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Cell balancing of Lithium-ion batteries

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Abstract

Over the years, the consumption of electric batteries has increased. In almost every electronic device, batteries can be found. This research focuses specifically on lithium-ion batteries. Because the rising popularity of Li-ion battery, it is crucial to have an adequate battery management system with an optimal balancing technique. The research question in this study is: What is the most suitable cell balancing technique for a lithium-ion battery? Three different cell balancing techniques are taken into consideration: switching shunt resistor technique, the transformer multiple winding and the switch matrix technique. To find out which cell balancing technique is the most suitable for a lithium-ion battery, MATLAB/Simulink has been used as the research method. It allows the easy use and design of electrical circuits and algorithms. The results showed that the most suitable cell balancing technique for a lithium-ion battery is the switching matrix technique. This method showed the most advantages. This method can balance the cells at high speed. Although the method has complex extra circuitry, it has control over the individual cells. In case one of the cells is detected as damaged, it can be bypassed. Therefore, the cell equalizing technique is critical to have a proper battery performance, increase the lifespan and prevent from dangerous situations due to overcharging and discharging processes.

Contents

Chapter 1

Introduction

Batteries are found in almost every electrical device, from small gadgets like smartphones to more significant dimensions like electric cars. Over the years, the consumption of electric batteries has been increased. As an example, there is a demand for electric vehicles. In 2018, around five million electric cars were on the road, and their popularity grew over the years. By 2021 it reached more than 10 million vehicles [1].

Battery packs are in charge of providing energy to the circuit. One of the most common battery type is the lithium-ion battery. It is a rechargeable battery with a low manufacturing cost. Moreover, the high energy density with no memory effect is the most valuable strength. High energy density refers to the amount of energy stored in an amount of space. In this case, the Li-ion batteries can save a considerable amount of power in a small volume. Once the batteries are connected to an external circuit during the discharging process, Li-ion electrode flows from the negative pole, also known as the anode, to the positive side, also called the cathode. Although the most popular material for the anode is graphite, different materials can be chosen for the cathode. Depending on the requirement of the user, the anode is selected [2] [3].

Battery cells are composed of battery modules, and the battery modules make up the battery pack. To have a reliable, safe operation and prolong the battery pack's life span, the battery management system (BMS) is implemented. The inputs to the BMS are current, voltage, and temperature.The output voltage of every cell is measured as well as that of the pack. In addition, the temperature and currents of the pack are measured. In operation, the state of charge (SOC) of the cell is estimated. Moreover, the state of health and the safe operating envelope is calculated based on the input data. In order to prevent dangerous situations, the battery must run in the range of the safe operating envelope. Although all the battery cells form the same model have the same manufacturing process, they are not identical [4].

Multiple cells are connected in series or parallel to provide the required voltage and current of the battery pack. The existing battery manufacturing process cannot reassure consistency among the cells. Daily usage can worsen the cell to cell difference. Also, internal characteristics produce cell imbalance due to the internal resistance or capacitance. Over time, this will lead to energy imbalance among the cells in the battery pack [5]. Regarding the cell imbalance for the battery pack, the difference of state of charge between cells is a significant problem. When one cell reaches the highest SOC level or the lowest SOC level, the battery pack will stop charging or discharging. When the highest SOC level is reached, the rechargeable capacity of the battery pack is limited. Furthermore, it can be causative factor for battery degradation. If the lowest level of SOC is reached, the usable capacity of the battery pack will be restricted [6].

Cell balancing approaches can be divided into passive, active, and switching matrix methods [7]. First, starting with the passive methods. In the passive process, the excess charge is removed from the cells. Shunt resistors dissipate the extra energy. Secondly, there are active methods. The active cell balancing methods make use of cell equalizing circuits. With these circuits, cells with higher SOC will deliver energy to the cells with lower SOC [8]. It is possible to perform active cell balancing in different ways. It can be from cell-to-cell and cell-to-pack to pack-to-cell and cell-to-pack-to-cell. Finally, there is also the option of switching matrix method. It does not need extra components like capacitors, resistors, or inductors. An array of switches are placed around the cells. These switches provide the isolation of cells for the equalization of cells [9].

In this research, the cell balancing of the lithium-ion battery has been studied. Since the popularity of lithium-ion batteries has been increasing, it is vital to have an adequate BMS with an optimal cell balancing technique. Previous research has been performed on different cell balancing techniques. The three cell balancing methods analyzed are passive, active, and switching matrix. Although different topologies are in each section, the switching shunt resistor method, switched capacitor, and switching matrix technique are used in this research. The research question that will be studied is: *What is the most suitable cell balancing technique for a lithium-ion battery?*

To start the research, the different existing literature about this topic has been studied. The theoretical framework has been divided into three different topics: type of lithium batteries, battery management system and cell balancing techniques. After the theoretical framework, the research methodology is formulated. The research method used in this study is the simulation on Matlab Simulink of the passive, active, and switch matrix cell balancing techniques. Three lithium-ion cells connected in series are simulated. The three different topologies are simulated separately for the same battery cells. Each battery cell has an initial state of charge. As for the result section, the cell balancing methods are compared. The level of SOC must be equalized for each technique. The results indicate the times for the various methods to converge. Moreover, a table with the characteristics of the described methods can be found. Finally, in the conclusion the research question is answered, followed by the recommendations.

Chapter 2

Theoretical Framework

2.1 Type of lithium batteries

Because rechargeable lithium-ion batteries have a high energy density, low self-discharge, and long life cycle, they are used in a significant number of applications. From electric vehicles to consumer electronics [5].

There are various types of batteries characterized by different materials, capacity, cost, or dimensions. Batteries are composed of electrochemical cells that constitute the electrodes, they create the positive and negative poles. The negative side is called the anode, while the positive is the cathode. It is the electrolyte that enables the ions to flow from the positive pole to the opposing. [10].

Moreover, the electrolyte can be composed of any material that allows the chemical reaction to flow smoothly; it can be liquid or solid. Finally, there is a semipermeable separator to control the process between the two poles. When a circuit is connected to the battery, an electrical reaction initiates. The electrons flow from the anode to the cathode. However, when the electrons leave the anode, there remains the positive charges. The electrolyte helps the remainder ions to flow from the anode to the cathode all inside the batteries. This process is also known as a reduction-oxidation reaction or redox reaction. Oxidation is when the material loses electrons, while reduction is the opposite [11].

For battery performance it is essential to take into consideration the power and energy density. Energy density is the capacity of energy stored in a given mass. On the other hand, power density defines the amount of output energy going in a certain amount of time. The relation between these two is significant because the amount of time the battery can run can be known. [12]

These batteries are rechargeable. When a circuit is connected to lithium-ion batteries, the electrons go through the external circuit, producing electricity. Inside the batteries, the remaining positive ions on the anode flow to the cathode through the electrolyte. Once the charger is connected, the whole procetheess is done, but backward. Depending on the requirements of the consumer, the materials of the positive electrode are chosen. By these, there are different types of electric ion batteries [12].

2.1.1 Lithium Cobalt Oxide(LiCoO2) — LCO

The cathode of the battery is made of cobalt oxide and the anode by graphite carbon. The structure of the cathode is layered. It makes it easier for the lithium-ion to travel during the discharge process. However, it has weaknesses; the life span of this material is relatively short. Also, it has problems with thermal stability, and cannot reach high load capabilities [12]. To avoid fast deterioration of the Li-cobalt charge and discharge, current must not exceed the C-rating. In case the load exceeds this rate, it provokes overheating and undue stress.

The popularity of LCO batteries has increased over the years. It has been used in cellphones, laptops, and digital cameras. It is because the typical operating range is 3.0-4.2V/cell. Also, the capacity is around 150-200Wh/kg. The charge rate is between 0.7-1C, usually takes about 3 hours, and charges at 4.20V in almost every cell. The battery's life cycle depends on the temperature in which it has been exposed. Also it depends on the load, and the maximum discharge. It can vary between 500-1000. And at the temperature of 150℃, it is the thermal runaway [12].

2.1.2 Lithium Manganese Oxide (LiMn2O4) — LMO

The cathode material is lithium manganese oxide. Once this material is utilized, the internal resistance is low, and the control over the current increases. Although the advantages of this material are safety and high thermal stability, the life cycle is restricted. [12]

The time of charging in this type of battery is relatively fast because the internal resistance of the cells is low. But it has a downside. The heat build up is produced to the amount of power density it has. The cell temperature has to maintain a temperature lower than 80℃ in case not to lead to damage. The most common application of these batteries is on medical instruments as well as in electric vehicles.

The framework structure of the Li-manganese battery is spinel. Compared to the cobalt structure, the specific energy is more moderate because of the low resistance on the spinel.

Batteries made of pure Li-manganese are not commonly consumed anymore. It is because of the weaknesses it provides. One of them is that the capacity is one-third of the Li-cobalt. At the time of building the battery, the engineer can design depending on the requirement. It can be chosen to maximize the life span (longevity), the load current (specific power), or the capacity (energy). To increase safety, longevity, and specific power or load current, the LMO battery is blended with lithium-nickel-manganese-cobalt oxide. On most of the electric automobiles, this type of batteries are implemented. The high current boost is provided by the LMO while the NMC is used for the life span [12].

2.1.3 Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2) — NMC

The combination of niquel-manganese-cobalt(NMC) on the cathode is one the most successful prosperous systems. On the anode side Silicon is added to the graphite. The combination of nickel and manganese allow to take the advantages of both materials. While manganese has a property to achieve a low internal resistance, nickel provides a high specific energy. It tackles the downside of pure lithium manganese batteries.

This type of batteries is gaining popularity and is chosen for different application as batteries of powertrains, electric bikes and power tools. The cathode is composed by three different materials, nickel manganese and cobalt, all one third respectively. However the cost of cobalt is high. The reasoning of the use of cobalt is to stabilize nickel. NCM has the lowest selfheating rate and good performance on specific energy becoming the most appropriate option for electric cars. [10]

2.2 Battery Management System

The battery management system (BMS) is in charge to keep the battery pack safe and in a reliable operation. The current, the voltage, and the temperature are the inputs of the BMS. Inside the algorithms calculate state of charge (SOC), state of health (SOH) and safe operating envelope (SOE) . SOC estimates the amount of the remaining charge on the battery pack. Then SOH establishes the amount of capacity that can be stored compared as when it is used for the first time. SOE provides information about how much current it can be charged or discharged at a given time. Finally, the BMS can show the number of faults or status signals the operation controller must be aware of. [13]

BMS monitors the voltage of every individual cell which conforms to the battery pack. Also, it measures the overall voltage and current. Finally, a master disconnect is found. If dangerous values are reached during the charge or discharge process, the master disconnect is allow to disconnect the battery. The BMS has an adequate monitoring of the charge and discharge process and can communicate by common interface to the external circuit. [14]

2.2.1 BMS in lithium batteries

To prevent the excessive increment in the temperature of the battery cells is essential to have an adequate measurement of the individual cells. To prevent dangerous situations like fire, it is crucial to maintain the cell working in the safe operating area (SOA).

SOA can be found by the graph of voltage over temperature on the cells. The boundaries on the x-axes are the minimum and maximum temperatures that the cell can operate. On the y-axes, the boundaries are the typical maximum and minimum voltages it can operate. In case the temperature exceeds the SOA it is known as a thermal runaway. It is when inside li-ion cells the temperature increases until they reach temperatures above 100° and the aluminum can melt. In case the battery cell is below the minimum temperature while it is in the charge or the discharge process, the ions are not able to move from the anode to the cathode. This disruption exacerbates into dendritic growths and eventual short circuit of the cell [15].

On the other hand, there is the charge axes. The typical voltage for a Li-ion cell is around 4.5V but, if voltage is higher than the maximum voltage is known as overcharge regime. When the battery cell is working on the overcharge regions it is dangerous and it can get fire or explosion. [2]

Moreover, if the battery's cell is working below the minimum voltage it is known as the over-discharge condition. In this case, it can reduce capacity and generate dendritic growth or lithium plating. During the charging process under abnormal conditions, the extra lithium-ions concentrate on the surface of the negative pole of the cell and it cannot be absorbed. This accumulation causes metallic micro-structures and it can produce short circuits. The Samsung Galaxy Note 7 where the batteries produce a short circuit and set fired in 2016 is a clear example [2].

2.2.2 State of charge (SOC)

The state of charge (SOC) is the capacity remaining over the total capacity of the battery pack. The units are in amp-hours. There are several methods to obtain the SOC or the depth of discharge (DoD). In order to calculate the percentage of battery consumed the most common methods are the Coulomb counting method and Open Circuit Voltage (OCV) [9].

The voltage on the terminals is dependent on the amount of battery charge. While the battery is consumed, the voltage at the terminal decreases. When the battery is fully charged the highest voltage is obtained. For the correct measurement, the discharge curve is analyzed. As the Figure A.1 shows there is a range where the curve is flattened. This means that the voltage at the terminals variates very slightly over a wide range. The flatter the curve, the harder it is to estimate the SOC. In order to tackle this problem calibrated charge indicators are used [9].

Coulomb counting is another method. A shunt resistor are implemented on the BMS, it measures the input and output current. The integration of the current over the consumption of the cell is the actual capacity. The batteries do not need to be in a specified state to use this method. The sampling frequency can produce error measurement. To avoid this, each load cycle the Coulomb counting is recalibrated.

In order to have a better estimation of the SOC both are integrated into the BMS and are compared by algorithms [14].

2.2.3 State of Health (SOH)

The battery consumption lasts for less time then as it was used for the first time. As the cell is used overtime of the cycle of charge and discharge, the capacity decreases. The state of health (SOH) is defined as the total capacity over the beginning of life capacity.

The cell of the battery can be represented as a source and a resistance in series. When the cell is new, it has a certain resistance, while it goes through the charge and discharge cycles the impedance of this cell grows. These elements are measured by the BMS and are essential. As the cycles occur and the resistance impedance grows, the thermal output also increases provoking more heat over discharges [13].

2.2.4 Safe Operating Envelope (SOE)

The safe operating envelope (SOE) is defined to be boundary of the maximum charge and the maximum discharge current. The current flow must be within the boundaries, which in this case are the maximum charge and the maximum discharge current. This algorithm is occupied in order to avoid any interruption by the BMS. Moreover, it produces a safe use of the battery. In case the current is not on the regime, the charging process is terminated.

Another advantage of the SOE is it prevents faults. So in effect it avoids shut down of the whole process on the battery pack. Also, it helps to maintain the lifetime.The safe operating envelope maintaining the charge and discharge process into a range limiting the processes [14].

2.3 Cell Balancing Techniques

Battery cells are composed of battery modules, and the battery modules make up the battery pack. The structure is in series or parallel of the individual cells. It depends on the amount of current and voltage required. However, every single cell's balance has its characteristics. In each cell there are different capacities, self-discharge rates, and internal resistances. External factors can affect the qualities of the cells. Unequal temperature distribution over the battery pack intervenes in the cell characteristics and produces a variation in the performance [6]. These intrinsic and extrinsic differences in the battery cells make imbalanced cells as shown in Figure 2.1 [9].

Obtaining proper balancing provides optimal life cycles. It also extends the battery's lifespan and prevents dangerous situations in which the cell is exposed to extreme charge or discharge ranges. When there are different states of charge on the cells, it is known as cell unbalance.

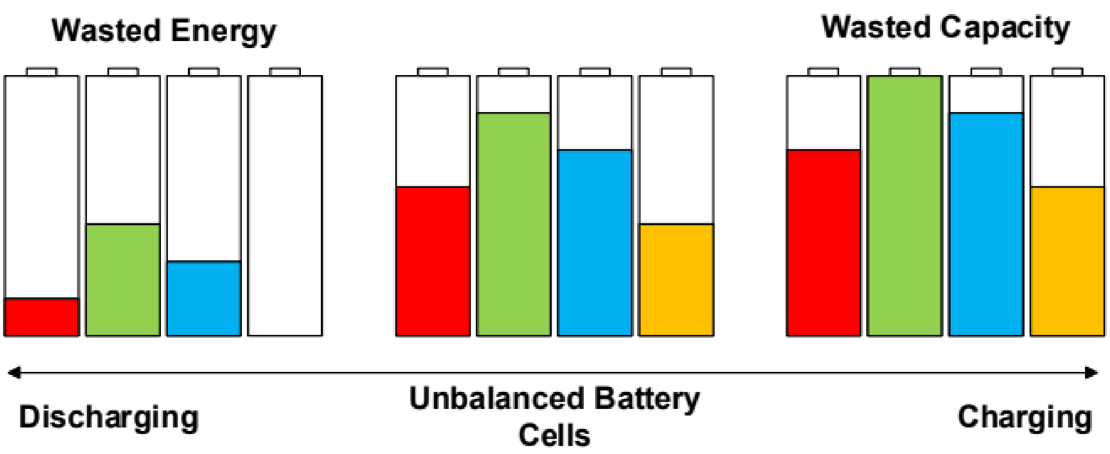

Figure 2.1: Cell Balancing techniques [9].

Methods existing are the passive,the active and switch matrix methods. Figure 2.1 shows the based approach of the cell balancing techniques. In comparison, the passive balance focuses on the consumption of excess energy. It chooses the cell with higher SOC and dissipates the power, making all the cells at the same SOC equivalent to the cell with the lowest SOC. The active method is focused on the distribution of energy. It takes the cell with the higher SOC and distributes it to the other cells, finalizing them with the same SOC [16]. The third approach has control over individual cells during the charge or discharge process equalizing the battery cells [9].

2.3.1 Passive Method

In case the level of SOC of a cell is higher than the other cells, a resistor dissipates the excess of energy. This method can be classified as a fixed shunt resistor and switching shunt resistor. They are only utilized during charging mode because there is no reverse direction switching. Otherwise, this produces a higher imbalance in each cycle [16].

Fixed shunt resistor

The fixed shunt resistor circuit is shown in Figure 2.2. Where V1, V2, V3,... Vn represents the cells. They are connected in series, and a resistor is placed with the corresponding cell.

This technique dissipated the exceed of voltage over the resistor, limiting the voltage of each cell. The fixed resistor is connected in parallel with each cell and based on the required cell balance current. The advantages are the low cost and complexity. It is because it does not occupy a large number of components. On the other hand, the energy loss over the resistor is a weakness. This method is more suitable for nickel and lead-acid batteries since they can handle overcharge conditions without damage [16].

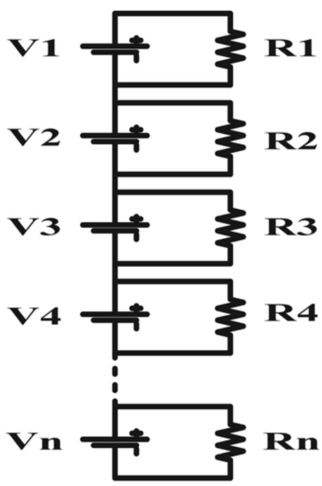

Figure 2.2: Schematic fixed shunt resistor [16]

Switching shunt resistor method

The circuit of the switching shunt resistor method is shown in Figure2.3. V1, V2, V3, ... Vn represent the cell voltages connected in series with Q1, Q2, Q3, .. Qn switches of the corresponding cell and resistors R1, R2, R3,... Rn. To equalize the SOC of the individual cells, they are connected in parallel with the resistor and controlled by the on/off semiconductors switches. A controller is required in this method. It must give information to the semiconductors/relay. The controller receives information about the state of charge and voltage of each cell. Then it decides which switch must conduct to dissipated the exceed current. The value of the resistor is chosen in favor of the required balance current. This method has a simple controller and is easy to implement. The algorithm is based on the SOC and SOH. However, the drawback is the low speed and also the consumption of energy on the resistors. This method has been used for Lithium-ion batteries, suitable for balancing current of 10mA/Ah [16] [17].

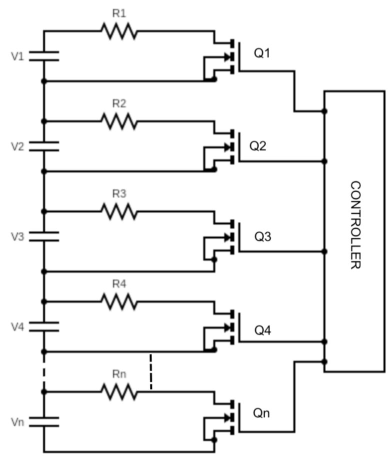

Figure 2.3: Schematic switching shunt resistor

2.3.2 Active Method

The distribution of charge between cells is occupied in the active method. The discharge produced in one cell with high SOC is passed to another cell with a lower SOC. It is possible by storing energy on capacitors or inductors. Since energy is not dissipated, this method becomes more reliable and efficient. Moreover, this method can be used in charge and discharge operations [9]. The active method is classified depending on the components that are used. The components are divided into capacitors, inductors, and power electronic converters.

Switched capacitor

Research has been done on the shuttling capacitor balancing. There are some pros and cons about it. The advantages are that it has a simple control strategy and it is highly efficient. The disadvantages are that there is a long equalization time and high costs. In Figure 2.4 is shown how the shuttling capacitor balancing methods are divided into four configurations [18].

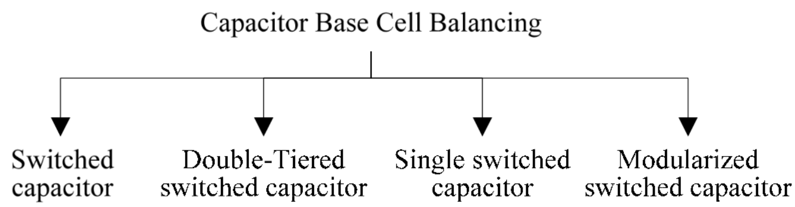

Figure 2.4: Capacitor active cell balancing topologies [18]

Shuttling capacitor cell balancing topologies in fact uses capacitors as external energy storage elements for shuttling the energy between the cells to carry out the charge balancing of the cells. There are four ways in which to divide the capacitor shuttling: the basic switched capacitor, double-tiered switched capacitor, single switched capacitor and the modularized switched capacitor topologies [18].

In Figure 2.5 the basic switched capacitor can be found. For balancing n cells, n-1 capacitors and 2n bi-directional switches are required. The basic switched capacitor (SC) has only two states: frequently moving the switches from the upper position to the lower position and back to the upper position. Between each transition is a small resting period.

The advantages of the SC is that there is no need for any intelligent control strategy. The SC is highly efficient and works in charging modes as well as in discharging modes. The disadvantages of SC is that it has a rather long equalization time [18].

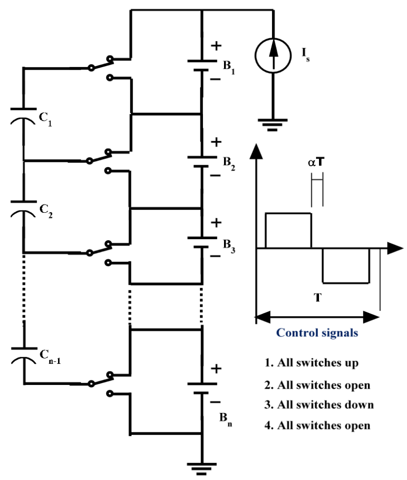

Figure 2.5: Schematic switched Capacitor [18]

Inductors

To equalize the battery cells, the energy from the cell with higher SOC is transferred to multiple cells with a lower level of SOC. The power which is delivered is not equal. If one cell has a lower SOC, higher energy is delivered to that cell. The mediums that can transfer this energy are transformers or inductors. The time that it takes for balance is directly dependent on the balancing current. However, the drawback of a high-speed balance is the high production cost. Moreover, there exists a loss on transformers which might be considered on the balanced phase. It is because of the high-frequency switching that it has. [19]

The schematic for the single inductor cell balancing is shown in the Figure 2.6. V1, V2, V3, . . . Vn represent the cell voltages connected in series with Q1, Q2, Q3, .. Qn switches of the corresponding cell, and the inductor is represented by L. Once the voltage of each cell is determined. The algorithm chooses the cell with a higher voltage and selects different cells to deliver the energy. To prevent a short circuit of the cells it is necessary to have semiconductors switches (MOSFET) and a diode connected in series. Unequal energy is moved to the inductor when the switches are turned on and off. In this method, the cell energy is transferred from higher to lower SOC cells by unequal cell energy through an inductor.

The advantages of this method are the high speed for balancing and better efficiency than capacitor-based methods. But the price for implementation is high be-

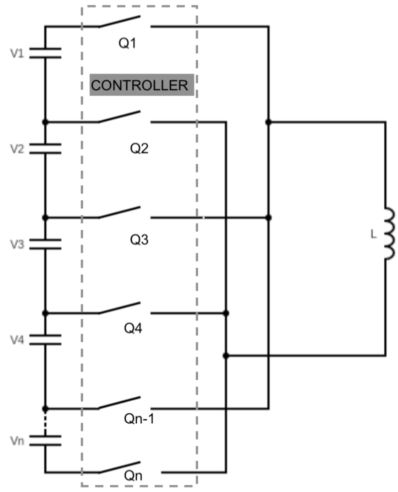

Figure 2.6: Schematic inductor cell balancing

cause of the semiconductor switches, the intelligent control which allows controlling the switches [16].

Transformer

The technique is based on a single transformer and several transformers that use equalization methods. The single balancing method needs n + 5 semiconductor switches and just one transformer. The transformer equalises the n number of cells charge levels. The single balancing transformer circuit relies on the pack-to-cell and the cell-to-pack technique [16].

In this part the difference between the pack-to- cell technique and the cell-to-pack technique are explained. With the pack-to-cell technique the current of the whole battery pack is switched into the transformer. The output of the transformer will be rectified. After it, it will be carried into the lowest charge cell via corresponding semiconductor switches.

With the cell-to-pack technique the higher energy cell is the target. The higher energy cell will be moved into the battery pack via the transformer. This is to balance the voltage of the higher energy cell with the rest of the cells in the battery pack.

Next to the single balancing transformer circuits, there are also several winding transformers based cell equalizing circuits. These circuits are based on the transformer magnetic-core. The single magnetic-core transformer can also be known as a shared transformer. A shared transformer consists of a single magnetic core and has only one primary winding for the whole battery pack. Besides that, for each cell it has multiple secondary windings. The winding transformers based cell equalizing circuits rely on the pack-to-cell and the cell-to-pack technique.

With the pack-to-cell technique each cell will receive a different current. This is because there are different terminal cell voltages in the battery pack. The cell-to-pack technique can be categorized as a forward topology. The transformer balances the voltage of the target cell with the other cells in the battery pack. Minimum losses are produced in a multi-cell battery with this balancing circuit. The downside of this circuit is that it is only suitable for the expected maximum number of cells that are connected in series in string. Including additional secondary windings in this circuit to extend the battery string is hard.

Fast balancing and a better modular design are advantages of this method. Also it is easy with this method to extend battery packs without having to change the magnetic core. What are disadvantages of this method is that it is more expensive and also the circuit is more complex.
[16] [20].

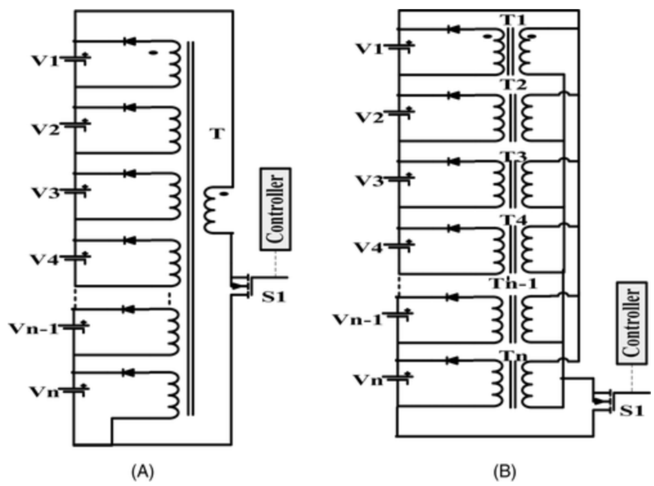

Figure 2.7: Schematic single transformer cell balancing [16]

2.3.3 Switch matrix

The switch balance method contains an array of switches as shown in Figure 2.8. The function of the switches is to control and access the cell. By these switches, the energy is transferred from cells with a higher SOC to cells with lower SOC. The cell batteries are connected in series. If one of the cells is unbalanced, the switches are on/off dependent on the SOC of each cell. [21]

The algorithm calculates the cell with the highest and lowest state of charge. The remaining cell batteries are bypassed. The cell with a higher SOC distributes the energy to the lowest. The cell with a higher state of charge decreases the energy until it reaches another cell with the same SOC. When this happens, the cells are connected in series, and both distribute the energy to the cell with lower SOC, decreasing its cell energy at the same time.

The advantage of the switching matrix is that it can be applied during the charge and discharge process. Moreover, the circuit can be considered lossless since the charge of the cells with exceed SOC is not dissipated through a resistor. In case of an emergency, the battery or the cells in danger can be isolated by the switches. [21]

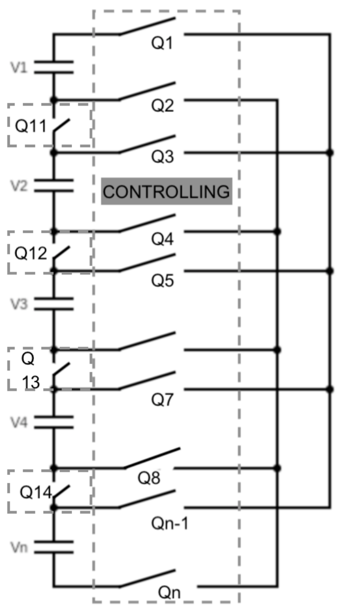

Figure 2.8: The switch Matrix

Chapter 3

Research Method

MATLAB/Simulink is chosen due to the extensive libraries that it has and the number of users. It allows the easy use and design of electrical circuits and algorithms. Moreover, it has become one of the most predominant software for modeling and simulating dynamic systems [18].

The simulation of three different cell balancing techniques is shown in this research. Firstly, for the passive method, the switching shunt resistor method is chosen. Secondly, for the active method the transformer multiple winding technique is selected. And finally, the switching matrix technique is used as a balancing method.

Firstly a single battery cell is simulated in MATLAB. This battery cell is a lithium-ion cell. The features of the batteries are obtained from the datasheet Lithium-Ion battery NCR186550PF [22]. The nominal voltage is 3.6 V, and the rated capacity is 2.75 Ah. The battery discharge characteristics can be found in Figure A.2 in the appendix. These battery cells are connected in series for all three simulations.

The battery model facilitates the measurement of the state of charge, current, and voltage. To be able to read this data, a bus selector is connected to each battery cell. The data is graphed on the scope to demonstrate the different states of charges, current, and voltages.

The initial state of charge of each cell is 98%, 96% and 91%, which means that the cells are unbalanced.

3.1 Simulation of Switching shunt resistor method

The reason why the switching resistor method is chosen instead of the other passive method is because the control on each battery cell prevent as much as possible the overcharge regime. The schematic 2.3 is used. On the following Figure 3.1 the simulation on Simulink is shown. Each battery cell is connected to an ideal switch. The algorithm determines if the switches are activated or deactivated. The algorithm can be find in Figures A.3,A.4,A.5,A.6. The algorithm selects the battery with the highest state of charge. As battery 1 has a SOC of 98%, the switch is activated. Once the switch is activated, the energy is consumed by the resistor, and it is dissipated by heat. The value of the resistor is 36 OHMS. While the SOC level of battery 1 is reducing, the switches of batteries 2 and 3 are OFF. When battery 2 reaches the SOC of battery 1, the algorithm recognizes and both switches are activated. This balancing method can only be occupied in the discharging process.

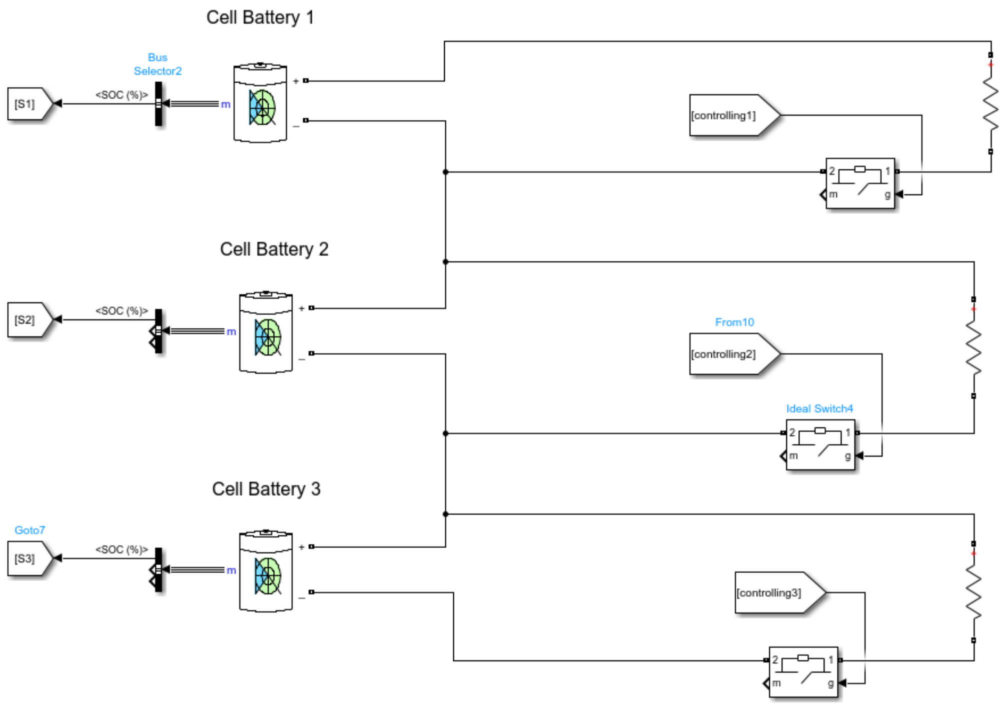

Figure 3.1: Simulation circuit of switching shunt resistor

3.2 Simulation Transformer multiple winding

The active method is the distribution of excess energy between cells. The cell with higher SOC would distribute power to cells with lower SOC. The energy would be stored in a capacitor or inductor before it is distributed. There are several topologies; it depends on the component which is used as mentioned before. Between the capacitor inductor and converter, the converter is more suitable for lithium-ion batteries. The voltage over the cell battery is measured. The energy from the cells with higher SOC goes through inductors or capacitors. The battery cell's discharge graph is shown in Figure A.2. It demonstrates that the battery's voltage is almost constant during a long period of the discharging process, which must be very precise on the voltage measurement to store and release energy.

On the other hand, the multiple winding transformer is occupied. The schematic 2.7 is occupied. On the following Figure 3.2 the simulation on Simulink is shown. The input of the transformer is the addition of the cell voltages. Initially, as the system is unbalanced, the voltages of the batteries are different because each cell battery has another SOC. The secondary side of the transformer has three windings, each carrying the same voltage. The ratio of it is 40:12. The output is connected to a diode which allows the flow of current in only one direction. Also, it is only possible to pass energy if the anode voltage is greater than the cathode. The algorithm of this circuit calculates the voltages of the individual cell batteries. When all the voltages are equalized the switch is OFF. The MOSFET is used as a switch. By these, the equalizing process is done in the transformer multiple windings. This method can be applied during the charge and discharge process.

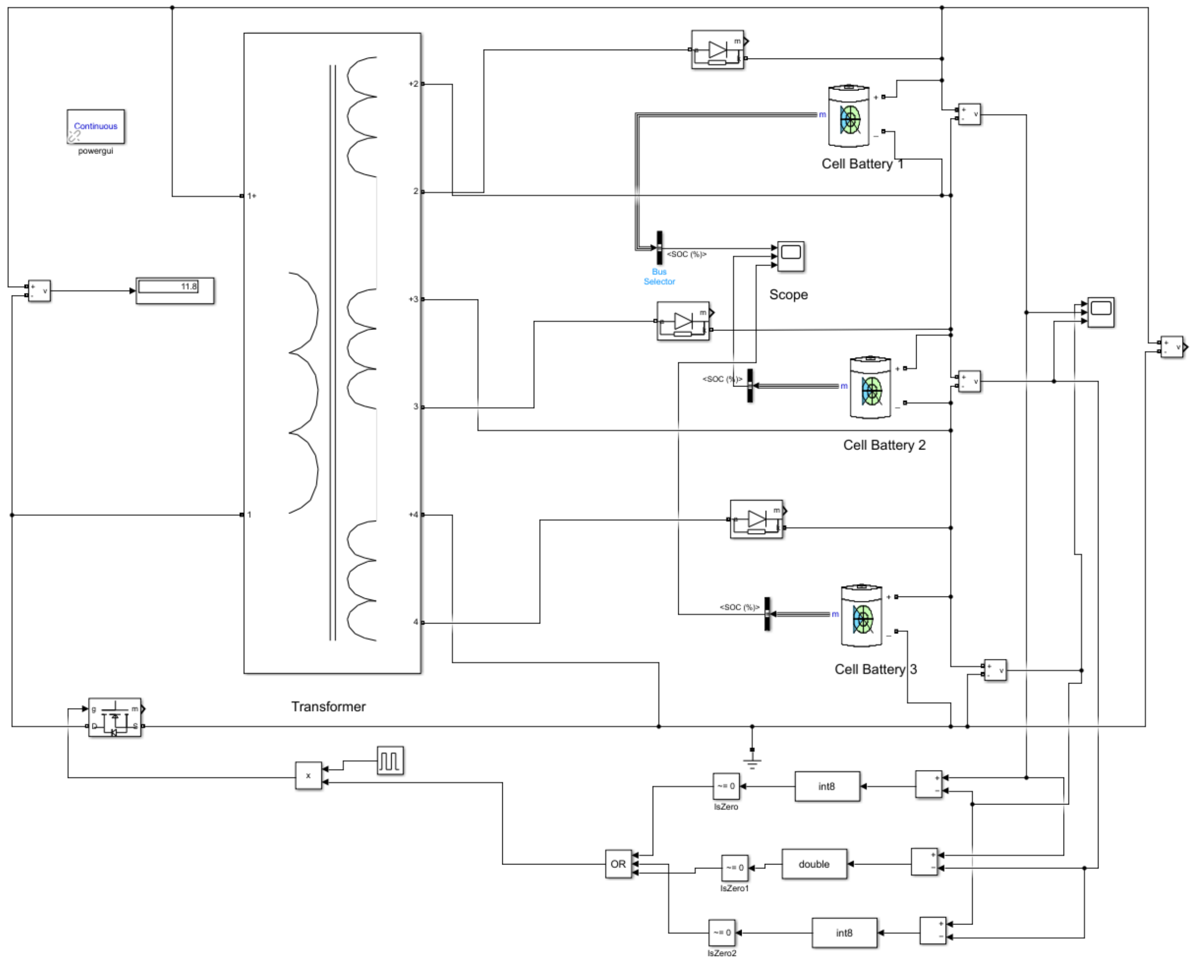

Figure 3.2: Simulation circuit transformer multiple winding

3.3 Simulation Switch matrix

With the switching matrix method, three battery cells are connected in series. As mentioned before, the cell with a higher level of state of charge is isolated during the discharge process. To be able to separate the cells, switches have been implemented. The following Figure 2.8 has been used for the schematic. As shown in Figure 3.3,it cannot be found in any other component than switches. This balancing method only depends on the algorithm. In this case, the ideal switches are used. Each cell battery has one ideal switch connected in series with the positive side of the battery and one in the negative pole. Also there is one switch between the battery cells. This switch is activated if the battery is isolated. All the positive poles of the batteries are connected after the switch. The negative side follows the same procedure.

The switches are activated depending on the SOC. The algorithm identified the batteries with the highest and lowest SOC. In this case, batteries 1 and 3 respectively. The algorithm chooses the switches to be opened. It produces an increment in the state of charge in battery 3.

On the other hand, the battery level of battery 1 is decreasing.The cell battery 2 does not suffer any alteration. The switches do not switch until the SOC of battery 2 reaches another cell with the same SOC. In this case, until the SOC of battery 2 is 96%. Then the algorithm identified that both batteries have the same SOC and switch S1, S4, S5, S6, and B1 are closed. The reason for that is that batteries 1 and 2 are connected and discharged together, while battery 3 receives the energy. When all the batteries have the same level of SOC, the cell's batteries are equalized. This method can be used during the charge and discharge process. The algorithm can be find in Figures A.7, A.8, A.9, A.10, A.11, A.12.

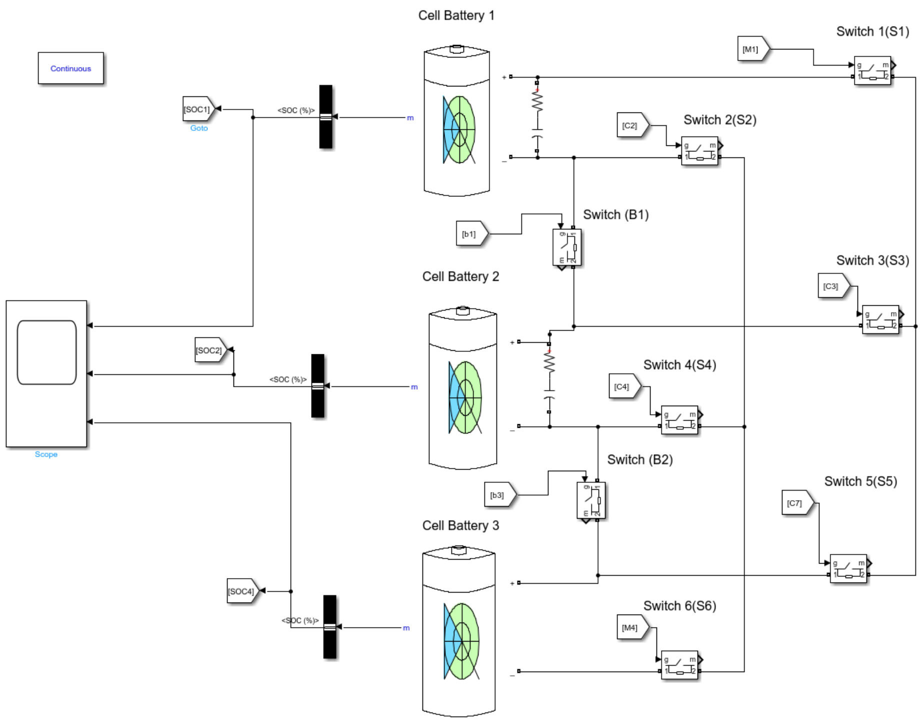

Figure 3.3: Simulation circuit of switching matrix

Chapter 4

Results & Discussion

4.1 Switch shunt resistor

The following Figure 4.1 refers to the equalizing balance of the switching shunt resistor. The SOC of battery 1 has started decreasing. It means that the switch corresponding to this battery is ON. The remaining switches must be OFF. Therefore there is not a change in the SOC of batteries 2 and 3. Once the SOC of batteries 1 and 2 are equalized, the corresponding switches are activated and begin to dissipate energy. The process finished when all battery cells meet at 10500 s.

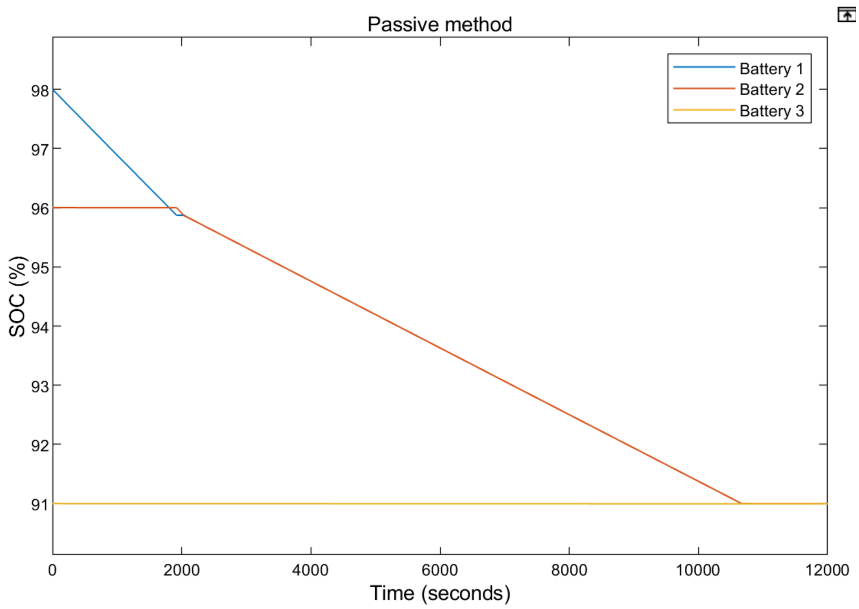

Figure 4.1: Result of switched shunt resistor

4.2 Transformer multiply winding

The simulation of the transformer multiply winding is displayed on Figure 4.2. The SOC decreased in cell batteries 1 and 2 and the increase in cell 3. This was as expected because the energy of batteries 1 and 2 are distributed to battery 3. It can be clearly seen that the SOC values are converging.

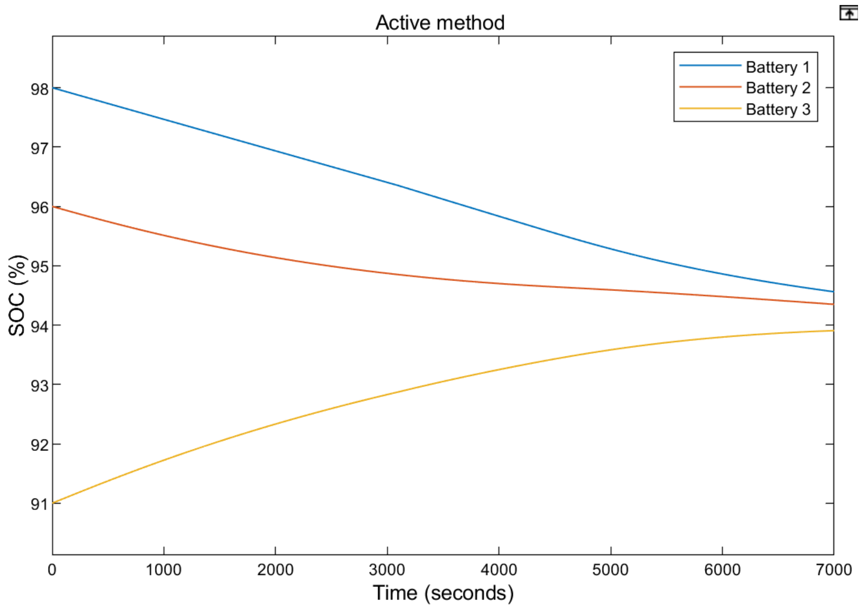

Figure 4.2: Result of transformer multiple winding

4.3 Switch matrix

The following Figure 4.3 corresponds to the switch matrix balancing method. As it is expected, the battery with the highest SOC distributes the energy to the lowest batteries. It is seen that when battery 1 and battery 2 reach the same SOC, the algorithm realized and distributed the energy of both battery cells to battery 3. When all battery cells have the same state of charge at 4500 s the process concludes.

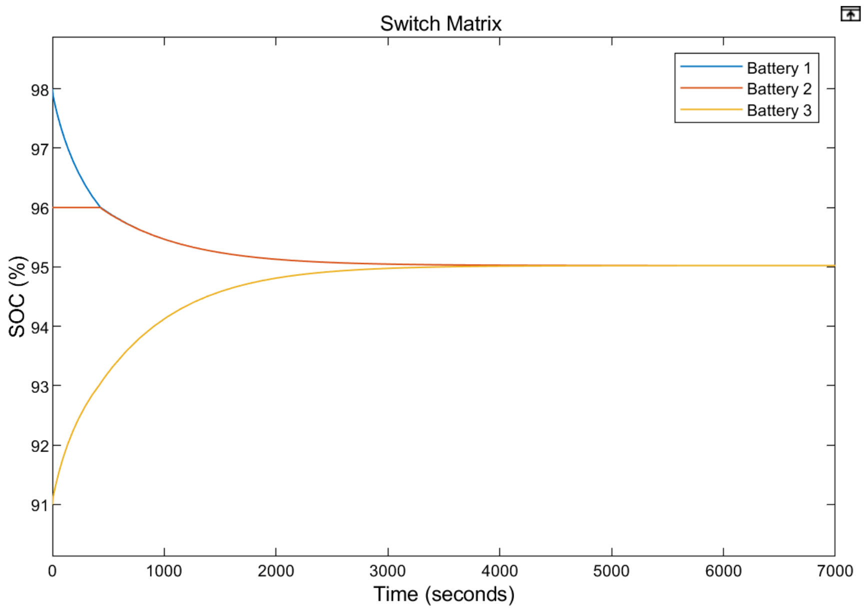

Figure 4.3: Result of matrix switching

4.4 Comparison balancing methods

The comparison between the three researched methods can be seen on the table 4.1. The description of the method is found in the second column of the table, it is followed by the advantage and disadvantages.

One of the outstanding characteristics of passive balancing techniques is the dissipation of energy in its resistors. The external circuitry characterizes the second approach with higher efficiency over the passive method, multiple winding, that is used. Finally, the switch matrix, although the complex algorithm and amount of switches are on the drawbacks, it has the highest speed. Also, it is able to be used during the charge and discharge process.

Type	**Process**	**Advantages**	**Dissadvantages**
Switched Shunt resistor	A resistor dissipates cell batteries with a higher level of SOC. By controlling the switches it is decided which battery cell is chosen.	Easy algorithm of the controller. Suitable for low-power applications.	Energy is dissipated through a resistor. It can only be used during charging process.
Transformer multiple winding	Battery Cells with higher SOC distribute energy to cells with lower SOC. Energy is transferred and delivered by the transformer.	Minimum losses during the balancing method. Fast Balancing technique.	External circuitry involves a transformer. Therefore, big size of the circuitry and high cost. Complex control system.
Switching matrix	Switches control the isolation of battery cells.	Control over individual battery cells. Fastest Balancing technique.	Complex algorithm for controlling the switches.

Table 4.1: Comparison between cell balancing techniques

4.5 Discussion

The battery cells might differ in capacity, resistance, state of charge, and temperature characteristics. These features of the individual cell cause an imbalance during the charge or discharge process. The importance of cell balancing is the proper functioning of the battery pack in the safe operating area and extend the life span. Therefore, three methods have been analyzed the active, the passive, and the switch matrix balancing method. MATLAB simulation was utilized to analyze the operation time of each equalized topology.

In this research three Lithium-ion battery cells are connected in series, each with an initial state of charge of 98%,96%, and 91%, respectively. The capacity and nominal voltage for the battery cells correspond to 3.6 (V) and 5.4 (Ah). The result in 4.3 shows that the switch matrix balancing technique at 4500 (s) completes the balancing process, becoming the fastest method.

Due to the fact that individual cells are controlled by the switch matrix technique, if one is damaged, the algorithm is able to detect and bypass it. A process which the other techniques have not reached. In order to transfer energy from one cell to another, the cell is chosen by the algorithm. Hence the system relapses on the switches, a complex algorithm is used. By these results, the most suitable technique for lithium-ion batteries is encountered.

It is crucial to take into consideration that all the components of the simulations are ideal. Therefore the implantation in real-life varies from the simulation.

Since the consumption of batteries has increased, the importance of proper cell balancing rises. Future researches must be directed on the combination of the balancing techniques. Sensors can be required for the implementation of intelligent techniques.

Chapter 5

Conclusions & Recommendations

5.1 Conclusions

In this research, several cell balancing methods have been analyzed. The switch matrix balance method has been chosen for a lithium-ion battery. The cell balancing techniques were compared considering several characteristics like cell balancing speed, application, and the algorithm's complexity. The three cell balancing methods analyzed in this research are the switching shunt resistor method, switched capacitor, and switching matrix technique. The central research question in this study is: *What is the most suitable cell balancing technique for a lithium-ion battery?*

Firstly the switched shunt resistor, a passive cell balancing technique was used. This technique has drawbacks such as long balancing, low current consumption, and heat dissipation. Secondly, the transformer multiple winding, which is an active cell balancing, was used. It has a higher efficiency than the passive cell balancing. But this active equalizing method requires complex external circuitry. Finally, the switching matrix can control individual cells during the charge and discharge process. Although this method has a complex algorithm control; it can balance the cells at high speed. The simulation of the proposed topologies shows the convergence of the switch matrix techniques is at 4500 (s), switching shunt resistor is at 10 500 (s) and transformer multiple winding more than 7000 (s). The fastest method is the switch matrix method. This method has a large number of MOSFETs places around the battery cells but this implementation does not waste energy on dissipation. Therefore, the cell equalizing technique is crucial to have a proper battery pack's performance, increase the lifespan, and prevent dangerous situations due to overcharging and discharge process.

To answer the research question, the most suitable cell balancing technique for a lithium-ion battery is the switching matrix technique. Compared to the other balancing techniques, the switching matrix technique has the most advantages.

The results of this study showed that the most suitable method is the switching matrix method. However there are still some gaps that need to be studied in the future. For example future researches can elaborate more on all the advantages together such as cost, efficiency and cell balancing speed.

5.2 Recommendations

MATLAB/Simulink is able to have a suitable simulation of battery and measurement systems. However, the values are taking in consideration with all the values. Therefore, it is hard to use all the values when they have to be compared on the control logarithm. One way to solve this problem is round the numbers. The block data type conversion was used to fulfill this objective.

Although the matrix switching cell balancing technique has tackled several drawbacks as dissipating energy and slow speed on the balancing process, there is no method to have met all the advantages of all the proposed methods. Therefore, there is a need to optimize the topologies and consider a technique that obtain all the benefits from the methods discussed. Ideal balancing techniques not only develop the functionality of the BMS. It will also be able to maintain the battery in a safe operating system, avoid dangerous situations, and increase the life span of lithium-ion batteries.

Bibliography

[1] W. Azeez, *5 things to know about the future of electric vehicles*, May 2021.

[2] J. Mullen and J. K. Kwo, *Samsung is recalling the Galaxy Note 7 worldwide over battery problem*, Sep 2016. [Online]. Available: https://money.cnn.com/2016/09/02/technology/samsung-galaxy-note-7-recall/index.html

[3] L. Leiva, *Memory effect now also found in lithium-ion batteries*, Apr 2013.

[4] *What is a Battery Management System?* YouTube, Jul 2020. [Online]. Available: https://www.youtube.com/watch?v=GXYJ1xC10j4&t=161s

[5] Q. Ouyang, J. Chen, and J. Zheng, "Optimal cell-to-cell balancing topology design for serially connected lithium-ion battery packs," *IEEE Transactions on Sustainable Energy*, vol. PP, pp. 1–1, 07 2017.

[6] A. Manenti, A. Abba, A. Merati, S. M. Savaresi, and A. Geraci, "A new bms architecture based on cell redundancy," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 9, pp. 4314–4322, 2011.

[7] S. Mukhopadhyay and F. Zhang, "A high-gain adaptive observer for detecting li-ion battery terminal voltage collapse," *Automatica*, vol. 50, no. 3, pp. 896–902, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0005109813005700

[8] J. Gallardo-Lozano, E. Romero-Cadaval, M. I. Milanes-Montero, and M. A. Guerrero-Martinez, "Battery equalization active methods," *Journal of Power Sources*, vol. 246, pp. 934–949, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378775313013669

[9] J. Qi and D. D.-C. Lu, "Review of battery cell balancing techniques," Oct 2014. [Online]. Available: https://ieeexplore.ieee.org/document/6966514

[10] T. Mller, "Lithium ion battery automotive applications and requirements," in *Seventeenth Annual Battery Conference on Applications and Advances. Proceedings of Conference (Cat. No.02TH8576)*, 2002, pp. 113–118.

[11] C. Catherine Hinga Haustein, “Oxidation-reduction reaction,” *The Gale Encyclopedia of Science*, Dec 2019.

[12] X. Chen, W. Shen, T. T. Vo, Z. Cao, and A. Kapoor, “An overview of lithium-ion batteries for electric vehicles,” in *2012 10th International Power Energy Conference (IPEC)*, 2012, pp. 230–235.

[13] L. Buccolini, A. Ricci, C. Scavongelli, G. DeMaso-Gentile, S. Orcioni, and M. Conti, “Battery management system (bms) simulation environment for electric vehicles,” in *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, 2016, pp. 1–6.

[14] X. Hu, F. Feng, K. Liu, L. Zhang, J. Xie, and B. Liu, “State estimation for advanced battery management: Key challenges and future trends,” *Renewable and Sustainable Energy Reviews*, vol. 114, p. 109334, 2019.

[15] A. Proffitt, “Battery power online: A look inside your battery: Watching the dendrites grow,” Aug 2020. [Online]. Available: https://www.batterypoweronline.com/news/a-look-inside-your-battery-watching-the-dendrites-grow/

[16] H. S, “Overview of cell balancing methods for li-ion battery technology,” Sep 2020. [Online]. Available: https://onlinelibrary.wiley.com/doi/full/10.1002/est2.203

[17] N. Samaddar, N. Senthil Kumar, and R. Jayapragash, “Passive cell balancing of li-ion batteries used for automotive applications,” *Journal of Physics: Conference Series*, vol. 1716, p. 012005, 2020.

[18] M. Daowd, M. Antoine, N. Omar, P. V. D. Bossche, and J. V. Mierlo, “Single switched capacitor battery balancing system enhancements,” *Energies*, vol. 6, no. 4, p. 2149–2174, 2013.

[19] Y. Lee, S. Jeon, and S. Bae, “Comparison on cell balancing methods for energy storage applications,” *Indian Journal of Science and Technology*, vol. 9, no. 17, 2016.

[20] J.-W. Shin, G.-S. Seo, C.-Y. Chun, and B.-H. Cho, “Selective flyback balancing circuit with improved balancing speed for series connected lithium-ion batteries,” in *The 2010 International Power Electronics Conference - ECCE ASIA -*, 2010, pp. 1180–1184.

[21] B. Lawson, *A Software Configurable Battery*, May 2012.

[22] ***Lithium Ion***, Panasonic, Apr 2018.

[23] Silicon lightworks. [Online]. Available: https://siliconlightworks.com/li-ion-voltage

Appendix A

Appendix

A.1 Dishcarge Lithium-ion battery

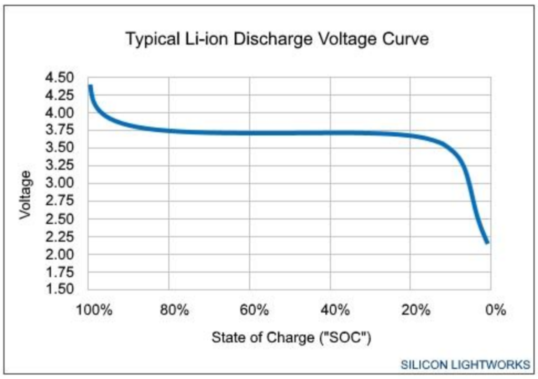

Figure A.1: Discharge curve of lithium-ion battery [23]

A.2 Lithium-ion battery simulation

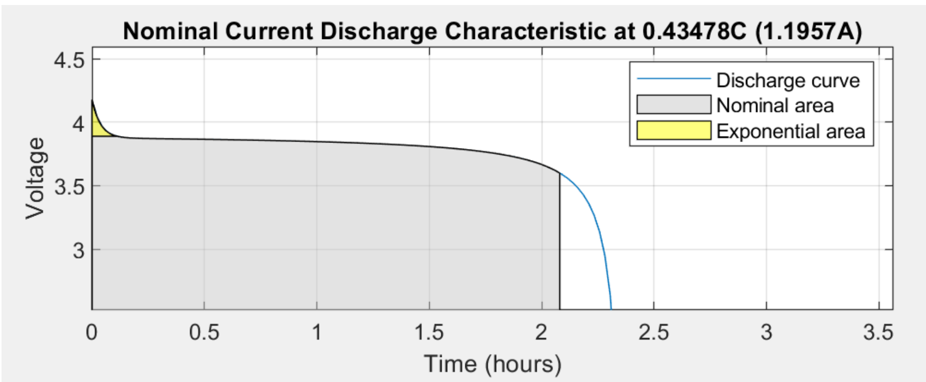

Figure A.2: Discharge curve of lithium-ion battery simulation

A.3 Algorithm Switching Shunt resistor

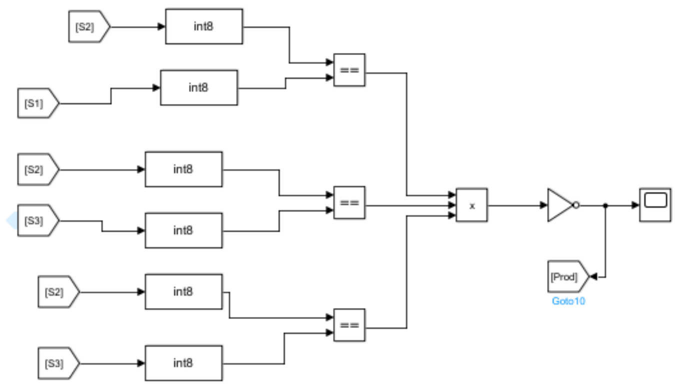

Figure A.3: Recognize if all cells are balanced

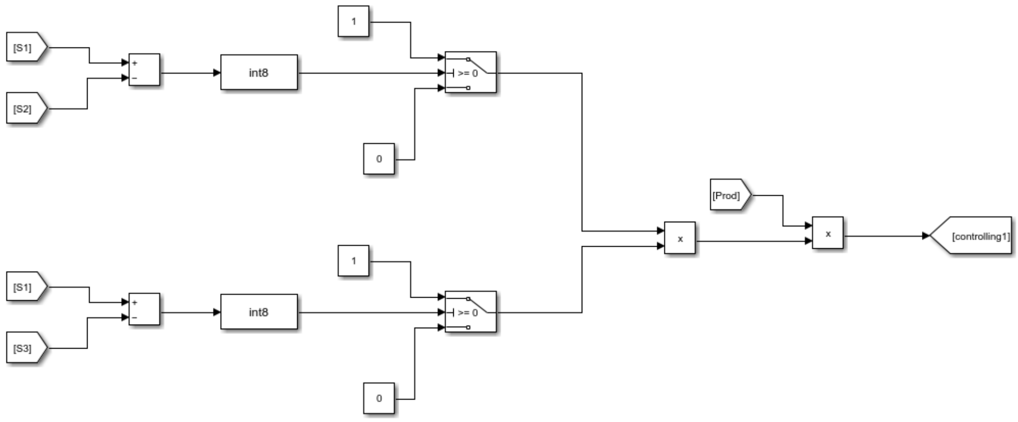

Figure A.4: Determined if cell 1 switch is on/off

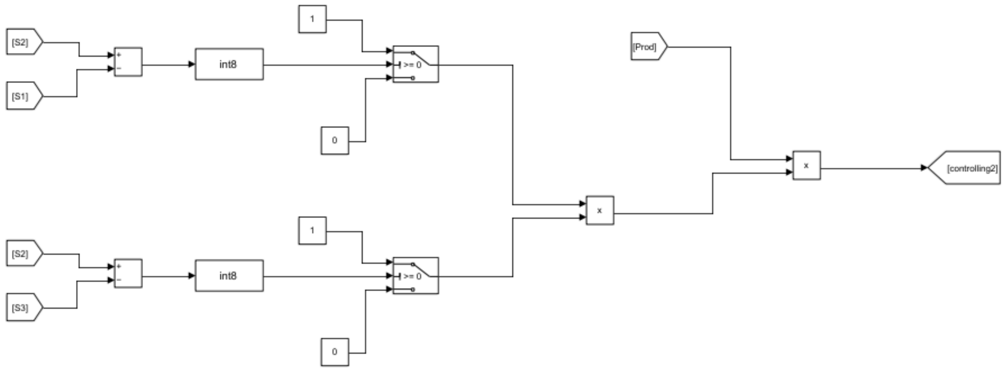

Figure A.5: Determined if cell 2 switch is on/off

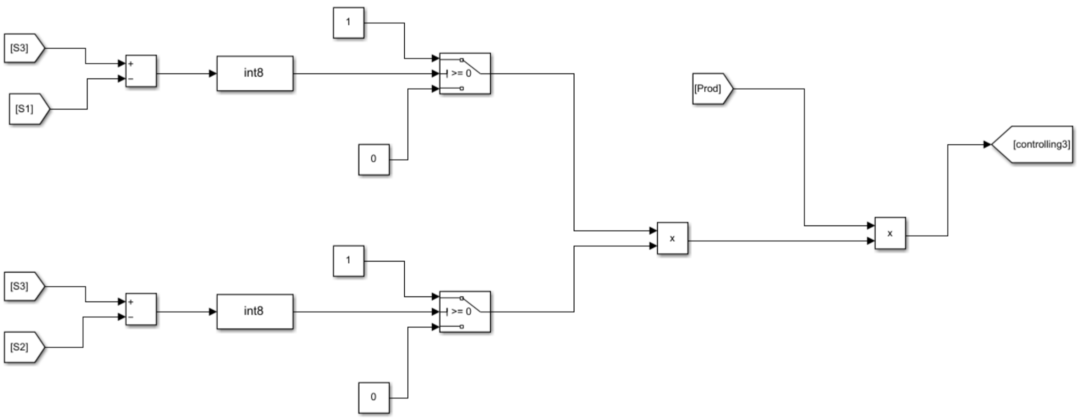

Figure A.6: Determined if cell 3 switch is on/off

A.4 Switch Matrix

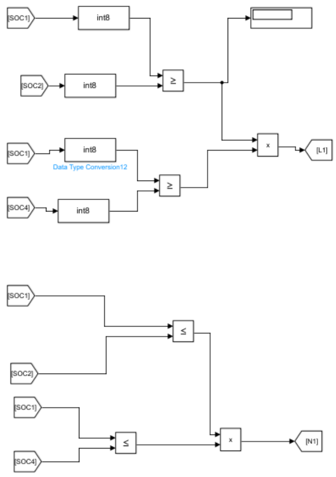

Figure A.7: Battery 1 has smallest or highest level of soc

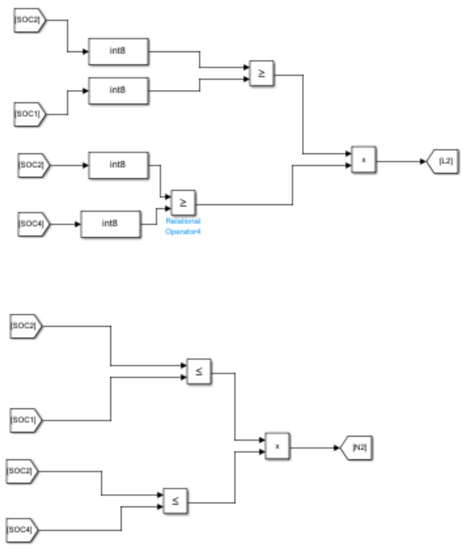

Figure A.8: Battery 2 has smallest or highest level of soc

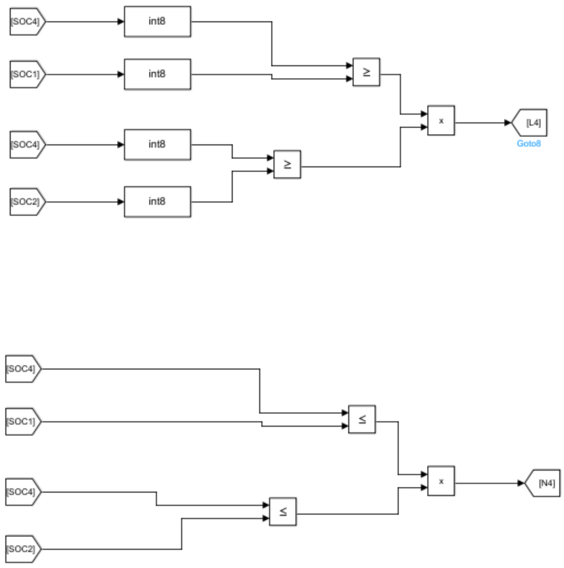

Figure A.9: Battery 3 has smallest or highest level of soc

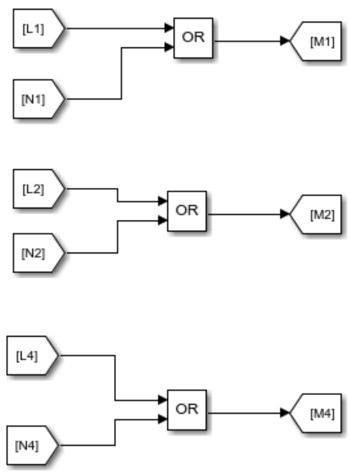

Figure A.10: Determine if has the highest or lowest SOC based on A.7, A.8,A.9

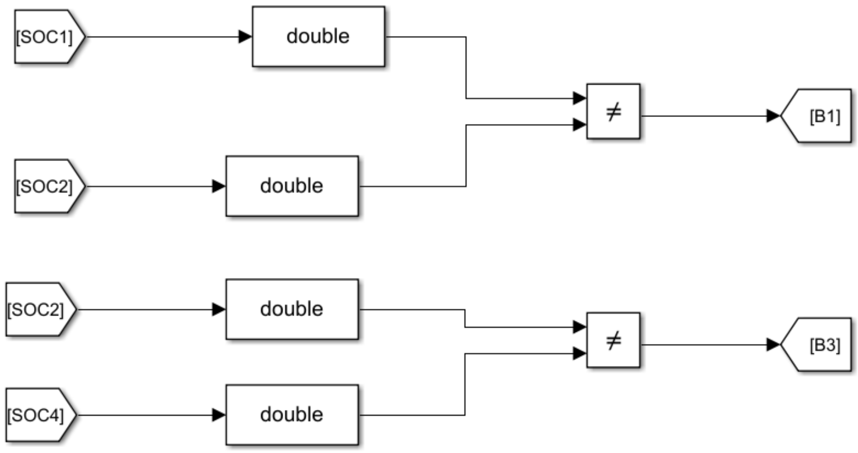

Figure A.11: Determine if battery cell has same SOC

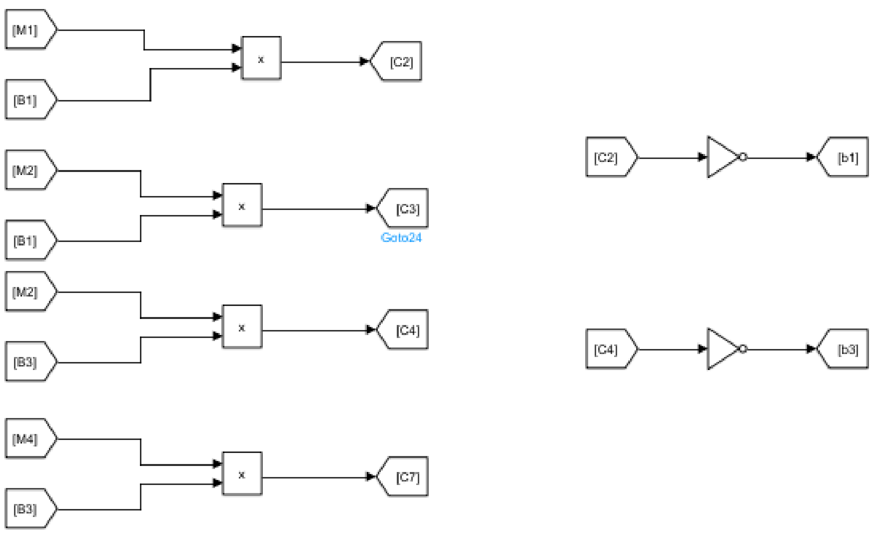

Figure A.12: Send information to switches