In the SRT balancing circuit, the battery pack is divided into two groups according to cell numbers.
(cells with odd numbers and cells with even numbers) and the adjacent cells share one secondary winding, as shown in Figure 2-7 (a). In each balancing cycle, the charge is transferred from the pack to the cells with lowest voltages in each group.

![Selective ramp transformer (SRT) balancing circuit](image1)

![Class E (CE) balancing circuit with resonance](image2)

Figure 2-7(a). Selective ramp transformer (SRT) balancing circuit [104, 105] (b) class E (CE) balancing circuit with resonance [106].

The other balancing circuit that shares the secondary side winding is the class E (CE) balancing circuit [106] shown in Figure 2-7(b). The balancing operation is controlled by only one switch on the primary side. The balancing speed is slow since it can only balance the whole pack rather than the selected battery pairs with the lowest voltages, like the SRT balancing circuit.

Balancing circuits that can balance the battery pack with strings in parallel have also been invented and one multi-winding parallel transformer (MPT) balancing circuit [107] is shown in Figure 2-8. As shown at the top of the figure, there are two strings in parallel in this battery pack. In the middle of the figure, each cell is connected to other
cells through wires shown in black or through a transformer shown by the red lines. One transformer connects cell B11 and B23 is shown in detail at the bottom of the figure. There is no switch among them and the balancing happens automatically. The speed of this balancing circuit is quicker than that of the transformer-based balancing circuit for one string. However, when the number of cells increases, the number of transformers rises exponentially, causing high costs in implementation.

![Multi-winding parallel (MPT) balancing circuit](image)

**Figure 2-8.** Multi-winding parallel (MPT) balancing circuit [107].

### 2.2 Balancing circuits with SOC or voltage as balancing criterion

In this section, balancing circuits that can apply SOC or voltage as the balancing criterion are reviewed. Some of these balancing circuits are described with the voltage as their balancing criterion based on the literature. However, all the balancing circuits
reviewed in this section have the potential to apply the SOC as the balancing criterion. As discussed in Chapter 1, the SOC can accurately reflect the battery state and is not affected by the voltage characteristics of the batteries. Many balancing systems have been designed to use the SOC as the balancing criterion. In these balancing systems, the balancing procedure can generally be divided into four stages: measurement, SOC estimation, control and balancing. In the first stage, the terminal voltages and currents of each battery cell are measured. In the second stage, the SOC is estimated using different methods, based on the measured voltage and current and a battery model. In the control stage, the non-uniformity of the pack is calculated, based on SOC difference. This SOC difference can be the difference between cells or the difference between the cell and the averaged SOC of the pack. The differences are compared with a pre-set threshold. If any difference is higher than the threshold, the balancing operation commences. In the fourth stage, the charge can be transferred from the cell with the highest SOC to the cell with the lowest SOC, or from the cell to its adjacent cell (cell-to-cell mode), or the charge can be transferred from the cell with the highest SOC to the battery pack (cell-to-pack mode), or the charge can be transferred from the battery pack to the cell with the lowest SOC (pack-to-cell mode). The balancing continues until all the differences are less than the threshold. During the balancing stage, the duration of the switch-on or switch-off can be fixed or changeable.

When the SOC is used as the balancing criterion, the accuracy of SOC estimation in the battery pack during the balancing process is critical. Two methods are used to accurately estimate the SOC in the battery pack with the balancing operation. The first method estimates the cell SOC through an observer, which needs the whole battery pack including the balancing circuits [108]. However, this requires a very high calculation load and it is therefore only tested with simulation in the literature. The second method applies the traditional SOC estimation methods developed for single cells to the battery pack by adding the balancing current, which is unique for pack with balancing operation compared with a single cell, as presented in this thesis. The balancing current changes dynamically, since the balancing operation is generally running at high frequency.
Therefore, the sensors with high sample rate are used for balancing the current. The number of current sensors determines the implementation cost, since the number is proportional to the cell number in many balancing circuits.

### 2.2.1 Transformer-based balancing circuits

One of the transformer-based balancing circuits that can use SOC as the balancing criterion is the switched multiple winding transformer (SMWT) balancing circuit shown in Figure 2-9(a) [109-111]. In this balancing circuit, each battery cell has one transformer controlled by a separate switch on the battery side. The diode on the primary side of the transformer decides the direction of the balancing current. This balancing system transfers charges from the strongest cell to the pack. The balancing process has two steps. First, the switch of the strongest battery cell is turned on. The charge of this cell is sent to the transformer and stored in a magnetic field. Second, the switch is turned off and the charge in the transformer is transferred to the whole pack. The balancing current can also be described by Equation (2-7). The SMWT balancing circuit is expensive since each cell needs its own transformer and switch.
Figure 2-9(a). Switched multiple winding transformer (SMWT) balancing circuit [109-111] (b) and bidirectional multi-winding transformer (BMWT) balancing circuit [41, 75, 112].

To reduce the cost, a bidirectional multi-winding transformer (BMWT) balancing circuit has been proposed as shown in Figure 2-9 (b) [41, 75, 112]. In the BMWT balancing circuit, each cell has its own secondary side winding and shares one primary winding. The switch on the primary side decides when the balancing operation starts and the switches on the secondary side choose the cell to be balanced. The balancing procedure is the same as that of the SMWT balancing circuit.

Another balancing circuit is the flyback balancing circuit shown in Figure 2-10 (a) [113-115]. In this balancing circuit, each battery cell has two switches and it works only in pack-to-cell mode. In the balancing process, first the switch on the primary side is turned on and the charge from the pack is transferred to the flyback converter. This primary switch is then turned off and the switches with the chosen cell in the secondary side are turned on at the same time, which allows the charge to transfer to the selected
cell. To reduce the number of switches and save costs, a flyback two-stage switching matrix (FTSM) balancing circuit has been proposed, in which each cell has only one switch.

Figure 2-10(a). Flyback balancing circuit (b) flyback two-stage switching matrix (FTSM) balancing circuit [113-115].

On the other hand, a time-shared flyback (TF) balancing circuit with cell-to-pack mode has been invented to reduce the number of switches referring to Figure 2-11 [49]. In the TF balancing circuit, the cell with the highest SOC is discharged and the charge is then transferred to the pack through the flyback converter. This cell-to-pack mode is preferred, particularly during the charging process.
Figure 2-11. Time-shared flyback (TF) balancing circuit [49].

These transformer-based balancing circuits are good candidates for modularization, which reduces the pressure on the switches in a long string [83, 84, 86, 116-120]. Modularization has two different methods: encapsulation and interrelation.

In the encapsulation method, every module can be taken as a single battery cell. The balancing circuit balances the cells in the module first and then the module works as a cell to participate in the pack-balancing operation. Different balancing circuits can be modularized based on this principle. One example is the capacitor modularization (CM) balancing circuit shown in Figure 2-12(a) [82], where the balancing circuit within a module is a multiple-winding transformer.
Figure 2-12(a). Capacitor modularization (CM) balancing circuit [82] (b) two-stage capsulated modularization (TCM) balancing circuit [116, 117].

The cascade technique can also be applied to the modularization with capsulation method, as shown in Figure 2-12 (b), where a two-stage capsulate modularization (TCM) balancing circuit is proposed [116, 117]. This balancing circuit inherits the advantages of cascaded balancing circuits, such as low voltage pressure and cost. In this balancing circuit, the high balancing current from the pack can be transferred to the weakest cell in a module directly, increasing the speed.

In the inter-relation method, each module is cooperative with the adjacent modules. Therefore, each modularization with inter-relation is specially designed. One modularization approach designed with the interrelation method is the dynamic switch-changing (DSC) balancing circuit, shown in Figure 2-13(a) [121]. In the DSC balancing
circuit, buses A and B connect different modules with switches. Charge from different modules can be injected into one selected cell to accelerate the balancing speed.

Figure 2-13(a). Dynamic switch-changing (DSC) balancing circuit [121] (b) interrelated-transformer (IT) balancing circuit [84].

Another modularized balancing circuit using the inter-relation method is the inter-related-transformer (IT) balancing circuit shown in Figure 2-13(b) [84]. In the IT balancing circuit, each cell connects to the secondary side of its separate transformer. The primary side of the transformer can be connected to other modules by changing the switch states. When a cell with low voltage is targeted, two modules in the string
transfer the charge to this cell at the same time. This increases the balancing speed. However, the design of this balancing circuit and controller is complicated.

The last group of transformer-based balancing circuits is balancing circuits with inductor coupling. One version is the bidirectional coupled-inductor (BCI) balancing circuit [48] shown in Figure 2-14(a). In this balancing circuit, each battery cell has two switches for bidirectional operation and two cells share one coupled inductor. Compared with the traditional bidirectional adjacent inductor-based balancing circuit, the number of inductors is halved. At the same time, the speed of the BCI balancing circuit is accelerated, because the charge can be transferred between any two cells through the coupling in two steps.

Another version is the bridged multi-winding transformer (BMT) balancing circuit [85] presented in Figure 2-14 (b). The pack is modularized using multi-winding transformers. Every four cells share one transformer with four windings. Two of the windings balance the adjacent cells and the other two windings connect to the transformers in the adjacent modules.
2.2.2 Inductor-based balancing circuits

Inductor-based balancing circuits can use SOC as the balancing criterion, since an inductor can transfer the charge to the selected cell arbitrarily and the cell voltages do not affect charge transfer. Generally, they can be categorized into three groups: buck-boost converter-based balancing circuits, Ćuk converter-based balancing circuit and interleaved converter-based balancing circuit.
A. Buck-boost converter-based balancing circuits

The buck-boost converter (BBC) balancing circuit [122, 123] shown in Figure 2-15(a) is based on the buck-boost converter. The balancing operation can be divided into two steps. In the first step, the inductor is set in parallel to the cell with higher SOC by the switch and the charge is transferred to the inductor. In the second step, the switch sets the inductor in parallel with the adjacent battery cell and the charge in the inductor is transferred to the adjacent cell.

\[
I_{i,j+1} = \frac{1}{2} \left( \frac{V_{\text{cell},i} D^2 - V_{\text{cell},i+1} (1 - D)^2}{L_{i,j+1} f_{sw}} \right)
\]  

(2-8)

Figure 2-15(a). Buck boost converter (BBC) balancing circuit [122, 123] (b) improved buck boost converter (IBBC) balancing circuit [47].
where, $f_{sw}$ is the switching frequency, $D$ is the duty cycle and $L_{i,i+1}$ is the inductor value between $Cell_i$ and $Cell_{i+1}$.

The energy loss can be calculated by

$$P_{loss} = I_L^2 R_{sw} + I_L^2 R_L$$  \hspace{1cm} (2-9)$$

The BBC balancing circuit has been improved with the coupling of adjacent inductors in the improved buck boost converter (IBBC) balancing circuit [47] shown in Figure 2-15(b). It increases the power density at the cost of complicated coupling. In this balancing circuit, it is hard to obtain accurate cell-balancing current since each cell needs an accurate current sensor to achieve the goal. This presents a challenge to applying the SOC as the balancing criterion.

The resonant technique is used to improve the efficiency and reduce the stress on the components in the BBC balancing circuit shown in Figure 2-16, where a capacitor and inductor pair is added to produce resonance [77, 124]. The drawback of this balancing circuit is that the number of the component is increased, which leads to higher cost.
Another improvement to the BBC balancing circuit is a centralized buck-boost (CB) balancing circuit, as shown in Figure 2-17. In this balancing circuit, the charge transfer is unidirectional and therefore half of the switches are replaced with diodes to reduce the cost. The CB balancing circuit transfers the charge to the central cell first and then the charge in the central cell is injected back into the pack through a flyback transformer [46]. Compared with the BBC balancing circuit, this balancing circuit halves the transfer steps for a battery pack when two imbalanced cells are located at the ends of the string.
Figure 2-17. Centralized buck-boost (CB) balancing circuit [46].

Some of the balancing circuits derived from the BBC balancing circuits are good candidates to apply the SOC as the balancing criterion for two main reasons. Firstly, the cells can be chosen and balanced arbitrarily through the switch matrix. Secondly, all of them have two buses, which means that only one balancing current sensor is needed to obtain the balancing current for all cells. This helps to obtain the accurate cell current required for SOC estimation at low cost.

The first of this type is the single inductor (SI) balancing circuit shown in Figure 2-18 [52]. In the SI balancing circuit, one centralized inductor is used to reduce the cost. This inductor is shared by all the cells through a switch matrix. In the SI balancing circuit, the weakest cell and the strongest cell in the pack can be balanced directly in one step, leading to fast balancing speed. On the other hand, since all the cells share one inductor, there is congestion when many cells need to be balanced. This affects the speed of balancing.
The balancing current is

$$I_L = \frac{1}{2} \left( \frac{V_{cell} D^2 - V_{bat} (1-D)^2}{L f_{sw}} \right)$$

(2-10)

The energy loss can be calculated by

$$P_{loss} = 2I_L^2 R_{sw} + I_L^2 R_L$$

(2-11)

Figure 2-18. Single-inductor balancing circuit [52].

The second is the integrated inductor and capacitor (IIC) balancing circuit, where a super capacitor is added in series with the inductor in the SI balancing circuit to temporarily store the charge, as shown in Figure 2-19 [59]. The charge is then transferred to the battery pack through a buck-boost converter. The use of the capacitor in the circuit improves efficiency. In the IIC balancing circuit, the balancing procedure needs to be well designed to avoid short circuits.
The third is the dual inductor (DI) balancing circuit, which is designed with a parallel capacitor to store the energy before it is transferred to the pack, as shown in Figure 2-20 (a) [125]. The DI balancing circuit shares the same switch matrix as the SI balancing circuit. The design of the DI balancing circuit helps alleviate the challenge caused by the switch operation with high frequency in the balancing process.
The fourth type is the resonant LC and boost converter (RLBC) balancing circuit shown in Figure 2-20 (b) [126]. The RLBC balancing circuit also uses a switch matrix to select the battery cell. The charge transfer part combines advantages of the boost converter and the LC converter. In addition, resonance is used in the LC converter to increase efficiency.

Another two balancing circuits are derived from BBC balancing circuit [127-132]: the capacitor-assisted boost converter (CABC) balancing circuit shown in Figure 2-21 (a) and the inductor-based boost converter (IBBC) balancing circuit shown in Figure 2-21 (b). In the CABC balancing circuit [127-130], the cell with highest voltage is identified first. In the charging operation, firstly, the switch of the selected cell is turned on and its charge is transferred to its inductor. Then the switch is turned off and the charge in the inductor is stored in the capacitor through the downstream batteries.
Finally, the charge stored in the capacitor is transferred back to the pack by a paralleled inductor. The IBBC balancing circuit uses only inductors [131, 132]. For the cell on the top of the string, the charge of this cell is transferred to its inductor first and then the charge in the inductor is sent to the downstream batteries. For the other cells, their charges are stored in their inductors first and then transferred to the upstream batteries. The control algorithms of these two balancing circuits must be carefully designed to ensure that all the cells are dynamically balanced. These balancing circuits are not good candidates to use the SOC as the balancing criterion since each cell needs one current sensor to obtain the balancing current.

![Diagrams](image)

**Figure 2-21(a).** Capacitor assisted boost converter (CABC) balancing circuit [127-130] (b) inductor based boost converter (IBBC) balancing circuit [131, 132].

Finally, based on the BBC balancing circuit, a multi-switched inductor (MSI) balancing circuit shown in Figure 2-22 has been designed to further reduce the number of switches and reduce costs [50, 74]. In this MSI balancing circuit, each battery cell needs only one switch and one inductor. This balancing circuit has the fewest
components per cell. However, a complicated control algorithm is required, due to the shared components and the controller needs to be designed carefully to avoid short circuits.

![Multi-switched inductor (MSI) balancing circuit](image)

Figure 2-22. Multi-switched inductor (MSI) balancing circuit [50, 74].

**B. Cûk converter-based balancing circuit**

The Cûk converter (CC) balancing circuit shown in Figure 2-23 belongs to the third group. In this balancing process, the charge is first transferred to the capacitor from the cell with higher voltage or SOC and then the charge in the capacitor is transferred to the adjacent cell. The CC balancing circuit combines the advantages of high efficiency and controllable balancing current. Different FL controllers have been proposed to improve their balancing speed and efficiency [60, 133].
The average balancing current of the Cûk balancing circuit for the inductors can be calculated as

\[
I_{L1} = \frac{1}{2} \left( \frac{V_{cell} D^2 + (V_{cell1} - V_{C12})(1 - D)^2}{L_1 f_{sw}} \right)
\]  

(2-12)

and

\[
I_{L2} = \frac{1}{2} \left( \frac{(V_{cell2} - V_{C12}) D^2 + V_{cell2}(1 - D)^2}{L_2 f_{sw}} \right)
\]  

(2-13)

respectively, where \( D \) is the duty cycle, \( f_{sw} \) is the switching frequency and the \( L1 \) and \( L2 \) are the inductor values.

**C. Interleaved converter-based balancing circuit**

The multiphase interleaved converter (MIC) balancing circuit [134, 135] shown in Figure 2-24 is implemented with the inductor as the main balancing component. In the literature [134], the voltage is used as the balancing criterion and the MIC balancing
circuit can balance the battery pack automatically with a pre-set duty cycle. This MIC balancing circuit can also use SOC as the balancing criterion with a dynamically-changing duty ratio.

The balancing current with the MIC balancing circuit is shown below

\[ I_{l,_{i+1}} = \frac{DV_i - (1-D)V_{i+1}}{DR_{cell_i} + (1-D)(R_{cell_{i+1}} + R_{sw} + R_{l,i+1})} \]  \hspace{1cm} (2-14)

![Figure 2-24. Multiphase interleaved converter (MIC) balancing circuit [134, 135].](image)

**2.2.3 Switch-based balancing circuit with cell bypass**

Switches can also be used as the main balancing components in balancing systems. One example is the shunting switch (SS) balancing circuit in Figure 2-25. This battery pack is designed to have a redundant battery cell and therefore one of the cells can be chosen to connect or disconnect from the pack dynamically, based on the control
algorithm [136] such as a decision-making algorithm [137]. The drawback of the SS balancing circuit is that it disconnects the main current path frequently, which limits the pack capacity.

![Shunting switch (SS) balancing circuit](image)

Figure 2-25. Shunting switch (SS) balancing circuit [136].

The other balancing circuit with switches as the main balancing component is the full bridge (FB) balancing circuit shown in Figure 2-26 [138-141]. In the FB balancing circuit, each cell has four switches, as shown in the top part of the figure. In the charging or discharging process, the states of the switches in the full bridge decide whether the cell is dynamically connected and disconnected to the string or not, ensuring that all the cells can be fully charged or fully discharged simultaneously. Since the main current path needs to be connected and disconnected frequently, it limits the capacity of the battery pack.

This balancing circuit can use SOC as the balancing criterion. However, it is hard to implement it in practice, since each cell needs a current sensor to obtain the accurate balancing current. The cost is very high when the string is long.
2.3 Conclusions

This chapter has systematically reviewed existing active balancing systems, which include balancing circuits, balancing controls and balancing criteria. The balancing circuits have been analysed and are categorized into two groups based on the balancing criterion: balancing circuits that can only use voltage as the balancing criterion and balancing circuits that can use both voltage and SOC as the balancing criteria. The balancing circuits that can apply the SOC as the balancing criterion are further explored to find candidates suitable for real applications at low cost and with easy implementation.

Balancing circuits with two buses have been selected in this thesis, which are transformer-based or inductor-based, as shown in Figure 2-1 denoted with green circles. In a battery pack with balancing systems, the current flowing through each cell in the
pack is affected by the balancing current, which generally changes at high frequency. Balancing circuits with two buses can obtain the balancing current at low cost, since only one additional balancing current sensor is needed in addition to the existing charging or discharging current sensor for the battery pack. This significantly reduces the implementation cost. Accurate measurement of the cell current helps accurate SOC estimation and finally improves the balancing speed of the balancing system during the charging and discharging processes. The details are described in Chapters 3 and 5, respectively.

The balancing circuits that can apply the SOC as the balancing criterion are controllable. The controllability of these balancing circuits focuses on increasing the balancing current of the balancing systems that have low cost. Therefore, the MSI balancing circuit, which has the fewest components per cell, has been selected. The goal of its balancing control is to maintain the balancing current at the initial high value using a newly-designed FL controller for the MSI balancing circuit. The detailed implementation is explained in Chapter 4.
Chapter 3

Active cell balancing approach based on dynamically-estimated state of charge

In this chapter, battery state of charge (SOC) is proposed as the balancing criterion in the charging process and the implementation is reported in detail. The aim is to complete cell equalization in the charging process to charge more capacity into the battery pack, which is presented as one of the main gaps in application in Chapter 1. In this approach, a battery equivalent circuit model (ECM) is used to model the battery. Based on the state space equation derived from the battery ECM, an adaptive extended Kalman filter is applied to dynamically estimate cell SOCs with robustness against model uncertainties. With the selected balancing circuit in Chapter 2, only one additional current sensor is required to detect the balancing current and calculate the current of each cell for SOC estimation. Finally, the results of experiments are reported for a battery pack with three cells in series, and the results show that the proposed approach can charge more capacity into the battery pack than terminal voltage-based approaches. This active balancing approach can be applied to the battery packs in UMEVs and will significantly increase the pack capacity during fast charging operations.
3.1 Introduction

Owing to their high energy density, long life cycle and low self-discharge rate, as discussed in Chapter 1, lithium iron phosphate (LiFePO₄) batteries have become one of the main power candidates for electric vehicles (EVs) [12, 142, 143]. However, since power and energy demands in EVs are high and the voltage of battery packs in EVs is normally above 300 V, battery cells must be connected in series (or parallel) to form a battery pack to meet the demands. For serially-connected cells, state of charge (SOC) imbalance will occur due to their slightly different characteristics and exposure to different operating temperatures. As a consequence of the SOC imbalance, the cells in the pack cannot reach the fully charged state simultaneously and the cell with the least chargeable capacity determines the pack capacity in the charging process, leading to less capacity being charged into the battery pack. Active cell balancing is required to move charge within the pack to equalize cell SOCs, which enables all the cells to be fully charged. As a result, more capacity can be charged into the battery pack at the end of the charging process [118].

Battery terminal voltage is widely used as the balancing criterion in the charging process as it can be easily measured and embedded into all kinds of balancing circuits [45, 58, 133]. However, it has certain limitations. Firstly, the battery terminal voltage may not be able to represent the open circuit voltage (OCV) and therefore SOC. Balancing the terminal voltage of each cell in the pack may not result in balancing the SOC in each cell. Secondly, LiFePO₄ batteries have flat voltage outputs in the range of SOCs from about 20% to 90%, as shown in Figure 3-1. The voltage difference during this plateau may be less than 0.1V. With the terminal voltage as the balancing criterion, balancing may only happen in the initial and final stages of the charging process, which is too short to achieve the balancing goal before the end of charging.

Battery SOC is also used as the balancing criterion. The existing SOC-based approaches are mainly used for cell balancing without charging (off-charge period) [108, 111, 115]. In [97], the SOC-based approach is applied to equalize the cells,
and the capacitor-based balancing topology relies on the voltage difference between the chosen cell and the capacitor to generate the balancing current. For a LiFePO$_4$ battery pack, the small voltage difference in the flat voltage plateau leads to a small balancing current, which will not allow the balancing process to be completed before the end of charging. In addition, there is lack of detailed explanation of SOC estimation in the balancing process [144]. Another issue is that there are current differences for the serially-connected cells in the pack due to the superposition of a balancing current to a charging current. Ignoring the balancing current may cause significant SOC estimation errors, particularly when the balancing current is designed to be a high value comparable with the charging current in this study, with the aim of completing the balancing operation before the end of charging. One way to solve this problem is to add current sensors for all cells in the pack to measure the current, which will be very expensive.

Figure 3-1. Relationship between terminal voltage and SOC of LiFePO$_4$ battery in charging process through experiment.
In this chapter, an active cell balancing approach for a LiFePO$_4$ battery pack is proposed to complete the balancing process before the end of charging. The main contributions of this chapter are: 1. An adaptive extended Kalman filter (AEKF) is applied to dynamically estimate cell states of charge (SOCs) in the balancing process. 2. Based on the dynamically-estimated SOC, an active cell balancing approach is used to equalize the cells in a LiFePO$_4$ battery pack in the charging process. 3. Balancing can be completed in the charging process to allow more capacity to be charged into the battery pack. 4. Only one additional balancing current sensor is required to measure balancing current, and together with the already-embedded charging current sensor, the current of each cell can be calculated in real time for accurate SOC estimation.

The remainder of this chapter is organized as follows: Section 3.2 explains the battery model and parameter extraction. Section 3.3 presents the adaptive extended Kalman filter (AEKF) for SOC estimation. Section 3.4 introduces the balancing circuit topology, together with the current calculation of each cell in the pack for SOC estimation. In Section 3.5, the proposed active balancing approach based on the SOC is experimentally verified and compared with the active balancing approach based on terminal voltage. The conclusions are presented in Section 3.6.

3.2 Battery modelling and parameter identification

Currently, capacitors are widely used to represent batteries in cell balancing [93, 116]. In the present study, the battery equivalent circuit model (ECM) shown in Figure 3-2 is adopted to accurately reflect the dynamic behaviours of LiFePO$_4$ batteries [145-147], where $V_t$ and $I$ represent battery terminal voltage and current, respectively; $R_{in}$ is an internal resistance characterizing the instant voltage drop; a parallel branch of a resistance $R_{pe}$ and a capacitance $C_{pe}$ represent electrochemical polarization and another parallel branch of a resistance $R_{pc}$ and a capacitance $C_{pc}$ represent concentration
polarization; these two branches reflect the short-term and long-term transient responses of the battery. The symbols $\Delta V_{oc}$, $\Delta R_{in}$, $\Delta R_{pc}$, $\Delta C_{pe}$, $\Delta R_{pc}$, and $\Delta C_{pc}$ are associated with process errors and noises. They stand for the differences (errors) between a real battery cell and the model, which are caused by two reasons. Firstly, there are the modelling errors. The battery basically relies on electro-chemical reactions and its responses change with the temperature and the SOC. The ECM cannot represent all battery characteristics. Secondly, there are linearization errors. The non-linear relationship between the OCV and SOC has been linearized in the following battery-state space equations for SOC estimation.

![Schematic diagram of battery equivalent circuit model.](image)

The capacitance $C_n$ represents the total charge stored in the battery by converting the capacity in Ah into the charge in Coulomb

$$C_n = 3600 \cdot C_{battery}$$  \hspace{1cm} (3-1)
where, $C_{\text{battery}}$ is the battery capacity in Ah. The voltage $V_{\text{SOC}}$ across the capacitance $C_n$ represents the SOC and its value is set between 0 and 1 V corresponding to 0% and 100%.

The SOC is a relative quantity that describes the ratio of the remaining capacity to the normal capacity for the battery. It is defined as

$$Z(t) = Z(0) + \left(1/C_n\right) \int_{t_0}^{t} I(\tau) d\tau$$  \hspace{1cm} (3-2)

where, $Z(0)$ is the initial SOC of the battery. The time deviation of the SOC gives

$$\frac{dZ}{dt} = I / C_n$$  \hspace{1cm} (3-3)

According to Kirchhoff’s voltage law, the battery terminal voltage and the derivatives of polarization voltages in Figure 3-2 are determined by

$$V_t = V_{oc}(Z) + V_{pe} + V_{pc} + I \cdot R_0$$  \hspace{1cm} (3-4)

$$\frac{dV_{pc}}{dt} = -V_{pc}/(R_{pc} \cdot C_{pc}) + I / C_{pc}$$  \hspace{1cm} (3-5)

$$\frac{dV_{pe}}{dt} = -V_{pc}/(R_{pe} \cdot C_{pe}) + I / C_{pe}$$  \hspace{1cm} (3-6)

The relationship between the OCV and the SOC is expressed as

$$V_{oc}(Z) = \lambda_0 + \lambda_1 \cdot Z + \lambda_2 \cdot Z^2 + \lambda_3 \cdot Z^3 + \lambda_4 \cdot Z^4 + \lambda_5 \cdot Z^5 + \lambda_6 \cdot Z^6 + \lambda_7 \cdot Z^7$$  \hspace{1cm} (3-7)

where, $\lambda_i (i = 0, \ldots, 7)$ are the coefficients which can be obtained by fitting the experimental data of the OCV versus the SOC.

Due to the fast sampling rate, the change rates of charging currents are taken as zero in each sampling period. Solving the current $I$ and substituting it into Eq (3-3) leads to
the equation for the derivative of the SOC. Therefore, the state-space equation of the battery is developed as follows

\[
\begin{align*}
\frac{dZ}{dt} & = \alpha_1 \cdot [V_i - V_{pc}(Z) + V_{pe} + V_{oc}] \\
\frac{dV_{pc}}{dt} & = \alpha_2 \cdot V_{pc} + b_2 \cdot I \\
\frac{dV_{pe}}{dt} & = \alpha_3 \cdot V_{pe} + b_3 \cdot I
\end{align*}
\]  

\tag{3-8}

where,

\[
\alpha_1 = \frac{1}{R_{pc} C_n} \quad \alpha_2 = -\left(\frac{1}{R_{pc} C_{pc}}\right) \quad \alpha_3 = -\left(\frac{1}{R_{pe} C_{pe}}\right)
\]

\[
b_2 = \frac{1}{C_{pc}} \quad b_3 = \frac{1}{C_{pe}}
\]

The model parameters are obtained by fitting the experimental data from the pulse constant current (PCC) test as shown in Figure 3-3. A LiFePO4 battery (A123 ANR26650) with the nominal capacity of 2.3Ah was tested under room temperature. The cell was first fully discharged with 2.3A until the voltage reached 2V. Then, the cell is rested for one hour to obtain the initial OCV. The current profile of the PCCs shown in Figure 3-3(a) was then used to charge the battery, and a one-hour rest was inserted to obtain the OCV for every 10% SOC increment in the charging process. Figure 3-3 (b) shows the transient voltage corresponding to the PCC, and the part circled in red is zoomed in Figure 3-3(c). Since the battery model parameters corresponding to the pulse at the SOC of 70% cause the highest SOC estimation error, the parameters obtained at this SOC were applied in the model for SOC estimation.

Intuitively, the relaxation voltage in Figure 3-3(c) can be represented by

\[
V_i(t) = V_{oc} - V_{pe} \exp(-t / \tau_{pe}) - V_{pc} \exp(-t / \tau_{pc})
\]  

\tag{3-9}

where, \(\Delta V_i\) represents the voltage drop caused by the internal resistance \(R_{in}\). Therefore, it can be calculated by
Next, the root mean square error method was used to determine \( V_{pe}, V_{pc}, \tau_{pe}, \) and \( \tau_{pc} \) in Eq. (3-9) [145], and the resistances and capacitances in the two parallel branches were calculated by

\[
\begin{align*}
R_{pe} & = \frac{V_{pe}}{I} \\
R_{pc} & = \frac{V_{pc}}{I} \\
C_{pe} & = \frac{\tau_{pe}}{R_{pe}} \\
C_{pc} & = \frac{\tau_{pc}}{R_{pc}}
\end{align*}
\]  

(3-11)

All these parameters were substituted into Eq. (3-9) to calculate the transient voltage. The transient responses obtained from Eq. (3-9) were then compared with the experimental results in Figure 3-3 (d). The fitted values show a good agreement with the experiment results. Table 3-1 lists all these parameters. From Figure 3-3 (a) and (b), the relationship between the OCV and the SOC is also obtained, as shown in Figure 3-4. This relationship is fitted by Eq. (3-7) and its coefficients are listed in Table 3-1.

Table 3-1. PARAMETERS FOR EQUIVALENT CIRCUIT MODEL OF A BATTERY CELL.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( C_n (F) )</th>
<th>( R_n (m\Omega) )</th>
<th>( C_{pe} (F) )</th>
<th>( R_{pe} (m\Omega) )</th>
<th>( C_{pc} (F) )</th>
<th>( R_{pc} (m\Omega) )</th>
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<td>16</td>
<td>3958</td>
<td>15.3</td>
<td>86094</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( \lambda_0 )</th>
<th>( \lambda_1 )</th>
<th>( \lambda_2 )</th>
<th>( \lambda_3 )</th>
<th>( \lambda_4 )</th>
<th>( \lambda_5 )</th>
<th>( \lambda_6 )</th>
<th>( \lambda_7 )</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2.819</td>
<td>9.432</td>
<td>-84.32</td>
<td>380.6</td>
<td>-927.9</td>
<td>1240</td>
<td>-854.2</td>
<td>237.1</td>
</tr>
</tbody>
</table>
Figure 3-3. Experimental results of PCC test (a) pulse charge currents (b) terminal voltage responses (c) zoomed transient terminal voltage response corresponding to seventh current pulse (d) comparison of curve fitting and experimental results.
3.3 Adaptive extended Kalman filter for cell SOC estimation in pack

Ampere hour (Ah) counting is a widely-used approach for SOC estimation because of its ease of implementation. The disadvantages are that it cannot decide the initial SOC and its estimation errors accumulate in the process over time. The battery OCV is taken to calibrate the SOC [116]. Unfortunately, it is hard to measure the OCV in real time and a small OCV error may lead to a significant SOC difference, particularly for the flat plateau of a LiFePO$_4$ battery. In the present study, the adaptive extended Kalman filter (AEKF) was applied to directly estimate the SOC.

The AEKF for SOC estimation combines the advantages of the Ah counting method and the battery ECM-based SOC estimation method [148]. The noises and errors are
Chapter 3 Active cell balancing approach based on dynamically-estimated state of charge

taken into consideration in the filter gain to obtain the optimal estimation results. A fading memory factor is used in the AEKF [149]. This fading memory factor serves to increase the uncertainty of the state estimation and give more credibility to the measurement.

When process errors and measurement noises are considered, the state space Eqs. (3-3 to 3-8) of the battery dynamic system can be generalized as

\[
\begin{align*}
    x_k &= f(x_k, u_k, \omega_k) \\
    y_k &= h(x_k, v_k)
\end{align*}
\]  
(3-12)

\[
\begin{align*}
    \omega_k &\sim (0, Q_k) \\
    v_k &\sim (0, R_k)
\end{align*}
\]  
(3-13)

where, \( x \) is a state vector \( [Z_k \ V_{pck} \ V_{pek}]^T \); \( y \) is an output vector which represents the battery terminal voltage; \( \omega_k \) is the process Gaussian noises with the covariance of \( Q_k \); and \( v_k \) is a measurement Gaussian noises with the covariance of \( R_k \).

The Jacobian matrixes of partial derivatives from the state space equation are listed as follows:

\[
A_{k-1} = \frac{\partial f}{\partial x} \bigg|_{x_{k-1}} = \begin{bmatrix} -\left( \lambda_1 + 2\lambda_2 \cdot Z_{k-1} + 3\lambda_3 \cdot Z_{k-1}^2 + 4\lambda_4 \cdot Z_{k-1}^3 + 5\lambda_5 \cdot Z_{k-1}^4 + 6\lambda_6 \cdot Z_{k-1}^5 + 7\lambda_7 \cdot Z_{k-1}^6 \right) \cdot \alpha_i & \alpha_i & \alpha_i \\ 0 & \alpha_2 & 0 \\ 0 & 0 & \alpha_3 \end{bmatrix}
\]

\[
B_{k-1} = \frac{\partial f}{\partial u} \bigg|_{u_{k-1}} = [0; b_2; b_3]^T
\]

\[
H_k = \frac{\partial h}{\partial x} \bigg|_{x_{k}} = \begin{bmatrix} \lambda_1 + 2\lambda_2 \cdot Z_k + 3\lambda_3 \cdot Z_k^2 + 4\lambda_4 \cdot Z_k^3 + 5\lambda_5 \cdot Z_k^4 + 6\lambda_6 \cdot Z_k^5 + 7\lambda_7 \cdot Z_k^6 & 1 \\
\end{bmatrix}
\]

The linearized state equation including noises can then be generalized as
The steps for optimal SOC estimation with the AEKF can be summarized as follows:

Step 1): Initialization: the initial \( x_0 \) is estimated as a Gaussian random vector with mean of \( x_0 \) and covariance of \( P_0 \).

\[
\begin{align*}
\hat{x}_0^i &= E[x_0] \\
\hat{P}_0^i &= E[(x_0 - \hat{x}_0^i)(x_0 - \hat{x}_0^i)^T]
\end{align*}
\] (3-15)

Step 2): Time update (from time \((k-1)^+\) to time \(k^-\)): the current state estimation is obtained, based on the state estimation and its covariance in the previous step.

\[
\begin{align*}
\bar{P}_k^- &= \alpha^2 A_{k-1}^T \bar{P}_{k-1}^r A_{k-1} + Q_{k-1} \\
\hat{x}_k^- &= A_{k-1} \hat{x}_{k-1}^r + G_{k-1} u_{k-1}
\end{align*}
\] (3-16)

where, \( \bar{P}_k^- = \alpha^{2k} P_{k^-} \), \( \bar{P}_{k-1}^r = \alpha^{2(k-1)} P_{k-1}^r \), \( \alpha \) is the fading memory factor and its value is equal to or higher than 1. It is set at 1.0001 in this study.

Step 3): Kalman gain update:

\[
K_k = \bar{P}_k^r H_k^T (H_k \bar{P}_k^r H_k^T + R_k)^{-1}
\] (3-17)

Step 4): Discrete measurement update: the estimated state \( \hat{x}_k^- \) is updated when the measurement is available. The covariance is also updated. The estimated state and covariance are presented by

\[
\begin{align*}
\hat{x}_k^+ &= \hat{x}_k^- + K_k (y_k - h_k(\hat{x}_k^-, 0, t_k)) \\
\bar{P}_k^+ &= (I - K_k H_k) \bar{P}_k^- (I - K_k H_k)^T + K_k R_k K_k^T
\end{align*}
\] (3-18)
where, $\tilde{P}_k^+ = \alpha^{2k} P_k^+$. 

The initial parameters of the AEKF are obtained based on the trial and error method with the general guideline to set large initial covariance values relatively to the parameters. For instance, the initial parameters of the battery cell for the PCC test are tuned to be

$$x_0 = [0.1 \ 0.01 \ 0.01], \quad R_0 = [20]$$

$$Q_0 = \begin{bmatrix} 0.05 & 0 & 0 \\ 0 & 0.2 & 0 \\ 0 & 0 & 0.2 \end{bmatrix}, \quad P_0 = \begin{bmatrix} 100 & 0 & 0 \\ 0 & 0.01 & 0 \\ 0 & 0 & 0.01 \end{bmatrix}$$

### 3.4 Current calculation of each cell with fly-back converter based balancing circuit

Battery SOC is the preferred balancing criterion to equalize LiFePO$_4$ battery cells in the pack. However, the SOC balancing criterion cannot be applied to all developed balancing circuits due to the nature of the balancing components and their topologies. Based on the main balancing components, active balancing circuits are divided into three groups: capacitor-based [58, 59, 69, 90, 91, 93, 95, 97, 99], inductor-based [1, 46, 50, 52, 60, 62, 74, 77, 114, 134, 150, 151], and transformer-based [41, 48, 49, 51, 66, 71, 72, 84, 86, 116]. In capacitor-based balancing circuits, the terminal voltage difference among the cells in the pack determines the peak amplitude and the direction of balancing currents. Therefore, there is no benefit in using the SOC as the balancing criterion in these circuits. In inductor- and transformer-based balancing circuits, generally the balancing currents in the circuits can be controlled, and the SOC can always be used as the balancing criterion, except that some transformer-based balancing circuits are specially designed to use terminal voltage as the balancing criterion to equalize the pack.
A flyback converter-based balancing circuit shown in Figure 3-5 [86], which is one kind of transformer-based balancing circuit, was selected to implement the balancing operation in this study. In this circuit, only one additional current sensor is added to calculate the current \( I_i(t) \) of each cell in the battery pack during the balancing operation. The balancing current sensor measures the balancing current \( I_{b1} \), and the existing charging current sensor measures the charging current \( I(t) \). The current of each cell \( I_i(t) \) is then calculated by

\[
I_i(t) = \begin{cases} 
I(t) - I_{b1} + I_{b2} & \text{Balanced cell} \\
I(t) + I_{b2} & \text{Other cells}
\end{cases}
\]  

(3-18)

The balancing current sensor measures the balancing current in the low voltage side to improve the accuracy of current measurement, and the current \( I_{b2} \) in the high voltage side is calculated by

\[
I_{b2} = (N_1/N_2) \cdot I_{b1} \cdot \eta 
\]  

(3-19)

where, \( N_1 \) and \( N_2 \) are the ratios of the flyback transformer and \( \eta \) is the efficiency of the flyback converter. In the balancing operation, as the switches are turned on/off at high frequency, the balancing current of each cell is averaged first and then added to the charging current to obtain \( I_i(t) \), which is used in the AEKF for SOC estimation at each step.

This balancing circuit can select any cells in the pack for the balancing operation through a switch matrix in two operation modes: the cell-to-pack mode (CTP) and the pack-to-cell mode (PTC). In the CTP mode, the cell with the highest SOC or terminal voltage is discharged and releases charges back to the pack via the flyback converter. In the PTC mode, the cell with the lowest SOC or terminal voltage is identified and the charges from the pack are injected into this cell.
In the experiment, the converter was running in discontinuous conduction mode with the peak balancing current limited to 1.5 A. The duty cycle of the PWM control signal for the MOFET was 0.4 and the frequency was 10kHz. The sampling frequency of the current sensor was set at 50 kHz. The inductor values of the flyback converter were 70uH and 930uH for the low voltage side and high voltage side, respectively. The efficiency of the converter is about 65%, based on the experimental data.

Figure 3-5. Flyback converter-based balancing circuit with battery pack.

3.5 Experimental verification

To evaluate the performance of the proposed active balancing approach, a testing platform for active cell balancing was established, as shown in Figure 3-6. It mainly consists of a battery pack charger, a serially-connected battery pack, a flyback converter-based balancing circuit, a NI controller, an Arbin BT2000, a power supply and a computer. The battery pack charger is a Serensen programmable power supply,
which can set the charging current and voltage. The battery pack is made of three A123 LiFePO$_4$ battery cells connected in series and their specifications are listed in Table 3-2. The NI controller consists of a FPGA module and a real-time control module. The FPGA module is responsible for the measurement of the current and terminal voltage of each cell in the battery pack and the control of the switches for the balancing circuit. The real-time module is the hardware implementation of the AEKF for the SOC estimation algorithm and the balancing control algorithm, which were developed using the LabVIEW program. The Arbin BT2000 is responsible for the initialization of each single cell before the charging process starts. The power supply supports the NI controller and the balancing circuit. Finally, the computer is responsible for data storage and analysis as well as being the control interface of the NI controller. It also sets the charging algorithm for the battery pack charger.

Figure 3-6. Configuration of the test platform for implementation of different balancing criteria.
To apply the AEKF to estimate the SOCs of the three cells in the battery pack, it was assumed that the model parameters and the OCV versus the SOC of three cells were the same, as shown in Table 3-1 and Figure 3-4, respectively. The true initial states of three cells were respectively 0%, 0% and 20% SOCs to create an imbalance scenario, and the Arbin BT2000 was used to fully discharge the first, second and third cells and then only the third cell was charged to 20% SOC. To validate the robustness of the AEKF for SOC estimation, the initial states of three cells for the battery model were unknown and set to the wrong values of 15% SOC. A resting time was allowed for the convergence of the SOC estimation of each cell before the charging process started. In the charging process, the balancing operation commenced when the maximum SOC difference was 2%. As a trade-off between charged pack capacity and charging time, the battery pack stopped charging when the voltage of any battery cell reached the cut-off voltage (3.6V for the selected battery cell). Figure 3-7 shows the experimental results for the proposed active balancing approach using the SOC as the balancing criterion.

Table 3-2. SPECIFICATION OF THREE LIFEPO₄ BATTERY CELLS IN THE PACK.

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Cell One</th>
<th>Cell Two</th>
<th>Cell Three</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal capacity (Ah)</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Tested capacity (Ah)</td>
<td>2.11</td>
<td>2.16</td>
<td>2.17</td>
</tr>
<tr>
<td>Internal resistance (mΩ)</td>
<td>20</td>
<td>16</td>
<td>20</td>
</tr>
</tbody>
</table>

The estimated SOC values of these three cells are shown in Figure 3-7 (a). It can be observed that the SOC difference continues converging with increasing balancing operation time, dropping from the highest SOC difference at the beginning to less than 2% after 2700 seconds. The terminal voltages of these three cells are shown in Figure 3-7 (b). Since cell three has the highest initial SOC, its extra charge is discharged to the pack in the balancing process, and it therefore has the lowest terminal voltage in the plateau. The errors between the estimated SOC and the SOC from the Ah counting...
method, which was taken as the benchmark during the charging process, are shown in Figure 3-7 (c). For cells one and two, the estimation errors are below 1% for most of the time. For cell three, the estimation errors are still well below 2% most of the time.

(a)
Figure 3-7. Pack balancing performance in charging process with the SOC as the balancing criterion. (a) Experimental results for estimated SOCs of three cells during
charging process. (b) Experimental results for terminal voltages of three cells during charging process. (c) SOC estimation errors of three cells during charging process.

To verify the effectiveness of the proposed SOC based balancing criterion, the active balancing results based on the traditional terminal voltage are displayed in Figure 3-8, where the experiment is implemented in the same testing platform with the same settings as shown in Figure 3-6 except the balancing criterion. Considering the accuracy of the voltage sensor, the balancing operation starts when the maximum terminal voltage difference is higher than 20mV.

Figure 3-8 (a) shows the SOC values calculated using the Ah counting method during the charging process. The SOC difference between cell three and the other two cells remains large during the entire charging process. The terminal voltages of the three cells are displayed in Figure 3-8 (b), indicating that there is no balancing operation during most of the charging process. The balancing happens at the beginning when the terminal voltage of cell three is the highest and the maximum voltage difference is larger than 20 mV. Then the terminal voltages of cell one and cell two rise quickly in the initial charging stage and reach the terminal voltage of cell three at around 700 seconds and the balancing stops since the maximum voltage difference in the pack becomes less than 20mV. The balancing starts again near the end of charging process. During the voltage plateau, the terminal voltage of cell three is even slightly lower than other two cells, even though its SOC is still the highest.
Figure 3-8. Pack balancing performance in the charging process with terminal voltage as balancing criterion. (a) Experimental results for Ah counting SOCs of three cells during charging process. (b) Experimental results for terminal voltages of three cells during charging process.
The balancing results with these two balancing criteria are compared in Table 3-3. When the SOC is applied as the balancing criterion, the values of the SOCs for these three cells are 97.86%, 96.65% and 97.61%, respectively, at the end of charging. This shows that the battery pack is well balanced and the charged pack capacity is 2.07Ah. When the terminal voltage is used as the balancing criterion, the values of the SOCs are 86.83%, 85.10% and 98.42%, respectively, at the end of charging. This shows that the battery pack is still unbalanced in terms of the SOC. This is due to the fact that the terminal voltages of the three cells are very close to each other during the voltage plateau, the small voltage difference cannot trigger the balancing process for most of the charging time. Since the cell with the lowest SOC decides the pack capacity, it is found that the charged pack capacity is only 1.83Ah, which is much less than 2.07Ah.

Table 3-3. COMPARISON OF PERFORMANCE OF ACTIVE BALANCING APPROACHES BASED ON SOC AND TERMINAL VOLTAGE AS BALANCING CRITERION

<table>
<thead>
<tr>
<th>Balancing Criteria</th>
<th>SOCs (%)</th>
<th>Charged Pack Capacity (Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cell One</td>
<td>Cell Two</td>
</tr>
<tr>
<td>SOC</td>
<td>97.86</td>
<td>96.65</td>
</tr>
<tr>
<td>Voltage</td>
<td>86.83</td>
<td>85.10</td>
</tr>
</tbody>
</table>

3.6 Conclusions

This chapter has presented an improved active balancing approach using the dynamically-estimated SOC for a LiFePO₄ battery pack in the charging process. The robust AKEF was proposed to estimate the SOC, based on the state-space equation derived from the ECM. The flyback converter-based balancing circuit was chosen to
implement the proposed method, as only one additional balancing current sensor was required to calculate the current of each cell for SOC estimation. The experimental results of the battery pack consisting of three series-connected cells with SOC imbalances showed that more capacity can be charged to the battery pack with the proposed SOC-based balancing approach than the terminal voltage-based balancing approach.
Chapter 4

Fuzzy logic control of multi-switched inductor balancing circuit for lithium-ion battery packs

In Chapter 3, dynamically-estimated SOC is proposed as the balancing criterion to increase the balancing speed. In this chapter, a fuzzy logic (FL) controller is proposed to control a battery pack balancing system in order to increase the balancing speed. The battery pack balancing system is based on the multi-switched inductor (MSI) balancing circuit selected in Chapter 2. In the proposed FL controller, the cell’s open circuit voltage (OCV) and its OCV difference in the pack are used as the inputs. The outputs of the FL controller are the inductor balancing currents. Because of the improved fuzzy membership function, the battery characteristics can be included in the control design. A prototype of a lithium-ion battery pack balancing system with the FL and PI controllers was built to evaluate balancing performances. The experimental results show that the balancing system with the FL controller achieves much faster balancing speed and recovers more pack capacity than that with the PI controller. This balancing control
method therefore has the potential to be applied in UMEVs to further improve balancing speed and increase useable pack capacity.

4.1 Introduction

Battery balancing systems are generally categorized into two groups: passive and active [152]. Passive balancing systems turn extra energy from the cells with higher voltage or SOC into heat through shunt resistance at low implementation cost. Owing to thermal concerns, the balancing current has to be small, resulting in low balancing speed. Active balancing systems transfer charge or energy within a pack through balancing circuits to maximize pack capacity. These balancing systems can potentially have high balancing currents and high balancing speed.

In active balancing systems, the balancing circuits (BCs) can be divided into three groups on the basis of the main component which transfers charge or energy among the cells in a pack: capacitor-based balancing circuits (CBCs) [56, 58, 69, 91, 95], transformer-based balancing circuits (TBCs) [41, 48, 49, 51, 71, 72, 84, 86, 153] and inductor-based balancing circuits (IBCs) [1, 46, 50, 60-62, 74, 77, 114, 122, 132, 134, 154, 155]. CBCs generally have low implementation cost, but their balancing speed is slow, especially when the voltage differences among the cells in the pack are low. TBCs typically have high balancing speed, but their cost is high due to the transformer. IBCs have overall better performance with a trade-off between balancing speed and cost [45].

In IBCs, two families of BCs are widely used [45]: Cuk converter-based BCs (CukBCs) [60-62, 77, 114, 154] and buck-boost converter-based BCs (Buck-BoostBCs) [1, 46, 50, 74, 155]. Generally, there are more components in the CukBCs than the Buck-BoostBCs. Among the Buck-BoostBCs, the multi-switched inductor BC (MSIBC) is the simplest to date, requiring only one MOSFET and one inductor for each cell [74]. Therefore, the MSIBC was chosen to implement the FL controller in this study.
A PI controller has been applied to the MSIBC [50]. In this balancing system, the balancing current is adjusted to the highest amplitude because the largest voltage difference of the cells is at the beginning of the balancing process and the balancing current declines quickly when the voltage differences between the cells become smaller in the process of balancing. A PI controller with constant gain cannot adjust its balancing current adaptively, which severely affects balancing performance.

A FL controller is proposed to replace the PI controller in the MSIBC in order to improve balancing performance. It controls the amplitudes and directions of balancing currents by changing the off-state duration of MOSFETs; it maintains high balancing currents and achieves high balancing speed during the balancing process, compared with the PI controller. The FL controller has also been applied to the CukBC by changing the frequency of MOSFETs [60-62, 154] and to the Buck-BoostBCs by changing the pulse modulation width of MOSFETs [81].

The following parts of this chapter are arranged as follows. In Section 4.2, the MSIBC and the operational principle of the MSIBC with the OCV as a balancing criterion are explained. The design of the FL controller is explained in Section 4.3. Section 4.4 describes the experimental results with the FL and PI controllers. These are discussed in Section 4.5. The conclusions and suggestions for future work are provided in Section 4.6.

4.2 Multi-switched inductor balancing system

4.2.1 Multi-switched inductor balancing circuit

Figure. 4-1 shows a MSIBC-based balancing system [50]. It mainly consists of a MSIBC and a FL controller. The MISBC is operated in different modes. In each mode, one cell is disconnected from the BC. The mode duration, namely, the MOSFET off-
state duration, affects the direction and amplitude of the balancing currents. The FL controller is implemented in the National Instruments (NI) data acquisition platform and FPGA module. The membership functions of the FL controller are designed based on the characteristics of both the balancing circuit and the battery cell.

In the following, a four-cell battery pack is taken as an example to explain the MSIBC, which comprises of three inductors and four power MOSFETs. There are four control signals for the MOSFETs, as shown in Figure 4-2, resulting in four working modes, as shown in Figure 4-3. A short dead-time (DT) is inserted in each mode to avoid short circuits.

Figure 4-1. MSIBC-based balancing system with FL controller.
Chapter 4 Fuzzy logic control of multi-switched inductor balancing circuit for lithium-ion battery packs

Figure 4-2. Control signals of MOSFET.

Figure 4-3. Operation modes of MSIBC in one cycle.
Assuming that the MSIBC operates in the steady state, according to Kirchhoff’s current law, the relationship between the cell balancing current and the mode duration can be expressed as

\[
\begin{bmatrix}
I_{b1} \\
I_{b2} \\
I_{b3} \\
I_{b4}
\end{bmatrix} =
\begin{bmatrix}
-(d_2 + d_3 + d_4) & -(d_3 + d_4) & -d_4 \\
d_1 & -(d_3 + d_4) & -d_4 \\
d_1 & d_1 + d_2 & -d_4 \\
d_1 & d_1 + d_2 & d_1 + d_2 + d_3
\end{bmatrix}
\begin{bmatrix}
I_{L1} \\
I_{L2} \\
I_{L3}
\end{bmatrix} \cdot \left(\frac{1}{T}\right)
\]

where, \(d_x\) represents the mode duration in percentage of one period for mode \(x\) (\(x=1,2,3,4\)) and \(T\) is the switching period. It can be seen from Eq. (4-1) that the cell balancing current is decided by both the inductor current and the mode duration.

According to the volt-second balance, the relationship between the cell voltage and the mode duration can be expressed as [156]:

\[
\begin{align*}
(V_{b2} + V_{b3} + V_{b4}) \cdot d_1 \cdot T + (-V_{b1}) \cdot (d_2 + d_3 + d_4) \cdot T &= 0 \\
(V_{b3} + V_{b4}) \cdot (d_1 + d_2) \cdot T + (-V_{b1} - V_{b2}) \cdot (d_3 + d_4) \cdot T &= 0 \\
V_{b4} \cdot (d_1 + d_2 + d_3) \cdot T + (-V_{b1} - V_{b2} - V_{b3}) \cdot d_4 \cdot T &= 0
\end{align*}
\]

(4-2)

In relation to the inductor resistance \((R_L)\) and the MOSFET conduction resistance \((R_{on})\) in the MSIBC, the relationship between the inductor balancing current and the MOSFET mode duration is given by [74]:

\[
\]
Chapter 4 Fuzzy logic control of multi-switched inductor balancing circuit for lithium-ion battery packs

\[
\begin{align*}
&\left\{ \frac{V_{b1}}{R_{on}} + I_{L1} + I_{L2} + I_{L3} + I_{L1} \frac{R_L}{R_{on}} \\
&\frac{V_{b1} + V_{b2}}{R_{on}} + I_{L1} + 2I_{L2} + 2I_{L3} + I_{L2} \frac{R_L}{R_{on}} \\
&\frac{V_{b1} + V_{b2} + V_{b3}}{R_{on}} + I_{L1} + 2I_{L2} + 3I_{L3} + I_{L3} \frac{R_L}{R_{on}} \right\} = \\
&\left\{ \frac{V_p}{R_{on}} - 2I_{L1} - I_{L2} \quad I_{L2} + I_{L3} \quad I_{L3} \\
&\frac{V_p}{R_{on}} - I_{L1} + I_{L3} \quad \frac{V_p}{R_{on}} + I_{L1} + I_{L3} \quad 2I_{L3} \\
&\frac{V_p}{R_{on}} + I_{L2} + 2I_{L3} \quad \frac{V_p}{R_{on}} + I_{L1} + I_{L2} + 2I_{L3} \quad \frac{V_p}{R_{on}} + I_{L1} + 2I_{L2} + 2I_{L3} \right\} \\
\cdot \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix} \\
\end{align*}
\]

(4-3)

where, \( V_p \) is the pack voltage.

4.2.2 Balancing Principle

The MSIBC uses the inductor to transfer the energy in the cell by switching MOSFETs in sequence. The direction of the energy transfer is decided by both the cell voltage and the mode duration. By changing the ratio of mode-duration to cell-voltage (RMV), the cell balancing current direction can be controlled. If the RMVs of all the cells are the same, the average cell balancing current is zero. If the RMV of one cell is higher than that of the others in the pack, the cell is charged. If the RMV of one cell is lower than that of the others, the cell is discharged. If cell one in the pack is taken as an example, it can be mathematically expressed as:
Based on this principle, the MSIBC can be controlled by constant equal mode duration and the simulation results are shown in Figure 4-4. It can be seen that the balancing current rises to the peak which may be too high for the battery and then drops quickly. This means slow balancing speed when the voltage difference decreases. To improve balancing performance, the FL controller is proposed to control the MSIBC by changing mode duration, leading to the regulation of the amplitude and direction of the balancing current.
Figure 4-4. Simulation results for MSIBC with constant equal mode duration.

4.2.3 Balancing Criterion $V_{oc}$ Estimation

The goal of the balancing operation is to equalize cell SOCs. The measured battery terminal voltage is only a rough indicator of the SOC, as the terminal voltage consists of three components, namely open circuit voltage (OCV), polarization voltage and voltage drop across internal resistances. Of these, only the OCV directly reflects the SOC. Figure 4-5 shows a commonly-used equivalent circuit model (ECM) of a battery. In the ECM, $V_b$ and I represent the battery terminal voltage and current, respectively. The resistance $R_{in}$ describes the instantaneous voltage drop. A parallel branch with a
resistance $R_{diff}$ and a capacitance $C_{diff}$ represents the dynamics of diffusion. When the sample rate of the voltage is high, the diffusion effect of $C_{diff}$ can be ignored [48]. Therefore, the OCV can be approximately calculated by

$$V_{oc} = V_b - V_{diff} - V_R = V_b - I \cdot (R_{diff} + R_{in})$$

(4-5)

where, $V_{oc}$ represents the OCV. $R_{diff} + R_{in}$ is obtained from the experiment and is taken as a constant during the balancing process.

Figure 4-5 Battery equivalent circuit model.
4.3 Fuzzy logic controller design

The fuzzy theory can process imprecise information by degree of membership and is a universal approximator for non-linear mapping between input vectors and scalar outputs in terms of firing fuzzy rules to some degree [157, 158].

A fuzzy logic (FL) controller is the application of the fuzzy theory. Its basic structure consists of three parts: fuzzification, fuzzy inference and defuzzification (see Figure 4-6). In fuzzification, crisp inputs are fuzzified into linguistic variables using membership functions (MFs). In fuzzy inference, there are two parts: an inference engine and a rule base. The inference engine decides the fuzzy logic operations and the rule base stores the control rules based on expert knowledge. The linguistic control outputs are generated by the inference engine. In defuzzification, the linguistic outputs are converted back to the crisp output using the centre of gravity method.

The FL controller of the MISBC is designed to control the inductor currents (see Figure 4-6). The inductor currents are then converted into the mode duration (d) through the balancing circuit model of the pack to turn MOSFETs on/off in sequence. The mode duration controls the amplitude and direction of the balancing currents. The $V_d$ in Figure 4-6 is cell OCV difference of adjacent cells and it is defined in Eq. (4-6).
4.3.1 Membership Functions

A MF defines how each point of the variable in the input space is mapped to a degree of membership between 0 and 1. There are two fuzzy input variables: cell OCV \((V_{oc})\) and cell OCV difference \((V_d)\), and one fuzzy output variable: inductor current \((I_L)\). The OCV difference of cell \(i\) is defined as:

\[
V_{d_i} = V_{oc_i} - V_{oc_{i+1}}
\]  

(4-6)

A LiFePO\(_4\) battery is used as an example to explain the membership design. The OCV of the LiFePO4 battery is described by five linguistic variables, i.e., VS (very small), S (small), M (medium), L (large), and VL (very large) in triangular and trapezoidal forms, as shown in Figure. 4-7. Since the LiFePO4 battery has a very flat voltage around 3.3V, the membership functions concentrate to 3.3V. The OCV difference \(V_d\) and the inductor current \(I_L\) are described by the same five linguistic variables as the OCV, i.e., NV (negative large), N (negative), Z (around zero), P
(positive) and PV (positive large), as shown in Figures 8 and 9, respectively. The $V_d$ range covers all the possible cell voltage differences in the pack. However, in most cases these difference values are between -0.1V and 0.1V, which is shown in the enlarged figure. Since the sum of the membership functions at one point is not required to be 1 in the FL system [159], the Gauss membership function is applied to the linguistic variable Z for the membership functions of $V_d$ and $I_L$. This causes the output inductor current drop quickly to near zero when $V_d$ is less than 20mV, reducing the balancing loss and the chance of divergence.

![Figure 4-7. Membership functions of OCVs.](image)
Figure 4-8. Membership function of OCV differences.

Figure 4-9. Membership function of inductor currents.
4.3.2 Fuzzy logic controller

The design of the proposed FL controller is explained and the procedure is summarized as follows [160, 161].

**Step 1**: Determination of fuzzy rules. The rules describe the knowledge about the behaviour of a complex system. These rules with two inputs can be generally expressed as:

\[ R^k: \text{If } X_1 \text{ is } A^k_1 \text{ and } X_2 \text{ is } A^k_2, \text{ Then } Y \text{ is } B^k \quad \text{for } k=1,2, \ldots, n. \] \hspace{1cm} (4-7)

where, \( n \) is the total number of the fuzzy rules and \( R^k \) denotes the \( k \) th rule. \( A^k_1, A^k_2 \) (\( k = 1, 2, \ldots, n \)) and \( B^k \) (\( k = 1, 2, \ldots, n \)) are the fuzzy sub-sets of \( X_1, X_2 \) and \( Y \), respectively. In this study, \( X_1 \) and \( X_2 \) are input linguistic variables \( V_d \) and \( V_{oc} \), respectively, and \( Y \) is output linguistic variable \( I_L \). The detailed fuzzy rules are given in Table 4.I. These rules describe the relation between input and output of the FL controller based on the expert knowledge of LiFePO\(_4\) battery balancing. There are a total of 25 rules. The following are two of the rules.

Rule 01: IF \( V_d = NV \) and \( V_{oc} = VS \) THEN \( I_L = NV \);

Rule 25: IF \( V_d = PV \) and \( V_{oc} = VL \) THEN \( I_L = PV \);
Table 4-1. RULE BASE OF FL CONTROLLER FOR LINGUISTIC VARIABLES.

<table>
<thead>
<tr>
<th>Balancing current</th>
<th>$V_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NV</td>
</tr>
<tr>
<td>VS</td>
<td>NV</td>
</tr>
<tr>
<td>S</td>
<td>NV</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>M</td>
</tr>
<tr>
<td>L</td>
<td>NV</td>
</tr>
<tr>
<td>VL</td>
<td>N</td>
</tr>
</tbody>
</table>

**Step 2:** Fuzzification of the input variables. Fuzzy sets for the variables are determined by the MFs. The crisp inputs are converted into the degree of membership between 0 to 1 using the following equation:

$$x_i = \mu_{d_i}(x_i)$$  \hspace{1cm} (4-8)

where, $x_i$ is the input value of $i$th input variable, and $\mu_{d_i}(x)$ is the fuzzy MF of the input linguistic variables $V_d$ and $V_{oc}$.

**Step 3:** Fuzzy inference. This step applies fuzzy rules to map the given inputs to an output fuzzy set with the FL operations. Max-min composition is utilized. First, the output fuzzy set of each rule with implication operation is computed, and then all the output sets are combined into a single fuzzy set with aggregation operation. Mathematically, the process can be written as

$$u_{k*}(I_L) = \min[u_{k*}(V_d), u_{k*}(V_{oc}), u_{k*}(I_L)], \quad k=1,2,...,n.$$  \hspace{1cm} (4-9)
Chapter 4 Fuzzy logic control of multi-switched inductor balancing circuit for lithium-ion battery packs

\[ u_g(I_L) = \max[k u_g^j(I_L)] \quad k=1,2,...,n. \]  \hspace{1cm} (4-10)

where, \( u_g(I_L) \) denotes the aggregated output fuzzy set.

**Step 4**: Defuzzification of the output. This step converts the inference fuzzy output set to the crisp inductor current \( I_L \). The centre of gravity method is used for defuzzification. It is given by:

\[ I_L = \frac{\int u_g(I_L) \cdot I_L dI_L}{\int u_g(I_L) dI_L} \]  \hspace{1cm} (4-11)

**Step 5**: Obtain the mode durations for each cell. With the inductor currents, the desired mode durations for the first three modes can be calculated by Eq. (4-12) and the fourth mode duration is obtained by subtracting the first three mode durations from the period.

\[ \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix} = \left( \begin{array}{ccc} \frac{V_p}{R_m} - 2I_{L1} - I_{L2} & I_{L2} + I_{L3} & I_{L3} \\ \frac{V_p}{R_m} - I_{L1} + I_{L3} & \frac{V_p}{R_m} + I_{L1} + I_{L3} & 2I_{L3} \\ \frac{V_p}{R_m} + I_{L2} + 2I_{L3} & \frac{V_p}{R_m} + I_{L1} + 2I_{L2} + 2I_{L3} & \frac{V_p}{R_m} + I_{L1} + 2I_{L2} + 2I_{L3} \end{array} \right)^{-1} \]

\[ \begin{pmatrix} \frac{V_{oc1} + V_{oc2}}{R_m} + I_{L1} + I_{L2} + I_{L3} + I_{L1} \frac{R_l}{R_m} \\ \frac{V_{oc1} + V_{oc2}}{R_m} + I_{L1} + 2I_{L2} + 2I_{L3} + I_{L2} \frac{R_l}{R_m} \\ \frac{V_{oc1} + V_{oc2} + V_{oc3}}{R_m} + I_{L1} + 2I_{L2} + 3I_{L3} + I_{L3} \frac{R_l}{R_m} \end{pmatrix} \]  \hspace{1cm} (4-12)

### 4.3.3 Adaptivity

The FL controller has good adaptivity. The inductor current can be regulated based on the feedback of \( V_{oc} \) and \( V_d \). For example, if \( V_d \) is large, a high inductor current is
desired; if $V_d$ is small, a low inductor current is desired. The FL controller can adaptively change the inductor current for different situations.

Considering only $V_d$ as the input with the constant OCV at 3.3V, the equivalent gain and the corresponding inductor current are shown in Figures 4-10 and 4-11, respectively. When $V_d$ is positively or negatively large, the equivalent gain is small to keep the inductor current under the limit. As $V_d$ becomes small, the equivalent gain increases. When $V_d$ is about 25 mV, the equivalent gain reaches its peak value of 70, corresponding to the peak inductor current of 3A. When $V_d$ continues decreasing to 15mV, the equivalent gain starts to decrease sharply to less than 20. At the same time, the inductor current declines to near zero. This prevents divergence for already-balanced cells. For comparison, the gain of the PI controller is shown in Figure 4.10 in the dotted line, which has the same peak inductor current.

Figure 4-10. Equivalent gain for desired inductor current with input $V_d$ at OCV of 3.3V.
Considering both $V_{oc}$ and $V_d$ as inputs, the inductor currents are shown in Figure 4-12. When $V_{oc}$ is higher than 3.5V, representing a SOC higher than 90%, the inductor current is reduced and less balancing current is charged to this cell. When $V_{oc}$ is lower than 3V (about 20% of the SOC), the inductor current is also reduced and less balancing current is discharged from this cell. This mechanism helps protect the battery cells and potentially extend their service life.
4.4 Experimental results

To evaluate its performance, a prototype of the MSIBC was built to balance a four-cell battery pack. A NI FPGA module was used to implement the FL controller for the generation of the PWM to control the MOSFETs in the MSIBC with the frequency of 5 kHz. Initially, all the four cells were fully charged using an Arbin BT2000, then one cell in the pack (e.g. cell four in this test) was discharged by 20% of the tested capacity to create an imbalance scenario.

Once the balancing operation was completed, all the four cells were fully charged again with the Arbin BT2000 to evaluate the balancing effects. Figure 4-13 shows the
performance evaluation platform for the MSIBC. In this platform, the PI controller is also implemented. The experimental results of the FL controller were compared with those of the PI controller.

The LiFePO₄ battery cells from the A123 Company and the NCA battery cells from Samsung were selected in this study. After a screening process, the cells with almost the same internal resistances and capacities in each type were connected in series to make the battery pack. The specifications of these two types of battery cells are listed in Table 4-2.
Table 4-2. SPECIFICATIONS OF TWO TYPES OF BATTERY CELLS.

<table>
<thead>
<tr>
<th>Battery type</th>
<th>LiFePO$_4$</th>
<th>NCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacture company</td>
<td>A123</td>
<td>Samsung</td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>2.3 Ah</td>
<td>2.5 Ah</td>
</tr>
<tr>
<td>Tested capacity</td>
<td>2.13 Ah</td>
<td>2.5 Ah</td>
</tr>
<tr>
<td>Internal resistance</td>
<td>13 m$\Omega$</td>
<td>22 m$\Omega$</td>
</tr>
</tbody>
</table>

The inductor current and the mode duration decide the cell balancing currents based on Eq. (4-1). The highest inductor current was set at 3A and the peak battery balancing current was 4A. The balancing stopped when the OCV difference was less than 10 mV or the balancing time was longer than 3000 seconds.

### 4.4.1 Experimental Results for LiFePO$_4$ battery pack

The LiFePO$_4$ battery has flat voltage characteristics. Figures 4-14 and 4-15 show the OCVs and average balancing currents with the FL and the PI controllers for the LiFePO$_4$ battery cells during the balancing process, respectively. The proportional parameter of PI controller is set as 4, which is decided by the maximum balancing current limit of the hardware and the integral parameter is set as 0.01.

The time to complete experiment depends on the OCV difference, where the difference is set to less than 10mV or the balancing time reaches 3000s, whichever comes first. In this setup, the maximum peak balancing current is set to 2A for both PI
and FL controllers. The balancing operations with the FL controller stopped at around 1000 seconds when the maximum OCV difference reached 10 mV. In contrast, the balancing operation with the PI controller stopped at about 3000 seconds. This is because the FL controller maintains the higher balancing current for a longer time than the PI controller, which can be seen in Figures 4-14 (b) and 4-15 (b), respectively. Furthermore, with the FL controller, the three cells with the same initial OCVs keep converging as the gains among them are very small, as shown in Figure 4-14 (a). With the PI controller, until the balancing operation runs out of time, there are still significant OCV differences, as shown in Figure 4-15 (a) due to the slow balancing speed as a result of the small average balancing currents in the balancing process.

Figure 4-14. Experimental results for LiFePO4 battery pack with FL controller. (a) OCV for each cell; (b) average balancing current for each cell.
4.4.2 Experimental Results for NCA Battery Pack

In contrast with the LiFePO$_4$ battery, the NCA battery has steep voltage characteristics. The OCVs and average balancing currents of the NCA batteries with the FL controller and the PI controller are shown in Figure 4-16 and Figure 4-17, respectively. With the FL controller, the balancing ends at 1500 seconds when the maximum OCV difference reaches 10 mV. The balancing time for the NCA battery is slightly longer than that for the LiFePO$_4$ battery, since the OCVs of the NCA battery drop slowly compared with those of the LiFePO$_4$ battery. The recovered pack capacity...
is the highest in all cases and this is discussed in the next section. With the PI controller, the maximum OCV difference still cannot reach 10 mV within 3000 seconds. The OCVs drop slowly and the average balancing currents for the NCA battery are slightly higher than those for the LiFePO$_4$ battery.

Figure 4-16. Experimental results for NCA battery pack with FL controller. (a) OCV for each cell; (b) Average balancing current for each cell.
Discussion

In the experimental results, accurate battery SOC values and the recovered pack capacities are calculated. In the battery pack connected in series, the weakest cell decides the pack capacity. Therefore, the recovered pack capacity (energy) is the ratio of the increased capacity of the weakest cell to the tested capacity (energy). The balancing results for the A123 LiFePO$_4$ battery pack and the Samsung NCA battery pack are shown in Table 4-3 and Table 4-4, respectively.
As shown in Table 4-3, the FL controller has better balancing performance than the PI controller in the LiFePO$_4$ battery pack. With the PI controller, the final SOC difference is still 10% and 0.1299 Ah is charged to the weakest cell as the recovered pack capacity, increasing the pack capacity by 6%. With the FL controller, the final SOC difference reduces to 7.5% and 0.1758 Ah is charged into the weakest cell as the recovered pack capacity, increasing the pack capacity by 8.25%.

Table 4-3. BALANCING RESULTS FOR LIFEPO4 BATTERY PACK.

<table>
<thead>
<tr>
<th></th>
<th>PI controller</th>
<th>FL controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge (Ah)</td>
<td>Charge (Ah)</td>
<td></td>
</tr>
<tr>
<td>Energy (Wh)</td>
<td>Energy (Wh)</td>
<td></td>
</tr>
<tr>
<td>Cell one</td>
<td>-0.0549</td>
<td>-0.0680</td>
</tr>
<tr>
<td></td>
<td>-0.1933</td>
<td>-0.2386</td>
</tr>
<tr>
<td>Cell two</td>
<td>-0.0680</td>
<td>-0.0697</td>
</tr>
<tr>
<td></td>
<td>-0.2387</td>
<td>-0.2444</td>
</tr>
<tr>
<td>Cell three</td>
<td>-0.0656</td>
<td>-0.0717</td>
</tr>
<tr>
<td></td>
<td>-0.2303</td>
<td>-0.2510</td>
</tr>
<tr>
<td>Cell four</td>
<td>+0.1299</td>
<td>+0.1758</td>
</tr>
<tr>
<td></td>
<td>+0.3675</td>
<td>+0.5327</td>
</tr>
</tbody>
</table>

Capacity (Energy) recovery of cell four

6% (5.1%) 8.25% (7.4%)

In the NCA battery pack, more charges are finally transferred, as shown in Table 4-4 and the final SOC difference is smaller. With the PI controller, 0.2382 Ah are charged to the fourth battery cell and the final maximum SOC difference is 6.5%. With the FL controller, 0.2989 Ah is charged into the fourth cell and the final maximum SOC difference is only 2.5%, which is the best of all cases. The recovered pack capacities are 0.2382 Ah (11.2%) and 0.2989 Ah (14%) for the PI controller and the FL controller, respectively.
Table 4-4. BALANCING RESULTS FOR NCA BATTERY PACK.

<table>
<thead>
<tr>
<th></th>
<th>PI controller</th>
<th>FL controller</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Charge (Ah)</td>
<td>Energy (Wh)</td>
</tr>
<tr>
<td>Cell one</td>
<td>-0.0801</td>
<td>-0.3363</td>
</tr>
<tr>
<td>Cell two</td>
<td>-0.1075</td>
<td>-0.4516</td>
</tr>
<tr>
<td>Cell three</td>
<td>-0.1067</td>
<td>-0.4478</td>
</tr>
<tr>
<td>Cell four</td>
<td>+0.2382</td>
<td>+0.8915</td>
</tr>
</tbody>
</table>

Capacity (Energy) recovery of cell four  

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11.2% (10%)</td>
</tr>
<tr>
<td></td>
<td>14% (12.74%)</td>
</tr>
</tbody>
</table>

4.6 Conclusions

This chapter has presented a FL controller for a battery pack balancing system based on the MSIBC. Experimental results have demonstrated that the proposed FL controller significantly improves the performance of the MSIBC compared with the PI controller. The two controllers were tested with two types of batteries: LiFePO$_4$ and NCA. For the LiFePO$_4$ battery pack, the FL controller achieved a two thirds shorter balancing time than that of the PI controller with the final maximum SOC difference of 7.5%. For the NCA battery pack, the FL controller was also better than the PI controller, reducing the
balancing time by half. With the FL controller, the SOC difference at the end of the balancing process was only 2.5%. In both cases, more pack capacity was recovered with the FL controller than with the PI controller.
Chapter 5

Novel active LiFePO$_4$ battery balancing method based on chargeable and dischargeable capacity

Battery chargeable and discharge capacity are proposed to be the balancing criterion to overcome the non-uniformity of cells in the battery pack in both the charging and discharging processes in this chapter. This balancing criterion can particularly deal with the non-uniformity of cell capacities in aged battery packs with severe capacity non-uniformity. A balancing simulation of a LiFePO$_4$ battery pack was conducted for moderate and severe capacity imbalance scenarios. The simulation results show that the proposed battery balancing method has better performance than the terminal voltage or SOC-based balancing methods. More capacity is charged into the battery pack in the charging process or discharged from the battery pack in the discharging process with the proposed balancing criterion. With this criterion, the usable battery pack capacity in the UMEV can be improved significantly.
Chapter 5 Novel active LiFePO$_4$ battery balancing based on chargeable and dischargeable capacity

5.1 Introduction

Currently, two common balancing criteria used in battery pack balancing are voltage and state of charge (SOC). All existing battery balancing methods (BBMs) can be categorized into two groups based on these two criteria. They are voltage-based BBMs (VBBBMs or VB$_3$Ms) [40, 45, 46, 60, 69, 87, 152, 162, 163] and SOC-based BBMs (SBBBMs or SB$_3$Ms) [4, 41, 97, 115].

VB$_3$Ms equalise cell terminal voltages or minimise differences of cell terminal voltages in the pack to a pre-set threshold voltage using the terminal voltage as a balancing criterion. VB$_3$Ms are the most popular method, as the terminal voltage of each cell can be easily measured during the battery equalisation process. However, these methods have two drawbacks. First, cell terminal voltage does not reflect the SOC directly, because it is the sum of open circuit voltage (OCV), polarization voltage and voltage drop across internal resistance, and only the OCV has an explicit relationship to the SOC. The equalisation of cell terminal voltage does not lead to a balanced SOC. Second, LiFePO$_4$ batteries have flat terminal voltage in the SOC range of about 20% to 90%, as shown in Figure 5-1, and the batteries in EVs normally operate in this SOC range [9]. The voltage variation in this range is less than 0.1V. Such slight voltage differences can hardly be used to effectively balance the SOCs of the cells in the charging and discharging processes.

SB$_3$Ms equalise cell SOCs and minimise differences of cell SOCs in the pack to a pre-set threshold SOC value using the SOC as a balancing criterion [4, 41, 97, 115]. SB$_3$Ms overcome these two drawbacks of the VB$_3$Ms, but still have issues in real applications. First, SOC estimation requires accurate current measurement for each cell. In principle the current sensors are required to add for each cell, which increases hardware complexity and implementation cost. Second, the SB$_3$Ms in [4, 115] apply ampere-hour counting to calculate the SOCs of the cells, which may not be accurate in
environments with high noises and uncertainties in the charging and discharging processes.

The above-mentioned BBMs are not suitable for cell imbalances caused by capacity differences of each cell in the pack due to battery ageing. To solve this problem, a novel BBM is proposed to equalise the cells in the pack through the use of newly-defined balancing criteria: the chargeable capacity (ChaC) during the charging process and the dischargeable capacity (DisC) during the discharging process. To implement the proposed method, the ChaC and DisC of each cell must be estimated. They are respectively defined as

\[
CC_i(t) = (1 - Z_i(t)) \cdot C_i
\]

\[
DC_i(t) = Z_i(t) \cdot C_i
\]

where, \( Z_i(t) \) is the dynamically estimated SOC of cell i at time t and \( C_i \) is the estimated cell capacity in each charging and discharging cycle.
Figure 5-1. Relationship between SOC and terminal voltage for LiFePO₄ battery.

Since the ChaC and the DisC combine the information of the SOC and the capacity of the cell, the proposed BBM can balance cells of different capacities in a series-connected battery pack from the initial stage of charging or discharging, while the differences of terminal voltages or SOCs of these cells at this stage are hard to be detected. This will provide more available balancing time during charging and discharging to maximise both the energy delivered to the cells during the charging process and the energy released from the cells during the discharging process.

The rest of this chapter is arranged as follows: Section 5.2 explains the working principle of the proposed BBM. Section 5.3 introduces the simulation platform established in MATLAB/Simulink. The simulation results of the proposed BBM are compared with those of the VB³Ms and SB³Ms to validate the effectiveness of the proposed BBM in Section 5.4. The conclusions are given in Section 5.5.

5.2 Novel battery balancing method

The novel BBM applies the balancing criterion of the ChaC in the charging process and the DisC in the discharging process. Therefore, it is essential to obtain the values of the ChaC and the DisC, which rely on the determination of the current of each cell and the estimation of the SOC and capacity of each cell in the battery pack.

5.2.1 Battery cell current determination

The proposed BBM is implemented on the specially-selected battery balancing circuit shown in Figure 5-2 [116]. It works in two operational modes: the cell-to-pack (CTP) mode and the pack-to-cell (PTC) mode. In the CTP mode, the strongest cell is identified to release energy back to the pack via the fly-back converter. In the PTC
mode, the weakest cell is identified to accept the energy from the pack. Due to safety concerns, the CTP mode is usually used in the charging process and the PTC mode is applied in the discharge process.

![Battery balancing circuits.](image)

The purpose of selecting this circuit is that only one extra balancing current sensor is needed to calculate the current of each cell. This balancing current sensor is responsible for measuring the current of the cell which is selected to release or accept energy for the balancing operation through a switch matrix. Since only one cell is selected and connected to the fly-back transformer at any given time, the resultant current of the selected cell and the other cells can be calculated as
Chapter 5 Novel active LiFePO$_4$ battery balancing based on chargeable and dischargeable capacity

\[ I_t(t) = \begin{cases} I(t) - I_{bl} + I_{b2} & \text{Selected Cell} \\ I(t) + I_{b2} & \text{Other Cells} \end{cases} \]  

(5-3)

\[ I_{b2} = (N_1 / N_2) \cdot I_{bl} \]  

(5-4)

where, \(I(t)\) is the charging or discharging current, \(I_{bl}\) stands for the average current to send or release to the selected cell, \(I_{b2}\) represents the average current to send or release to the battery pack, and \(N_1\) and \(N_2\) are the number of turns at the primary and secondary sides of the transformer, respectively.

5.2.2 Battery cell SOC determination

A. Battery modelling

Battery equivalent circuit models (BECMs) are widely used to capture the dynamic characteristics of LiFePO$_4$ batteries [147, 164, 165]. The BECM shown in Figure 3-2 in Chapter 3 was selected [166, 167]. In the BECM, \(V_t\) and \(I\) represent the battery terminal voltage and the current, respectively. The instant voltage drop is characterized by a resistance \(R_{in}\). Electrochemical polarization is represented by a parallel branch with a resistance \(R_{pe}\) and a capacitance \(C_{pe}\); the concentration polarization is represented by a parallel branch with a resistance \(R_{pc}\) and a capacitance \(C_{pc}\). These two branches reflect the short-term and long-term transient responses of the battery; \(C_n\) is the capacity of the battery which is decaying due to battery ageing. \(\Delta V_{oc}, \Delta R_{in}, \Delta R_{pe}, \Delta C_{pe}, \Delta R_{pc}\) and \(\Delta C_{pc}\) are associated with the model errors which are caused for the following two reasons. Firstly, the battery relies on electro-chemical reactions to deliver or store the energy, and the BECM cannot represent all battery characteristics electrically. Secondly,
the non-linear relationship between the OCV and the SOC has been linearized in the battery state-space equations for SOC estimation, which causes linearization error.

The SOC is defined as the ratio of the remaining charge to the capacity of the cell, which can be expressed as

\[
Z_i(t) = Z_i(0) - \left(\frac{1}{Cn_i(j)}\right) \int_{t_0}^{t} \eta \cdot i_i(\tau) d\tau
\]  

(5-5)

where, \(Z_i(0)\) is its initial SOC, \(Cn_i(j)\) is the cell capacity in cycle \(j\), \(\eta\) stands for the coulomb efficiency and \(i_i(\tau)\) is the current passing the cell; it will be positive if the cell is discharged or negative if the cell is charged.

The time derivative of the SOC gives

\[
\dot{Z}_i(t) = -\frac{\eta \cdot i_i(t)}{Cn_i(j)}
\]  

(5-6)

According to the Kirchhoff voltage law, the cell terminal voltage and the derivatives of polarisation voltages in Figure 3-2 are given by

\[
V_{ni} = V_{oc,i}(Z) - V_{pei} - V_{pci} - I_i \cdot R_{mi}
\]  

(5-7)

\[
\dot{V}_{pei} = -\frac{V_{pei}}{\left(R_{pei} \cdot C_{pei}\right)} + \frac{I_i}{C_{pei}}
\]  

(5-8)

\[
\dot{V}_{pci} = -\frac{V_{pci}}{\left(R_{pci} \cdot C_{pci}\right)} + \frac{I_i}{C_{pci}}
\]  

(5-9)

The relationship between the OCV and the SOC is shown in Figure 3-4 [168] in Chapter 3. Such a relationship is piecewise linearized by

\[
V_{oc,i}(Z_i) = \kappa \cdot Z_i + \lambda
\]  

(5-10)

where, the values of \(\kappa\) and \(\lambda\) vary with SOCs.
Due to the fast sampling rate, the changing rates of charging or discharging currents are taken as zero within one sampling period. Then, the time derivative of terminal voltage in Eq. (5-7), with the substitutions of Eqs. (5-8) - (5-10), gives

\[
\dot{V}_t = -\kappa \cdot (\eta \cdot I_i / Cn_i(j)) + V_{pei} / (R_{pei} \cdot C_{pei}) - I_i / C_{pei} + V_{pci} / (R_{pci} \cdot C_{pci}) - I_i / C_{pci} \tag{5-11}
\]

Solving \( I_i \) in Eq. (5-7) and substituting it into Eq. (5-6) and rearranging Eqs. (5-7) to (5-11) result in the state-space equations of the BECM as follows:

\[
\begin{align*}
\dot{V}_t & = -\alpha_1 \cdot V_t + \alpha_1 \cdot V_{oc}(Z_i) - \alpha_2 \cdot V_{pei} - \alpha_3 \cdot V_{pci} - b_1 \cdot I_i \\
\dot{Z}_i & = \alpha_2 \cdot [V_t - V_{pci}(Z_i) + V_{pei} + V_{pci}] \\
\dot{V}_{pei} & = \alpha_3 \cdot V_{pei} + b_3 \cdot I_i \\
\dot{V}_{pci} & = \alpha_4 \cdot V_{pci} + b_4 \cdot I_i
\end{align*}
\tag{5-12}
\]

where,

\[
\begin{align*}
\alpha_1 & = 1 / (R_{pei} \cdot C_{pei}) + 1 / (R_{pci} \cdot C_{pci}) \\
\alpha_2 & = 1 / (R_{ini} \cdot C_i) \\
\alpha_3 & = -1 / (R_{pci} \cdot C_{pci}) \\
\alpha_4 & = -1 / (R_{pei} \cdot C_{pei}) \\
b_1 & = \kappa \cdot \eta / Cn_i(j) + R_{ini} / (R_{pci} \cdot C_{pci}) + R_{ini} / (R_{pci} \cdot C_{pci}) + 1 / C_{pci} + 1 / C_{pci} \\
b_3 & = 1 / C_{pci} \\
b_4 & = 1 / C_{pci}
\end{align*}
\]

The parameters in the model are obtained by fitting the experimental data from the pulse charge current (PCC) test as shown in Figure 3-3 in Chapter 3. According to the experimental results of the selected LiFePO₄ battery with the nominal capacity of 2.3 Ah and nominal voltage of 3.6 V, the parameters are extracted at the seventh pulse
current because the SOC estimation error at this pulse is the highest within the plateau, which is expected to severely affect the balancing operation. The corresponding part is circled in red and is amplified in Figure 3-3(c).

Since the capacitance value $C_n$ of the battery model is very large, if this value is used in the simulation with high balancing frequency, it will take several days with MATLAB. To reduce the simulation time, a scaled-down battery model which keeps all the voltage characteristics of the battery is proposed in this study. As a result, all capacitances in the battery model are scaled down by 10,000 times. Table 5-1 shows the parameters of the BECM and the scaled-down BECM.

Table 5-1. PARAMETERS OF BECM AND SCALED-DOWN BECM.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>BECM</th>
<th>Scaled-down BECM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Capacity(Ah)$</td>
<td>2.1369</td>
<td>2.1369e-4</td>
</tr>
<tr>
<td>$R_m(\Omega)$</td>
<td>0.016</td>
<td>0.016</td>
</tr>
<tr>
<td>$C_{pc}(F)$</td>
<td>3958</td>
<td>0.3958</td>
</tr>
<tr>
<td>$R_{pe}(\Omega)$</td>
<td>0.0153</td>
<td>0.0153</td>
</tr>
<tr>
<td>$C_{pe}(F)$</td>
<td>86094</td>
<td>8.6094</td>
</tr>
<tr>
<td>$R_{pe}(\Omega)$</td>
<td>0.009</td>
<td>0.009</td>
</tr>
</tbody>
</table>

A. SOC estimation

The battery SOC with the Coulomb counting method relies on the measurement of the battery current. This measurement is usually polluted by noises and sensor errors, particularly in the charging and discharging processes. The Kalman filter (KF) can obtain the minimum mean-square state error estimation and alleviate the influence of measurement noises on the estimated state. The extended KF (EKF) is the non-linear version of the KF and the system’s dynamics are linearized around the estimated state.
EKF is widely used for SOC estimation [167]. Although a battery is a continuous system, the measured voltage and current are discrete. The hybrid EKF (HEKF) is applied for dynamic SOC estimation in the charging and discharge processes for balancing operations [149]. When the process errors and measurement noises are considered, Eq. (5-12) can be generalized as

\[
\begin{align*}
{x'} &= f(x,u,w,t) \\
y_k &= h_k(x_k,v_k)
\end{align*}
\]

(5-13)

\[
\begin{align*}
w(t) &= (0,Q) \\
v_k &= (0,R_k)
\end{align*}
\]

(5-14)

where, \(x\) is the state vector \(\begin{bmatrix} V_i & Z & V_{pc} & V_{pe} \end{bmatrix}^T\); \(y\) is the output vector and represents the measured battery terminal voltage. The battery terminal voltage is represented by Eq. (5-7); \(w(t)\) is the process Gaussian noises with mean of 0 and covariance of \(Q\) caused by model errors; and \(v_k\) is measurement Gaussian noise with mean of 0 and covariance of \(R_k\). This battery model is non-linear and therefore it is linearized at each step. Linearization errors are also treated as a part of the process noise. The Jacobian matrices of partial derivatives from Eq. (5-12) are listed as follows:

\[
A = \frac{\partial f}{\partial x} = \begin{bmatrix}
\alpha_1 & \kappa \cdot \alpha_1 & \alpha_3 & \alpha_4 \\
\alpha_2 & -\kappa \cdot \alpha_2 & \alpha_2 & \alpha_2 \\
0 & 0 & \alpha_3 & 0 \\
0 & 0 & 0 & \alpha_4
\end{bmatrix}
\]

\[
B = \frac{\partial f}{\partial u} = \begin{bmatrix} h_1; 0; b_3; b_4 \end{bmatrix}
\]

\[
L = \frac{\partial f}{\partial w} 
\]

\[
H_k = \frac{\partial h}{\partial x} = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}
\]

\[
M_k = \frac{\partial h}{\partial v} = \begin{bmatrix} \end{bmatrix}
\]

The linearized state equation including noises can be generalized as follows:
\begin{align}
\dot{x} &= Ax + Bu + LQl^T \\
y_k &= H_kx_k + M_kR_kM_k^T
\end{align}
(5-15)

The steps for optimal state estimation with the HEKF can be summarized as follows:

**Step 1**: Initialization: The initial $x_0$ is estimated as a Gaussian random vector with mean of $x_0$ and covariance of $P_0$

\[
\begin{aligned}
\hat{x}_0^e &= E[x_0] \\
\hat{P}_0^e &= E[(x_0 - \hat{x}_0^e)(x_0 - \hat{x}_0^e)^T]
\end{aligned}
\]  
(5-16)

**Step 2**: Time update (from time $(k-1)^+$ to time $k^-$): The current state estimation is obtained based on the state estimation and its covariance in the previous step.

\[
\begin{aligned}
\dot{\hat{x}} &= f(\hat{x}, u, 0, t) \\
\hat{P} &= AP + PA^T + LQl^T
\end{aligned}
\]  
(5-17)

**Step 3**: Discrete measurement update: The estimated state $\hat{x}_k^-$ is updated when the measurement is available. The covariance is also updated and they are presented in the following equations:

\[
\begin{aligned}
K_k &= P_k^-H_k^T(H_kP_k^-H_k^T + M_kR_kM_k^T)^{-1} \\
\hat{x}_k^- &= \hat{x}_k^- + K_k(y_k - h_k(\hat{x}_k^-, 0, t_k)) \\
P_k^+ &= (I - K_kH_k^-)P_k^-(I - K_kH_k^-)^T + K_kM_kR_kM_k^TK_k^-
\end{aligned}
\]  
(5-18)

Based on the trial and error method, the initial parameters for the HEKF are tuned to be

$$x_0 = [3.0 \quad 0.1 \quad 0.01 \quad 0.01], \quad R = [20]$$
Chapter 5 Novel active LiFePO₄ battery balancing based on chargeable and dischargeable capacity

\[ Q = \begin{bmatrix} 10 & 0 & 0 & 0 \\ 0 & 0.05 & 0 & 0 \\ 0 & 0 & 0.2 & 0 \\ 0 & 0 & 0 & 0.2 \end{bmatrix}, \quad P_0 = \begin{bmatrix} 100 & 0 & 0 & 0 \\ 0 & 100 & 0 & 0 \\ 0 & 0 & 0.01 & 0 \\ 0 & 0 & 0 & 0.01 \end{bmatrix} \]

The above-described HEKF for the SOC estimation has been verified in our previous work [169].

5.2.3 Battery cell capacity determination

When the EV is being driven, it is not possible to obtain the exact capacity of a cell by fully charging or discharging each cell completely. The capacity has to be estimated, particularly for aged battery packs [108, 170]. In the present study, the capacity is estimated with the information of the estimated SOC and ampere hour counting as follows [171]:

\[
C_{n_i}(j) = C_{\alpha,\beta} = \frac{Q_{\alpha} - Q_{\beta}}{SOC_{\alpha} - SOC_{\beta}} = \frac{\int_{t_{\alpha}}^{t_{\beta}} I_i(t)dt}{SOC_j(t_{\alpha}) - SOC_j(t_{\beta})} \tag{5-19}
\]

where, \( t_{\alpha} \) and \( t_{\beta} \) are the starting time and the end time of the estimation, respectively. They should be in the same charging or discharging process. Since the cell capacity declines slowly, it is estimated every ten cycles in this study.

5.2.4 Balancing procedures of proposed BBM

The proposed BBM applies the ChaC and the DisC as balancing criteria in the charging and discharging process, respectively. Since the balancing procedure of the proposed BBM in the discharging process is similar to that in the charging process, only
the balancing procedure in the charging process is explained in detail. It is divided into five steps.

**Step i:** Initialization and charge. At the beginning, the battery management system (BMS) is initialized. The BMS acquires the battery cell states, such as current, voltage, temperature and the SOC, and checks whether all of these parameters meet the safety conditions. If there is no safety violation, the charging process starts.

**Step ii:** Measurement update. While the charging process continues, the terminal voltages of each cell are measured for safety checks and SOC estimation. If the balancing operation is on, the charging current and balancing currents are also measured. The charging current is measured one sample per second (S/S) as they are almost constant, and if the charging current is less than 0.05A, the pack is considered as fully charged and the charging process terminates. The balancing currents are measured at a much higher sampling rate of 50K S/S to capture accurate data in the high frequency balancing operation, and these balancing currents are then averaged per second to synchronize with the charging current. Finally, the currents of each cell are calculated based on Eqs. (5-3) and (5-4).

**Step iii:** ChaC update. Based on the calculated currents and measured voltages of each cell in Step ii, the SOCs and the capacity of each are estimated. Then, the ChaCs are updated. The capacity is estimated based on Eq. (5-19) every ten cycles when no balancing operation is carried out and taken as constant until the next estimation. The ChaCs of each cell are compared, and if the maximum ChaC difference exceeds the pre-set threshold D, the balancing operation commences. Otherwise, it goes back to step ii.

**Step iv:** Balancing operation. The balancing operation moves the charges within the pack. In the charging process, the CTP strategy is applied. The cell with the highest ChaC is selected and discharged back to the battery pack. After each second, the procedure goes back to step ii.
Step v: Stop charging. In the charging and balancing processes, the voltage and SOC values are checked, and if they violate the thresholds, the charging and balancing processes stop immediately.

Figure 5-3 shows the flowchart of the balancing procedure in the charging process.
5.3 Simulation Platform

A simulation platform has been established to investigate the BBMs with different balancing criteria. In the platform, eight cells are connected in series to make a battery pack. The parameters of the cell extracted from the experimental data for the scaled-down BECM as shown in Table 5-1 are adopted as the mean values to generate the parameters for the eight cells according to the normal distribution with the covariance of 0.01. These generated parameters for the eight cells are used as the base values. Furthermore, the cell in the middle of the battery pack has the highest temperature and its maximum temperature difference from the cell in the outside is five degrees [35]. This uneven temperature distribution [35, 36] can cause capacity imbalance. The LiFePO$_4$ ageing model is incorporated in the cell model in the simulation platform [37] to reflect the influence of life cycle on cell capacity. Consequently, two scenarios of capacity imbalance are considered: a pack with moderate capacity imbalance (equivalent to 500 cycles) and a pack with severe capacity imbalance (equivalent to 800 cycles). The average cell capacities for the moderate and severe capacity imbalances are 89% and 83% of their nominal capacities, respectively, and their final cell capacity distributions for each scenario are listed in Table 5-2.
Table 5-2. CELL CAPACITY DISTRIBUTIONS IN PACKS FOR MODERATE AND SEVERE CAPACITY IMBALANCES SCENARIOS.

<table>
<thead>
<tr>
<th>Initial Scenario (Ah)</th>
<th>Scenario I Imbalance(Ah)</th>
<th>Scenario II Imbalance(Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1 2.1364</td>
<td>1.94</td>
<td>1.8301</td>
</tr>
<tr>
<td>Cell 2 2.1369</td>
<td>1.9003</td>
<td>1.7679</td>
</tr>
<tr>
<td>Cell 3 2.1375</td>
<td>1.9247</td>
<td>1.8056</td>
</tr>
<tr>
<td>Cell 4 2.1386</td>
<td>1.8794</td>
<td>1.7344</td>
</tr>
<tr>
<td>Cell 5 2.1358</td>
<td>1.7917</td>
<td>1.6019</td>
</tr>
<tr>
<td>Cell 6 2.1375</td>
<td>1.9106</td>
<td>1.7837</td>
</tr>
<tr>
<td>Cell 7 2.1367</td>
<td>1.9242</td>
<td>1.8053</td>
</tr>
<tr>
<td>Cell 8 2.1361</td>
<td>1.9211</td>
<td>1.8008</td>
</tr>
</tbody>
</table>

The ChaC and the DisC values are the keys to the proposed BBM and are applied as the new criteria for the balancing operation. The ChaC and the DisC are explained in detail in section 5.1. The balancing circuit and balancing procedure are discussed in step 1 and 5 in this section, respectively. The peak balancing current is limited to 0.2A. The operational frequency of the MOSFET is 10 kHz.

The BMS sets the simulation environment. First, it sets the balancing thresholds for different criteria. The VB\textsuperscript{3}M starts to balance when the maximum voltage difference is higher than 20 mV. The SB\textsuperscript{3}M starts to balance when the maximum SOC difference is higher than 2%. The proposed BBM commences the balancing operation when the
maximum ChaC or DisC difference is higher than 2% of the cell’s nominal capacity. These thresholds are set to offset the measurement or estimation errors and the effects of the noise. Second, it sets the profile of the charging and discharging process. To make this balancing operation suitable for real EV applications, five hours are taken as the average driving time with fully-charged LiFePO₄ batteries for EVs in [7] and also the time in which the present study aims to complete the balancing operation. As a result, the discharging current is set at 0.13C and the charging current is set at 0.33C. Third, it sets the safety constraints and the stop conditions. In the charging process, when the SOC or terminal voltage of any cell in the pack reaches 100% or 3.6 V, the charging stops. In the discharging process, the cut-off SOC or terminal voltage is set at 20% or 2 V.

### 5.4 Simulation Results and Discussion

#### 5.4.1 Simulation Results

Using the established platform, three different balancing methods, namely VB³M, SB³M and the proposed BBM, were investigated for two capacity imbalance scenarios in the charging and discharging processes. To show the simulation results, the figures are arranged in this way: the top and middle show the SOC values and the balancing currents in the balancing process, respectively. The bottom shows the zoomed SOCs of all the cells around the end of the charging process marked in the square in the middle.
A. Moderate capacity imbalance scenario

Figure 5-4 shows the simulation results of the battery pack with the moderate capacity imbalance using three balancing methods. Figure 5-4(a) illustrates the simulation results of the VB$^3$M. As indicated by the balancing currents, the balancing operation only happens at the end of the charging process and the beginning of the discharge process. This is caused by the flat voltage plateau of the LiFePO$_4$ battery, because in this plateau the terminal voltage differences among all the cells are very small and hardly be detected. Since this plateau constitutes most of the charging and discharging time, this makes the balancing time very short and leads to poor balancing performance, as shown at the bottom of the figure, where the SOC differences are significant at the end of the charging process.

Figure 5-4(b) shows the simulation results of the SB$^3$M. As indicated by the balancing currents, the balancing operation still works in the voltage plateau which extends the balancing time. Therefore, the SB$^3$M can allow more capacity to be charged and discharged than the VB$^3$M. However, the balancing operation is only concentrated at the end of both the charging and discharging processes. For the beginning of both the charging and discharging processes, the detectable SOC imbalance has not yet been developed to trigger the balancing operation. As a result, on the one hand, the battery pack may not have sufficient time to be fully balanced; on the other hand, the current passing the cell at the end stages of both the charging and discharging processes increases as the balancing currents are superimposed on the charging current. This high current may affect the life of the cells, as the cell charging and discharging capabilities decrease sharply in these periods.

Figure 5-4(c) shows the simulation results of the proposed BBM. This method has the best performance, and has several advantages compared to the VB$^3$M the SB$^3$M. First, the proposed BBM can use the charging and discharging time fully. It starts the
balancing operation at the beginning of the charging or discharging process, based on the difference of the ChaC or DisC values among all the cells, even when the SOC or voltage difference has not yet been detected. The proposed BBM makes the balancing time longer than the other two BBMs. Second, the proposed BBM causes the balancing operation to coincide with the charging and discharging capabilities of the battery cell. This is due to the fact that the balancing operation in the proposed BBM is concentrated at the beginning of the charging and discharge processes, which helps avoid the constant voltage charging period in the charging process and the low SOC period in the discharging process when the cell has weak ability to accept high charging or discharging currents.
Chapter 5 Novel active LiFePO$_4$ battery balancing based on chargeable and dischargeable capacity

(b)
Figure 5-4. Simulation results for battery pack with moderate capacity imbalance using (a) VB3M (b) SB3M and (c) proposed BBM.

B. Severe capacity imbalance scenario

The simulation results for the battery pack with severe capacity imbalance (e.g. the aged battery pack) are shown in Figure 5-5. The VB3M still has the worst performance, whilst the proposed BBM has the best results. This scenario fully displays the adaptivity of the proposed BBM. There are several features worth mentioning. Firstly, the performance of the VB3M shows little improvement, as indicated in Figure 5-5(a). It still has short balancing time, as shown in the middle of the figure. This indicates that
the VB<sup>3</sup>M is not suitable for the LiFePO<sub>4</sub> battery pack in operational conditions. Secondly, the SB<sup>3</sup>M performs well and the balancing time increases dramatically, as shown in Figure 5-5 (b). The balancing time is longer than that in the moderate capacity imbalance scenario in both the charging and discharging processes. However, the disadvantages of this method still exist. The proposed BBM has the longest balancing time, as illustrated in Figure 5-5(c). In fact, this is the only method that achieves the balancing goal before the discharging process ends. This method has the best adaptivity to different scenarios.

(a)
Chapter 5 Novel active LiFePO₄ battery balancing based on chargeable and dischargeable capacity

(b)
5.4.2 Discussion

For EVs, the driving distance or time is the main concern, and depends on the available capacity of the battery pack being delivered. This in turn relies on the charged capacity during the charging process and the discharged capacity during the discharging process. Therefore, the simulation results for the charged capacity and discharged capacity of the battery pack using three different BBMs for two scenarios are compared.
in Table 5-3. The results of the scaled-down model have been scaled up and those without balancing are used as a benchmark.

In the moderate capacity imbalance scenario, the discharged capacity using the VB\textsuperscript{3}M is almost the same as that without balancing (the benchmark). The discharged pack capacity using the SB\textsuperscript{3}M has slightly increased by 1.7% to 1.414Ah and the battery pack with the proposed BBM has been improved by 3.6% to the highest discharged pack capacity of 1.444Ah. Therefore, the proposed BBM can extend driving distance or time compared with the pack without the balancing operation or with the VB\textsuperscript{3}M. In the severe capacity imbalance scenario, the discharged pack capacity using the VB\textsuperscript{3}M is still almost the same as that without balancing and has dropped from about 1.40 Ah to 1.275 Ah due to ageing and capacity imbalance. With the SB\textsuperscript{3}M, the discharged pack capacity has risen by 4.36% to 1.312Ah. The discharged pack capacity using the proposed BBM has risen by 7.28% to 1.349 Ah. Therefore, the proposed BBM can extend the driving distance or time further compared with the battery pack without balancing system or with the VB\textsuperscript{3}M.

In the severe capacity imbalance scenario, it can be seen from the simulation results that the proposed BBM has significantly improved the battery pack capacity compared with the SB\textsuperscript{3}M and VB\textsuperscript{3}M. These results are particularly useful for aged battery packs as the battery packs in EVs experience many cycles of charging and discharging and gradually start to show the effects of ageing. With the proposed BBM, the potential of the balancing circuit attached to the battery pack is fully used and the battery pack capacity is significantly increased.
Table 5-3. Performances of different BBMs at two capacity imbalance scenarios.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Without Balancing</th>
<th>VB$^3$M</th>
<th>SB$^3$M</th>
<th>Proposed Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario I</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate Imbalance Battery Pack</td>
<td>Charged Pack Capacity (Ah)</td>
<td>1.39</td>
<td>1.4</td>
<td>1.445</td>
</tr>
<tr>
<td></td>
<td>Discharged Pack Capacity (Ah)</td>
<td>1.39</td>
<td>1.39</td>
<td>1.414</td>
</tr>
<tr>
<td></td>
<td>Discharged Pack Capacity Comparison (%)</td>
<td>100</td>
<td>100</td>
<td>101.7</td>
</tr>
<tr>
<td><strong>Scenario II</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Severe Imbalance Battery Pack</td>
<td>Charged Pack Capacity (Ah)</td>
<td>1.2745</td>
<td>1.2746</td>
<td>1.3489</td>
</tr>
<tr>
<td></td>
<td>Discharged Pack Capacity (Ah)</td>
<td>1.2569</td>
<td>1.257</td>
<td>1.3119</td>
</tr>
<tr>
<td></td>
<td>Discharged Pack Capacity Comparison (%)</td>
<td>100</td>
<td>100</td>
<td>104.36</td>
</tr>
</tbody>
</table>
5.5 Conclusions

This chapter has presented a novel balancing criterion of chargeable and dischargeable capacity to balance a LiFePO$_4$ battery pack. The battery equivalent circuit model was used to establish state-space equations of batteries for state of charge (SOC) and capacity estimation. The proposed battery balancing method (BBM) provides sufficient time to complete the balancing operation within the charging and discharging process for the LiFePO$_4$ batteries with flat terminal voltage. This strongly contrasts with the existing BBMs, and the VB$^3$M could not effectively detect the voltage imbalance due to the flat terminal voltage and the SB$^3$M could not handle the capacity imbalance for most of the charging and discharging time. To verify the effectiveness of the proposed BBM, a balancing simulation of the battery pack using the proposed BBM, VB$^3$M and SB$^3$M at the moderate and severe capacity imbalance scenarios was conducted. The simulation results show that the proposed BBM has the best performance in both scenarios of the three BBMs, particularly for the severe capacity imbalance scenario. In this scenario, the proposed BBM increased the discharged pack capacity by 7.28%.
Chapter 6

Conclusions and Future Directions

The major contributions of this thesis are summarized in this chapter, and potential future research directions are discussed, based on the content of this thesis.

6.1 Main Contributions

Balancing circuits have been the main research area for battery balancing systems for the last decade. However, the balancing criteria and the control methods also affect the performance of balancing systems. In relation to the former, Chapters 3 and Chapter 5 propose new balancing criteria to detect battery pack non-uniformity accurately and extend the available balancing time. With these new balancing criteria, the balancing operation can be completed during the charging and discharging processes. In relation to the latter, Chapter 4 proposes an improved fuzzy logic (FL) control method to regulate the balancing circuits. The proposed method increases the balancing current in the balancing process, due to its adaptivity. Both of these methods increase the balancing speed of the balancing systems to maximise battery pack capacity. The detailed contributions of this thesis are summarized below.
A. Pack cell SOC as the balancing criterion in charging process

The first contribution is that pack cell SOC with high accuracy and robustness is proposed as the balancing criterion in the charging process. The experimental results show that the SOC-based balancing criterion has much better performance than the terminal voltage-based balancing criterion. This contribution can be further explained as follows. Firstly, the relationship between the balancing circuits and the balancing criteria was analysed in Chapter 2. Different balancing circuits are categorized into two groups: those which can only use voltage as the balancing criterion and those which can use either voltage or SOC as the balancing criterion. The difficulty of implementation of the balancing circuits of the second group was further reviewed. Balancing circuits with two main buses were chosen as candidates to apply the proposed balancing criteria.

Secondly, accurate cell current, which is critical for accurate SOC estimation, can be obtained with the chosen balancing circuits. In battery packs with the balancing operation, cell currents are superimposed on the charging or discharging currents and the balancing current with high frequency. With the selected balancing circuits, the battery cell current can be calculated by adding only one balancing current sensor with a high sampling rate. This makes the cost affordable.

Finally, the adaptive SOC estimation method is integrated in the balancing system. In the battery pack, obtaining the parameters of battery cells on-board is challenging. In addition, the noise is higher due to the high frequency balancing current. An adaptive SOC estimation algorithm is preferred. In this thesis, a fading memory AEKF is applied. This observer-based SOC estimation method relies on both the measurement data and the model to achieve optimization. Since the measured cell current is more reliable, the fading memory AEKF places more weight on it. This increases its robustness to modelling errors in the battery pack. The proposed method based on the balancing criterion was tested with a LiFePO$_4$ battery pack in the fast charging process. The
results show that the SOC-based balancing system has better performance than the voltage-based balancing system and more pack capacity is charged.

B. Improved FL controller

The second main contribution is the design and implementation of a FL controller for the multi-switch inductor (MSI) balancing circuit. This MSI balancing circuit has the fewest components per cell since the components are shared in sequence in each balancing cycle. Compared with the existing PI controller, the proposed FL controller can better handle the balancing process under dynamic operational conditions.

Firstly, the control parameters change adaptively to maintain high balancing current when the OCV difference is above the threshold. Secondly, the balancing current can drop sharply to near zero once the OCV difference is below the threshold. This improves the stability and efficiency of the balancing system. Thirdly, the battery OCV is used as control input, which can avoid overcharge and over-discharge.

The proposed FL control method has been verified in a LiFePO$_4$ battery pack and a NCA battery pack and the results compared with those of the PI control method. The FL controller increases the balancing speed significantly for both battery types.

C. New criterion based on chargeable and dischargeable capacity

The third main contribution is that the chargeable and dischargeable capacity is proposed as a balancing criterion. The balancing system based on this criterion further extends the balancing time in the charging and discharging process to significantly increase useable pack capacity, particularly for severely imbalanced battery packs due to ageing. The proposed method has several advantages. Firstly, the problem of over-
equalization is solved, since the chargeable and dischargeable capacities are known. Furthermore, the chargeable and dischargeable capacity used as the balancing criterion rather than the voltage or SOC can identify non-uniformity, from the beginning of the charging or discharging process, which makes the balancing time longer. This is very important in the charging or discharging process when the available balancing time is limited. To verify the proposed method, a battery pack simulation platform was built in MATLAB. A LiFePO$_4$ battery pack with eight cells was simulated with the balancing criteria of the SOC, terminal voltage and chargeable and discharge capacity. The last has the best performance.

6.2 Future Directions

6.2.1 Improve pack cell SOC estimation

Pack cell SOC estimation is challenging. It involves heavy estimation load and there is difficulty in obtaining the balancing current in each cell in the balancing process. In this thesis, the adaptive extended Kalman filter is used as the pack cell SOC estimation and the SOC of each cell in the pack is calculated. This pack cell SOC estimation deals with problems related to non-uniformity, such as cell parameters and current differences. When the number of cells increases, the calculation load may be heavy. In the research literature, pack SOC estimation methods have been proposed to reduce the calculation load [170, 172, 173], on the assumption that the balancing states have been achieved. In the future, research on pack SOC estimation can be carried out, together with reducing the calculation load and improving SOC estimation accuracy during the balancing process.

Furthermore, when battery non-uniformity deteriorates and leads to larger modelling errors, the sliding-mode observer can be used to overcome modelling errors with uncertainty [174] and obtain better balancing performance.
6.2.2 Improve capacity estimation

Capacity estimation is another challenging topic when it is applied as the balancing criterion. In its application, battery cells in the pack are generally not fully discharged or charged and therefore it is not possible to simply use ampere-hour counting to obtain the capacity. However, capacity can be calculated as a ratio of the ampere hours accumulated to the SOC differences at the beginning and end of this accumulation [38, 171]. Therefore, this capacity estimation method relies on accurate current measurement and SOC estimation through OCV. In this thesis, capacity estimation was carried out only in simulation. In the future, the capacity estimation method used in this thesis can be verified by experiments. Furthermore, an alternative capacity estimation method based on an electrochemical model and the OCV curve can be used to improve the accuracy of SOC estimation [38, 175], which will in turn improve the accuracy of capacity estimation and help to charge more capacity into the battery pack.

6.2.3 Combine FL controller and chargeable and dischargeable capacity criterion in one balancing circuit

In this thesis, balancing criteria and the FL controller are proposed based on different kinds of balancing circuits. The chargeable and dischargeable capacity are proposed as a balancing criterion for the balancing circuit with low implementation cost and also increase the balancing time [41, 63, 176]. In the future, a balancing circuit can be designed with the least number of components per cell [50, 74, 177] that can apply both the newly-proposed balancing criterion and the FL controller. With this integration, the balancing time available during the charging and discharging process is expected to be further extended and the balancing current is also expected to increase, improving the balancing performance of the balancing system with the newly proposed balancing criterion.
Publications by the Author

Journal Papers


3. **Xiudong Cui**, W. X. Shen, Yunlei Zhang, Cungang Hu, “Improved performance of Lithium iron phosphate battery packs with active cell balancing approach using state of charge as balancing criterion in fast charging process” to be submitted to Energy Conversion and Management.

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Publications

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