

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**ADVANCED BATTERY MANAGEMENT SYSTEM FOR
LITHIUM BASED ENERGY STORAGE APPLICATIONS**



MURAT CEYLAN

A THESIS OF DOCTORATE
DEPARTMENT OF ELECTRONICS ENGINEERING

ADVISOR: PROF. DR. ABDULKADİR BALIKÇI

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GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

LİTYUM TABANLI ENERJİ DEPOLAMA
UYGULAMALARI İÇİN İLERİ BATARYA YÖNETİM
SİSTEMİ

MURAT CEYLAN

DOKTORA TEZİ
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*To my parents
and my family*

ABSTRACT

Batteries have revolutionized science and technology, and paved the way for many other discoveries and inventions for two centuries. They are everywhere in our lives. Lithium-ion batteries (LIB) have especially gained attention in the last few decades. One of the crucial aspects of a LIB system is battery management.

In this thesis, three main conceptual subdivisions of a battery management system (BMS) were developed and experimentally validated: an intermodular active balancing (AB) topology, a parametric state of health (SoH) model, and a safety oriented simplified thermal model (TM).

Realtime operation of both the intermodular active balancing and the thermal model were verified by industrial BMS circuit and embedded microcontroller. Under realistic operation conditions, the required tasks can be fulfilled successfully within a temporal resolution of 1 second. Realtime controlled active balancing with both standard module voltage and high package voltage in various pack configurations and the safety oriented cell temperature estimation works properly.

Keywords: Battery Management System, BMS, Battery Model, Thermal Model, State of Health, Balancing.

ÖZET

Bataryalar ilk icat edildiğinden beri iki yüz yıldır bir çok başka önemli keşif ve icata yol açarak bilim ve teknolojiye devrim yaratmıştır. Yaşamımızın her alanında yer almaktadırlar. Özellikle son yıllarda lityum-iyon bataryalar (LIB) öne çıkmıştır. LIB sistemlerinin en kritik bileşenlerinden biri de batarya yönetimidir.

Bu tez kapsamında, bir batarya yönetim sistemini (BYS) oluşturan üç ana başlığa ait katkı sunulmuş ve geliştirilen yöntemler deneysel olarak gerçekleştirilmiştir; modüller arası ve modül içi dengeleme yapabilen intermodule aktif dengeleme (AD) topolojisi, parametrik sağlık durumu (SD) kestirim modeli, ve güvenlik odaklı bir basitleştirilmiş termal model (TM).

Hem aktif dengeleme, hem de termal model, gerçek zamanlı çalışarak endüstriyel BYS devresi ve gömülü mikrodenetleyici ile doğrulanmıştır. Gerçekçi uygulama koşulları altında 1 saniyelik zaman çözünürlüğü içinde istenen görevler başarıyla yürütülebilmektedir. Farklı paket yapıları içinde hem standart modül voltajı hem de yüksek paket voltajı ile gerçek zamanlı kontrol edilen aktif dengeleme ve güvenlik odaklı hücre sıcaklık tahmini düzgün şekilde çalışmaktadır.

Anahtar Kelimeler: Batarya Yönetim Sistemi, BYS, Batarya Modeli, Termal Model, Sağlık Durumu, Dengeleme.

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As this thesis marks the final point of my formal education path, I would like to thank many individuals who made it possible for me to go this far over many years of toil, blood and tears. First and foremost, I am forever grateful to Prof. Dr. Abdulkadir BALIKÇI, who had kindly accepted me as his M.Sc. student at Gebze Institute of Technology, for transferring his knowledge and experience, patiently providing his astute mentoring and morale support, always helping me whenever I needed and always believing in me. I wouldn't have been able to pursue an academic career without him. I also would like to thank the thesis steering committee members, Prof. Dr. M. Hakan HOCAOĞLU and Assoc. Prof. Dr. Uğur HASIRCI, for their thoughtful guidance and fruitful discussions during the semi-annual thesis progress meetings. Additionally, I'm thankful to all jury members of my thesis defence, Prof. Dr. Serkan AKSOY and Assoc. Prof. Dr. M. Tahir GÜNEŞER, for their valuable suggestions. I would also like to take this opportunity to thank all my teachers in the past, each and every one of them since my kindergarten days, throughout my primary, secondary and high schools, my alma mater, and my final destination, GTU. They made me who I am now.

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Last but not least, I am forever indebted to my dearest family for their unconditional, endless love and unwavering support. They have always encouraged me since the day I was born, without complaining once about my mistakes. There is no word available in any language to express the level of my gratitude and appreciation for them. Abdullah (RIP) – Yıldız - Arzu, and Tuğba... I love you all so much.

This thesis is dedicated to the cherished memories of two people who passed away during the last phase of my studies, a most unfortunate coincidence with the covid19 pandemic. Prof. Dr. Abdullah CEYLAN, my father and my hero, inspired me to persevere and never give up under any circumstance. He worked very hard until his last breath, literally, and sacrificed himself to cure ill children all around the country. One of the earliest members of our department since its first establishment, Prof. Dr. Oleg A. TRETYAKOV, a.k.a. "the professor of professors", apart from his immense scientific background, was a genuinely nice person and always wore a smile that cheered everyone up. Both of you are sorely missed, and will be forever remembered with your kindness and contributions to humanity.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	: Surface area
Bi	: Biot number
C	: C-Rate
$^{\circ}C$	: Celsius degrees
c_p	: Specific heat capacity
ΔSoC_{max}	: Maximum SoC deviation
ΔT	: Temperature difference
ΔV_{max}	: Maximum voltage deviation
h	: Convection coefficient
k	: Conduction coefficient
L_c	: Characteristic length
m	: Mass
Q_{nom}	: Nominal capacity
$Q_{transfer}$	: Transferred heat
SoC	: State-of-Charge
SoC_{avg}	: Average SoC value
SoC_{min}	: Minimum SoC value
SoH_h	: State-of-Health
$SoH(Q)$	: SoH with respect to capacity decrease
$SoH(R)$	: SoH with respect to resistance increase
SoC_{th}	: SoC threshold for balancing
V_{avg}	: Average voltage value
V_{th}	: Voltage threshold for balancing
AB	: Active balancing
ADC	: Analog to digital converter
AFE	: Analog front end
BESS	: Battery energy storage system
BMS	: Battery management system
CTC	: Cell-to-chassis construction
CTP	: Cell-to-pack construction
DC	: Direct current
DG	: Distributed generation
DMM	: Digital multimeter
DPDT	: Double-pole double-throw
EIS	: Electrochemical impedance spectroscopy
ESR	: Equivalent series resistance
ESS	: Energy storage system
EV	: Electric vehicle
GITT	: Galvanostatic intermittent titration technique
H/EV	: Hybrid/electric vehicle
HV	: High voltage
IC	: Integrated circuit
LFP	: Lithium-iron-phosphate
LIB	: Lithium-ion battery
MOSFET	: Metal-oxide semiconductor field effect transistor
NMC	: Nickel-manganese-cobalt

OCV	: Open circuit voltage
OV	: Over-voltage
PB	: Passive balancing
PC	: Personal computer
PCB	: Printed circuit board
P-S	: Parallel connection of series cells
RCN	: Reference cycle number
REP	: Renewable energy plant
SC	: Super capacitor
S-P	: Series connection of parallel cells
SPI	: Serial peripheral interface
UPS	: Uninterrupted power supply
UV	: Under-voltage
USB	: Universal serial bus



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1. INTRODUCTION

Followed by the green energy transition momentum worldwide, the increasingly high necessity and number of installations for renewable energy plants (REP) have strengthened the role of energy storage systems (ESS) as a crucial component in decarbonized grid. Probably the only downside of REP is the fact that the provided energy is intermittent and dependent on natural conditions, hence, contrary to conventional power plants, a constant supply of energy cannot be available. In a distributed generation (DG) scheme of power transmission network [1],[2] that includes REPs, the intermittent electrical energy must first be converted and stored as other energy types by ESS such as thermal, mechanical, electromechanical, and electrochemical storage [3],[4]. Then, after being converted back to electricity, it is delivered to supply the grid demand when needed. Regarding the ESS and renewables integration into an exceedingly complex grid, different aspects such as energy storage duration, DG optimization and resiliency are becoming highly important [5],[6].

One of the most convenient ESS technologies is battery based systems which store and release energy directly by means of very efficient electrochemical reactions. For three decades now, lithium-ion batteries (LIB) have proven themselves to be the main viable choice of energy storage medium to be used in portable electronics, hybrid/electric vehicles (H/EV), naval and aerospace applications. The advancements in electrochemistry field in the last few decades has enabled the LIB technology to become ubiquitous thanks to its merits of high cell voltage, high efficiency, high capacity, high energy density, low self-discharge and relatively longer life than the previous generation of lead-acid (Pb-A), nickel-cadmium (Ni-Cd) and nickel-metal-hydrate (Ni-MH) batteries, replacing them in almost all applications. They also perform well in stationary battery energy storage systems (BESS) by providing energy during power outages, mitigating grid overload by assisting the continuous low-stress operation of the grid, frequency regulation, peak shaving etc. Stationary BESS is an attractive field also for repurposing of the retired cells from EVs, enabling some more years of second-life service for usually less aggressive energy storage use before being finally recycled [7], [8].

A typical BESS consists of many cells connected to each other in different combinations. Since the nominal voltage (in the range of 1.2 V to 3.7 V per cell) and capacity (can be in the range of hundreds of mAh to tens of Ah) of an individual cell is not sufficient, they are grouped together and assembled in series and parallel configuration of adequate number of cells in order to meet the rated bus voltage and current specification of a power electronics system [9]-[11]. The total number depends both on the cell chemistry and the capacity of each cell. The chemical composition dictates the number of series connected cells with respect to the rated charge and discharge voltage range, whereas the nominal cell capacity is used for determining the total capacity based on the multiplication of individual capacity by the parallelization number. In general, for modularity and safety purpose, the cells are initially assembled into identical modules of several cells, and then the modules are connected to each other, forming a battery pack. Recently, direct cell-to-pack (CTP) and cell-to-chassis (CTC) constructions that reduce the overall pack size and weight are also studied [12].

1.1. Motivation and Thesis Contribution

There are three main contributory goals of the thesis. Each section corresponds to a crucial subcomponent of battery management systems (BMS), and are indispensable for safe and efficient operation of battery packs.

1.1.1. BMS Subcomponent 1 - Develop and Validate a State-of-Health Model

The relative capacity and State-of-Health (SoH) of a battery decrease over its lifetime. Therefore, accurate estimation of these parameters is essential. In this study a parametrical approach for estimation of battery state of health is proposed. A battery model, based on our previous work [13],[14] was enhanced and used to estimate the relative capacity of the battery by taking the performance decline into account. The method was validated by two different set of experiments. The first set was conducted with batteries that were aged by a controlled process and the second set were carried out with randomly aged batteries. The proposed method works successfully in both conditions with a maximum error less than 5% [15].

1.1.2. BMS Subcomponent 2 - Develop and Validate a Thermal Model

Battery thermal models (TM) are valuable tools for estimating cell temperatures. Temperature is a vital aspect for safe and efficient operation of battery packs, and it must be carefully monitored and controlled by a thermal management system (TMS). In order to provide temperature information for predictive control and individual cell temperatures with higher granularity, a thermal model is necessary to complement the sensor measurements. There are very advanced thermal models that can simulate heterogeneous temperature distribution of a cell from 1D to 3D, however they are mostly used for initial pack design stage and are not fast enough to be used in embedded microcontrollers in a typical BMS. In this thesis, a safety oriented, simplified 0D thermal model with very low computational cost was developed and validated. The maximum error remains below 2 °C.

1.1.3. BMS Subcomponent 3 - Develop and Validate an Active Balancing Architecture

In order to meet the load voltage and power requirements for various specific needs, a typical lithium-ion battery (LIB) pack must consist of different parallel and series combinations of individual cells in modules, which can go as high as tens of series and parallel connections in each module reaching hundreds and even thousands of cells at high voltage levels. The inhomogeneity among the cells and modules results in voltage imbalance during operation and reduces the overall system efficiency. In this thesis work, a robust and flexible active balancing topology is presented. It can not only mitigate the charge imbalance within a module (intramodular equalization), but also help balance the State-of-Charge (SoC) level of the modules in a high voltage pack as well, i.e. intermodular equalization, which is an often overlooked topic. The proposed concept was proven by experimental verification on parallel and series configuration of cells in realistically sized modules, including high voltage intermodular balancing and practical battery management system (BMS) hardware, both when the LIB was idle and under load. When the subjected to a nominal discharge current during the experiments, runtime and energy delivery were increased by >15% without using any other energy source than the LIB itself [16].

1.2. Thesis Structure

The thesis consists of the following chapters. Chapter 2 explains the BMS, battery models, and modelling techniques. In Chapter 3, the development and validation of a simplified thermal model is presented. Next, Chapter 4 presents the SoH concept, battery degradation reasons, and a parametric SoH model. In Chapter 4, a robust and flexible inter-intramodular active balancing topology for high voltage battery packs is presented including its experimental verification with commercial BMS hardware under different imbalance scenarios. In the final chapter, conclusion and outlook are provided.



2. BATTERY MANAGEMENT SYSTEM AND BATTERY MODELS

2.1. Battery Management System

One of the most critical components of a battery energy storage system (BESS) is battery management. A battery management system (BMS) has very important and critical duties such as functional safety, current-voltage measurement, temperature measurement, isolation monitoring, state of charge (SoC) estimation, SoH estimation, cell balancing and communication. A conceptual diagram of a typical BMS is given in **Figure 2.1**.

In order to estimate the SoC and SoH accurately, battery models are required. In the next subchapter, the model types are explained.

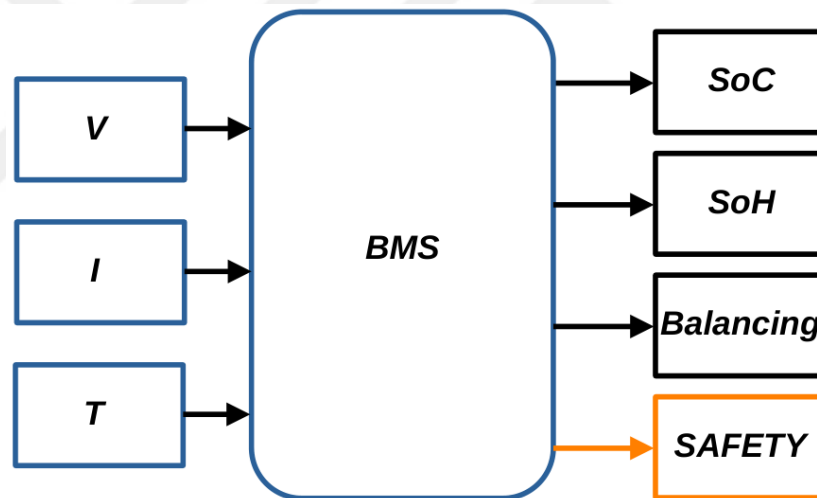


Figure 2.1: Battery management system conceptual diagram.

2.2. Battery Models

Battery models can be considered as three main model types according to their working principle for predicting actual behaviour. The parameters of different models depend on each other, usually non-linearly, in complex interactions. The interdependency of battery models is presented in **Figure 2.2**.

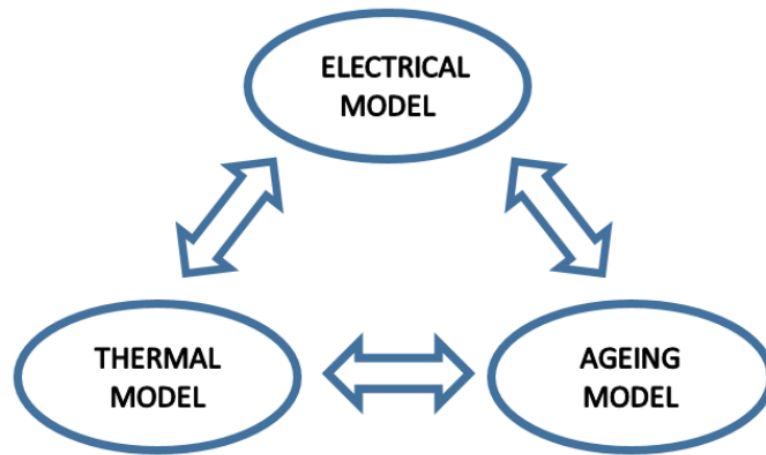


Figure 2.2: Battery model interactions.

Electrical Model (EM): Electrical model is the fundamental model to predict voltage, SoC and power as output. Its main input is current. Temperature and SoH can also be used to update the model parameters with respect to various operating conditions. If they are assumed to be constant, EM can run on its own to simulate a fresh cell continuously.

Thermal Model (TM): A thermal model is necessary if an estimation of battery temperature is required. Its input is power to calculate the heat generation, it can also require specific information about the material properties and cooling/heating system.

Ageing Model (AM): An ageing model is necessary to predict the lifetime and SoH with respect to the battery degradation. Its inputs can be temperature, current, SoC and voltage.

The input and output parameters of interdependent battery models are given in **Table 2.1**.

Table 2.1: The input and output parameters of interdependent battery models.

Model Type	Inputs	Outputs
Electrical	Current, SoH, Temperature	Voltage, SoC, Power
Thermal	Power	Temperature
Ageing	Current, SoC, Temperature	SoH

2.2.1. Electrical Equivalent Circuit Models

Modelling of a battery is a tedious task because of the complex electrochemical structure and nonlinear characteristics. The criteria needed to design an accurate battery model and to compare it with existing models can be summarized as accuracy, calculation time and the number of parameters required. Electrical equivalent circuit models (ECM) are the main choice in embedded microcontroller systems thanks to their reasonable accuracy and relatively lower complexity than physical/electrochemical models that need many parameters and require the solution of several partial differential equations simultaneously [17]. Although being highly accurate, as of writing this thesis, physical/electrochemical models are not feasible for realtime operation of BMS.

ECM can also be classified according to their level of complexity. A typical 1st order ECM, which was first introduced by Randles in 1947 [18] and have been used countless times ever since, is illustrated in **Figure 2.3**.

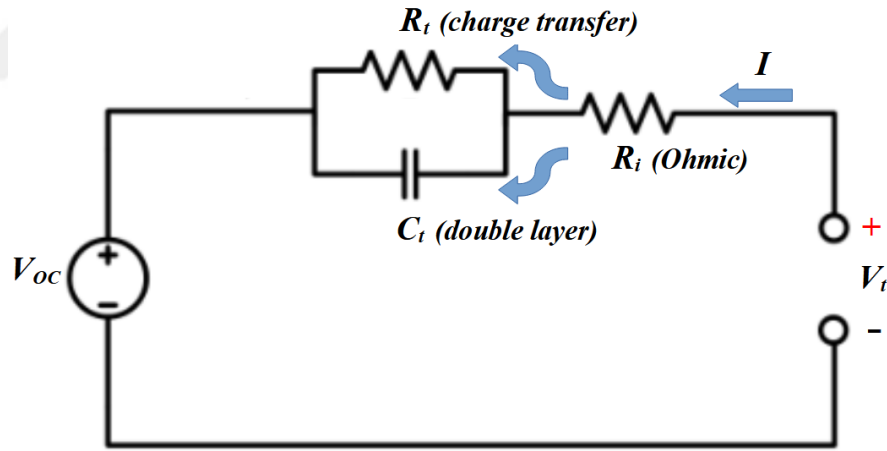


Figure 2.3: Electrical equivalent circuit model.

The SoC dependent open circuit voltage (OCV) of the cell, V_{oc} , can be obtained by measuring the terminal voltage, V_t , at equilibrium, and SoC can be found by using several methods such as Coulomb counting or Kalman filter [19]. For the rest of the circuit elements, a set of characterization experiments can be performed for ECM parameterization by electrochemical impedance spectroscopy (EIS) as introduced in the original paper, or galvanostatic intermittent titration technique (GITT) which can provide diffusion information [20]. GITT involves applying constant current [21]

pulses at specific SoC intervals, such as 10%, after waiting for a sufficiently long enough time to let OCV reach equilibrium, such as 120 min. The voltage response of 1 C pulses with 1% resolution and ECM parameter extraction for an exemplary of 5% resolution [22] are depicted in **Figure 2.4** and **Figure 2.5** respectively.

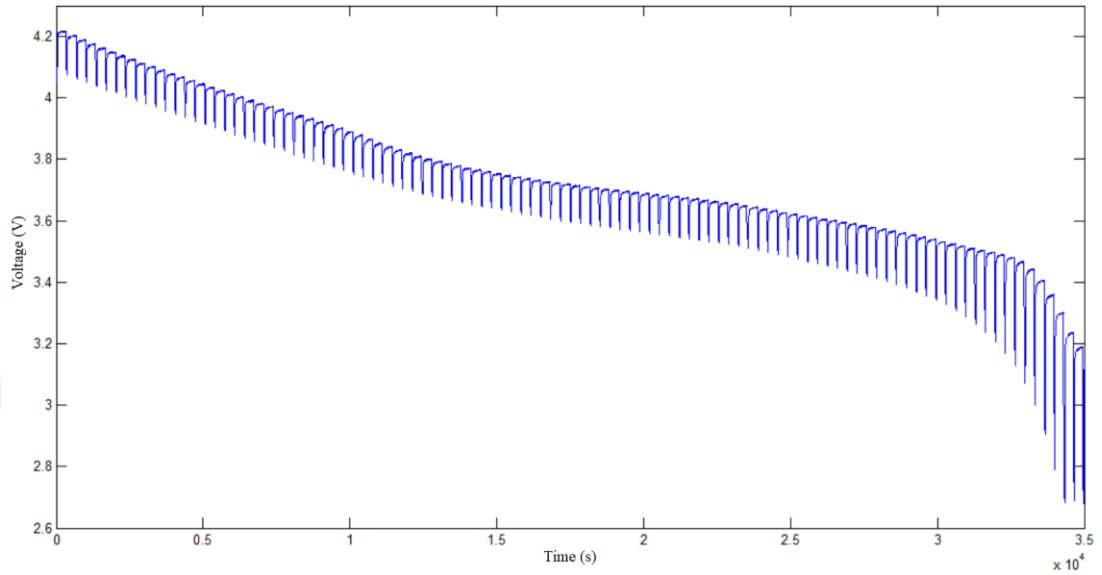


Figure 2.4: ECM characterization experiment with 1% SoC resolution [13].

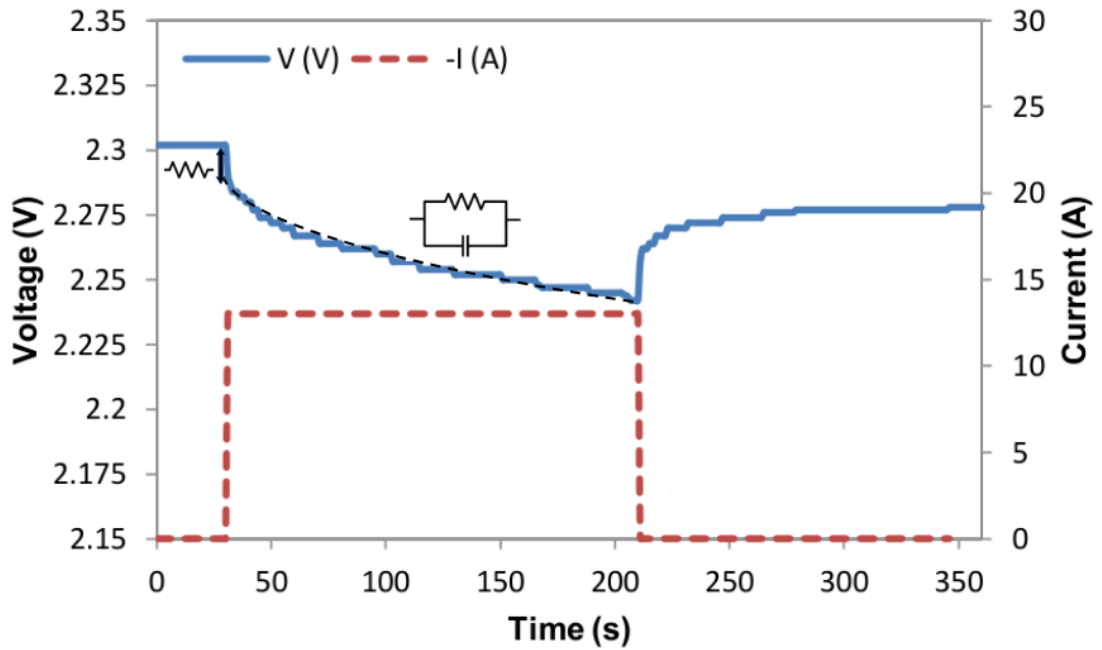


Figure 2.5: ECM parameter extraction.

The equivalent circuit components can be identified at each SoC level. The initial voltage drop corresponds to the fast dynamics and can be considered as the main resistive component R_i .

$$R_i = \frac{V_{oc} - V_t}{I} \quad (2.1)$$

The transient response can be modelled by the resistor-capacitor network which corresponds to the slower dynamics of charge transfer resistance and double layer capacitance by (2.2).

$$\tau = R_t C_t \quad (2.2)$$

The voltage source can be modelled by interpreting the experimental results and assuming the terminal voltage has the same value of OCV at equilibrium. OCV can be defined as a function of SoC by (2.2).

$$OCV = -1.035e^{-35SoC} + 0.325SoC^2 - 0.325SoC + 3.575 \quad (2.3)$$

In order to determine the accuracy of the model, a simulation was set-up and run in Simulink environment as given in **Figure 2.6**. A constant discharge current of 11 A was applied to the battery model. The OCV values were generated by a mathematical function block that employs (2.1) depending on the SoC level. Thus, terminal voltage, V_t , could be produced as seen in **Figure 2.7** faithfully, representing the terminal voltage curve of an actual battery under load. The measured and experimental data were in close agreement. The average error was 0.422% while the maximum error was less than 3%.

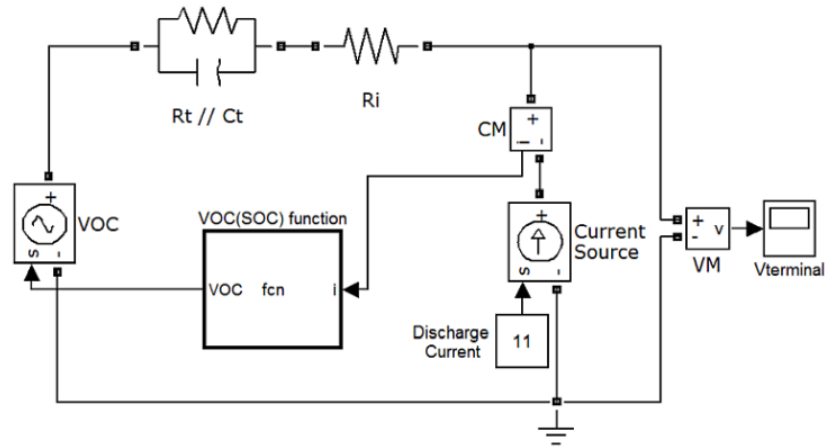


Figure 2.6: Simulation setup.

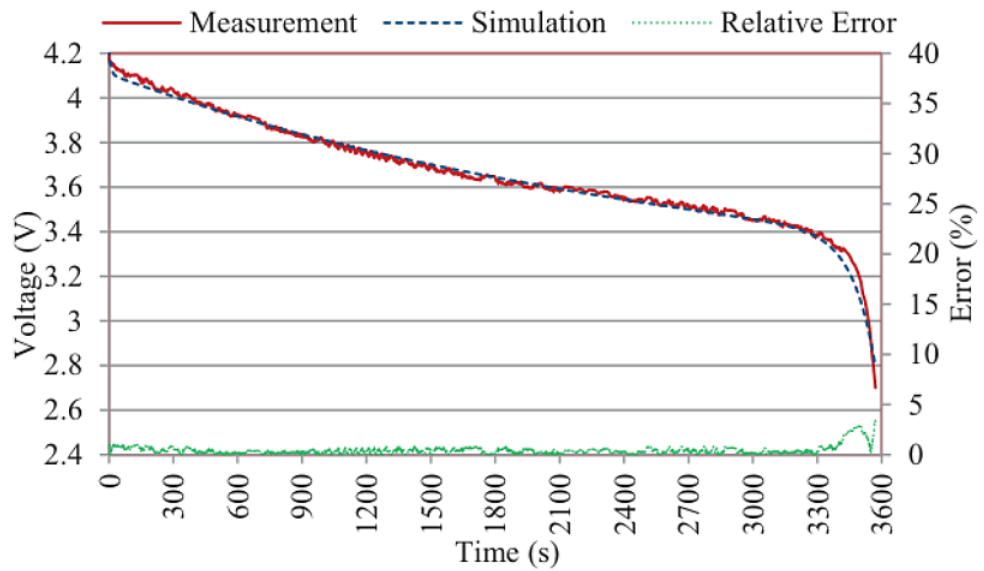


Figure 2.7: Electrical equivalent circuit model validation.

In order to prove the general applicability, the same ECM approach was used for other chemistries later on throughout the thesis progress. The comparison of simulation results and measured data for Li-S and LTO cells are in **Figure 2.8** and **Figure 2.9**, respectively [23].

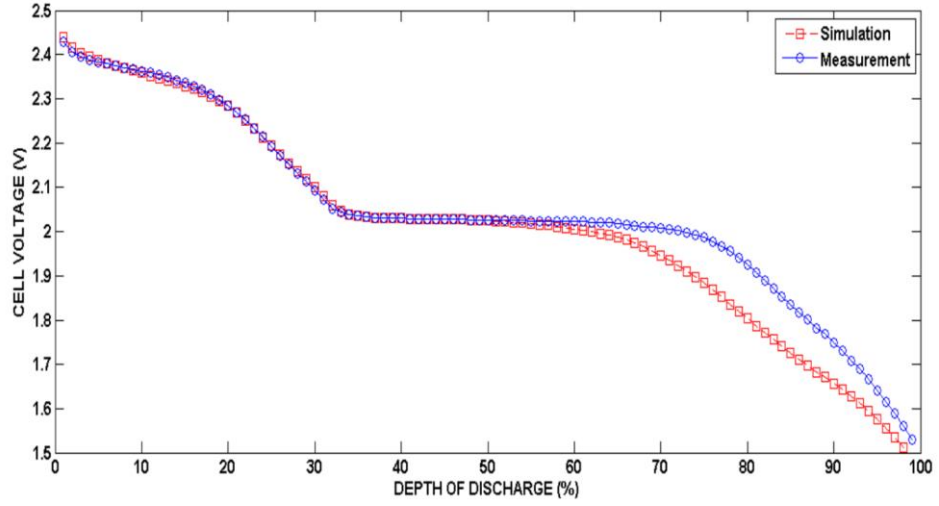


Figure 2.8: ECM validation for Li-S [22].

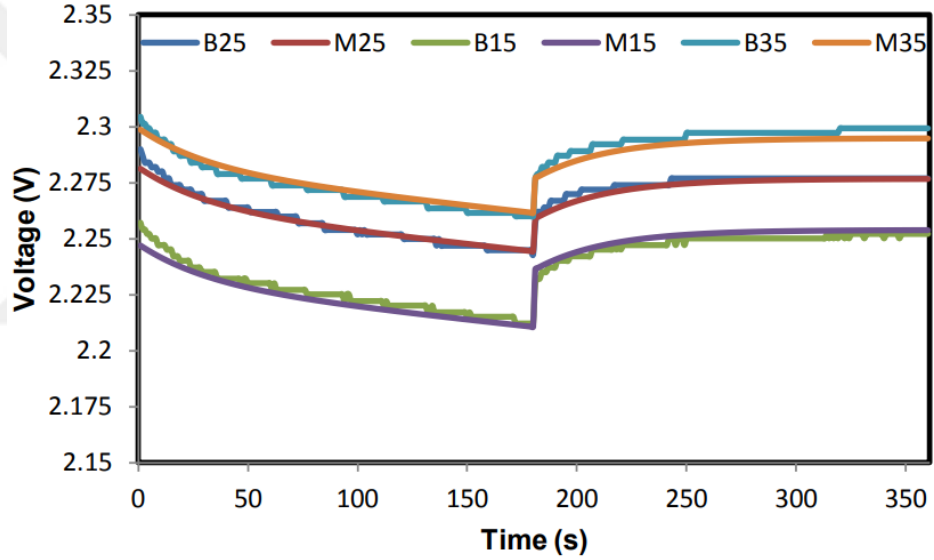


Figure 2.9: ECM validation for LTO at different temperatures [23].

2.2.2. Thermal Models

Battery safety, performance, degradation and the parameters of ECM all depend on temperature. Therefore, of temperature of LIB must always be continuously monitored by BMS with several temperature sensors at different locations in the battery pack. There are two main disadvantages of temperature sensors, they have thermal inertia delay of at least a few seconds which can be much larger according to the sensor type and location, and it is not practical to use an individual sensor for each cell, especially

in a large battery pack. Therefore, temperature measurements should be complemented with a thermal model (TM) to estimate individual cell temperatures.

2.2.3. Ageing Models

Accurate knowledge regarding the remaining battery capacity is crucial for ensuring dependable performance and accurate runtime estimation. SoH is a figure of merit which essentially provides information on the battery condition. It represents a quantitative assessment of the disparity between the current state and the initial state of a battery, usually expressed in percentage points, where 100% indicates that the battery possesses the exact specifications of a brand new, fresh battery. Ageing models can be simple or very complicated, depending on the modeling complexity and degradation modes to simulate the decline in cell performance. SoH can be defined both by the fade of capacity, which limits the amount of energy, and the increase in internal resistance, which limits the power delivery before reaching the cut-off voltage, as in

$$\text{SoH}(Q) = \frac{Q}{Q_{\text{nom}}} \quad (2.4)$$

or

$$\text{SoH}(R) = \frac{R_0}{R} \quad (2.5)$$

where $\text{SoH}(Q)$ is the ratio of available capacity, Q , to the nominal capacity of a fresh cell, Q_{nom} , $\text{SoH}(R)$ is the ratio of internal resistance values of a fresh cell, R_0 , and an aged cell, R , respectively. Usually a cell is considered to have reached its end of useful life (EoL) when $\text{SoH}(Q)$ decreases to 80% or $\text{SoH}(R)$ decreases to 66.7%. It should be kept in mind that these figures are application dependent and can change according to a specific usage case.

3. STATE OF HEALTH MODEL

There are several reasons and modes of battery degradation. They can be summarized as copper cracking, aluminum corrosion, binder decomposition and contact loss; solid electrolyte interphase (SEI) decomposition and precipitation, particle cracking, SEI thickening, lithium plating, dendrite formation, loss of active material, loss of lithium inventory and electrolyte leakage. These phenomena result in capacity fade and internal resistance growth, which in turn result in degraded performance, i.e. reduced SoH, and safety issues.

There is an ambiguity in the definition of SoH in the literature, and there is a wide spectrum of methods regarding SoH estimation as well [24]-[27]. A very detailed review can be found in [28]. SoH can be accurately determined by using electrochemical impedance spectrometry measurement [29], [30]. However, advanced techniques are needed for measurement of SoH and online measurement is not possible. Therefore, estimation-based methods are more favorable. A statistical parametric model was developed in order to estimate failure [31]. There have been many studies on the topic from adaptive observer [32] and support vector machine approach [33], to Bayesian implementation [34] and wavelet transform [35].

The method proposed in the present study is a simple semi-empirical approach that requires less computational effort while providing accuracy. Battery performance is related to several factors such as voltage imbalance in a stack, temperature, or decreased SoH of a battery. In EVs battery temperature and cell balancing are controlled by thermal or battery management systems. Therefore, assuming a stable battery temperature and balanced cells in the stack, performance degradation can be a measure that indicates battery health. The capacity of a battery can simply be defined as the length of time that a fully charged battery can be totally discharged under nominal discharge current. The maximum capacity of a battery decreases as battery ages. The main purpose of the present study is to indicate the SoH of a battery in terms of its relative capacity (RC). In order to achieve this goal the reference cycle number of the battery (RCN) is used. RCN is defined as the cycle number of a battery that was aged by the same cycling procedure and environmental conditions as mentioned in the technical specifications manual by the cell manufacturer. If the condition of a battery is represented in terms of RCN, SoH can also be calculated by this relationship. The

relative capacity, or capacity retention, of a 11 Ah Kokam cell (SLBP55205130H) with respect to number of cycles is given in **Figure 3.1** [36].

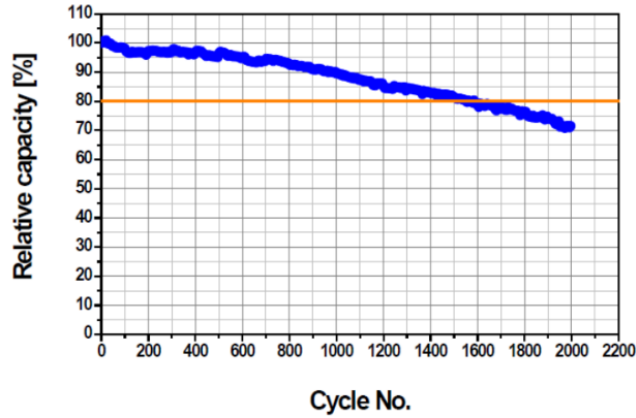


Figure 3.1: Kokam SLBP55205130h capacity vs number of cycles [36].

Battery response must be defined to develop a mathematical relationship between aging and SoH. For this purpose, a model capable of reflecting aging effects of the battery is needed. Within the scope of this thesis, previously employed battery model was improved and used to develop a parametric SoH estimation model. A relationship between battery cycle life and battery terminal voltage was established and adopted to the battery model, which was originally characterized for a Kokam LBP55205130H 11 Ah automotive grade NMC cells. The proposed model is able to obtain terminal voltage of the battery, V_t , with respect to open circuit voltage, OCV, which was recorded in no-load condition. The value of OCV is calculated by a mathematical function that represents the correlation between battery capacity and OCV. In the model a parallel RC block in series with a resistor is used to increase accuracy in transient conditions. Although both the accuracy and the complexity of the model increase by increasing the number of RC blocks, a single RC block yielded satisfactory results without sacrificing simulation performance. The model can be seen in **Figure 2.1**. RCN is obtained by a parametrical method in which the simulation results are used. The method is validated by experiments in which both batteries aged by a controlled process and randomly aged batteries were used. The proposed method works successfully in both conditions with a maximum error less than 5%. Assuming that an EV should have a proper thermal management system to keep battery temperature around the optimum operating temperature, changes in temperature are not reflected in the battery model. Thus both the battery model and the SoH estimation method are independent of temperature.

3.1. Experimental Setup

The experimental setup consisted of a programmable DC power supply (Chroma 62050P), a load (Chroma 63297), data acquisition cards (NI 9206 and NI 9213), and a system control software (Labview). There were two power supplies but only one load and this meant a single DC bus and single channel testing possibility. In order to save time and perform two tests simultaneously, the system was arranged such that one cell was charged while the other one was being discharged, by timesharing of the load and avoiding short circuiting the cells with the help of algorithmic contactor switching. The block diagram and the photo of the setup are demonstrated in **Figure 3.2** and **Figure 3.3**, respectively.

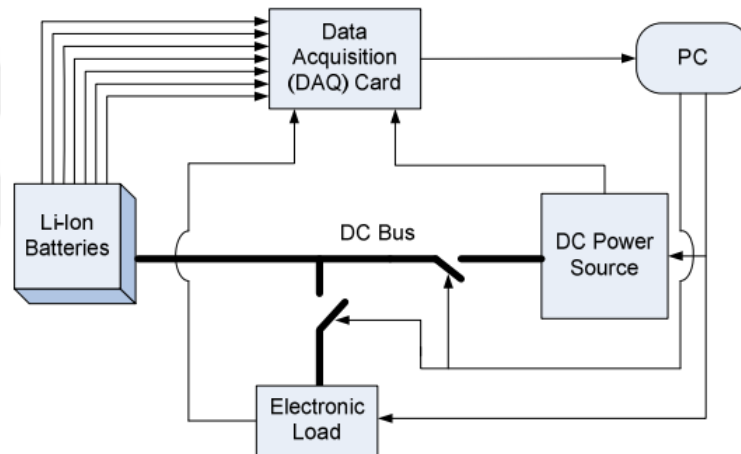


Figure 3.2: Experimental setup block diagram.



Figure 3.3: Experimental setup photograph.

3.2. SoH Estimation Model

First, in order to extract parameters for the SoH estimation model, an arbitrarily modified ECE 15 type profile was applied to the fully charged cell, with respect to the maximum discharge C-rate (6C). The load profile response of two cells at different SoH are presented in **Figure 3.4**.

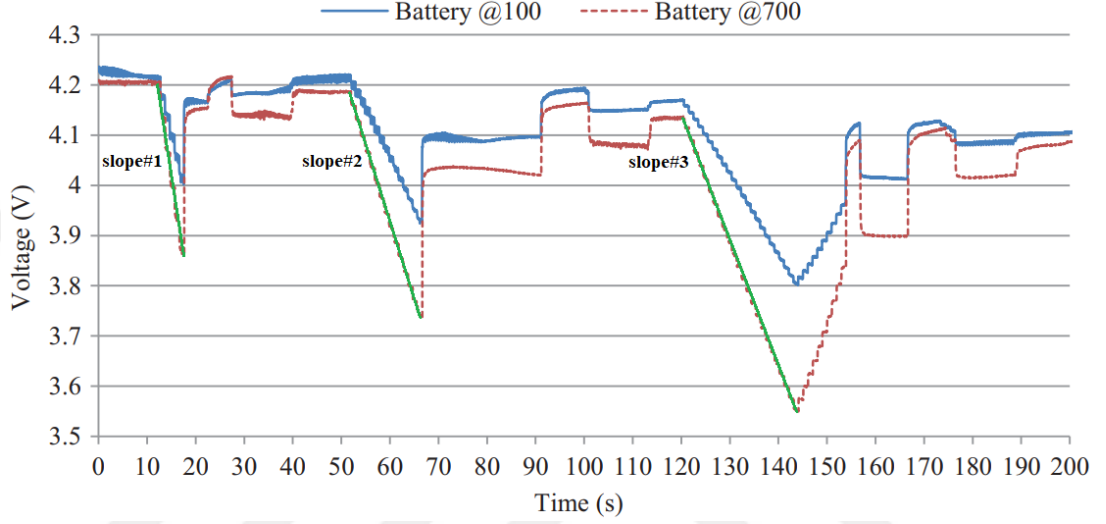


Figure 3.4: Voltage response and capacity decline vs number of cycles.

The slope of the voltage decrease can be represented by a parameter set for comparison of cell response in three zones of the applied arbitrary load profile. A voltage signal can be represented as in equations (3.1)-(3.3), where V_t is voltage, t is time, a and b are the parameters that define the difference between slopes, and V_1 and V_2 are the voltage at the instances t_1 and t_2 , i.e. the beginning and end of the slopes, respectively.

$$V_t = \frac{b}{a+t} \quad (3.1)$$

$$a = \frac{V_2 t_2 - V_1 t_1}{V_1 - V_2} \quad (3.2)$$

$$b = \frac{V_1 V_2 (t_2 - t_1)}{V_1 - V_2} \quad (3.3)$$

3.2.1. RCN Estimation

In the experimental test cycle the first, the second, and the third zones lasted between 1–6 s, 41–56 s, and 111–136 s, respectively. Since the test cycle was used in both simulation of the model and validation tests for the method, time values were set as $t_1 = 1$ s, $t_2 = 6$ s (1st slope), $t_1 = 1$ s, $t_2 = 16$ s (2nd slope), and $t_1 = 1$ s and $t_2 = 16$ s (3rd slope) for consistency. As an example, the voltage output results of the model for a battery of every 400 cycles for the first zone are given in **Table 3.1**. The corresponding parameters obtained by equations (3.1-3.3) are listed in **Table 3.2**.

Table 3.1: Simulation of voltages for the first zone.

Time (s)	Cycle 1	Cycle 400	Cycle 800	Cycle 800	Cycle 1200	Cycle 1600	Cycle 2000
1	4.310	4.310	4.310	4.310	4.310	4.310	4.310
2	4.294	4.294	4.294	4.294	4.294	4.294	4.294
3	4.274	4.274	4.274	4.274	4.274	4.274	4.274
4	4.249	4.249	4.249	4.249	4.249	4.249	4.249
5	4.219	4.219	4.219	4.219	4.219	4.219	4.219
6	4.187	4.187	4.187	4.187	4.187	4.187	4.187

Table 3.2: Parameters for the first zone.

Parameter	Cycle 1	Cycle 400	Cycle 800	Cycle 800	Cycle 1200	Cycle 1600	Cycle 2000
a	169.3	169.3	169.3	169.3	169.3	169.3	169.3
b	733.9	733.9	733.9	733.9	733.9	733.9	733.9

By using the parameter values given in Table 4.2, the values of RCN can be found as a curve fitted function of parameters a and b, for each zone as follows, where the index corresponds to the zone the parameter was originally calculated for.

$$RCN(a_1) = -0.00137a_1^3 + 0.486a_1^2 - 58.15a_1 + 2579 \quad (3.4)$$

$$RCN(b_1) = -0.00171b_1^3 + 0.0263b_1^2 - 13.71b_1 + 2637 \quad (3.5)$$

$$RCN(a_2) = -0.000319a_2^3 + 0.179a_2^2 - 58.15a_2 + 2642 \quad (3.6)$$

$$RCN(b_2) = -(4.019 \times 10^{-6})b_2^3 + 0.0973b_2^2 - 8.29a_1 + 2678 \quad (3.7)$$

$$RCN(a_3) = -(1.612 \times 10^{-4})a_3^3 + 0.1074a_3^2 - 25.82a_3 + 2233 \quad (3.8)$$

$$RCN(b_3) = -(2.055 \times 10^{-6})b_3^3 + 0.00588b_3^2 - 6.09b_3 + 2259 \quad (3.9)$$

Finally, the SoH can be found in terms of RCN by curve fitting of the capacity retention data by the polynomial expression in (3.10).

$$\text{SoH} = -(4.997\text{E} - 6)RCN^2 - 0.005RCN + 100 \quad (3.10)$$

3.3. Validation Results

The validation results for four different cells of the same type and different ageing levels are presented in **Table 3.3**, where FEC corresponds to full equivalent cycle and it is equal to RCN. The maximum error between the estimated SoH and the true SoH of the experimental cells remains below 5% for all cases.

Table 3.3: Validation results.

Zone		Cell 1	Cell 2	Cell 3	Cell 4
1	Estimated FEC	180.5	251.6	1872.6	193.3
	Estimated SoH	97.124%	97.018%	74.808%	97.085%
	Measured SoH	99.722%	98.583%	77.666%	101.33%
	Error	2.605 %	3.679%	4.192%	4.037%
2	Estimated FEC	136.9	290.9	1836.7	170.7
	Estimated SoH	97.360%	98.122%	75.452%	97.162%
	Measured SoH	99.722%	98.583%	77.666%	101.33%
	Error	2.369%	1.124%	2.85%	4.116%
3	Estimated FEC	114.6	240.1	N/A	155
	Estimated SoH	97.549%	97.021%	N/A	97.241%
	Measured SoH	99.722%	98.583%	77.666%	101.33%
	Error	2.179%	1.584%	N/A	4.038%

4. THERMAL MODEL

Within the scope of the thesis, a safety oriented simplified thermal model (TM) was developed and validated. The conceptual diagram is illustrated in **Figure 4.1**.

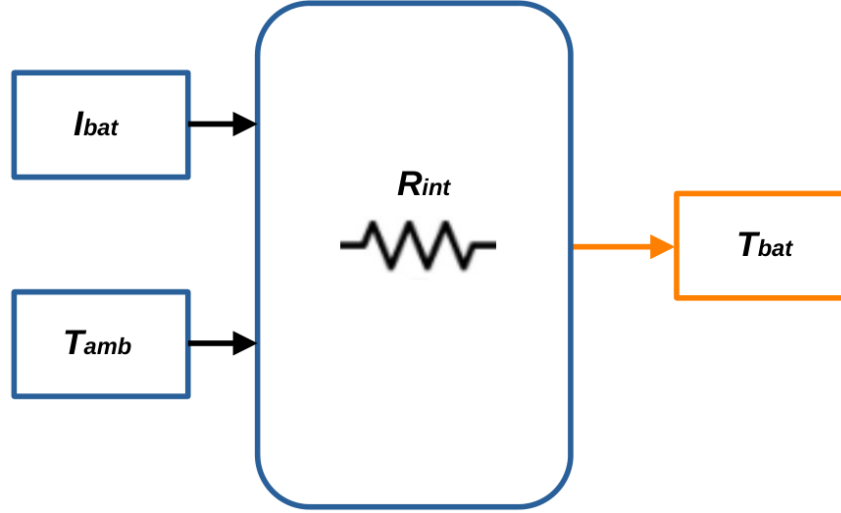


Figure 4.1: Simplified thermal model.

The basic internal resistance model provides the source of heat generation with respect to the power input only. The entropic contribution, enthalpy of mixing, and radiative heat transfer effects are neglected [37]. The temperature rise then can be calculated by taking the material properties and heat transfer to the ambient into account. The main component is the cell internal resistance that is used to calculate the temperature rise, ΔT , by Ohmic heat generation, also known as Joule heating, according to

$$\Delta T = I^2 \frac{R}{mc_p} \quad (4.1)$$

where I is current, R is internal resistance, m is mass of the cell, and c_p is the specific heat capacity.

Transient heat transfer to the ambient by natural air, Q_{transfer} , can be found by

$$Q_{\text{transfer}} = hA(T_{\text{cell}} - T_{\text{ambient}}) \quad (4.2)$$

where h is the heat transfer coefficient, A is surface area, T_{cell} is the cell temperature, and T_{ambient} is the ambient temperature. Convective and conductive heat transfer were combined in an overall heat transfer coefficient [38].

The simplified model in this thesis assumes that heat distribution is homogenous for the entire cell and the core temperature is equal to the surface temperature, hence it is

considered as a lumped model that satisfies the Biot argument. For this assumption, the dimensionless Biot number, Bi , must be less than 1, which implies that the conductive heat transfer within the cell is stronger than the convective heat transfer, h , between the cell and the ambient, where L_c is the characteristic length and k is the thermal conductivity (4.3).

$$Bi = \frac{hL_c}{k} \quad (4.3)$$

The other assumption is that the cell properties do not change with temperature.

4.1. Experimental Setup

The basic experimental setup consisted of a 3.2 Ah cylindrical 18650 cell (LG INR18650 MH1), two temperature sensors (DS18B20) and the cell cycling equipment as described earlier. The sensors were specified to have $\pm 0.5^\circ\text{C}$ accuracy, and they were calibrated with two point calibration method by immersing the sensors into icy-water and boiling water. One of them was used for measuring the ambient temperature, whereas the other one was attached to the cell with thermal paste and kapton tape in order to measure the temperature of the warmest zone, i.e. the positive terminal. Since temperature is a slow signal, it was sampled with a frequency of 0.5 Hz in order to filter out most of the sensor noise. The setup is given in **Figure 4.2**.



Figure 4.2: The thermal experimental setup.

4.2. Thermal Model Parameters

The model parameters are listed in **Table 4.1**. It should be noted that, for the basic model, the internal resistance was assumed to be the average value of internal

resistance independent of SoC, SoH, and temperature. This simplification can be modified with look-up tables of corresponding interdependency if higher accuracy is desired.

Table 4.1: Simplified thermal model parameters.

Parameter	Value	Unit
m	0.0451	kg
c_p	0.0451	J/kg.K
h	10	W/m ² .K
A	0.004185	m ²
R	0.052	Ohm

4.3. Validation Results

The result of a CC-CV charge of 3.1 A and 0.155A cut-off current is is given in **Figure 4.3-Figure 4.5**. The error stays below 2 °C, and it is always higher than the measured temperature, i.e. the reported temperature is always higher than the actual temperature, if not the same. Therefore, the aim of developing a safety oriented simplified thermal model with very low computational cost, was fulfilled. The TM can be used in predictive control to limit charge/discharge current or as a feed forward signal to warn the system controller and end user against hazardous temperature with a predefined safety margin.

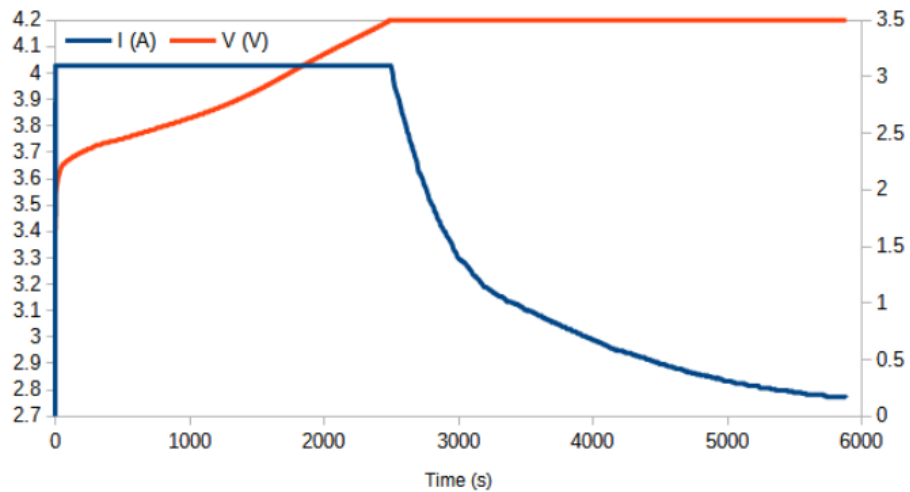


Figure 4.3: Applied current and cell voltage.

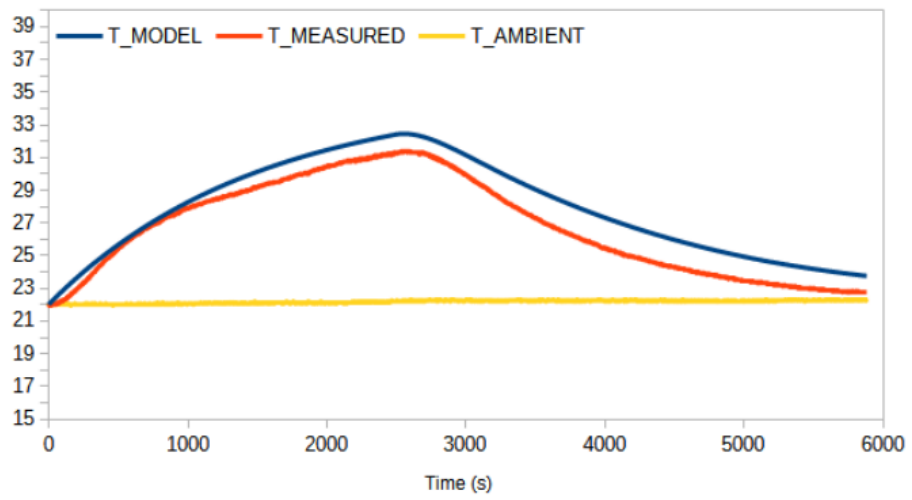


Figure 4.4: Simplified thermal model validation.

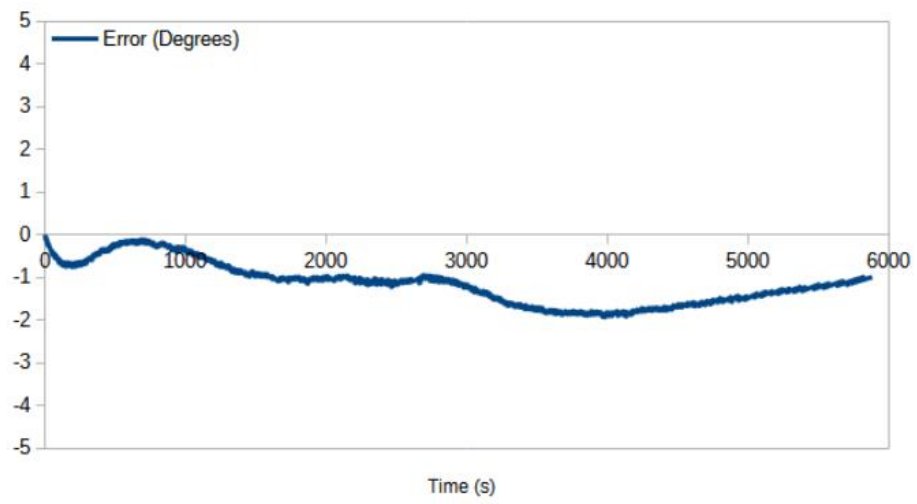


Figure 4.5: Error in °C.

5. ACTIVE BALANCING

Lithium-ion cells are delicate electrochemical devices that must be operated within strict voltage, current and temperature range, such as 2.7 V to 4.2 V and 0° to 40° C for nickel-manganese-cobalt (NMC) chemistry. In order to maintain safe and efficient operation, the voltage, current and temperature of the LIB pack must be continuously measured by a battery management system. Since the functional safety is of highest priority, the BMS constantly acquires individual cell voltage, pack current and temperature data. In order to avoid hazardous conditions such as fire and explosion, it can halt the system operation if necessary. As its simplest operation principle, if any cell voltage goes out of the pre-defined safety limits, the BMS must block the energy flow to the load, or from the charger, by opening the contactors to prevent damage to the user and the system. Since the BMS must protect the weakest cell and takes the lowest and highest voltage cells into account for safety related decisions, if one or more of the series connected cells deviate from the pack average values in an imbalance condition and reach the safety limits of under voltage (UV) or over voltage (OV) faster than the rest of the cells during discharge or charge, the operation must immediately stop even if a certain amount of energy could still be transferred otherwise. Therefore, the imbalance condition reduces the BESS efficiency.

The imbalance problem has intrinsic and extrinsic causes [39]-[42]. At different temperature values due to thermal gradients in a large pack, and also because of the deterioration and corrosion of contacts and cabling over time, the resistance and voltage values are prone to shift from those of a fresh cell with perfect electrical connection at constant temperature. Moreover, the inhomogeneous resistance spread among the cells causes uneven current sharing inconsistency within a parallel block as well, which cannot be easily detected due to the common voltage sensing connection of parallelized cells. Prolonged use of uneven cells further increases the inhomogeneity and in turn worsens the imbalance. In the worst case, a battery pack may be rendered unusable if it reaches to a point where it cannot be charged or discharged at all as a result of severe cell inhomogeneity although some unreachable capacity may still exist in the pack. Hence, cell balancing is an indispensable task for all BMS.

Cell balancing methods can be broadly classified as dissipative (passive), and non-dissipative (active) balancing. In passive balancing (PB) scheme, a resistor network

can dissipate the excess energy during charging if one or more of the cells in a module has higher voltage than one or more of the weaker cells, making it possible for the uneven cells to approach the module average. Although PB is the most commonly preferred method in practical applications because of easy applicability, reliability and low cost, it is also the most inefficient one.

The goal of active balancing (AB), on the other hand, is to redistribute the excess energy and to equalize the state-of-charge (SoC) among the cells. SoC, which is usually expressed in percentage, can be defined as the amount of available charge in the cell by

$$\text{SoC} = \text{SoC}_0 + \frac{1}{Q_{\text{nom}}} \int_0^t i(t) dt \quad (5.1)$$

where Q_{nom} is the nominal capacity in Ah and SoC_0 is the initial condition. Several SoC estimation techniques are available [43]. The initial value relative to the nominal capacity, SoC_0 , can be determined after establishing the SoC relationship with the open circuit voltage (OCV) by cell characterization experiments and then finding the reciprocal of OCV using a look-up table or a cell model.

There is a plethora of AB methods in literature. AB can operate in several different topologies with respect to the energy flow direction such as cell-to-cell, pack-to-cell, cell-to-pack, and regarding the energy transfer element, can also be classified as capacitor based, inductor based, transformer based, power converter based etc [44]-[51]. Even though it might seem to be an obvious choice for high efficiency operation, AB is very rarely employed in practical applications because of its disadvantages. They can be summarized as complicated control schemes, volume/weight restrictions of the energy storage system, high cost, and, statistically a higher probability of failure due to an increased number of critical circuit components such as diodes, switches, inductors and transformers. With some AB types, there are additional challenges and intricacies such as impedance mismatch and production difficulties of obtaining identical properties, for instance, considering the non-ideal multi-winding transformer based approach. [52], [53]. In **Figure 5.1**, the most common balancing topologies of switched resistor (dissipative), switched capacitor (cell-to-cell direction), adjacent cell-to-cell converter (cell-to-cell direction), multiple converter (pack-to-cell and cell-to-pack direction), multiple converter with an auxiliary voltage source that can be

another battery or a super capacitor (SC) bank for hybridized operation (cell-to-pack-to-cell direction), are depicted. For simplicity the DC-DC converters are only shown as boxes.

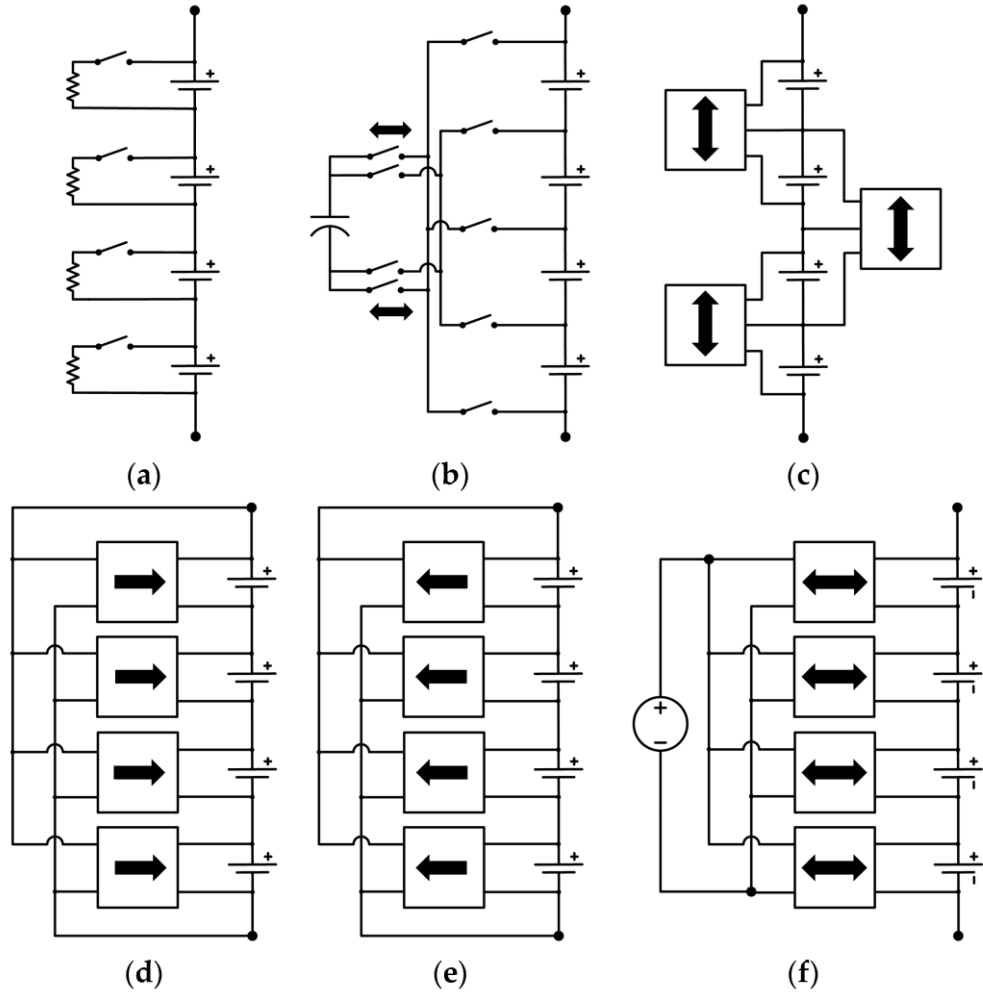


Figure 5.1: (a) switched resistor (b) switched capacitor (c) adjacent cell-to-cell (d, e) multiple converters (f) multiple converters with auxiliary voltage source [16].

In this thesis work, we introduce an AB topology, to the best of author's knowledge, that has not been previously investigated and implemented the way it is presented here. It consists of a high-voltage capable switch array and only a single isolated DC/DC converter that can perform both intramodular and intermodular active balancing. Excess energy can be independently transferred from any module to any cell and vice versa by floating connections. Hence, it can be considered as a switched (flying) converter topology. The archival value and contributory goals are;

- (i) to present a robust, relatively low-cost and flexible bidirectional AB topology that eliminates the requirement for multiple power converters, power diodes, transformers, power inductors, power diodes and/or auxiliary accumulators that need two additional steps of conversion, thus achieving reduced complexity, failure rate and cost by minimizing the number of components;
- (ii) to implement a hardware prototype including a commercial BMS circuit, DC/DC converter and switch matrix in order to prove that the presented method can be implemented in a real-world application with readily available off-the-shelf components;
- (iii) to verify the AB operation by not only equalizing cells within a module but also among the modules as a proof of intermodular balancing concept, and achieving pack level homogeneity both for series-connected and parallel-connected configurations of realistically sized 24 V modules, including a large high voltage (HV) battery pack scenario;
- (iv) to demonstrate the increased runtime and energy delivery of proposed AB topology when LIB is under load.

It should be noted that, although not having been investigated in this study, the same topology can also be used for charging and non-dissipative balancing of SC banks that supply high instantaneous power in LIB-SC hybrid energy management applications, in which the voltage level needs to be equal for each single SC.

5.1. The Switched (Flying) Converter Topology

In this section, the architecture and balancing method of the switched converter are presented. The main component is an isolated DC/DC converter whose input and output ports can be flexibly connected to any module and any cell. Its operation in all possible module and pack configurations are detailed below.

5.1.1. S-P (Series of Parallel) Configuration

In S-P configuration, the cells can be connected in series singularly, or pre-parallelized for increased capacity needed by a specific application. The general form of an S-P module configuration, and as a common example, a 7S1P module of 24 V with 7 cells

in series is depicted in **Figure 5.2** and **Figure 5.3** respectively. The number of cell switches is $(N+1)$, where N is the number of cells in series which are supervised by BMS. Four additional switches (SP_1 - SP_4) in double-pole double-throw (DPDT) arrangement are used for directing the correct polarity to the rails. Hence, the total number of switches is $(N+5)$. Rails A and B serve as the negative and positive bus in accordance with the cell switches (S_1 - S_8) that connect individual cells (C_1 - C_7) to the converter. For clarity, the balancing operation of two different cells with odd and even order is explained by alternating switch positions and conduction path in Figure 3. If an odd-numbered cell is to be balanced, the polarity switches SP_1 and SP_2 are enabled. If an even-numbered cell is to be selected, then the polarity switches SP_3 and SP_4 are enabled, and the rail polarities are reversed. This switch matrix requires the minimum number of switches for intended operation. In step-down (buck) pack-to-cell direction, which is the investigated operation mode in this study, the balancing is performed by converting the module voltage to cell voltage. In step-up (boost) cell-to-pack mode, the cell voltage is converted to the module voltage. If a bidirectional DC/DC converter is used, the AB can be performed in both ways [54], [55].

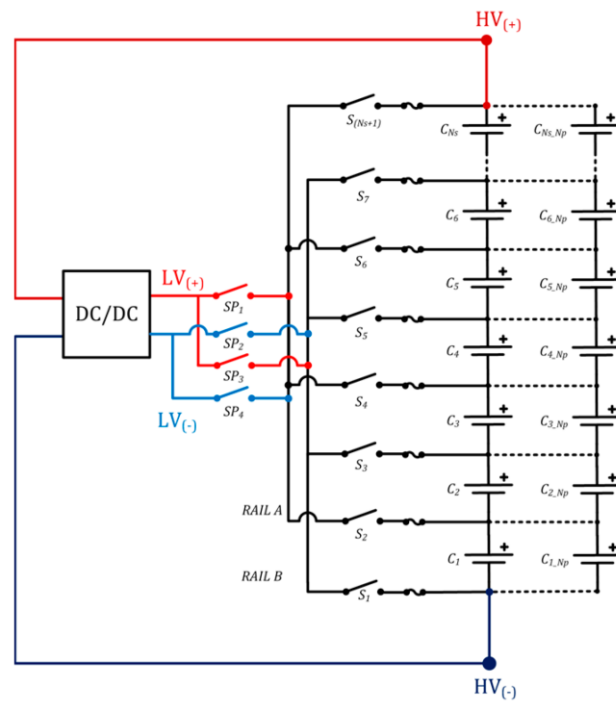


Figure 5.2: S-P module (N_S = number of series cells, N_P = number of parallel cells) [16].

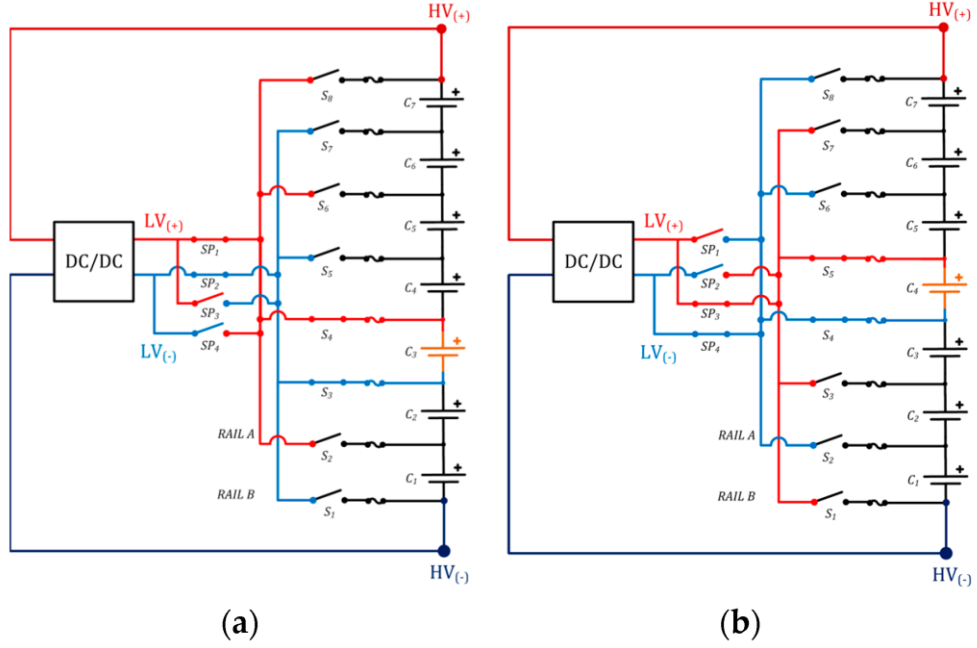


Figure 5.3: 7S1P module in detail: **(a)** balancing the third cell **(b)** balancing the fourth cell [16].

A 7S1P module built with NMC cells resulting in 24 V nominal voltage can be considered as the standard building block for industrial and e-mobility applications with higher voltage level requirements, which are usually the multiples of 24 such as 48 V, 96 V, 120 V, 480 V etc for HV energy storage. In **Figure 5.4**, such an extended version is given.

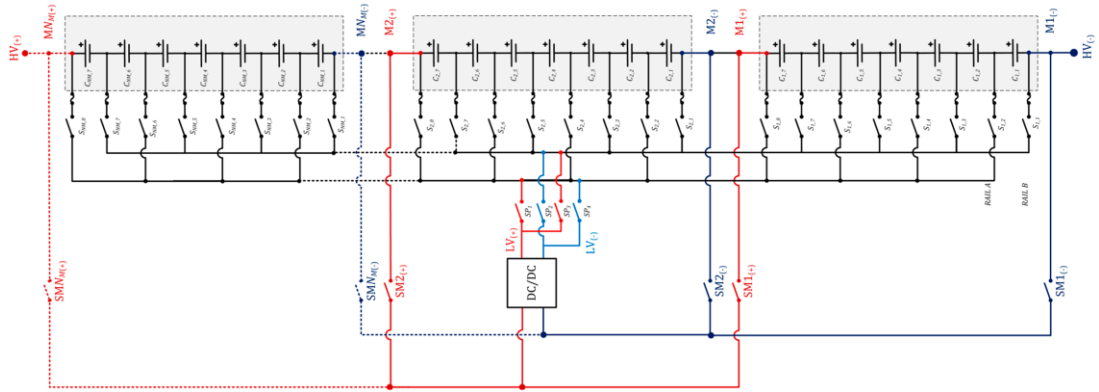


Figure 5.4: Multimodule S-P configuration with modules connected in series (14S1P pack without the dashed lines) [16].

During the multimodule operation, the module switch pairs (SM_1 - SM_{NM}) connect the power converter to module top and bottom points, avoiding the entire pack high voltage (HV) level by floating connection. Two additional switches are required for

each module, and as before, four switches (SP₁-SP₄) direct the correct polarity to the rails. The total number of switches is $N_M \cdot (N+3) + 4$, where N_M is the number of modules connected in series for intermodular balancing applications with more than one module, and N is the number of series cells in each module. As mentioned before, if the pack consists of a single module, then the number of switches is $(N+5)$. Since the floating isolated converter is connected only to a single module at a time, and the input/output range is never exceeded, the number of cells and series connected modules that are interleaved by the converter can be increased as long as its isolation barrier is intact, and its input/output range covers the module voltage. In addition to a large pack that consists of separate modules, a direct cell-to-pack (CTP) and cell-to-chassis (CTC) assembly can also be balanced by dividing the whole pack into virtual modules without exceeding the limits of the power converter. This feature makes the presented architecture a reliable and feasible candidate for HV e-mobility, heavy duty EV, and HV stationary BESS applications with easily achievable converter properties, such as 1:2 or 1:4 input ranges and moderate step-up/step-down ratios, whereas isolated DC/DC converters with very wide input ranges and high step-up/step-down ratios are usually less efficient and costlier to manufacture. The experimental results of intermodular balancing in an HV configuration are presented in the next section.

5.1.2. P-S (Parallel of Series) Configuration

In the P-S configuration, pre-serialized S-P modules are stacked as parallel banks. The configuration is identified by the number of parallel and series connections as $N_p N_s$. The switched converter topology for this configuration is shown in **Figure 5.5**. Battery packs in P-S arrangement can be utilized in scalable stationary BESS for renewables, integrated grids, uninterrupted power supplies (UPS), and some specialized applications, such as telecommunications infrastructure, aerospace equipment, and naval systems, to provide redundancy, hot plugging, and scaling-up capabilities. As an example, retired modules can be removed from EVs and, after a mandatory safety and performance assessment, can be transferred to a stationary BESS site and connected to a DC bus of a matching voltage range in this fashion without modifying the already installed infrastructure. By directly reusing the retired modules, the tedious and dangerous process of disassembly and reassembly of the cells, which is usually impossible without damaging at least some of the original cells, can be

avoided; the existing BMS circuitry in each module can be reused; and the total energy storage capacity can be increased modularly as needed. Even if the bus voltage is equal for all modules thanks to the parallel multimodule connection, any imbalance within one or more modules that can exist especially in second-life applications can still hinder the overall system performance since the safety limit will again be reached by the weakest cell. The proposed topology can also provide intermodule balancing in this case, the experimental results of which are presented in the next section. Moreover, if the potential difference between the modules is too high before hot plugging, to minimize the inrush current flowing between the packs and the main bus, a pre-balancing routine can be employed via the balancing connectors before the modules are actually connected to each other. The total number of switches is $N_P \times (N + 1) + 4$, where N_P is the number of parallel modules, and N is the number of cells in series in each module. The same as the fundamental architecture, four switches (SP_1 – SP_4) are used for polarity control.

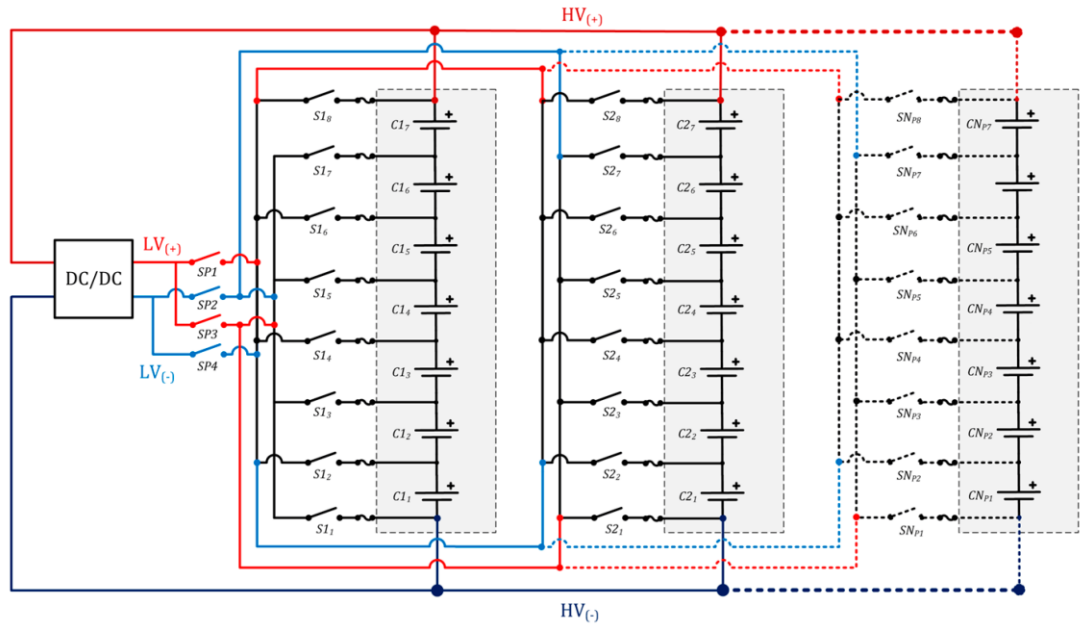


Figure 5.5: Multimodule P-S configuration with modules connected in series (2P7S pack without the dashed lines) [16].

5.2. Balancing Algorithm

For voltage-based balancing, the algorithm considers a pre-defined threshold, V_{th} , in the order of millivolts and runs the AB routine until satisfying its termination criterion (1), i.e., when the voltage level of all cells converge within a band of

$(V_{avg} \pm V_{th})$, where V_{avg} is the average voltage, and ΔV_{max} is the maximum deviation from average.

$$|V_{avg} - \Delta V_{max}| < V_{th} \quad (5.2)$$

First, as the main task of any BMS, the voltage of each cell is measured, and the cells are sorted. The average voltage and the cells with the minimum and maximum voltage values are determined. If there is more than one module in the pack, the modules are sorted as well. After checking the overall LIB for faults and enabling the switch matrix according to the desired direction, either the strongest module energy is transferred to the weakest cell in the pack, or the strongest cell energy is transferred to the weakest module until the threshold is reached. If there are other uneven cells with discrepancies, the process continues until all cell voltages are equalized. The excess energy is always redistributed from the strongest element to the weakest one that may exist in any location in the entire pack, eventually equalizing all cells and modules and achieving both intramodular and intermodular homogeneity. The balancing algorithm flowchart is depicted in **Figure 5.6**.

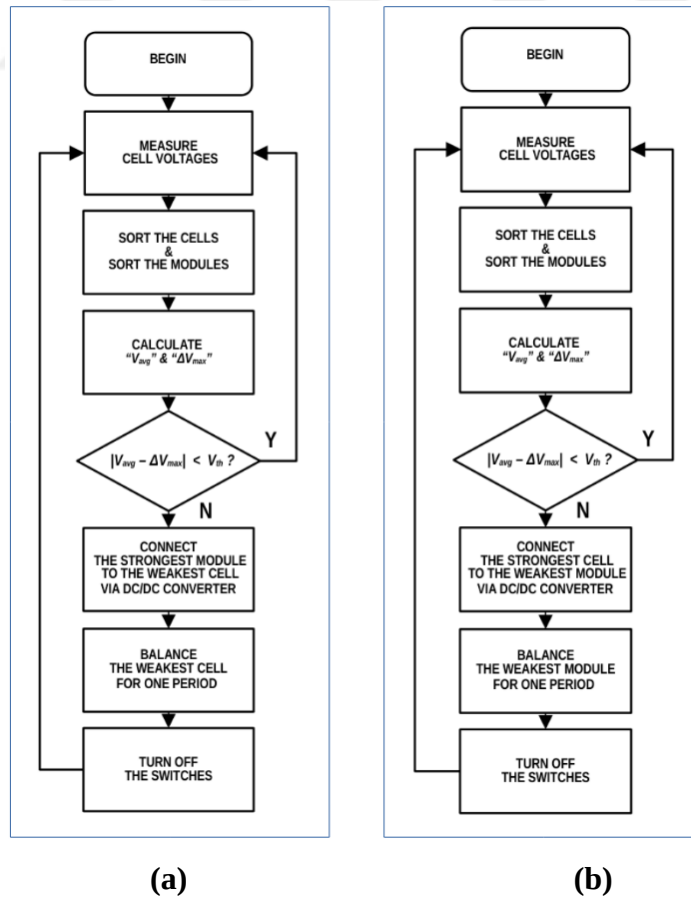


Figure 5.6: The AB algorithm (a) module-to-cell (b) cell-to-module direction [16].

In general, the algorithm must ensure that both of the polarity switch pairs cannot be simultaneously enabled. If the pack consists of more than one series module, then the module switches must also conduct with respect to the algorithmic decision so that only a single module or cell provides energy at a time. A small delay for proper break-before-make operation must be used for all switches to avoid short circuit failures.

Despite being the most straightforward approach, voltage equalization may not necessarily provide charge equalization. If there exists an aging deviation or a temperature gradient within the pack, different SoC levels may have approximately the same voltage values due to altered capacity and impedance. This situation can lead to erroneous balancing decisions made by the controller, and continuing with the balancing operation can disturb the homogeneity even further. Therefore, an SoC-based AB is better suited for larger packs instead of voltage balancing (5.3).

$$|\text{SoC}_{\text{avg}} - \Delta\text{SoC}_{\text{max}}| < \text{SoC}_{\text{th}} \quad (5.3)$$

The disadvantage of this method is the need to precisely measure the balancing current in addition to the main pack current and to keep track of individual SoC values of all cells, which may occupy a considerably large amount of memory in an embedded microcontroller.

Within the scope of this thesis, only the voltage-based balancing method was investigated. Nevertheless, aiming to provide an insight regarding the amount of charge that was balanced with respect to the initial and final voltage difference, the SoC values before and after the AB operation are still listed in tables. The experimental SoC-OCV curve of the cells that was used for linearly interpolating the OCV look-up table is given in **Figure 5.7**.

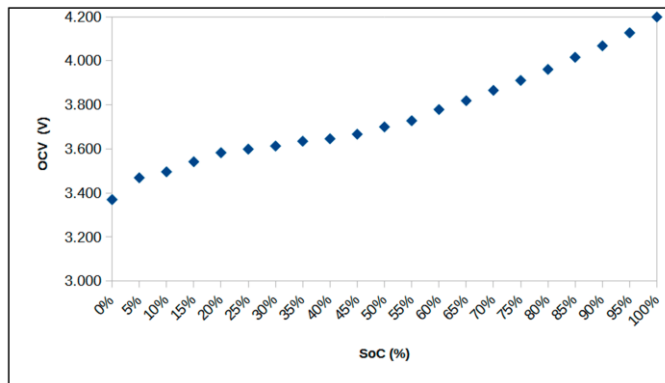


Figure 5.7: The SoC–OCV curve of Samsung INR18650-20R cells [16].

5.3. Experimental Setup, Materials and Component Selection

Regarding the hardware implementation, the main design criterion of AB balancing current had to be determined beforehand. Considering the nominal capacity of experimental cells $Q_{\text{nom}} = 2\text{Ah}$, it was chosen as at least to be $i_{\text{bal}} = 200\text{ mA}$, corresponding to 0.1 C , a comparable value with the most commonly used dissipative passive balancing (PB) method. A current in the range of 50 mA to 250 mA is the *de facto* standard for commercial PB applications due to the fact that the maximum power rating of the balancing resistors, which are most often surface mount type, is usually less than 2 W . Two identical hardware prototypes to accommodate and monitor two modules were designed and built with the aforementioned design criteria. One of them is shown in **Figure 5.8**. For repeatability, a list of all materials is presented below.

Cells: The cells were INR18650-20R from Samsung SDIEM, of 2000 mAh nominal capacity. They were from the same manufacturing batch purchased at the same time. The technical specifications are in **Table 5.1** [56]. A custom printed circuit board (PCB) was designed with cell holders and balancing terminals for 7 cells in series, forming a $24\text{ V } 7\text{S1P}$ module, and two of them were used to investigate different module combinations with a total of 14 cells. Switch matrix: In order to perform switching, CPC1218 (IXYS/Clare), a metal oxide semiconductor field effect transistor (MOSFET) based solid-state relay (SSR) was preferred [57]. It has built-in isolated gate drive which is optically coupled to the bidirectional semiconductor switch and was therefore chosen to simplify the hardware implementation. Throughout this work the same SSR was used for all switching operations. A basic PCB was designed for two SSRs. As a safety measure, 750 mA fuses were installed between each switch and cell holder connection.

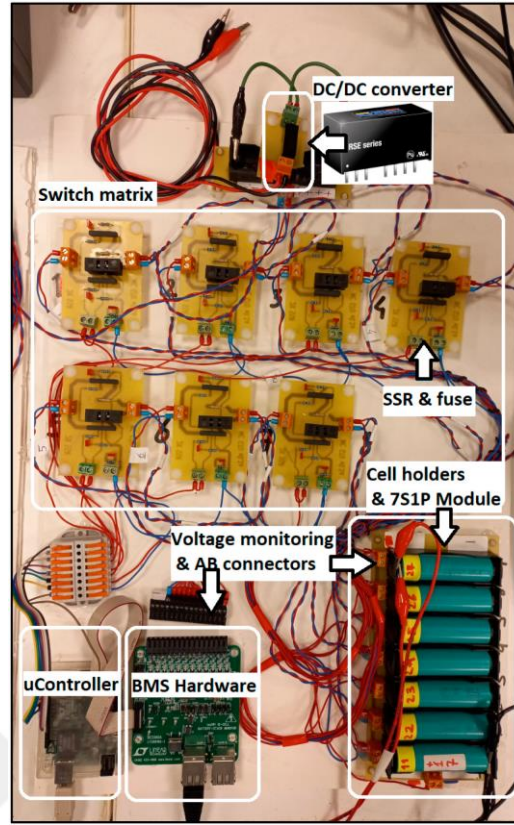


Figure 5.8: The experimental test setup for a single 7S1P module [16].

DC/DC converter: Since the focus of this study is to prove the concept of switched converter AB topology rather than the power converter itself, an off-the-shelf isolated converter was selected to facilitate the realization of hardware implementation and investigate unidirectional (module-to-cell) energy flow. The DC isolation barrier rating, input/output isolation resistance, voltage input range and voltage conversion ratio were important criteria. For a nominal module voltage of 24 V and a maximum balancing current of $i_{bal}=400$ mA, a small low-cost 2 W DC/DC isolated converter, RSE-2405S/H2 (Recom), with 18-36 V input and 5 V output was deemed to be appropriate. The technical specifications can be found in **Table 5.2** [58]. As the output voltage is regulated but not adjustable, a limiting mechanism at the output side is necessary in order to protect both the cells and the power converter itself. The equivalent series resistance (ESR) of the switches, fuses, cell holder tabs and wiring connections along the power path was measured to be approximately 2.5Ω during conduction. This ESR provides sufficient current limiting.

Cell monitor: Unlike measuring the voltage of a single independent cell, a special analog front end (AFE) circuitry is necessary to measure each voltage separately in

presence of high common mode voltage of a module comprising of many cells connected in series. There are a few specialized integrated circuits (IC) available on the market that encompass AFE, analog-to-digital converter (ADC), PB, temperature measurement and communication features. To fulfill the cell voltage measurement task, a commercial BMS IC from the LTC6804 (Linear Technology/ADI) series was used. It can measure the voltage of 12 cells with an accuracy of 1.1mV, and send out the data via serial peripheral interface (SPI) bus [59]. Two units were connected together via the proprietary isoSPI bus to independently monitor each module of 7 cells. Their sole purpose was cell voltage monitoring (at a data rate of 1 s/s) during AB, hence the PB functionality was disabled.

Microcontroller: The microcontroller unit was a 8-bit, 16 Mhz ATMEGA328 (Atmel/Microchip) based Linduino (Linear Technology/Analog Devices Inc.) platform [60]. Its tasks included communicating with the LTC6804 ICs via SPI, communicating with the PC via USB, running the state machine and controlling the switches according to the balancing algorithm. The main reason for selecting a basic industrial 8-bit microcontroller was to verify the applicability of the presented online AB algorithm with limited computational power and resources typically available in a real-world commercial BMS hardware.

Other: A Fluke 189 digital multimeter (DMM) was used for essential electrical measurements and the consistency of cell voltage data transmitted by BMS ICs was checked by comparing the voltage values measured by DMM. A Chroma 62050P programmable DC power supply and 63207 load were used for charging/discharging the cells and modifying cell voltages according to the experimental scenarios. Additionally, two GW-Instek GPE 3321 DC power supplies were used for the verification of high voltage operation which will be detailed in the next section.

Table 5.1: Samsung INR18560-20R cell properties.

Cell Form Factor	Capacity	Cathode Material	Anode Material	Nominal Voltage	Maximum Charge/Discharge Voltage	Maximum Charge/Discharge Current
18650	2 Ah	NMC	Graphite	3.7 V	4.2 V/2.5 V	4 A/22 A

Table 5.2: Technical specifications of the DC–DC converter.

Input Voltage Range	Output Voltage	Maximum Output Current	Typical Efficiency	Isolation Voltage Rating	Isolation Resistance
18–36 V	5 V	400 mA	80%	2000 VDC	$10^9 \Omega$

5.4. Validation Results

This section deals with the experimental validation results of the proposed AB topology for all possible battery pack configurations, starting with the fundamental topology verification.

5.4.1. S-P Single Module (Intramodular) Balancing

For the fundamental experiment, the case of a single 24 V module in 7S1P configuration was investigated, as shown in Figure 2. The 24 V block was considered as a basis to verify the intramodular balancing capability. One of the seven cells had been previously discharged to a lower voltage than the other cells in order to create a fundamental imbalance scenario. The rest of the cell voltages were arranged to be as close as possible to each other. The threshold of voltage difference from the module average was set as $V_{th} = 10 \text{ mV}$ (1). The balancing period, T_{bal} , and the duty cycle, D , determines the balancing time, t_{bal} , for each period (5.4). The AB period was set as 20 seconds with 90% duty cycle, resulting in a balancing duration of 18 seconds. In **Figure 5.9**, an exemplary detail of AB operation during the first five periods is depicted.

$$t_{bal} = T_{bal}D \quad (5.4)$$

First, according to the balancing algorithm, the cell with the minimum voltage was detected, then the required cell and polarity switches were enabled to connect the output of the power converter to the weakest cell for the predefined switching period. The AB operation ended when its voltage value, V_1 , satisfied the termination threshold. The initial and final module voltage values were 28.051 V and 27.881 V, respectively, whereas the initial and final average voltage values were 4007.2 mV and 3983.1 mV. The results are presented in **Figure 5.10**, **Table 5.3** and **Table 5.4**, where the asterisk denotes the imbalanced cell.

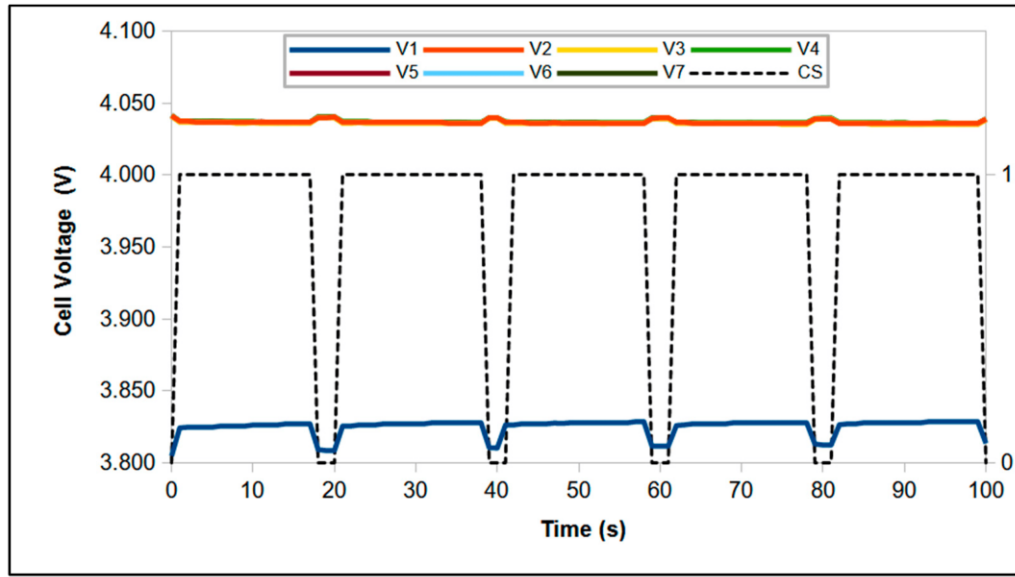


Figure 5.9: Equalization during the first five periods of AB (CS = control signal) [16].

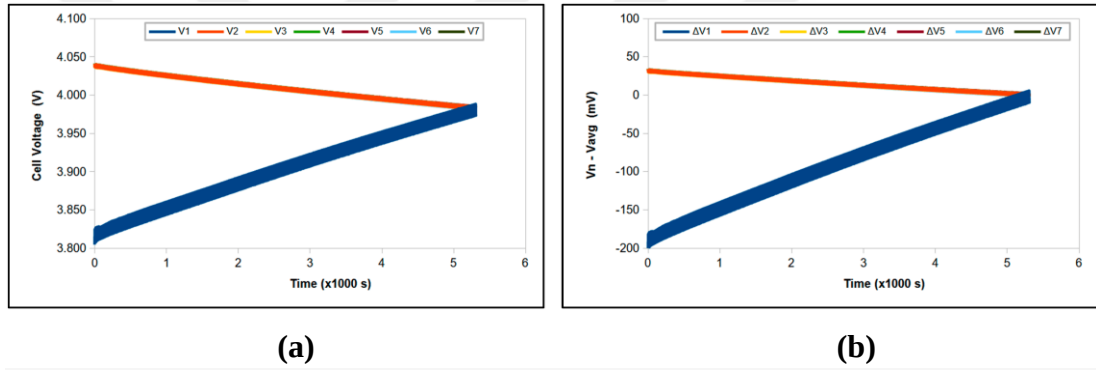


Figure 5.10: 7S1P single module intramodular balancing (the fundamental topology) (a) cell voltage values (b) the difference from module average [16].

Table 5.3: The initial and final voltage values of 7S1P single module (intramodular AB).

Cell Number	Initial Voltage (mV)	Initial ΔV (mV)	Final Voltage (mV)	Final ΔV (mV)
1*	3804.7	-202.5	3974.4	-9.7
2	4041.4	34.2	3984.7	1.2
3	4040.6	33.4	3984.6	1.6
4	4041.5	34.3	3985.1	2.0
5	4041.3	34.1	3984.9	1.8
6	4040.6	33.4	3983	0.1
7	4040.5	33.3	3984.3	1.2

Table 5.4: The initial and final SoC estimation values of 7S1P single module (intramodular AB).

Cell Number	Initial SoC (%)	Initial Δ SoC (%)	Final SoC (%)	Final Δ SoC (%)
1*	63.2	-20.7	81.2	-0.8
2	87.4	3.4	82.1	0.1
3	87.4	3.4	82.1	0.1
4	87.4	3.4	82.1	0.1
5	87.4	3.4	82.1	0.1
6	87.4	3.4	82.1	0.1
7	87.4	3.4	82.1	0.1

5.4.2. P-S Multimodule (Intermodular) Balancing

As the second step of validation, two 7S1P modules were connected in parallel to form a 2P7S pack of 24 V as shown in **Figure 5.5**. This pack was built to investigate the equalization of uneven cells by intermodular balancing in a P-S configuration where there may be an inhomogeneity among the cells even though the bus voltage is equal for all independent modules. The intermodular parallel balancing operation was tested with three unbalanced cells in module 1 (M_1), all at different initial values, in order to simulate an aggressive imbalance scenario at the lower part of the SoC range. The rest of the cell voltages in M_1 and M_2 were arranged so that both of the module voltages were as close as possible to each other before connecting them together.

After cell voltage sorting and detecting the global weakest cell that had minimum voltage, the required cell and polarity switches were enabled to connect the output of the power converter to the worst cell accordingly. The first phase was completed when the voltage of the weakest cell, V_7 , reached the vicinity of V_6 , i.e. the cell with the second highest initial deviation. From that point on, the switched converter started to transfer the pack energy to the new weakest cell with respect to the voltage difference from the module average, and the process continued with balancing all weak cells consecutively until the threshold was reached, after which all uneven voltages of the cells were equalized by intermodular AB. The initial and final module voltage values, i.e. the parallel bus voltage, were 25.509 V and 25.405 V. The results are presented in **Figure 5.11** and **Table 5.5-5.8**. Considering the case of P-S packs, the imbalance cannot be detected if the BMS measures only the parallel bus voltage or the cell voltages of a single module; therefore, each parallel module must be monitored separately. Moreover, even with a stringent threshold voltage of $V_{th} = 10$ mV, the

maximum SoC deviation at the end of AB routine was higher than that of the previous experiment. This result indicates the benefit of using an SoC based algorithm instead of voltage equalization for a better charge equalization and convergence especially at lower SoC region ($< 50\%$) or with chemistries such as lithium-iron-phosphate (LFP) having a more flattened OCV curve along the whole SoC range.

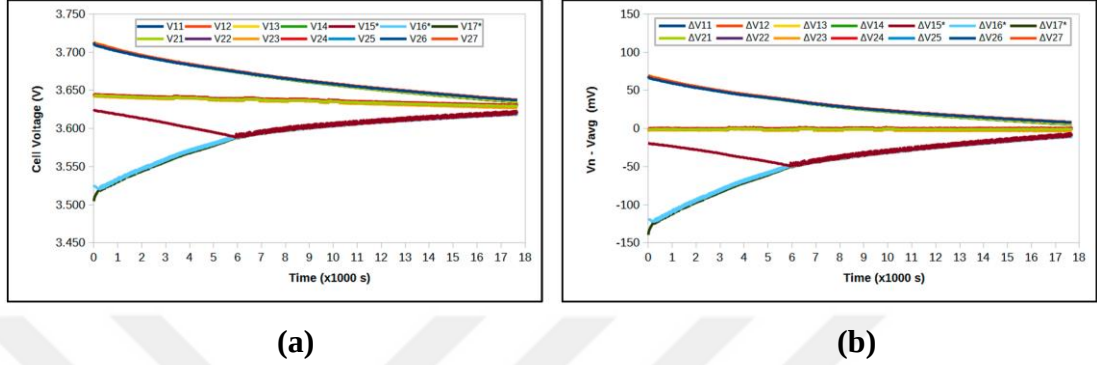


Figure 5.11: 2P7S pack intermodular balancing (a) cell voltage values (b) the difference from module average value [16].

Table 5.5: The initial and final cell voltage values of 2P7S pack with two modules (intermodular AB).

Cell Number	Initial Voltage (mV)	Initial ΔV (mV)	Final Voltage (mV)	Final ΔV (mV)
1 ₁	3712.8	68.6	3636.8	7.6
1 ₂	3713.3	69.1	3637.7	8.5
1 ₃	3714.2	70.0	3635.7	6.5
1 ₄	3713.3	69.1	3634.6	5.4
1 ₅ *	3625.2	-19.0	3619.4	-9.8
1 ₆ *	3525.8	-118.4	3621.0	-8.2
1 ₇ *	3504.6	-139.6	3619.5	-9.7
2 ₁	3645.6	-0.2	3628.8	-0.2
2 ₂	3645.6	-0.2	3629.1	0.1
2 ₃	3644.7	-1.1	3627.4	-1.6
2 ₄	3646.9	1.1	3630.2	1.2
2 ₅	3645.5	-0.3	3628.6	-0.4
2 ₆	3645.6	-0.2	3628.9	-0.1
2 ₇	3646.4	0.6	3630.2	1.2

Table 5.6: The initial and final module voltage values of 2P7S pack with two modules (intermodular AB).

Module Number	Initial Voltage (V)	Initial ΔV (mV)	Final Voltage (V)	Final ΔV (mV)
M ₁	25.509	-5.5	25.405	1
M ₂	25.520	5.5	25.403	-1

Table 5.7: The initial and final cell SoC estimation values of 2P7S pack with two modules (intermodular AB).

Cell Number	Initial Voltage (mV)	Initial ΔV (mV)	Final Voltage (mV)	Final ΔV (mV)
1 ₁	52.3	14.2	35.8	2.0
1 ₂	52.4	14.3	36.2	2.4
1 ₃	52.5	14.5	35.3	1.5
1 ₄	52.4	14.3	34.9	1.0
1 ₅ *	32.8	-5.3	31.5	-2.4
1 ₆ *	13.2	-24.8	31.8	-2.0
1 ₇ *	10.9	-27.1	31.5	-2.4
2 ₁	39.8	0.2	33.6	-0.1
2 ₂	39.8	0.2	33.7	0.0
2 ₃	39.4	-0.2	33.3	-0.4
2 ₄	39.4	-0.2	33.9	0.3
2 ₅	39.4	-0.2	33.5	-0.1
2 ₆	39.4	-0.2	33.6	0.0
2 ₇	40.1	0.5	33.9	0.3

Table 5.8: The initial and final module SoC estimation values of 2P7S pack with two modules (intermodular AB).

Module Number	Initial SoC (SoC _{min}) (%)	Initial Δ SoC (%)	Final SoC (SoC _{min}) (%)	Final Δ SoC (%)
M ₁	10.9	-14.25	31.5	-0.9
M ₂	39.4	14.25	33.3	0.9

5.4.3. S-P Multimodule (Intermodular) High Voltage Balancing

The HV experiment was aimed at investigating the intermodular AB capability of the presented architecture considering a pack configuration with many modules in series connection, which is also a valid test scenario for CTP and CTC pack construction if the continuous array of cells is virtually divided into modules. To this end, two 7S1P modules were serially connected with two 60-V DC power supplies between them, forming a pack of 178.8 V, as illustrated in **Figure 5.12**. One of the cells in each module was imbalanced, while the rest of them had very small discrepancies. The M₁ voltage was altered to be lower than that of M₂ with the purpose of establishing an imbalance situation between the modules as well. The total voltage of the DC power supplies was 120 V, emulating five balanced modules of 24 V connected in series. By this experimental setup, the AB operation between two extreme modules across a

49S1P HV pack consisting of seven 24-V modules could be elaborated. The threshold voltage was set at $V_{th} = 6$ mV for a more stringent AB.

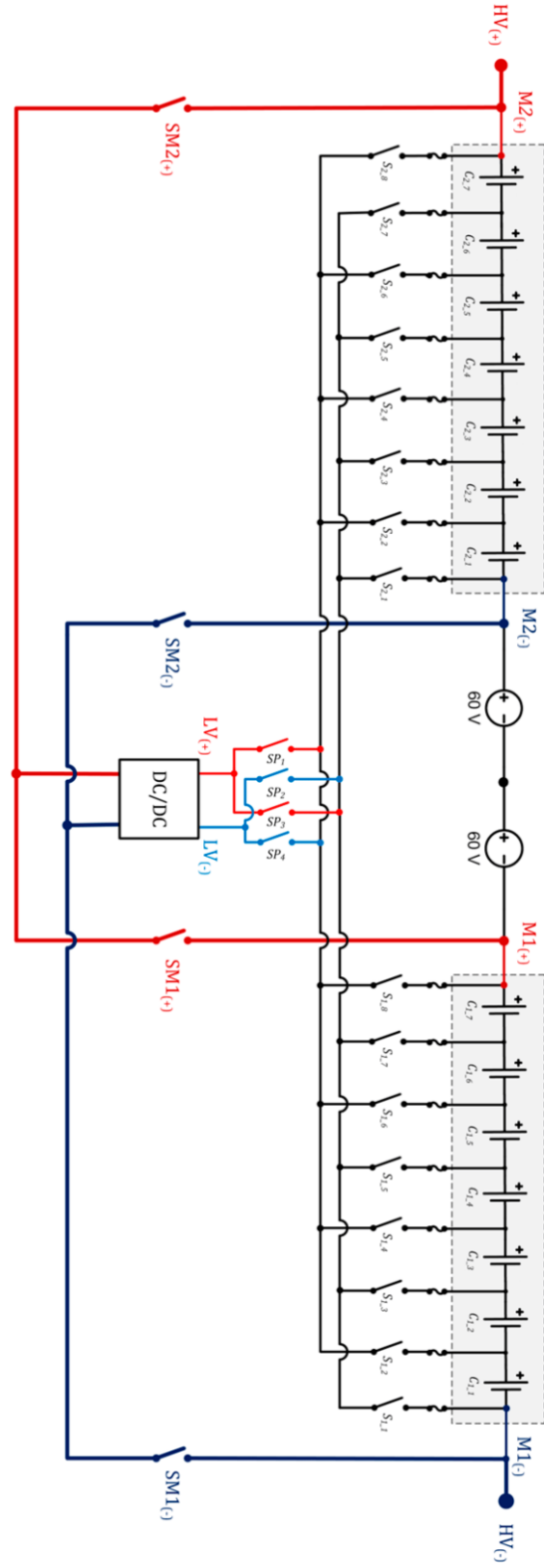


Figure 5.12: HV intermodular AB (49S1P pack with emulation) [16].

After module sorting and determination of the weakest cell in the HV pack, the input port of the switched converter was connected to M_2 , i.e. the strongest module with the highest voltage, via module selection switches to transfer its excess energy to the cells in M_1 . First, the cell with the maximum voltage deviation in M_1 , V_{11} , was balanced until the threshold voltage was reached. In the second phase, the voltage of the weakest cell in M_2 , V_{21} , was balanced until the homogeneity in M_2 was achieved with respect to its own module average. After ensuring the intramodular balance for both modules, the switched converter continued redistributing the excess energy from M_2 to the cells in M_1 one by one until satisfying the termination condition, eventually equalizing all cell voltages in independent modules as well. Thus, HV pack level AB was fulfilled by means of intermodular charge transfer from the strongest module, as presented in **Figure 5.13** and **Table 5.9-5.12**.

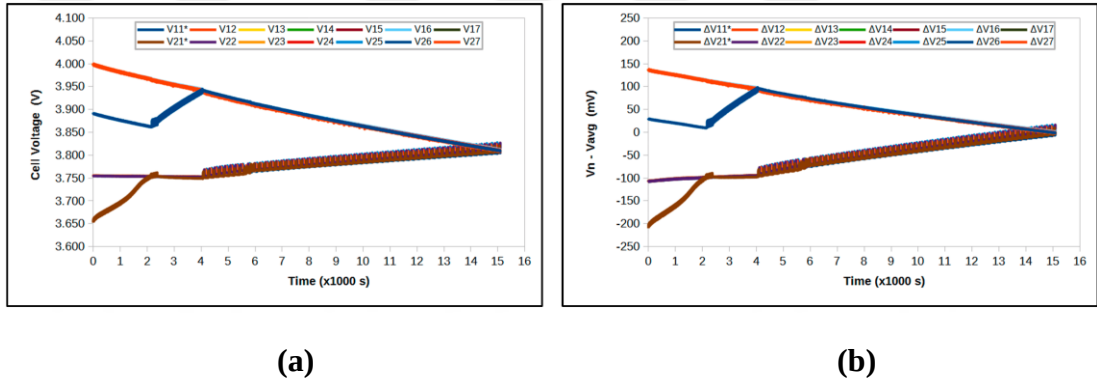


Figure 5.13: HV pack intermodular balancing (a) cell voltage values (b) the difference from pack average value [16].

Table 5.9: The initial and final cell voltage values of HV pack with two modules (intermodular AB).

Cell Number	Initial Voltage (mV)	Initial ΔV (mV)	Final Voltage (mV)	Final ΔV (mV)
1 ₁ *	3892.8	-92.2	3809.0	-0.1
1 ₂	4000.8	15.8	3807.9	-1.2
1 ₃	4000.3	15.3	3808.7	-0.4
1 ₄	4000.3	15.3	3808.4	-0.7
1 ₅	4000.1	15.1	3809.3	0.2
1 ₆	4000.4	15.4	3811.0	1.9
1 ₇	4000.4	15.4	3809.5	0.4
2 ₁ *	3562.4	-87.7	3808.2	-2.3
2 ₂	3754.7	14.6	3815.8	5.3
2 ₃	3754.9	14.8	3811.5	1.0
2 ₄	3754.7	14.6	3812.2	1.7
2 ₅	3754.8	14.7	3814.6	4.1
2 ₆	3754.6	14.5	3805.3	-5.2
2 ₇	3754.8	14.7	3805.9	-4.6

Table 5.10: The initial and final module voltage values of HV pack with two modules (intermodular AB).

Module Number	Initial Voltage (V)	Initial ΔV (mV)	Final Voltage (V)	Final ΔV (mV)
M ₁	27.895	857	26.664	5
M ₂	26.181	-857	26.674	5

Table 5.11: The initial and final cell SoC estimation values of HV pack with two modules (intermodular AB).

Cell Number	Initial Voltage (mV)	Initial ΔV (mV)	Final Voltage (mV)	Final ΔV (mV)
1 ₁ *	73.0	-9.1	64.1	0.0
1 ₂	83.6	1.5	63.9	-0.2
1 ₃	83.6	1.5	64.0	-0.1
1 ₄	83.6	1.5	64.0	-0.1
1 ₅	83.6	1.5	64.1	0.0
1 ₆	83.6	1.5	64.3	0.2
1 ₇	83.6	1.5	64.1	0.0
2 ₁ *	41.5	-13.8	63.6	-0.3
2 ₂	57.6	2.3	64.6	0.7
2 ₃	57.6	2.3	64.1	0.1
2 ₄	57.6	2.3	64.1	0.2
2 ₅	57.6	2.3	64.5	0.5
2 ₆	57.6	2.3	63.3	-0.6
2 ₇	57.6	2.3	63.4	-0.6

Table 5.12: The initial and final module SoC estimation values of HV pack with two modules (intermodular AB).

Module Number	Initial SoC (SoC _{min}) (%)	Initial Δ SoC (%)	Final SoC (SoC _{min}) (%)	Final Δ SoC (%)
M ₁	73.0	15.75	63.9	0.3
M ₂	41.5	-15.75	63.3	-0.3

5.4.4. AB Verification Under Load

All of the above experiments were carried out to verify AB operations when the modules were idle; i.e. no load was present. To demonstrate the complete operational capability of the proposed AB architecture, the S-P and P-S modules were subjected to a significant load current as well. With this experiment, a scenario in which adequate idling time may not be available for full equalization can also be tested.

First, the 7S1P configuration with one imbalanced cell in the same fundamental AB test setup was investigated. The AB algorithm was disabled, and a constant current (CC) load of 2000 mA (1.0 C) was applied until the weakest cell reached the predefined discharge cut-off voltage limit of 2700 mV. The runtime was found to be $t = 2195$ s with an energy delivery of $E = 30.562$ Wh, according to the trapezoidal integration as given in equation (5.5).

$$E = \int_0^t V(t)I(t)dt \quad (5.4)$$

where V is the module voltage, and I is the load current. Then, the discharged cells were exchanged with a second set of identical cells, the voltages of which had been previously arranged to be as close as possible to the initial voltage values of the first set. After applying the same load current while the AB algorithm was functional, the runtime extended to $t' = 2564$ s and the delivered energy was calculated to be $E' = 35.279$ Wh, resulting in 16.8% extra duration and 15.4% additional energy.

For the 2P7S configuration, the same procedure was repeated with one imbalanced cell in each parallel module, similar to the second idle AB experimental setup in the lower SoC range. A CC load of 2000 mA (0.5 C per module) was applied until the weakest cell reached the cut-off. The runtime was extended from $t = 2592$ s to $t' = 3037$ s, whereas the amount of energy increased from $E = 35.748$ Wh to $E' = 41.414$ Wh, yielding a 16.9% longer duration and 15.8% more energy delivered to the load. The resulting graphs and values are presented in **Figure 5.14** and **Table 5.13**. In addition, the detail of intermodular AB operation and its ability to support both of the weak cells consecutively during discharge is shown in **Figure 5.15** demonstrating the last 10 balancing periods before cut-off.

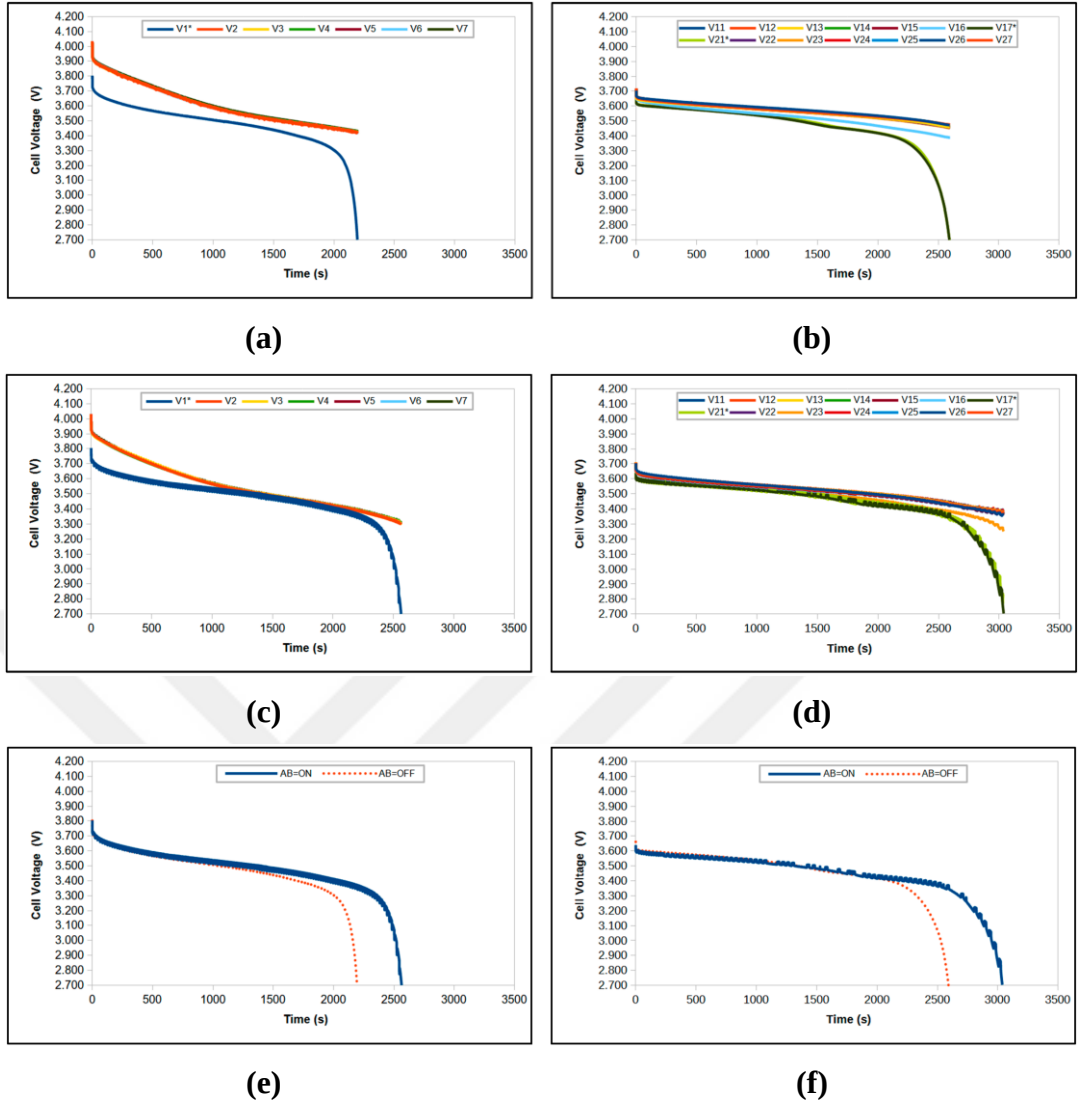


Figure 5.14: AB operation under a 2-A load current (a,c) 7S1P without and with AB (b,d) 2P7S without and with AB (e,f) direct comparison of 7S1P and 2P7S packs without and with AB [16].

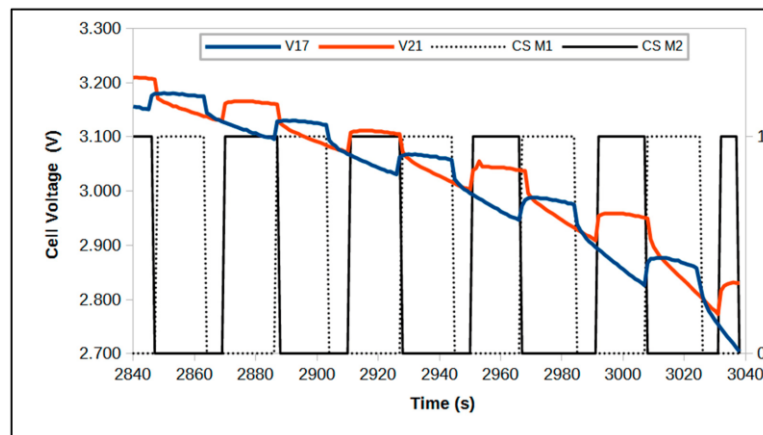


Figure 5.15: Intermodal AB operation during the last 10 periods (7P2S pack) [16].

Table 5.13: The comparison of 7S1P and 2P7S pack performance without and with AB under load.

Pack Type	Load	Min. Initial Voltage (mV)	Min. Initial SoC (%)	Runtime AB=OFF (s)	Energy AB=OFF (Wh)	Runtime AB=ON (s)	Energy AB=ON (Wh)
7S1P	3804.1	63	2195	30.562	2564	35.279	2195
2P7S	3804.1	37	2195	30.562	2564	35.279	2195

5.4.5. Efficiency

The overall energy efficiency, η , of the inter-intramodular AB architecture can be expressed as

$$\eta = \eta_c \eta_d \eta_{cnv} \quad (5.5)$$

where η_c , η_d and η_{cnv} are the efficiency values of cell charging, cell discharging and the DC/DC converter, respectively.

Additionally, the SoC increase for each balancing period with respect to the amount of transferred charge, ΔSoC^+ , can be calculated by

$$\Delta \text{SoC}^+ = \frac{\eta_{bal} i_{bal} t_{bal}}{Q_{nom}} \quad (5.6)$$

The average efficiency of the converter was found to be around 70%. If the cell energy efficiency values are assumed to be $\eta_c=98\%$ and $\eta_d=99\%$, the resulting SoC increase is $\Delta \text{SoC}^+=0.097\%$ for a constant current output of $i_{bal}=400\text{mA}$. This information can be used to estimate the time required to equalize a battery pack once the initial SoC values and the deviation from average are determined.

6. CONCLUSION

Within the scope of the thesis, three main conceptual subcomponents of a BMS were developed and validated with actual BMS hardware using an industry standard embedded microcontroller.

Active Balancing: A flexible intermodular AB architecture was presented and its real-world applicability was validated by commercial BMS hardware implementation and online balancing algorithm. The switched (flying) converter topology can perform both intramodular and intermodular AB at the pack level without requiring multiple converters or auxiliary accumulators. Moreover, it is capable of redistributing the excess energy from any module to any cell, and vice versa, both in series-connected (S-P) and parallel-connected (P-S) pack configurations. Theoretically, the number of cells and modules is only limited by the input/output isolation rating of the converter. Thus, the proposed architecture can be considered as a promising AB approach to mitigate the cellular and modular inhomogeneity of HV packs that consist of many modules typically necessary in heavy duty EV and high energy BESS applications. It is also possible to be used in packs with direct CTP and CTC construction by organizing virtual modules with respect to the input/output specifications of the switched converter. In addition, HEV and aerospace applications with strict volume and weight restrictions may also benefit from the reduced component count.

The performance of intermodular architecture was extensively investigated in various realistic S-P and P-S pack configurations. For all scenarios, the balancing algorithm was able to equalize the cells and modules successfully within the predefined threshold in terms voltage homogeneity in idle mode, including a HV pack of 49S1P configuration. When the imbalanced packs were tested under load, it was also able to redistribute the pack energy and provide extended runtime by supporting the weak cells during discharge. The runtime duration and energy output were increased by >15% in both 7S1P and 2P7 packs.

The main drawback of employing a single switched DC/DC converter is the increased total balancing time for a high number of uneven cells, because the converter must travel across the entire pack in order to balance a single cell at a time. The outlook includes the design of a SoC based realtime controller with current optimization which can increase the overall efficiency and/or decrease the total balancing time, since, as

presented in this thesis, the online AB algorithm runs in basic on-off control mode without any optimization routines. The experiments were carried out only in the module-to-cell direction, i.e. unidirectional energy flow. The design and implementation of a bidirectional isolated DC/DC converter with features such as wide input and output range, high efficiency, low quiescent current, high accuracy load/line regulation and low ripple remains to be an open power electronics topic for future work of the authors. This topology can also be used as a balancer for SC banks in hybrid energy management applications that will be investigated in another future study.

SoH Estimation: Accurate estimation of the SoH of a battery has vital importance for battery applications. In this study a novel, analytical approach for SoH estimation of an automotive grade lithium-ion-polymer battery is proposed. The proposed SoH estimation method is based on an accurate battery model and RCN estimation. Validation of the method was performed using two different test procedures and the results were compared with maximum usable capacities. Tests were carried out both with batteries aged by aging procedures of the manufacturer and with batteries randomly aged where average errors for SoH estimation are 2.02% and 2.823%, respectively. Although the method can only be employed in a specific driving cycle, it is obvious that slopes in the driving cycle used in SoH estimation can be adopted for online applications in EVs.

Thermal Model: A simplified thermal model was developed and validated against actual temperature measurements. It is a computationally low cost TM that can be embedded in a microcontroller with ease. The model can be used as an extra layer of safety for realtime prediction of temperature rise during operation. Since it was simplified with many assumptions and approximations and validated with a single cell, an improved model may be necessary for battery packs with numerous cells taking the thermal management system properties (pack configuration, cooling system etc.) into account.

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PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

Ceylan M., Balikci A., (2023), “An Intermodular Active Balancing Topology for Efficient Operation of High Voltage Battery Packs in Li-Ion Based Energy Storage Systems: Switched (Flying) DC/DC Converter”, *Energies* 16 (15), 5608.

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