INSTITUTE OF SCIENCES AND ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

DESIGN AND IMPLEMENTATION OF BATTERY MANAGEMENT SYSTEM

A Thesis

submitted by

GURKAN TOSUN

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

June 2019

Program: Power Electronics and Clean Energy Systems

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ABSTRACT

DESIGN AND IMPLEMENTATION OF BATTERY MANAGEMENT SYSTEM

With advancements in technology, new electronic devices are introduced that we need in everyday life and functionality of the devices we use increases. One of these fields is transportation. Increased number of internal combustion vehicles to meet our transportation needs negatively affect the environment and cause toxic gas emissions. Today, it is clear that the demand for zero emission electric vehicles are increasing due to challenging emission regulations for toxic gas. Developments in energy storage sector that is needed by electric vehicles is increasing every day and investments in this field are accelerating.

Energy intense batteries in electric vehicles must always be kept under control. Desired voltage level and capacity is created by combining multiple cells in battery cells. High number of cells are necessary to obtain high voltage and capacity needed for electric vehicles. To control each cell, battery management systems are needed to measure cell voltage and temperature. One battery management system can have multiple sub-control modules. During battery energy transfer, cell voltage and temperature are monitored to keep battery package on the safe side. Based on this information, power that battery package can instantly transfer is calculated, and power demanded by the system is kept below limits. Users are informed by using different control algorithms to identify duty cycle of battery packages and their health status. Battery packages that are subjected to constant charge and discharge loses usable capacity. Monitoring this and informing users correctly is one of the critical functions of battery management system. Additionally, due to chemical reactions in more than one cells, voltage difference can occur between these cells. To eliminate this problem, each battery management cell should have the functionality to keep each cell at equal level. Battery management systems with active and passive balancing property are critically important to increase the efficiency of battery package.

Within the scope of this thesis, the above requirements for the battery management system are fulfilled and applied to an electrical bicycle battery package. Initially the modeling and simulation of the cell is presented, then the charging and discharging performances of the battery bank are computed. The cell balancing technique is achieved by using Simulink State-Flow blocks. Voltage of each cell is applied as input to each state-flow block and control signals of MOSFETs that control the parallel balance resistance of each cell. This model is tested for different charge currents.

The experimental part of this study consists of the design and test of a battery management (BYS) system. The master-slave type of BYS is chosen and the detailed design and implementation procedures are presented. The 42 Volt battery pack is formed by using 10 serial Samsung ICR18650-25R cylindrical cells.

Finally, it should be mentioned that, the bicycle electric-supply battery-system is formed, a BYS is designed and, control and protection algorithms are embedded into the BYS. The experimental results yield that, the prototype system is functioning adequately to supply, control and protect the battery pack.

Keywords: Battery management system (BMS), li-ion cell modelling, lithium-ion cell, electric vehicle battery pack.

KISA ÖZET

BATARYA YÖNETİM SİSTEMİ TASARIMI VE UYGULAMASI

Teknolojinin gelişmesi ile birlikte her geçen gün ihtiyaç duyduğumuz elektronik cihazlara bir yenisi eklenmekte ve kullandığımız cihazların fonksiyonellikleri artmaktadır. Bunların başında ulaşım alanı en başta gelmektedir. Ulaşım ihtiyaçlarımızı karşılamak için artan içten yanmalı motorlu araçlar çevreye olumsuz yönde etkilemekte ve havaya zehirli gazlar salmaktadırlar. Günümüzde bu zehirli gazların zorlayıcı emisyon regülasyonlarından dolayı sıfır emisyona sahip elektrikli araçlara talebin arttığı aşikardır. Elektrikli araçların ihtiyaç duyduğu enerji depolama sistemlerindeki gelişmeler her geçen gün artmakta ve bu alanda yapılan yatırımlar ivme kazanmaktadır.

Elektrikli araçlarda kullanılan enerji yoğunluğu yüksek bataryaların sürekli olarak kontrol altında tutulmaları gerekmektedir. Batarya paketinin içerisinde birden çok hücrenin bir araya getirilmesi ile birlikte istenilen gerilim seviyesi ve kapasitesi oluşturulmaktadır. Elektrikli araçların ihtiyaç duyduğu yüksek gerilim ve kapasitenin elde edilmesi için çok fazla sayıda hücre kullanılmaktadır. Her bir hücrenin kontrol altında tutulması için hücre gerilimi ve sıcaklığının ölçülmesi için batarya yönetim sistemine ihtiyacı vardır. Bataryanın enerji transferi sırasında hücre gerilimleri ve sıcaklıkları izlenerek batarya paketi güvenli tarafta kalması sağlanmaktadır. Elde edilen bilgiler doğrultusunda batarya paketinin anlık olarak aktarabileceği güç hesaplanmakta ve sistem tarafından talep edilen güç bu limitlerin altında kalması sağlanmaktadır. Batarya paketinin doluluk oranının hesaplanması ve sağlık durumunun belirlenmesi için farklı kontrol algoritmaları kullanılarak kullanıcı bilgilendirilmektedir. Sürekli

olarak şarj ve deşarja maruz kalan batarya paketi zaman içerisinde kullanılabilir kapasitesini kaybetmektedir. Bu durumun sürekli olarak takip edilerek kullanıcının doğru bilgilendirilmesi batarya yönetim sisteminin kritik fonksiyonlarından biridir. Ayrıca birden çok hücrenin kimyasal tepkimeden dolayı birbirleri arasında gerilim farklılıkları oluşmaktadır. Bu düzensizliğin giderilmesi için batarya yönetim sistemi her bir hücreyi eşit seviyeye getirebilecek fonksiyonelliğe sahip olmalıdır. Aktif ve pasif dengeleme özelliğine sahip batarya yönetim sistemleri batarya paketinin verimliliğini arttırmak için kritik öneme sahiptir.

Tez kapsamında, batarya yönetim sistemi için yukarıdaki gereksinimler yerine getirilmiş ve bir elektrikli bisiklet batarya paketine uygulanmıştır. İlk olarak hücrenin modellenmesi ve simülasyonu yapılmış, daha sonra batarya paketinin şarj ve deşarj performansları hesaplanmıştır. Simulink State-Flow blokları kullanılarak hücre dengeleme tekniği elde edilmiştir. Her bir hücrenin gerilimi izlenerek hücrenin paralel denge direncini kontrol eden MOSFET'lerin kontrol sinyalleri oluşturulmuştur. Bu model farklı şarj akımları için test edilmiştir. Deneysel çalışma, bir batarya yönetimi (BYS) sisteminin tasarım ve testinden oluşmaktadır. Master-slave batarya yönetim sistemi seçilerek detaylı tasarım çalışmaları yapılmıştır. 42 Volt batarya paketi, 10 seri bağlı Samsung ICR18650-25R silindirik hücre kullanılarak oluşturulmuştur.

Son olarak, elektrikli bisiklet batarya yönetim sisteminin tasarlandığı, kontrol ve koruma algoritmalarının geliştirilerek entegrasyonunun yapıldığı belirtilmiştir. Deneysel sonuçlar, prototip sistemin fonksiyonel olarak batarya paketini kontrol etmek ve korumak için yeterli şekilde çalıştığını göstermektedir.

Anahtar Kelimeler: Batarya yönetim sistemi (BYS), lityum-iyon hücre modelleme, lityum-iyon hücre, elektrikli araç batarya paketi.

To My Family

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ABBREVIATIONS

BMS Battery Management System

ICE Internal Combustion Engine

HEV Hybrid Electric Vehicle

EV Electric Vehicle

SoC State of Charge

SoH State of Health

SoF State of Function

NiCd Nickel Cadmium

NiMH Nickel Metal Hydride

Li-Ion Lithium Ion

LiPo Lithium Polymer

LiFePO4 Lithium Iron Phosphate

Zn-Air Zinc Air

Li-S Lithium Sulphur

Li-Air Lithium Air

LCO Lithium Cobalt Oxide

LFP Lithium Iron Phosphate

NMC Lithium Nickel Manganese Cobalt

CC Constant Current

CV Constant Voltage

OCV Open Voltage Circuit

Ah Ampere Hour

MOSFET Metal Oxide Semiconductor Field Effect Transistor

ICP In Circuit Programmer

SPI Serial Peripheral Interface

CAN Controller Area Network

LED Light Emitting Diode

MCU Microprocessor Control unit

I. INTRODUCTION

In line with technologic developments and current needs, energy storing has become critically important for different sectors. In both civil and military applications, batteries that are used for storing electric energy for years required new research on advanced battery systems due to complex and advanced systems and increased importance of safety. Additionally, procuring, sustainability, safe operation and safety topics are increasingly becoming important where the manufacturing of high-efficiency systems are aimed by considering environmental factors.

Today, usage of electric vehicles is presented as a solution as a countermeasure for greenhouse gases of internal combustion vehicles. Electric energy as fuel offers more silent, more environmental and more economic transportation. Electric vehicles use rechargeable battery technologies. However, current battery technologies are far from desired performance and range. Therefore, there is need for increasing performances of current battery technologies and battery management systems (BMS) to increase life-cycle [1]. Today, there are three types of vehicle technologies. These are internal combustion engines (ICE), electric vehicles (EV) and hybrid electric vehicles (HEV). Full electric vehicles only have an electric motor driving force. Battery groups use super – capacitors or fuel cells as energy source. Although electric vehicles with fuel cell have extremely low emission, there are problems such as fuel cell and hydrogen technology [2].

Common battery technologies adopted in electric vehicles are lead-acid, nickel cadmium, nickel metal hydrate and lithium-ion batteries [3]. Lithium-ion cells are widely preferred for their outstanding advantages. High voltage, high energy density, long life, and no memory effect are the most important advantages [3]. Safety and performance of lithium-ion batteries are directly linked with the battery management system. In short, the battery management system is the data collection, data interpretation and balancing unit. The most important task of battery management system is to monitor battery charging status and provide balanced charging/discharging for the battery. Thus, battery management system can prevent excessive charging/discharging status of the battery and increase battery performance. Based on all these developments, BMS is extremely important to monitor current battery system, make parametric calculations, manage battery, take preventive precautions, data archiving, operating system safety as well as increasing battery life [4].

Battery management system function varies depending on usage area [6]. Battery cell of mobile phones that are commonly used today has single cell sequence which enables easier management and control. Additionally, in the automotive sector to reach high voltage level and high energy capacity with batteries used in hybrid electrical and full – electric vehicles, battery packages consisting of multiple serial and parallel cells are used. To operate all cells at desired safety level, battery management system is required. In battery management system, there are analogous inputs to read current, voltage and temperature values depending on number of cells. Additionally, there are digital outputs and communication ports for other passive control elements on battery package.

Fundamentally, battery management system is responsible from safe charging and discharging of all cells, increase battery life-cycle and determine battery status.

Battery packages that are formed by serial and parallel connection of multiple cells can experience voltage imbalances. Under these circumstances, battery management system is expected to eliminate these voltage imbalances [5]. Cell balancing function can be investigated under two groups as active and passive. In battery packages in the automotive sector, passive balancing is preferred due to cost. One of the most important functions of battery management system is assigning cell group status of charging (SoC) and cell status of health (SoH). There are different methods in the literature to calculate these functions. With the advancement in technology, studies in this field have accelerated and there are various academic studies on battery management systems.

1.1. Battery Basics

Battery systems have the purpose to store electrical energy and generally, these systems are classified as primary and secondary systems. The primary battery is a non-chargeable, single-use battery. The secondary battery is chargeable and reusable. In both groups, there are various batteries for different types of applications characterized by different electrochemical structure. Today, there are various battery technologies with different nominal voltage and energy intensity and new technologies are developed. Battery technologies and properties that are commonly used in electric vehicles and that are at research state are given in the table below [7].

Table I.1. Battery technologies used in electric vehicles [7].

Cell Type	Nom. Voltage [V]	Energy Density [Wh/kg]	Cycle Life	Memory Effect	Operating Temperature [˚C]
Pb-acid	2	35	1000	No	-15, +50
NiCd	1.2	50-80	2000	Yes	-20, +50
NiMH	1.2	70-95	<3000	Yes	-20, +60
Li-ion	3.6	118-250	2000	No	-20, +60
LiPo	3.7	130-225	>1200	No	-20, +60
LiFePO4	3.2	120	>2000	No	-45, +70
Zn-air	1.65	460	200	No	-10, +55
Li-S	2.5	350-650	300	No	-60, +60
Li-air	2.9	1300-2000	100	No	-10, +70

1.1.1. Lead Acid Batteries

Lead-acid batteries are the oldest and common technologies that are used in various application areas. This battery technology has advantages such as high discharging current, low self-discharging, no memory effect, and low cost. However, these batteries have low nominal voltage and energy intensity values. Additionally, when not used, the battery life-cycle decreases [8].

1.1.2. Nickel Cadmium Batteries

Nickel-cadmium batteries are reliable and cheap technology. These batteries that provide high discharging current have higher energy intensity compared to lead-acid batteries. However, this battery technology has a significant disadvantage. These are low charge/discharge efficiency, high self-discharging and memory effects [8].

1.1.3. Nickel Metal Hydride Batteries

Nickel metal hydrate battery technology is developed to provide an alternative to the disadvantages of nickel-cadmium batteries. Instead of a cadmium electrode, metal hydrate is used. Nickel metal hydrate batteries have higher self-discharging rate and lower safety in excessive charging conditions compared to nickel-cadmium batteries [8].

1.1.4. Lithium Ion Polymer Batteries

They have almost the same properties as lithium-ion batteries. The only difference is lithium-ion polymer batteries use polymer material as an electrolyte. The electrical conductivity of polymer electrolyte material is higher than other organic liquid electrolytes. Additionally, using this material enables easier, faster, and diverse manufacturing of lithium polymer batteries [8].

1.1.5. Lithium Iron Phosphate Batteries

These are lithium-based batteries that use lithium iron phosphate for positive electrode material. These batteries have advantages such as high energy intensity, high conversion rate, and safer usage. In addition to low cost and containing non-cancerogenic materials, these batteries are preferred due to lower fire risk. However, lithium iron phosphate batteries have 60% less energy intensity compared to traditional lithium cobalt oxide batteries. Since lithium iron phosphate as cathode material can be synthesized from common elements, overall costs can significantly decrease. Lithium iron phosphate batteries that are relatively safer are prominent due to high conversion life and relatively lower costs. Usage of these batteries are increasing in chargeable hand tools, electrical bicycles and among hobbyist. However, when compared to lithium-ion batteries, the performance of these batteries are lower [8].

1.1.6. Lithium Sulphur Batteries

These are among lithium-based battery groups that use Sulphur as a cathode material. When lithium Sulphur batteries are considered on a nanotechnological development basis, these are regarded as one of the future accumulator technologies. These batteries have high energy intensity, high charge efficiency, low cell voltage and low average cycle life [8].

1.1.7. Lithium Ion Batteries

In lithium ion batteries, lithium metal oxides are used due to lower toxicity levels compared to other materials, high capacity and lower costs. These batteries have higher nominal voltage and higher energy intensity compared to nickel-based battery groups. The operating principle of li-ion cells are simpler than other secondary batteries. During charging operation, lithium ions are transferred from the positive electrode to the negative electrode. During discharging, the opposite action is valid [8]. At the same time, lithium is the 31st most common element on earth. There are mining areas in China, North America, Brazil, Chile, Argentine, Bolivia, Russia, Spain and some regions of Africa.

Batteries with lithium chemical are generally called lithium-ion to indicate ion change of lithium. Lithium-ion batteries used for energy storing purposes, especially in portable equipment, are commonly used in electric vehicles due to high energy intensity developed parallel to advanced technology. In portable equipment, a pouch cell version called lithium polymer of lithium-ion technology is used due to the light weighed structure. The advantages and disadvantages of lithium-ion batteries are given below [14].

Advantages of Lithium-ion batteries;

- Lithium-ion batteries are lighter than other chargeable batteries
- Lithium-ion batteries have extremely high energy and can store more energy
- These batteries have a wide range of operating temperature
- These batteries can be charged fast
- Lithium-ion batteries can store 6 times more energy than other chargeable batteries with the same weight
- Lithium-ion batteries are 75% more advantageous than other batteries in terms of energy loss
- Lithium-ion batteries do not have a memory effect.
- Compared to other batteries, these batteries can be charged and discharged more

Disadvantages of Lithium-ion batteries;

- Lithium-ion batteries have 3-4 years of usage life starting from manufacturing date
- When subjected to heat, they lose more energy capacity compared to other batteries
- Lithium-ion batteries will break down if these batteries are completely discharged
- These batteries are more expensive compared to other batteries
- These batteries have higher flammability compared to other batteries
- These batteries need a battery management system

All these properties made lithium metal to be one of the commonly preferred elements in chargeable battery technologies and this metal has been at the focal point of battery technology among scientists and battery manufacturers.

Table I.2. Comparison of different lithium ion battery types [10].

	LCO	LFP	NMC
Nom. Voltage	3.60V	3.60V	3.60V
Specific Energy (capacity)	150-250 Wh/kg	150-250 Wh/kg	150-220 Wh/kg
Charge (C-rate)	0.8C, 1C maximum, 4.20V peak (most cells); 3h charge typical	1C typical; 3.65V peak; 3h charge time	1C, 4.20V peak; 3h charge time
Discharge (C-rate)	1C; 2.50V cut off	25-30C continuous, 2V cut off (lower than 2V causes damage)	2C continuous; 2.50V cut off
Cycle life	500-1000, related to depth of discharge, load, temperature	1000-2000, related to depth of discharge, load, temperature	1000-2000, related to depth of discharge, load, temperature
Thermal runaway	150˚C, full charge promotes thermal runaway	270˚C, very safe battery even if fully charged	210˚C, typical, high charge promotes thermal runaway
Comments	Very high specific energy, limited specific power, cobalt is expensive, serves as energy cell	Very flat voltage, discharge curve but low capacity, one of safest li-ions, elevated self-discharge	Provides high capacity and high power, serves as hybrid cell, this chemistry is often used to enhance li-manganese

1.2. Battery Markets

Due to increasing energy storage need of global lithium-ion battery market and increasing electrical vehicle technologies, market capacity was determined as 22.8 billion USD in 2016. It is expected that market volume will increase as electrical vehicle projects expand with decreasing manufacturing costs and initiating wind energy projects [11].

In addition to batteries used in consumer electronics, as electrical vehicles adopt these batteries, it is awaited that usage of lithium-ion batteries will exceed 53 billion dollars in the following 7 years. Important players of global lithium-ion battery industries include Hitachi Chemical, China BAK Accumulator, Samsung, A123 Systems, GS Yuasa International, Toshiba, Panasonic, LG Chemical Power and Automotive Energy Supply Corporation [12].

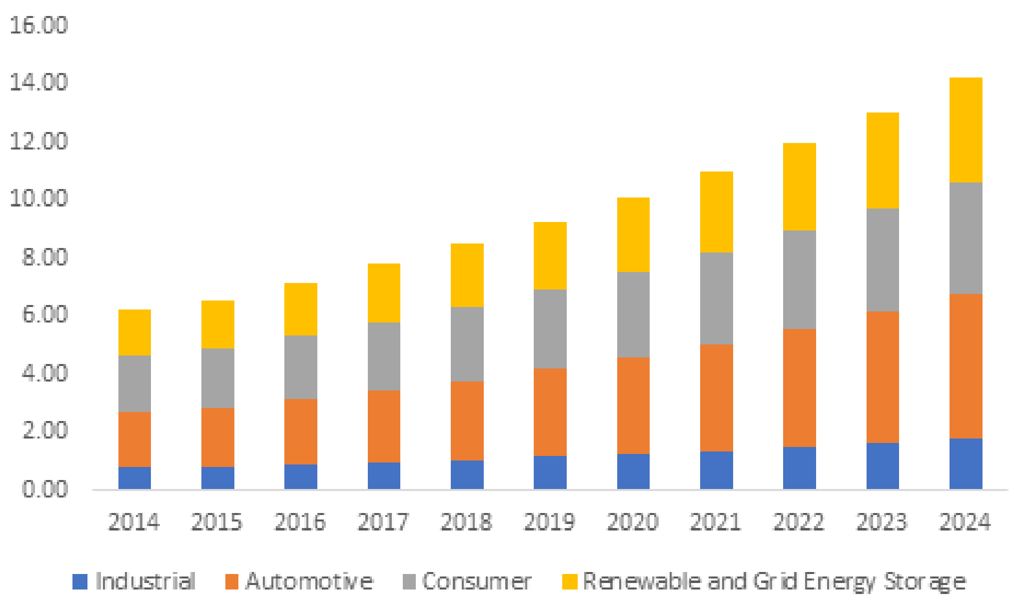

Figure I.1. Europe li-ion battery market size (USD Billion).

As batteries with longer usage duration and lower costs are developed for electric vehicles, smartphones, tablets, and PCs, this technology is reaching to a larger audience. As new suppliers are introduced to the battery market, it is expected that market competition of new battery technologies will increase [13].

1.3. Battery Management System (BMS)

Battery technologies have a wide range of usage areas from simple electronic devices to electric vehicles. Although usage areas are different, the performance and life of these batteries are linked with the operation area. This operation area prevents possible dangers of excessive charging and discharging of batteries and improve battery performance. Today, battery management systems are systems that are important for electric vehicles, hybrid electric vehicles, telecom application, uninterrupted power sources, laptops and cellular phones and these systems can vary depending on application [15]. In advanced technology batteries, the purpose is to develop structures to increase operational performance and system security under safety reasons and to decrease battery malfunctions to achieve the highest efficiency from the battery. During charging and discharging of battery, hardware and software systems where critical boundaries are processed and controlled and battery state of charging (SoC), state of health (SoH) and state of functionality (SoF) are controlled are called battery management system (BMS) [16].

The battery management system consists of three main functions including data monitoring, calculation, and protection. The data monitoring function is observing measurable instantaneous states such as voltage, current, and temperature of each cell in the battery pack. Calculation function calculates values such as battery duty cycle, battery health status, maximum and minimum charge/discharge current, maximum and minimum voltage, operation time and a number of cycles by using instantaneous values observed in data monitoring function. Values obtained from calculation function and high/low voltages during charge/discharge of cells and battery in protection function prevents high current, fault current and high/low temperature [17].

Another important task of the battery management system is identifying the battery duty cycle obtained from calculation function and balancing battery cells in battery packages during charge/discharge operation. Different methods are adopted for this balancing operation.

Battery management system should include the following functions [18];

- Safety;
  - Excessive charge/discharge
  - High temperature
- Data Processing;
  - State of charge (SoC)
  - State of health (SoH)
  - State of function (SoF)
- Communication;
  - Charge state and health state
  - Cell temperature
  - Excessive charge/discharge
- Measurement and Monitoring;
  - Cell voltage, total voltage, total current, cell temperature

While charging a battery package with lithium chemistry, controlling this structure by battery management system has vital importance and when battery cell research maximum charging voltage, charging current must be cut-off. As in charging state, battery management system is necessary since lithium chemistry is involved in discharging stage. When any cell reaches lower voltage level, discharging should be stopped. This is the primary function of battery management system. Here depending on importance of load, discharge can be continued, however, this might cause damage on battery package. Energy storing capacity of a damaged battery package will decrease and accordingly, in the following cycles, cycle time will significantly decrease.

At the same time, a battery management system should bring cells connected in series inside battery package to equal voltage level by using active and passive topologies and maximize battery capacity. Also, the system must keep cells in battery package on same voltage level and ensure energy efficiency and charging amount. For battery packages consisting of parallel-connected battery cells, according to Kirchhoff's law, since cell voltage is equal, there is no need for a battery management system to balance battery; for battery packages consisting of a serial-connected battery cell, benefiting from a battery management system with balancing property enables maximum benefit. To benefit from this battery package with maximum efficiency, cells forming the battery pack should be charged up to maximum cell voltage. However, since the manufacturing process is highly dependent on chemical reactions, cells do not have the same behavior in charging and discharging stages.

Battery cell balancing is one of the critical tasks of battery management system. In balancing operation, the purpose is to achieve balance on same battery charging state on all battery cells during charging/discharging operation. Balancing can be divided into two as active and passive balancing. Balancing topology of battery cells are given in Figure I.2.

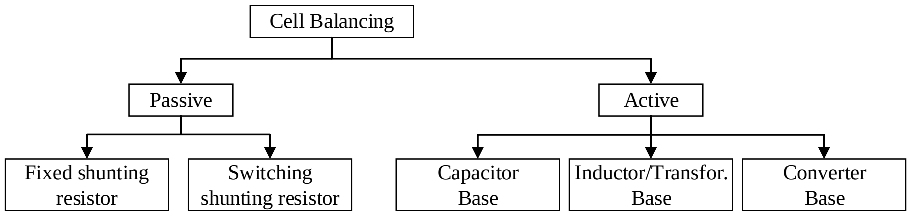

Figure I.2. Passive and active cell balancing topologies.

1.3.1. Passive Balancing

In battery cell balancing, the passive balancing method is a simple and easy-to-apply method. The passive balancing method is preferred in battery packages with high Ah values where energy recovery is secondary due to low cost and easy applicability. This method can especially be applied in electrical and hybrid electrical vehicles by considering the thermal design. Passive balancing method, in general, is based on the implementation of parallel resistance to high voltage cell and equalizing this cell voltage with other cells forming the package. Passive balancing circuit identifies the lowest voltage level of battery cells and lowers the voltage level of other battery cells to reference voltage by using these voltages on parallel resistance [19].

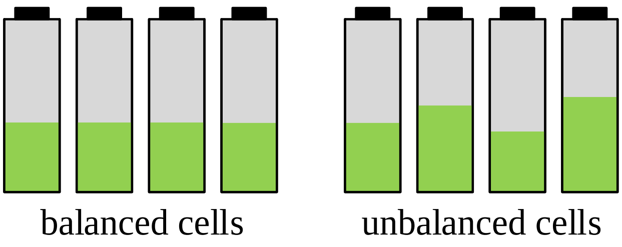

Figure I.3. Change in battery voltage levels at passive balancing.

The most important advantage of this system is low cost, easy application and smaller area coverage on the circuit. The main disadvantage is not having energy recovery, higher resistance needs due to the high Ah value of the battery package, high balancing current, semiconductor switch or relay usage due to high current value and mandatory application of thermal management. Although simplicity and low cost of passive balancing technique seem sufficient for use, in practice this is not possible. Since there is post-charging balancing, the average voltage is lowered with balancing before battery package is fully-charged, therefore, battery capacity cannot be used entirely.

As battery technologies become widespread, battery industry emerged as a problem that needs to be addressed. The design of new and effective charging and discharging control systems is extremely important for longer battery life.

1.3.2. Active Balancing

Another method adopted in battery cell balancing is an active balancing method. According to voltage level management of battery cells calculated by the active balancing circuit, voltage transfer is made to balance at an average level. Thus, energy consumed in passive balancing can be transferred to other battery cells in active balancing and more efficient balancing is achieved [19]. Purpose here is to transfer current from high voltage battery cell or from the complete package to cell with low voltage to keep cell voltages at highest level possible to use battery capacity at maximum level. Although this method can be applied during charging process, generally when a cell inside the package reaches maximum voltage level, charging is stopped and battery balancing operation is applied. Purpose for this is to ensure that at least one cell is fully charged. In a balanced battery package, differences will significantly decrease after each cycle and cell voltages inside the package will increase or decrease at the almost same level. Battery voltage level change in active balancing is given in Figure I.4.

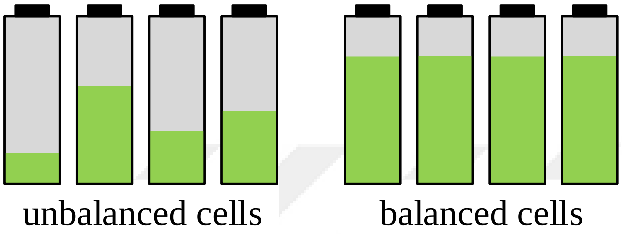

Figure I.4. Change in battery voltage levels at active balancing.

On contrary to passive balancing technique, active balancing has relatively higher costs. When application challenges and cost are considered, this technique is not preferred in low cost applications. If passive balancing provides results by increasing ampere hour value of battery package and this option has lower cost, active balancing is not applied.

1.3.3. Charging and Discharging of Lithium-Ion Batteries

Battery charge is one of the topics to be considered for healthy battery performance and long battery life. Charging methods are classified based on current and voltage rate applied during charging [30]. Depending on charging method, various parameters such as temperature produced during charging, battery life-cycle and number of cycles can vary based on charging method [33].

For li-ion and li-ion polymer electrochemical structures, recommended charging method is constant current-constant voltage charging method (CC-CV) [31], [32], [33].

Battery manufacturers determine I_{cc} and $V_{\square\square\square}$ values based on manufacturing methods. $I_{\square\square}$ charging current that is directly linked with current intensity can change between 0.7C and 1C for li-ion and li-ion polymer batteries. $V_{\square\square\square}$ voltage values vary depending on li-ion cell type and these values can be between 3.6V ± 1% or 3.7V ± 1% [33].

Each electro-chemical structure has different discharging capacity. For example, NiCd cell discharging capacity can go up to 20C value however peak current rate of li-ion polymer cells is around 5C. Additionally, constant discharging current for lithium-based cells is considered as 2C ratio.

The charge current can be controlled by constant current or constant voltage. A sample CC-CV charge profile is shown in Figure I.5. Fixed CC charging is applied to bring the voltage to CV level. When the voltage reaches the desired level, the CV charge starts and the current drops.

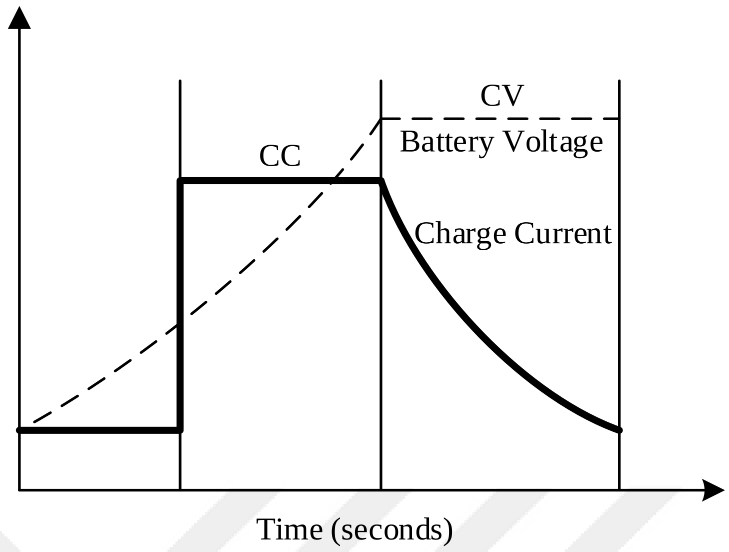

Figure I.5. Typical charge profile of a li-ion battery cell [31].

II. LITERATURE REVIEW

2.1. Review on Battery Management System

Balancing operation is important for chargeable batteries, generally balancing is used for protecting serial cell groups and extending life-cycle. In battery management systems, passive balancing is more commonly used, this method is cheaper and simpler than other methods. In passive balancing method, excess energy on the battery is consumed over a resistance and balancing is completed. While balancing high energy intensity battery packages of hybrid electrical vehicles and full electrical vehicles, higher current is balanced with lower resistance value. This way, balancing period is faster. In this study, balancing is applied over 1P 15S battery package. Instead of balancing resistance, internal resistance of switching element is used for high power balancing [20].

In this study, new cell balancing algorithm is proposed for battery management system. For the electric vehicles, cell balancing algorithms has an important place. To calculate abnormal value of each cell, distance-based outlier detection algorithm is used to identify unbalanced cells. During balancing operation, R=33 ohm resistance is used to analyse. In simulation results, it was observed that new proposed balancing system increased battery capacity by 0.614Ah (9.5%) [21].

Battery management system is an electrically critical component in electric vehicle applications. Purpose of battery management system is to complete state monitoring and evaluating, charging/discharging control and cell balancing functions to ensure battery reliability. Battery management system can vary for cell structures with different chemistry. In this case, uncertainty of battery presents a problem. In this study, concerns in current battery management system are considered and analysed. Critical task of battery management system is identification of battery status of health and status of life. In this study, state-of-art technology methodologies are analysed and solution recommendations are presented for possible future scenarios of battery package [22].

In commercial industrial application, battery is the most common energy storage tool. Although importance of batteries are increasing, it is challenging to characterize and manage batteries. Main problems are related with charges battery state (SoC) and health of battery (SoH). Duty cycle of battery is represented in percentage format and refers to capacity amount. In this study, Coulomb counter method is adopted to identify battery duty cycle [23].

Especially due to long cycle life and fast charging opportunities, lithium ion batteries are preferred in electric vehicles. Correct battery model is needed to identify battery duty cycle and health status with high sensitivity. In this study, MATLAB/Simulink is used for developing battery management system algorithm. To identify duty cycle and state of health in lithium ion cells, augmented Kalman filter is used and equivalent mathematical model of the cell is developed. With this developed model, the purpose is to predict correct battery [24].

In high energy intensity energy storing systems, lithium ion battery usage is potentially adopted. To obtain correct results from an efficient battery system, it is important to model the cell in simulation environment. In this study, cell model is developed in MATLAB/Simulink environment. When experiment results are compared, accuracy of developed cell model is achieved [25].

Lithium ion batteries are the most suitable options in electric vehicle applications. Special control algorithms are applied to protect lithium ion batteries from damage, to increase battery life and to ensure dynamic balancing. In this study, main focal point of proposed control strategy is to balance each cell in the battery package simultaneously and in a fast and efficient way. Under the scope of this study, proposed model showed superb performance in balancing four serial-connected lithium ion cells and results were validated with simulations and experimental work [26].

Battery duty cycle represent total remaining energy. Battery management system that has been analysed in various academic studies are tried to be predicted with different algorithms such as SoC, SoH, and SoF. In literature, Coulomb counting, model based open circuit voltage and neural network model algorithms are applied to predict battery status. In this study, a real-time, model-based prediction method for duty cycle of lithium ion batters, state of health and state of functionality is proposed [27].

Lithium ion batteries are commonly used in energy storage, electric vehicles and consumer electronic. This way, these batteries greatly contribute to technologic development. This study focused on equalizing all cells with passive balancing method during operation of lithium ion batteries. Balancing current significantly affect battery package balancing time and self-discharging status. Cell parameters play an important role in determining passive balancing current. Passive balancing optimization plays an important role on improving battery package inconsistency [28].

As interest towards electrical vehicles increase, lithium ion industry has rapidly developed. In literature, there are studies on prediction algorithms to increase safety of real-time applications of lithium ion batteries and to identify battery parameters. In this study, recently proposed prediction algorithms are compared for accuracy, redundancy and calculation and results are observed [29].

2.2. Review on Battery Modelling

2.2.1. Cell Modelling

In electrical circuit model of lithium ion batteries, system model is formed over equivalent circuits. Cell models created with equivalent circuit models play an effective role to identify battery models that enable mathematical operations. In literature, there are various equivalent circuit models [34], [35], [36]. There are two common approach method. In first approach, resistive load that represent inner resistance of the battery is sued for identifying battery parameters by applying various measurement methods. In second approach, different modelling methods are applied to predict parameters based on OHM’s law [37]. Additionally, ambient temperature and heat created during battery operation has great impacts on identifying battery parameters. In literature, temperature-based functions are integrated to battery model and changes in different ambient and operation temperatures are included in the model. Common equivalent circuit models in electrical circuit models are given below.

- **R_{int} Equivalent Circuit Model**

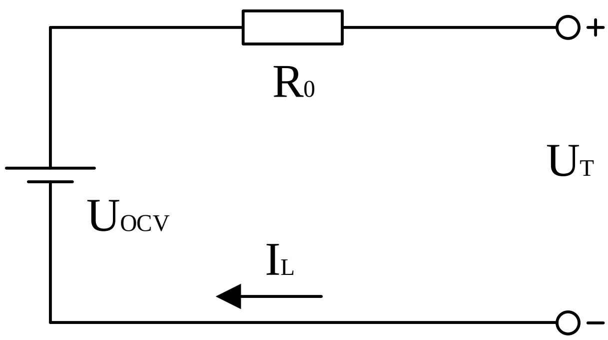

Figure II.1. R_{int} equivalent circuit model.

Here R_0 is in series, U_{OCV} is open circuit voltage, U_T is terminal voltage and I_L is load current. Mathematical equation of R_{int} model over equivalent circuit can be represented as follows.

$$U_T = U_{OCV} - R_0 I_L \qquad \text{(II.1)}$$

- **R_C Equivalent Circuit Model**

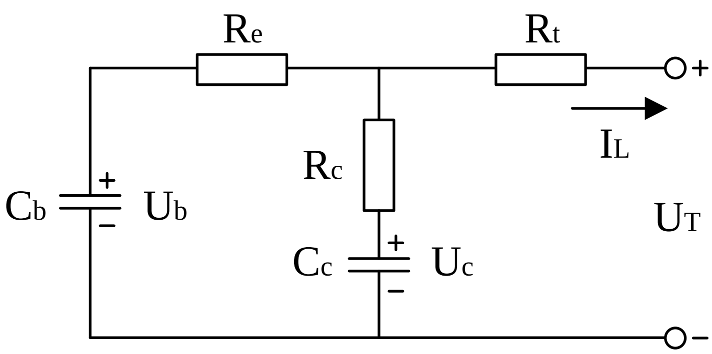

Figure II.2. R_C equivalent circuit model.

Here R_e is edge resistance, R_c is capacitor resistance, R_t is terminal resistance, C_b is bulk capacitor representing open circuit capacity of the battery, C_c is small capacity surface capacitor, U_b and U_c are voltages on C_b and C_c respectively, I_L is load current and U_T is terminal voltage. Mathematical equation of RC model over equivalent circuit can be represented as follows.

$$\begin{bmatrix} U'_b \\ U'_c \end{bmatrix} = \begin{bmatrix} -1/C_b(R_e+R_c) & 1/C_b(R_e+R_c) \\ 1/C_c(R_e+R_c) & -1/C_c(R_e+R_c) \end{bmatrix} \begin{bmatrix} U_b \\ U_c \end{bmatrix} + \begin{bmatrix} -R_c/C_b(R_e+R_c \\ -R_e/C_c(R_e+R_c \end{bmatrix} I_L \quad \text{(II.2)}$$

$$U_T = \begin{bmatrix} R_c/(R_e+R_c) & R_e/(R_e+R_c) \end{bmatrix} \begin{bmatrix} U_b \\ U_c \end{bmatrix} + \left[-R_t - \frac{R_e R_c}{(R_e+R_c)} \right] I_L \quad \text{(II.3)}$$

- **Electrical Equivalent Circuit Model**

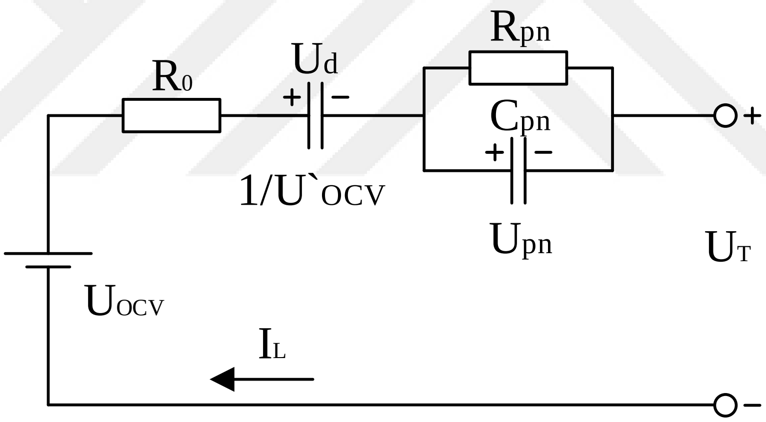

Figure II.3. Electrical equivalent circuit model.

Here R_0 is serial resistance, $1/U'_{OCV}$ is serial capacitor R_{pn} polarisation resistance, C_{pn} is polarization capacitor, I_L is load current, U_{OCV} is open circuit voltage and U_T is terminal voltage. Mathematical equation of electrical equivalent circuit model which can be represented as follows.

$$U'_d = U'_{OCV} I_L \tag{II.4}$$

$$U'_{pn} = -\frac{U_{pn}}{R_{pn}C_{pn}} + \frac{I_L}{C_{pn}} \tag{II.5}$$

$$U_T = U_{OCV} - U_d - U_{pn} - I_L R_0 \tag{II.6}$$

Thevenin equivalent circuit model in electrical circuit model can be modelled at different levels. Thevenin equivalent circuits at different levels are given below.

- **Different Degrees Thevenin Circuit Model**

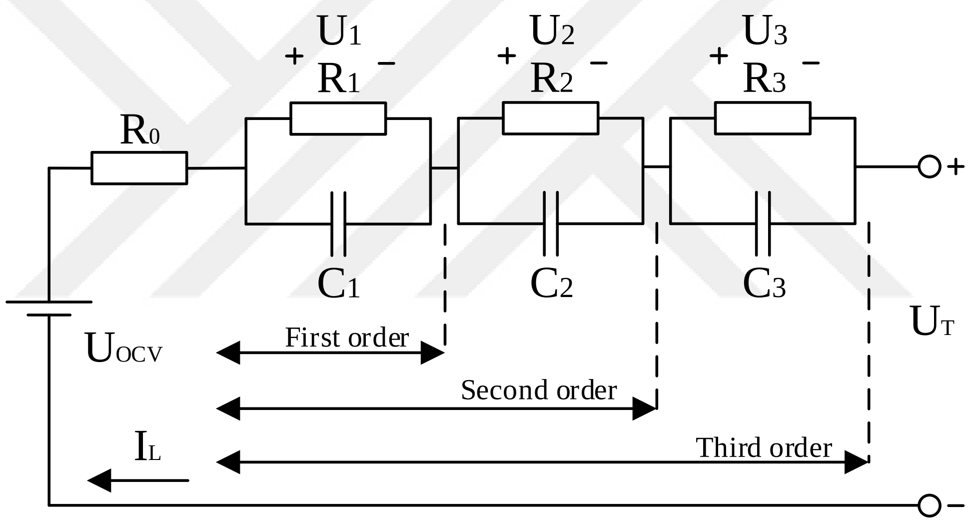

Figure II.4. Different degrees Thevenin circuit model.

Here U_{OCV} is open circuit voltage, R_0 is serial resistance, R_1, R_2, R_3 are block resistance parameters, C_1, C_2, C_3 are block capacitor parameters and U_T is terminal voltage.

First degree Thevenin equivalent circuit equations are as follows:

$$U_T = U_{OCV} - U_1 - R_0 I_L \tag{II.7}$$

$$C_1 \frac{dU_1}{dt} = -\frac{U_1}{R_1} + I_L \quad \text{(II.8)}$$

Second degree Thevenin equivalent circuit equations are as follows:

$$U_{\square} = U_{OCV} - U_1 - U_2 - R_0 I_L \quad \text{(II.9)}$$

$$C_1 \frac{dU_1}{dt} = -\frac{U_1}{R_1} + I_L \quad \text{(II.10)}$$

$$C_2 \frac{dU_2}{dt} = -\frac{U_2}{R_2} + I_L \quad \text{(II.11)}$$

Third degree Thevenin equivalent circuit equations are as follows:

$$U_{\square} = U_{OCV} - U_1 - U_2 - U_3 - R_0 I_L \quad \text{(II.12)}$$

$$C_1 \frac{dU_1}{dt} = -\frac{U_1}{R_1} + I_L \quad \text{(II.13)}$$

$$C_2 \frac{dU_2}{dt} = -\frac{U_2}{R_2} + I_L \quad \text{(II.14)}$$

$$C_3 \frac{dU_3}{dt} = -\frac{U_3}{R_3} + I_L \quad \text{(II.15)}$$

Here, U_1, U_2, U_3 are voltage drop on RC blocks.

- **Battery Parameters Estimation**

Parameters in non-linear mathematical model of the battery are predicted by using current and voltage values of real battery system. The relationship between the system and the time-invariant, linear input is determined by the mathematical model structure [37].

Relationship between input/output samples of standard structured system is created as follows.

$$V_{T(n+1)} = aV_{T(n)} + bI_{(n)} = \begin{bmatrix} V_{T(n)} & I_{(n)} \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} \tag{II.16}$$

$$V_{T(n+2)} = aV_{T(n+1)} + bI_{(n)+1} = \begin{bmatrix} V_{T(n+1)} & I_{(n+1)} \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} \tag{II.17}$$

$$\vdots \tag{II.18}$$

$$V_{T(n+k)} = aV_{T(n+k-1)} + bI_{(n+k-1)} = \begin{bmatrix} V_{T(n+k-1)} & I_{(n+k-1)} \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} \tag{II.19}$$

$$\begin{bmatrix} V_{T(n+1)} \\ V_{T(n+2)} \\ \vdots \\ V_{T(n+k)} \end{bmatrix} = \begin{bmatrix} V_{T(n)} & I_{(n)} \\ V_{T(n+1)} & I_{(n+1)} \\ \vdots & \vdots \\ V_{T(n+k-1)} & I_{(n+k-1)} \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} \tag{II.20}$$

Real output V_{T}, estimated output V'_{T}; calculation of the error between,

$$E = V_{T} - V'_{T} = V_{T} - \Phi_{\theta} \tag{II.21}$$

$$\Phi_{T} = \begin{bmatrix} V_{T(n)} & I_{(n)} \\ V_{T(n+1)} & I_{(n+1)} \\ \vdots & \vdots \\ V_{T(n+k-1)} & I_{(n+k-1)} \end{bmatrix} and\ \theta = \begin{bmatrix} a \\ b \end{bmatrix} \tag{II.22}$$

Minimization of the smallest quadratic error and estimation of the parameters are given below.

$$\begin{aligned} J &= E^{2}; E = (V_{T} - \Phi\theta)^{T} (V_{T} - \Phi\theta) \\ &= V_{T}^{T} V_{T} - 2\theta^{T} \Phi^{T} V_{T} + \theta^{T} \Phi^{T} \Phi\theta \end{aligned} \tag{II.23}$$

$$min\{J\} = \frac{dj}{d\theta} = -2\Phi^{T} V_{T} + 2\Phi^{T} \Phi\theta \tag{II.24}$$

$$\theta = (\Phi^{T} \Phi)^{-1} \Phi^{T} V_{T} \tag{II.25}$$

2.2.2. Series Connected Batteries

In application that require higher level of voltage which needs more than one cell, to create a battery package with high voltage, a set of cells are connected in series to create battery package. During operation of serial connected battery package, charging and discharging current provides same level of flow from all cells. Additionally, when voltages of cells in battery package are desired to be controlled separately, isolates measurement circuits are required. When battery package is charged and discharged, voltage difference occurs due to different chemistry of each cell. This creates disadvantage to charge or discharge cells at full capacity.

Depending on chemical structure of serial connected cells inside battery package, charging or discharging states can be completed in different times. If voltage differences between cells are not controlled by battery control system, limits published by cell manufacturers can be exceeded and batteries can be damaged.

If any cell in serial connected battery package is in open circuit conditions or short circuit condition, related line will go to faulty state and battery package cannot be used.

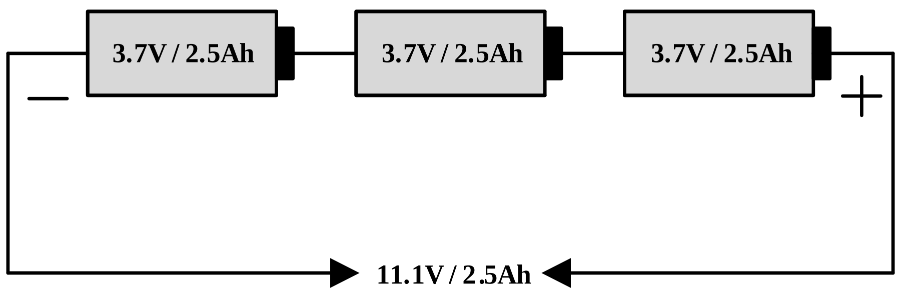

Figure II.5. Series connected batteries.

2.2.3. Parallel Connected Batteries

In application that demand higher current from individual cell, multiple cells can be connected in parallel to draw higher current. When cells are connected in parallel structure, voltages of each cell are equal. If there is voltage difference before these cells are connected in parallel form, cells with higher potential will transfer energy to lower potential cells to achieve voltage balance (to prevent potential large fluctuation of cells). In terms of monitoring circuit, parallel cells are beneficial since single circuit is needed to measure voltage of parallel group. However, since parallel cells do not follow each other, parallel branch currents are unknown. Open circuit condition of the cell cannot be determined and current values that can be drawn to parallel group on serial brand decreases. Although this is an undesired condition, this method is commonly adopted.

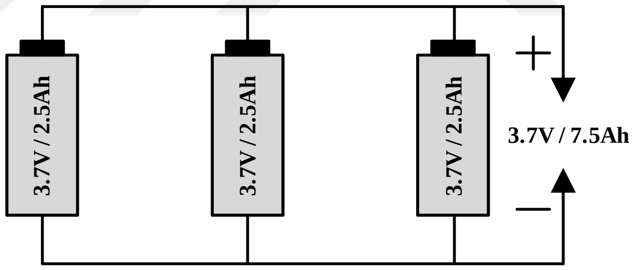

Figure II.6. Parallel connected batteries.

2.2.4. Series and Parallel Connected Batteries

In application that require both high voltage and higher current, serial and parallel connected cell combination is required to create battery package. In these combinations, parallel connected cell groups are connected in series. Cells with different voltage and power level are commonly preferred in electric vehicles in serial and parallel connection. If any one of parallel connected cell groups is short circuited, parallel group is deactivated and total battery package voltage decreases. Image below shows serial-parallel connected cell group scheme.

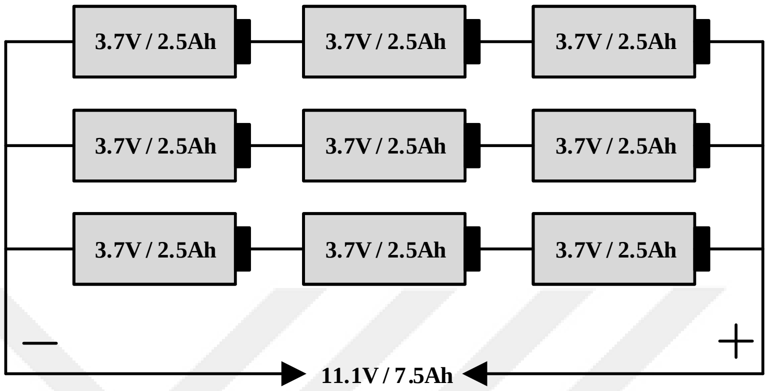

Figure II.7. Series and parallel connected batteries.

2.3. Function of the Battery Management System

A battery management system must critically have three main functions: State of Charge (SoC), State of Health (SoH) and State of Function (SoF).

2.3.1. State of Charge

State of Charge (SoC) is defined as percentage representation of current capacity on a battery or battery package. There are five main method to determine SoC. These are the chemical method, pressure method, impedance method, voltage method and current integration method. Due to low cost and easier application, two latter methods are commonly preferred [38].

Open circuit voltage method which is also known as static method is the simplest way to predict SoC. This method measures open circuit cell voltage (OCV) and reads

SoC value from SoC–OCV table provided by manufacturer. Additionally, for open circuit voltage method to make correct SoC prediction, this method should consider parameters such as ambient temperature and cell aging [39], [40].

Generally, SoC is defined by Coulomb number as discussed in following section. Additionally, it is undesirable to have a cell terminal voltage value below cut-off voltage given in manufacturer document. Accuracy of SoC has critical importance to determine operating voltage range of cell. Cell manufacturers publish open circuit voltage values based on different cell discharge currents.

To determine cell duty cycle, discharge current and open circuit voltage curve can be used for different discharge current rates and this could cause differences in battery energy. This phenomenon was first formulated by Peukert Law [41];

$$K\, I^{n-1} = const., n > 1 \qquad \text{(II.26)}$$

where K is as a function of discharge current refers to useable capacity [Ah], and n is specified by the characteristics of the battery. When the battery is ideal and its capacity is not affected by the discharge current. For n values are in the range from 1.2 to 1.5 [41].

Additionally, battery capacity is affected from ambient temperature and cell cut-off voltage. Battery operation temperature value is directly related with measuring from open circuit voltage. This variable effect battery discharge capacity.

When above hypothesis is considered, it can be stated that cells with similar SoC values defined by Peukert law are not in different states. Additionally, cells might have variable internal resistance. Therefore, SoC identified by Coulomb counting or Peukert modification method might cause changes in battery total capacity.

- **Coulomb Counting**

The most basic way to estimate SoC online is by coulomb counting. Given a fixed number of total coulombs available Q_{total} when SoC = 1, the current SoC can be found by:

$$SoC = \frac{Q_{total} - Q_{out}}{Q_{total}} \times 100\% \qquad \text{(II.27)}$$

In a quasi-stationary load scenario where the battery current is constant at a certain value for a significant amount of time before switching to another value, it is possible to normalize the current output's effect on SoC using the discharge curve for different discharge currents provided by the battery manufacturer. This provides a means of taking into account the capacity variation described by Peukert.

Many other variants of the coulomb counting method, often with Peukert modifications, exist in the literature [42], [43], [44].

Coulomb counting algorithm is affected by more than the increasing error amount due to errors occurring at the time of measurement. If the battery pack can be fully charged, the charging algorithm is assumed to operate correctly and the SoC prediction algorithm is reset at certain intervals.

Another problem of Coulomb counting method is during charging operation, all energy cannot be absorbed by cell [45]. Internal resistance of cell, temperature and energy transfer efficiency are directly related with SoC. Inability to measure energy transfer efficiency caused inability to determine total transferred energy. System efficiency and effect of temperature are considered as constant variables and total usable capacity is determined with certain error margin.

- **Voltage-Based Methods**

Another method to identify SoC is open circuit voltage. Open circuit voltage can be determined by measuring voltage at cell terminals certain period after charging operation. Since completion of recovery period is needed to measure voltage at cell terminals, it is not possible to determine SoC under load and this is not commonly preferred. Terminal voltage can be measured with the help of an external load but this voltage value fails to represent SoC accurately. Due to voltage release during measurement, it is not possible to obtain an accurate value.

- **Online Estimation Methods**

To determine energy stored on a battery, algorithms such as Kalman filter and impedance parameter can be used for determining instantaneously. Plett suggested working on Kalman filter to determine SoC [46], [47], [48].

Kalman filter approach model is adopted to predict SoC. When models are created, a relationship between cell terminal voltage and SoC should be formed. Current values determined in different discharge states can be used for predicting SoC with modelling approach method.

To predict internal state of a battery for electric vehicle applications, another proposed method is recursive system identification technique to predict impedance of a cell. Open circuit voltage later provides SoC predictions.

2.3.2. State of Health

SoH represent aging of battery over time. It has been claimed that the aging process comes from the effect of previous battery history. For lithium ion batteries, factors such as storage temperature and storage duration directly impact SoH. Additionally, uncontrolled temperature changes during battery operation can cause irrevocable chemical damages. These conditions are defined as accelerators for battery aging [49].

Aging can be identified by comparing two discharging cycles. Various battery manufacturers declare terminal voltages at different discharge currents. In an ideal battery, increasing internal impedance caused battery terminal voltage to decrease more.

Generally, there are two different reasons that effect battery aging status. First, loss of active material in the battery caused decreased capacity. Second, due to various reasons, cell internal resistance increases and contributes early ending of battery charging and discharging status.

2.3.3. State of Function

Depending on instantaneous SoC status of the battery, SoF term is used for representing provided power amount. To determine instantaneous charging and discharging currents and to calculate remaining energy, SoC and SoH states of the battery must be considered. SoF can normally be calculated by using cell terminal voltage. Under battery package discharge profile, if there is no decrease in cell terminal voltage, SoF might represent cell terminal voltage [50].

Key point here is that existence of remaining energy in battery does not mean that this energy is accessible for certain application [9]. Normally, SoF can be evaluated by using terminal voltage.

III. BATTERY MANAGEMENT SYSTEM; SIMULATION, DESIGN AND IMPLEMENTATION

3.1. Simulation of The Battery Management System

3.1.1. Simulation of the Single Cell

Within the scope of this thesis study, ICR18650-25R cell of Samsung is used. Technical properties of this cell are presented in Table III.1.

Table III.1. Samsung ICR18650-25R technical specification.

Type		**Spec.**	**INR18650-25R**
Chemistry		NCA	NCA
Dimension [mm]	**Diameter**	18.33	18.33
	Height	64.85	64.85
Weight [g]		Max. 45.0	43.8
Initial IR [mΩ AC kHz]		<18	13.20
Initial IR [mΩ DC (10A-1A)]		<30	22.15
Nominal Voltage [V]		43649	3.64
Charge Method [100mA cut-off]		CC-CV (4.2V)	CC-CV (4.2V)
Charge Time	**Standart [min], 0.5C**	180	134
	Rapid [min], 4A	60	55
Charge Current	**Std. Current [A]**	1.25	1.25
	Max. Current [A]	4.0	4.0
Discharge	**End Voltage [V]**	2.5	2.5
	Max. Con. Current [A]	20	20
	Max. Momentary Pulse [A, <1sec]	100	100
Rated Discharge Capacity	**Std. [mAh], 0.2C**	2,500	2,560
	Rated [mAh], 10A	2,450	2,539

To create cell models, 1st degree Thevenin equivalent circuit model was adopted. In cell simulation studies, $OCV - SoC$ relationship, $R_0 - SoC$ relationship, $R_1 - SoC$ relationship and $C_1 - SoC$ relationship provided by manufacturer and/or obtained from experimental measurements are given in Figures III.1, III.2, III.3, III.4 [51].

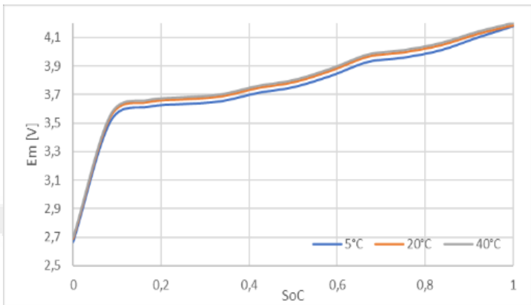

Figure III.1. $E_m - SoC$ graph.

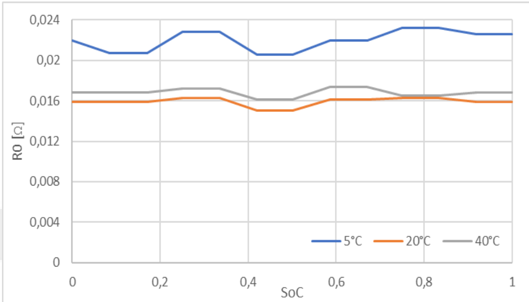

Figure III.2. $R_0 - SoC$ graph.

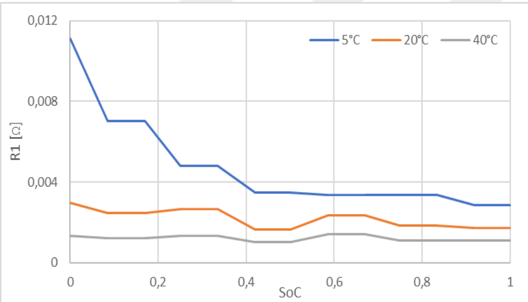

Figure III.3. $R_1 - SoC$ graph.

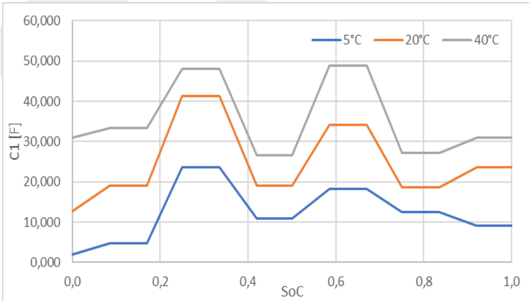

Figure III.4. $C_1 - SoC$ graph.

During modelling, Simscape tool in MATLAB/Simulink was adopted for simulation and 1st degree equivalent circuit model was built on Simulink. Thermal effects in the simulation model changes based on heat transfer coefficient while cell volume and areas are effective on this. Cell size was included in the system as modelling parameters. In Table III.2, values that were parametrically added to the system are presented.

Table III.2. Simulation parameters.

Name	Value
cell_area	0.0043
cell_height	0.0650
cell_thickness	0.0092
cell_colume	1.7290e-05
cell_width	0.0092
deltaV	0.0030
h_conv	4.7500
h_con_end	9.5000
I_cc	2,4,8
numCells	10
R	0.0100
R_bleed	0.0200
Temp	297
V_top	42

1st degree Thevenin equivalent circuit model was built in Simulink as follows.

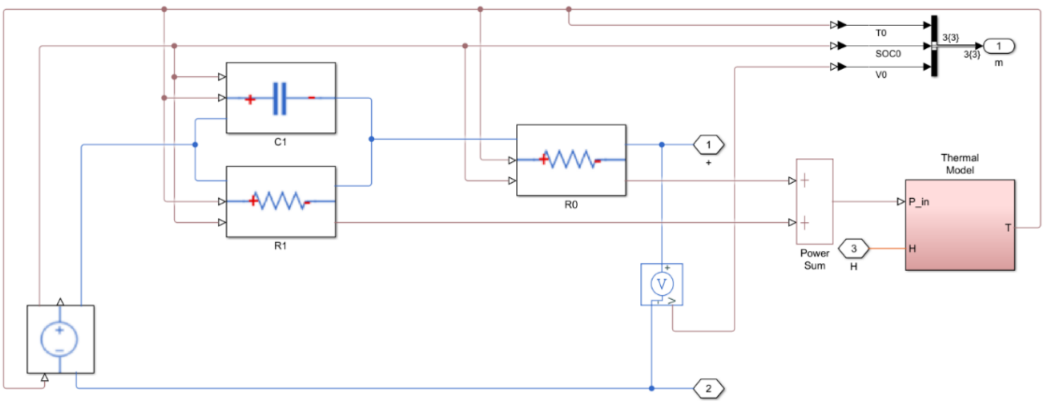

Figure III.5. 1st degree Thevenin equivalent circuit model.

Cell parameters in Figures III.1, III.2, III.3, III.4 were parametrically written to equivalent circuit model based on SoC. Simulations were conducted for different charge/discharge currents and cell voltage and SoC cell heating values were evaluated.

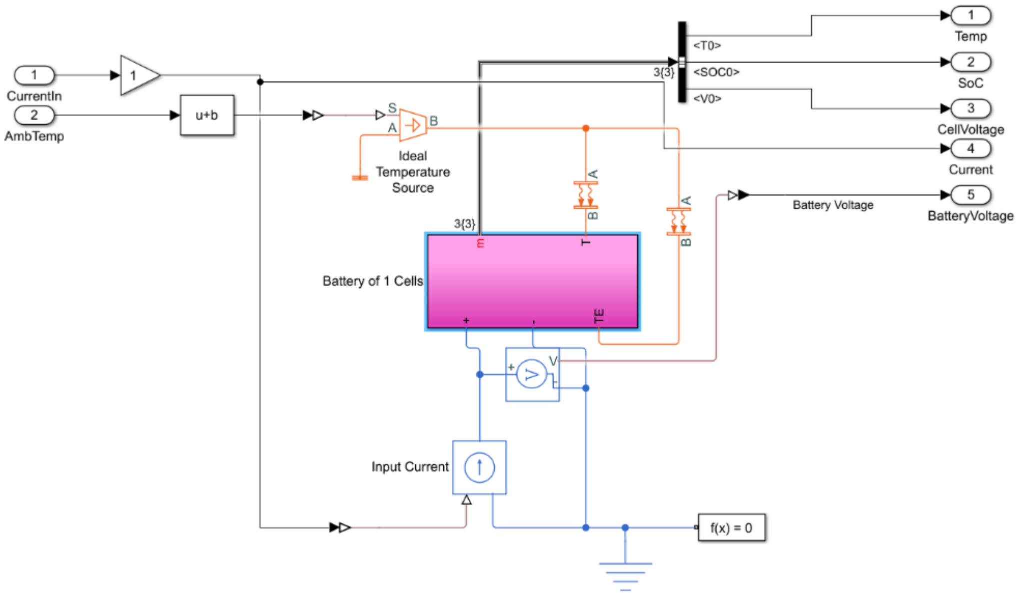

Figure III.6. Single cell simulating model.

To analyse simulation models at different ambient temperature, model in Figure III.7 was run in five different ambient temperature and outputs were obtained.

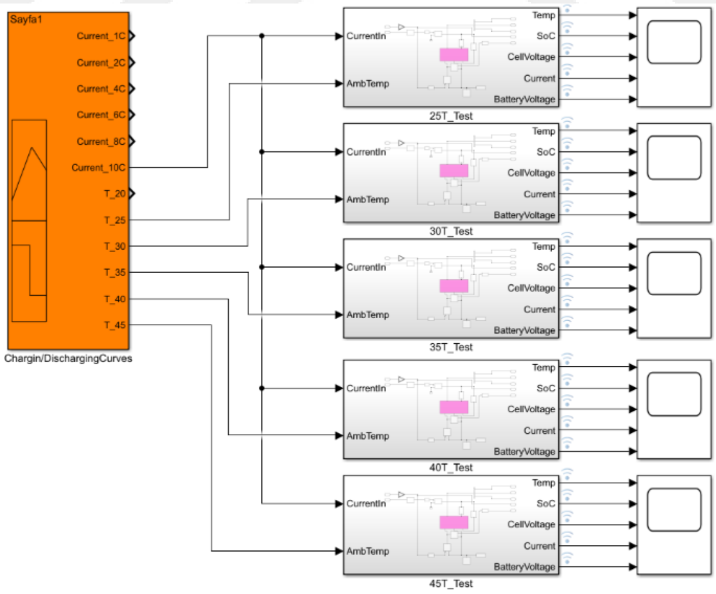

Figure III.7. Cell simulation model at different temperatures.

Cell model was charged and discharged for four different current values and outputs were obtained.

Cell charging curves

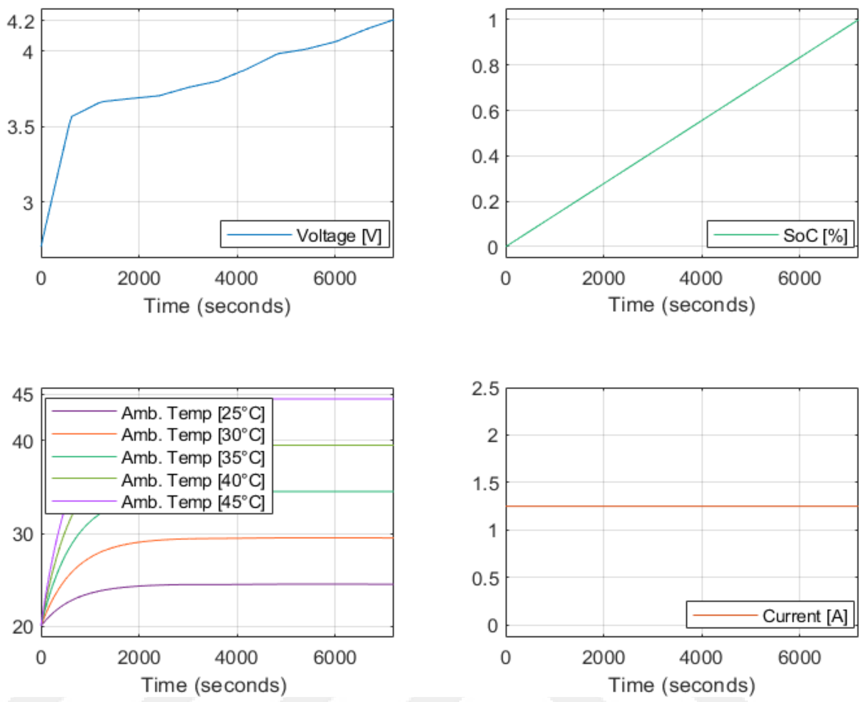

Figure III.8. Simulation result of 1.25A single cell charge.

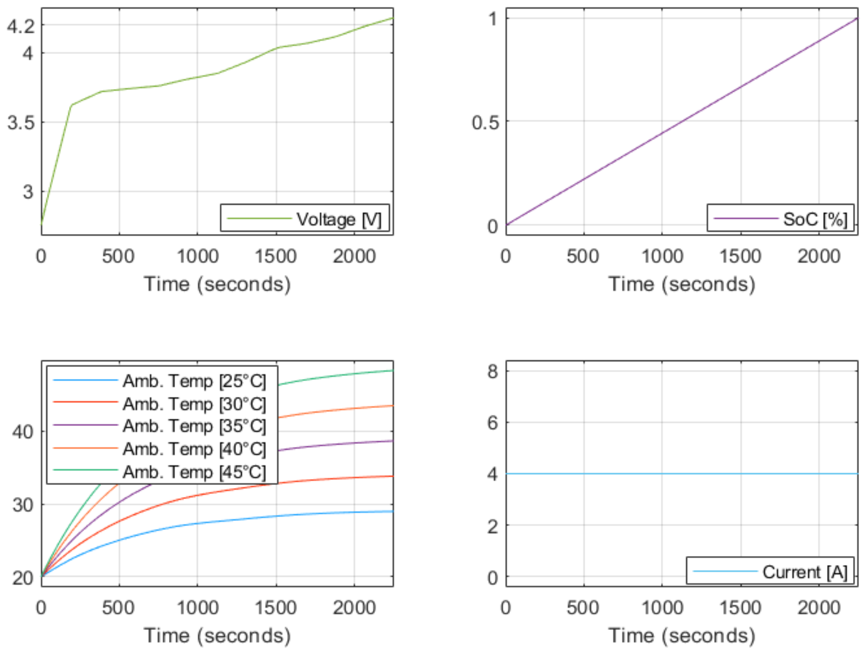

Figure III.9. Simulation result of 4A single cell charge.

Cell discharging curves

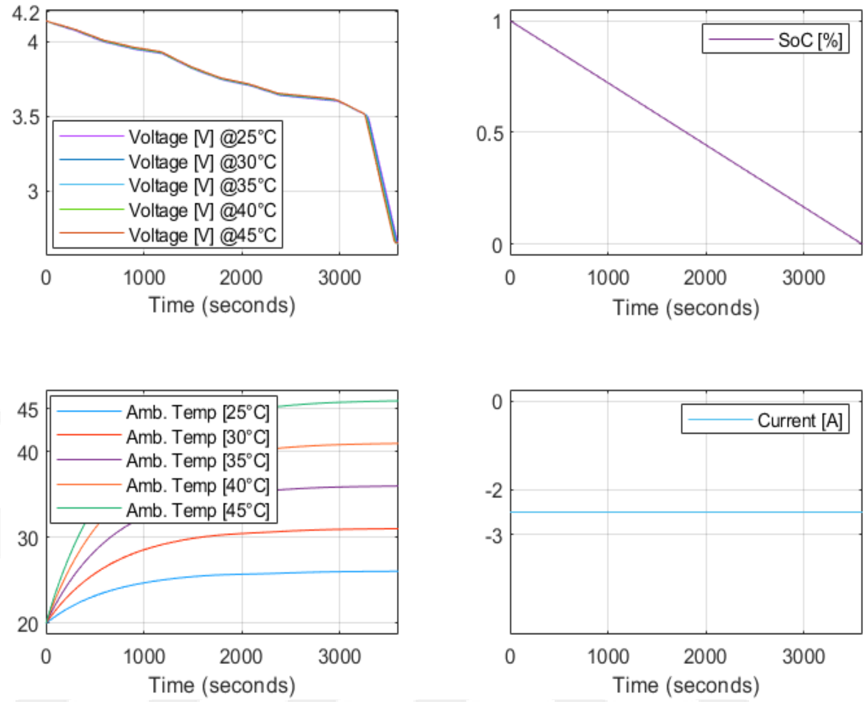

Figure III.10. Simulation result of 1C single cell discharge.

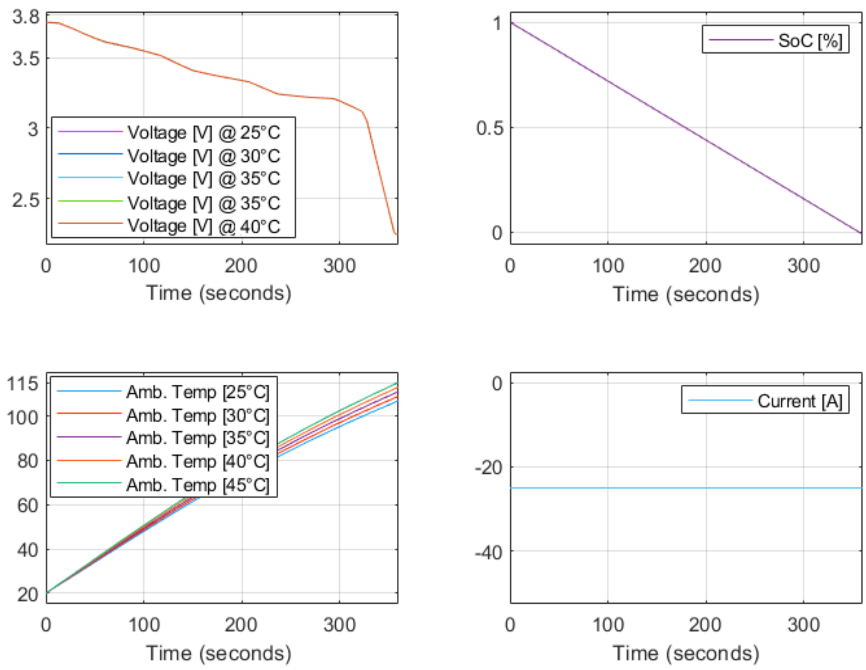

Figure III.11. Simulation result of 10C single cell discharge.

1.25A and 4A charge graphs are given in Figure III.8 and III.9. Cell was tested at normal and fast charge current values in cell specification document and cell temperature was analysed under different ambient temperature. Cell temperature reached maximum 49 ºC.

3.1.2. Simulation of the Battery Pack

In this thesis, modelling studies were conducted with 10S 3P battery package. Figure III.12 shows cell connection structure in battery package. Battery package with 4.2V maximum cell voltage had total of 42V maximum voltage. Total capacity of battery package configured as 3P was 7.5Ah.

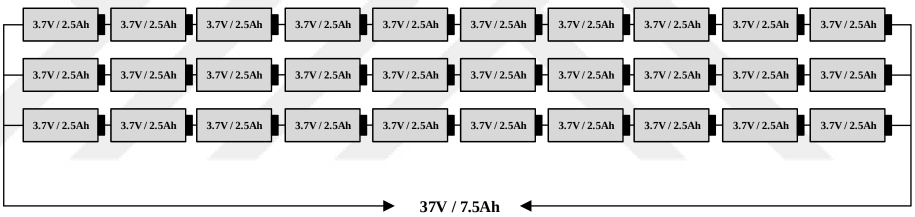

Figure III.12. Series and parallel connection of battery pack.

Cell simulation adopted in single cell model was modelled in battery package configuration and different current charge/discharge graphs are presented below. Figure III.13 presents 10S 3P model configuration.

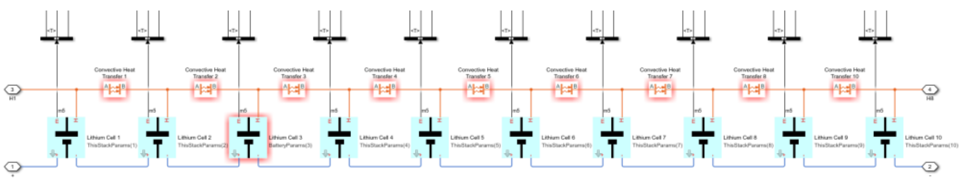

Figure III.13. 10S 3P battery pack connection.

Different temperature levels in single cell model were applied in 10S 3P configuration model and outputs were obtained.

Pack charging curves

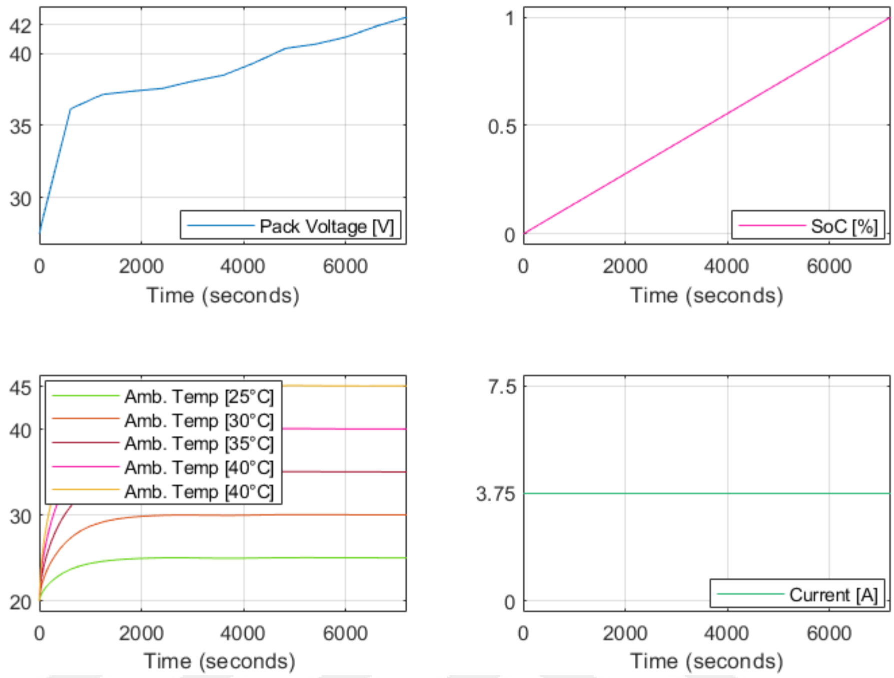

Figure III.14. Simulation result of 3.75A 10S 3P cells charge.

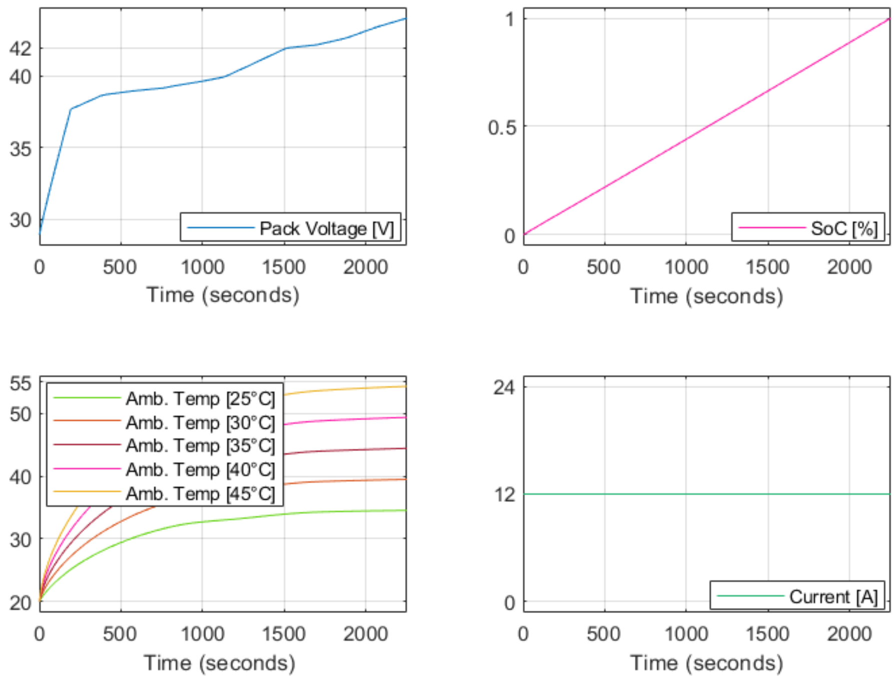

Figure III.15. Simulation result of 12A 10S 3P cells charge.

Pack discharging curves

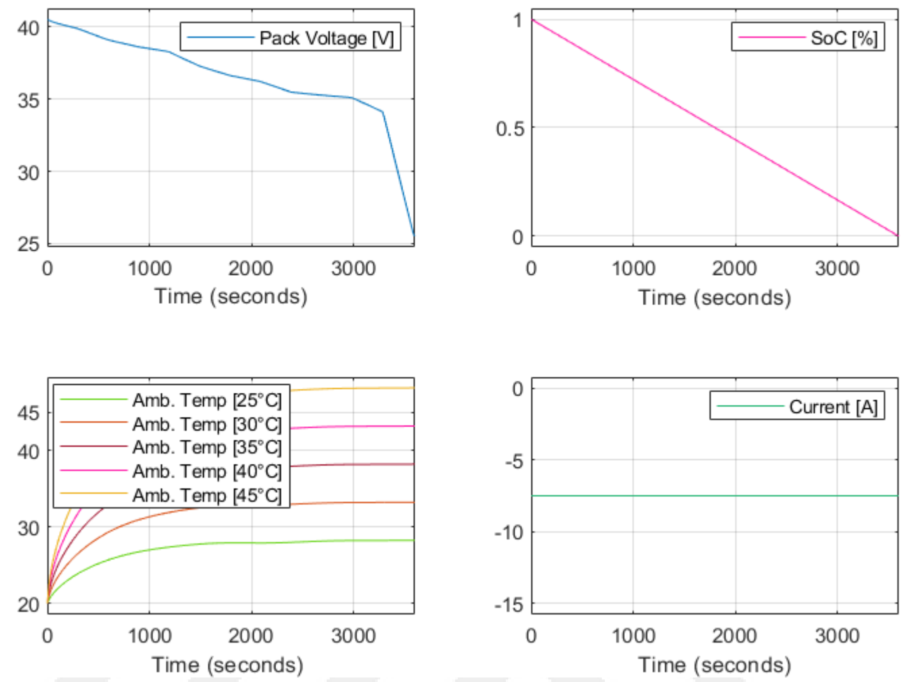

Figure III.16. Simulation result of 1C 10S 3P cells discharge.

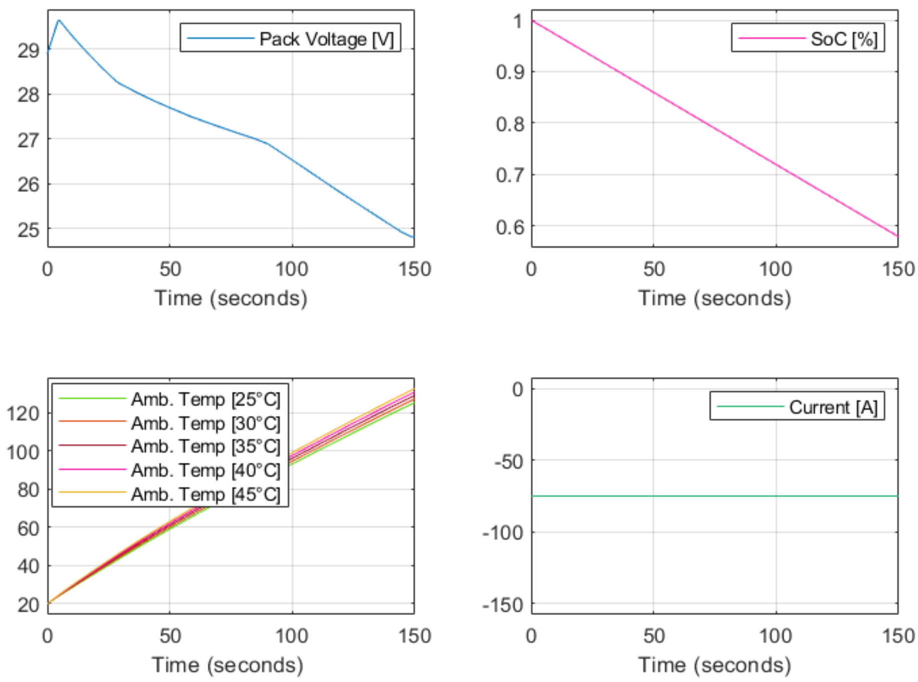

Figure III.17. Simulation result of 10C 10S 3P cells discharge.

Charge and discharge currents of battery packages that change instantly were evaluated after conducting simulations for different ambient temperature.

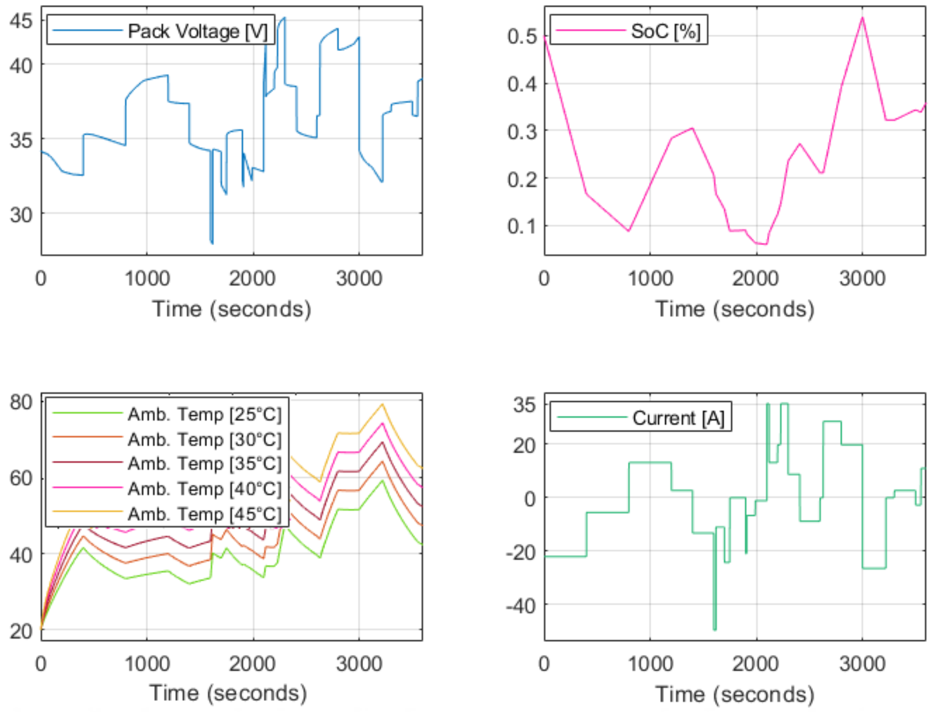

Figure III.18. Simulation outputs at different currents.

A current profile is applied to the simulation model shown in Figure III.18, which instantly is set to reach 35A level at maximum and minimum. When time-based average of current profile was calculated, total 1.14Ah capacity was measured.

The 50% SoC was selected as a simulation initial parameter and simulations were conducted accordingly. When battery capacity was 7.5Ah, 50% SoC value represents 3.75Ah usable capacity value. Average 1.14A current profile corresponds to with 1-hour consumption. This means 15.2% SoC capacity decrease on average. When total consumed energy was considered, it is expected that battery package will reach 34.8% SoC value at the end of simulation. When simulation result in Figure III.18 was analysed, it can be seen that simulation that started at 50% SoC was around 35% after 1-hour charge and discharge. It was observed that this simulation model presented correct results for different current values.

3.1.3. Simulation of the Balancing Circuit

In this thesis study, passive balancing circuit model was adopted for simulation studies. After completing battery package simulation studies, balance circuit model for 10 serial cells were established and presented in Figure III.19.

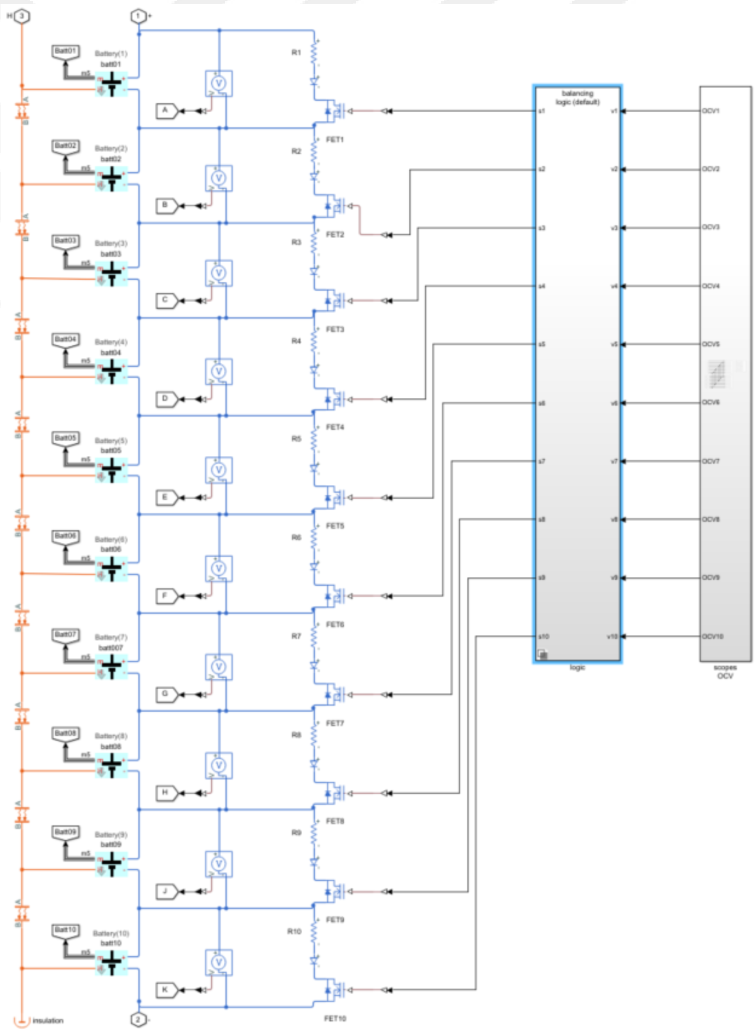

Figure III.19. 10 cells series connection balancing model.

To run balance algorithm, constant current/constant voltage was applied, and cell balancing is achieved by charging the battery package until maximum voltage. When battery package reaches maximum package voltage, package will transfer to constant voltage mode and excessive charging is prevented. Figure III.20 has constant current/constant voltage charge model.

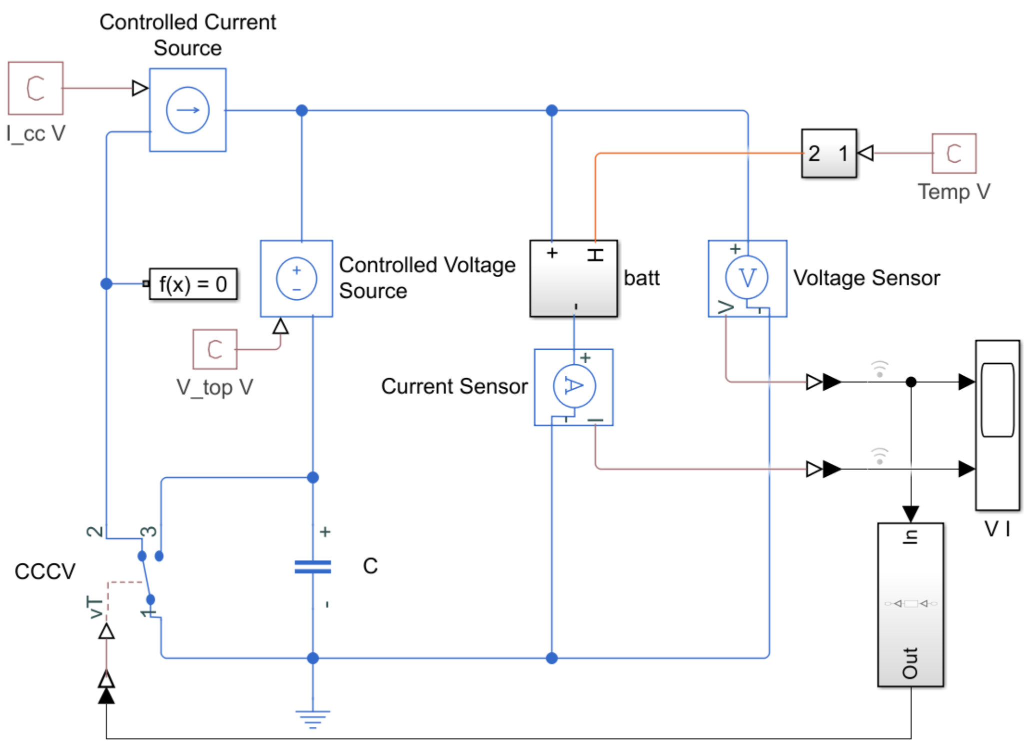

Figure III.20. Charging and discharging model (CC-CV).

In cell balancing algorithm, average voltage of all cells in each cycle are considered and MOSFET is implemented to bring delta voltage difference of all cells to average voltage. Balancing algorithm was formed with Simulink state-flow blocks. Voltage of each cell is applied as input to each state-flow block and control signals of MOSFETs that control parallel balance resistance of each cell. Figure III.21 has state flow block.

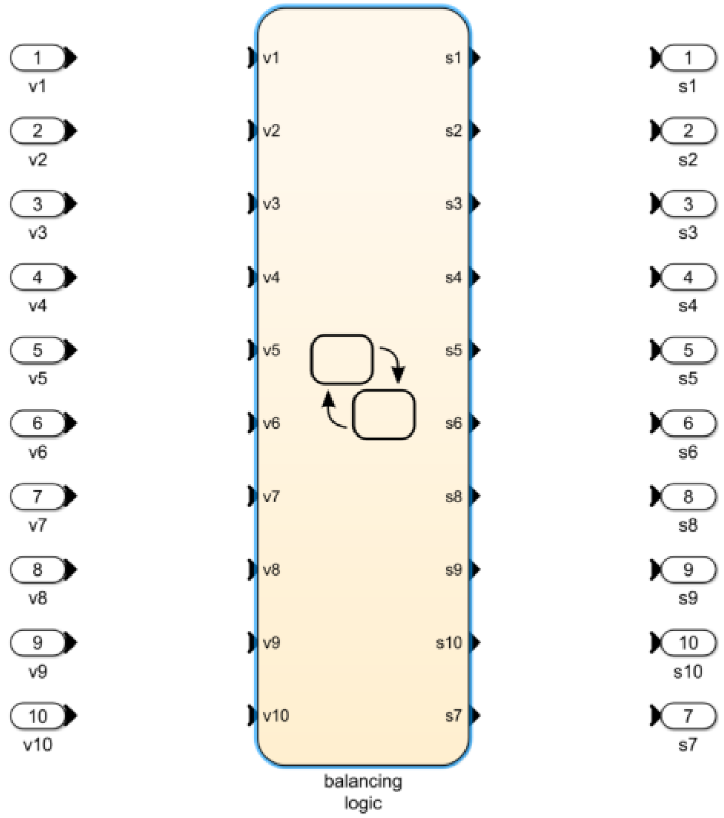

Figure III.21. Simulink state–flow.

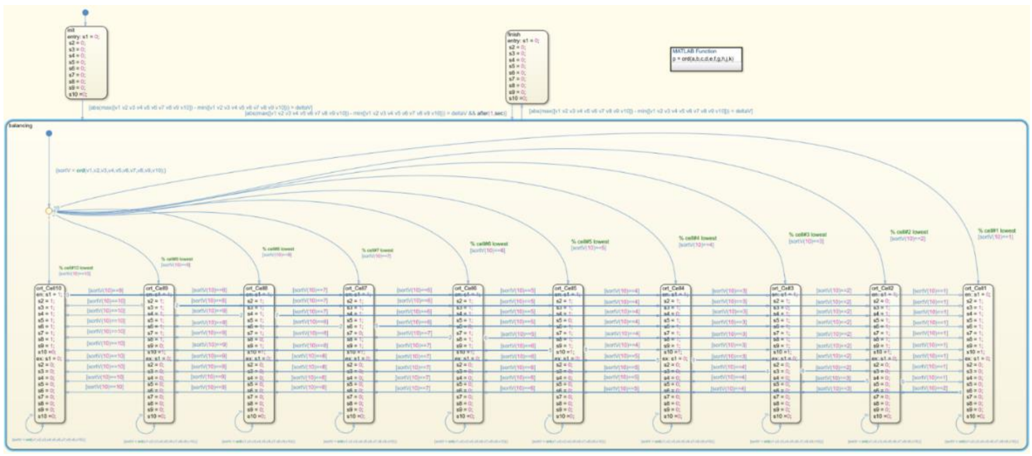

Figure III.22. State–flow diagram.

Cell balancing simulation model was tested for different charge current and system performance was evaluated.

Table III.3. Initial SoC for balancing simulation.

Cell ID	Initial SoC [%] (2A Test)	Initial SoC [%] (4A Test)	Initial SoC [%] (8A Test)
Cell#1	86.07	73.13	58.69
Cell#2	85.97	73.02	58.32
Cell#3	85.77	71.80	57.67
Cell#4	85.67	71.40	55.00
Cell#5	85.27	71.37	51.31
Cell#6	84.87	71.13	51.31
Cell#7	84.07	69.80	51.28
Cell#8	83.13	69.00	50.29
Cell#9	82.27	68.13	50.01
Cell#10	81.20	66.93	46.92

Measurement block was developed to monitor SoC, current and temperature parameters in simulation model.

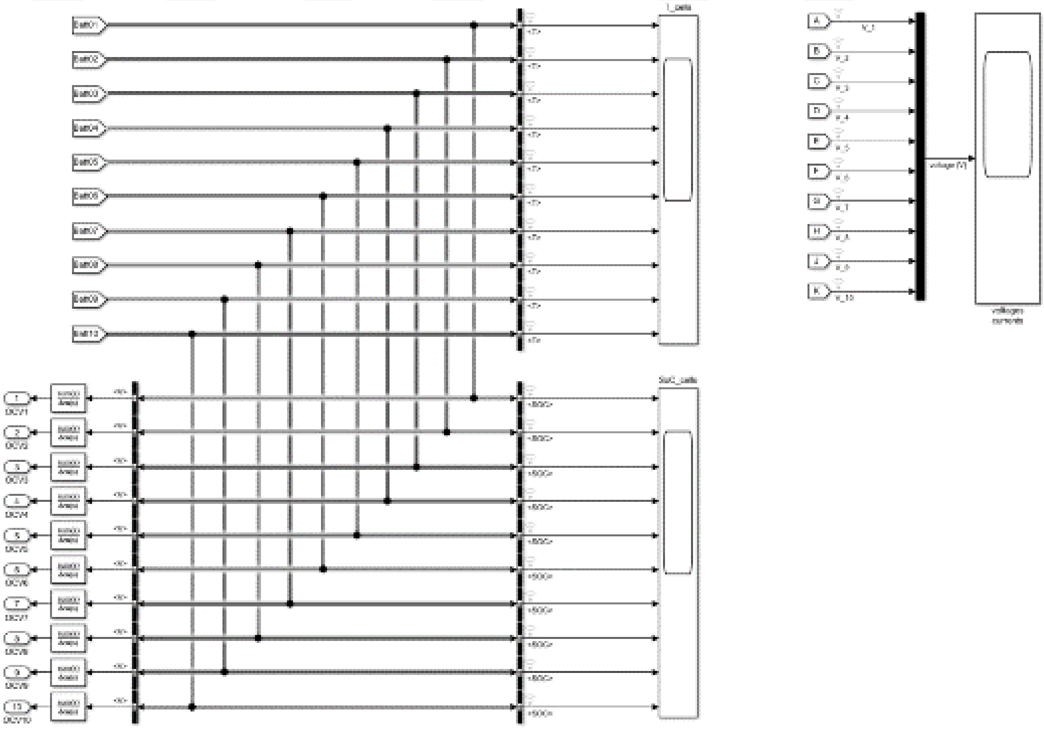

Figure III.23. Measurement block.

Test#1;

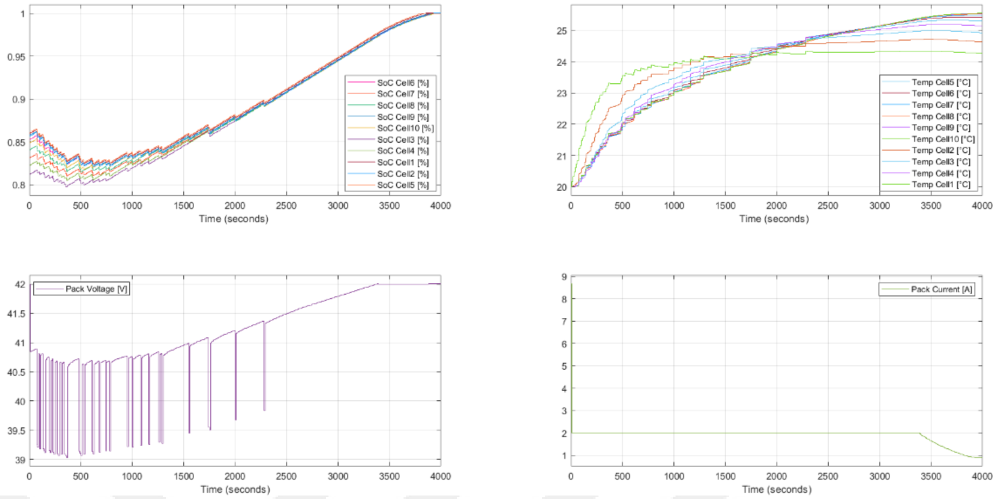

Figure III.24. Balancing test (2A charge current).

Test#2;

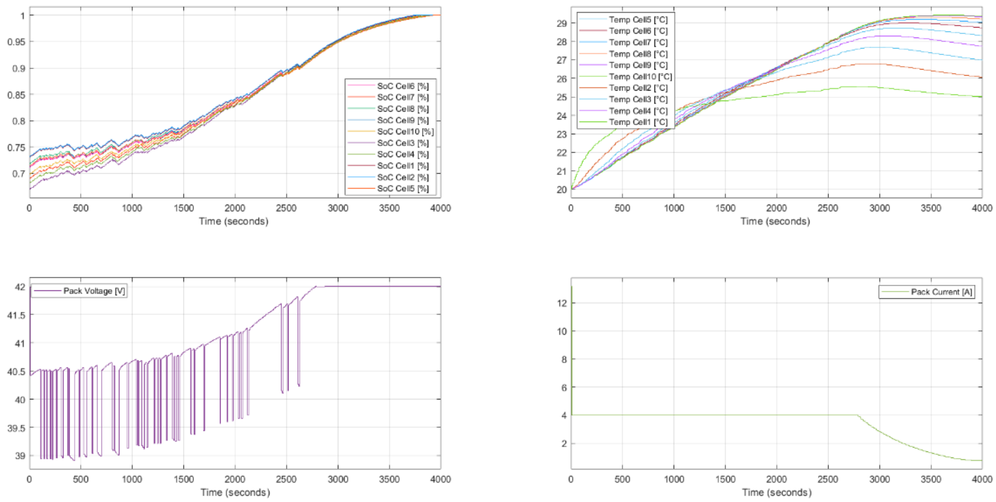

Figure III.25. Balancing test (4A charge current).

Test#3;

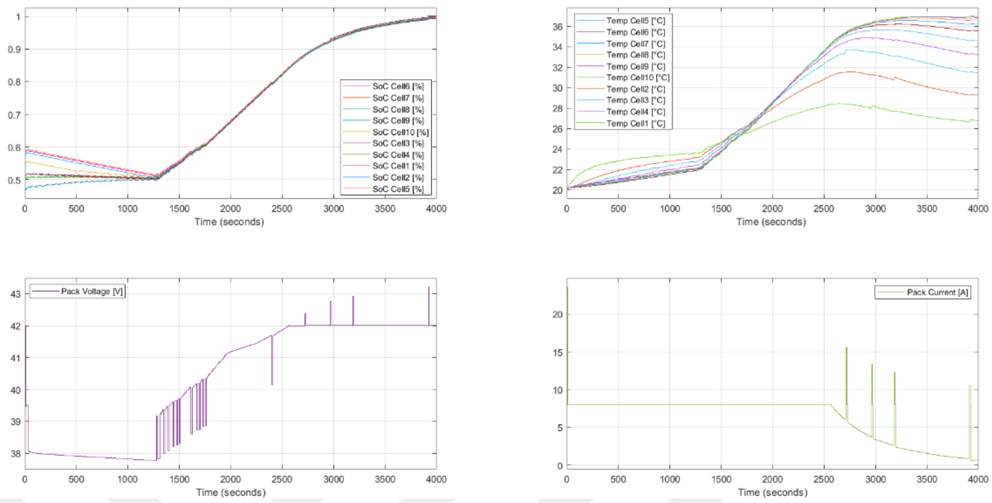

Figure III.26. Balancing test (8A charge current).

When simulation results were analysed:

Under Test#1, battery package was balanced at 2300s at 2A initial SoC charge current as given in Table III.3.

Under Test#2, battery package was balanced at 2700s at 4A initial SoC charge current as given in Table III.3.

Under Test#2, battery package was balanced at 1300s at 8A initial SoC charge current as given in Table III.3.

As a result of improvements in the cell balancing algorithm, the optimum balancing process can be determined and the energy consumption can be minimized during balancing.

3.2. Design of the Battery Management System

Power level of battery package was selected as nominal 37V/7500mAh in light electric vehicles. This power level was suitable for electric bicycles, electric motorcycles and hybrid electrical vehicles.

To shape battery package power level based on needs, design was separated into two sections. First section is considered as slave control card that has the capacity to monitor and conduct necessary operations for each battery cell. Second section is considered to communicate on related communication ports with external units and to conduct necessary management operations by communicating with all slave control cards.

With this target method, number of slave control cards will be increased and a battery package control at desired power level can be added. Since serial communication method will be applied for slave control cards, this number can be increased as desired.

Altium Designer PCB design program was used for hardware design. Special design requirements for 10S 3P configuration were set, schematic drawings were created and protype was produced after PCB design. Figure III.27 and III.28 presents master and slave board block schemes.

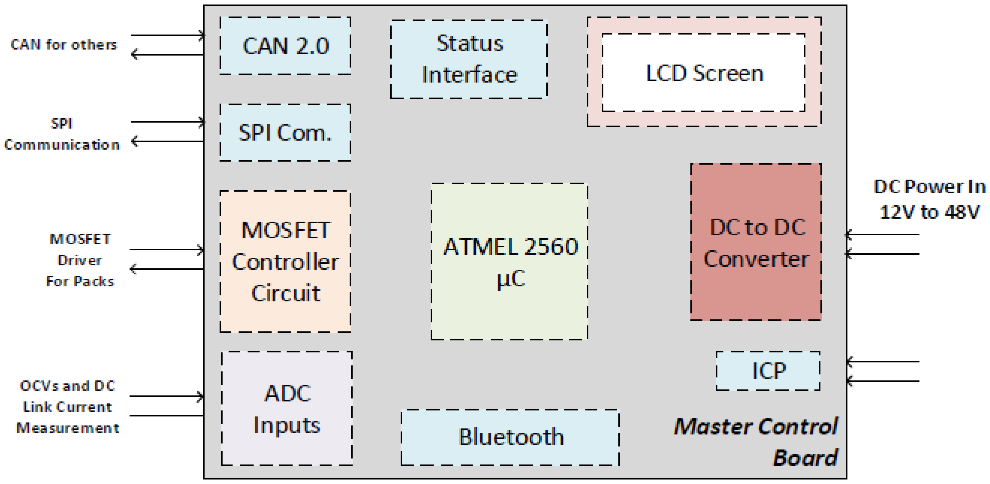

Figure III.27. Master board block schema.

Main control card has control signal input to communicate with slave control card. This way, communication with desired number of slave control card can be achieved. Additionally, on main control card, there is power electronic control block to separate each serial battery cell group from main system for a new method. This way, while system continues operations, malfunctioned serial group can be separated from main line where necessary control operations and open – end voltage can be separately detected. With this control method, battery package charge status can be calculated with high accuracy.

Additionally, on main control card, there is CAN communication port that is suitable for automotive standards. This way, battery package can communicate with management system inside the vehicle and ensure information transfer. For other usage areas, Bluetooth module can be added on control card and battery package status can be monitored online with a software that is developed on a mobile device. Additionally, battery package charge, discharge, excessive temperature etc. status limits can be changed over mobile device.

Master Control Board Hardware Features;

- ATMEL 2560 microcontroller
- ICP Programmer
- 1x CAN 2.0 Communication
- 1x SPI Communication
- 1x LCD Screen for battery pack information
- MOSFET Driver for 10 cell pack DC link connection
- Analog inputs for OCVs and DC link current
- LED status interface for emergency state
- Bluetooth connection for mobile devices (optional)

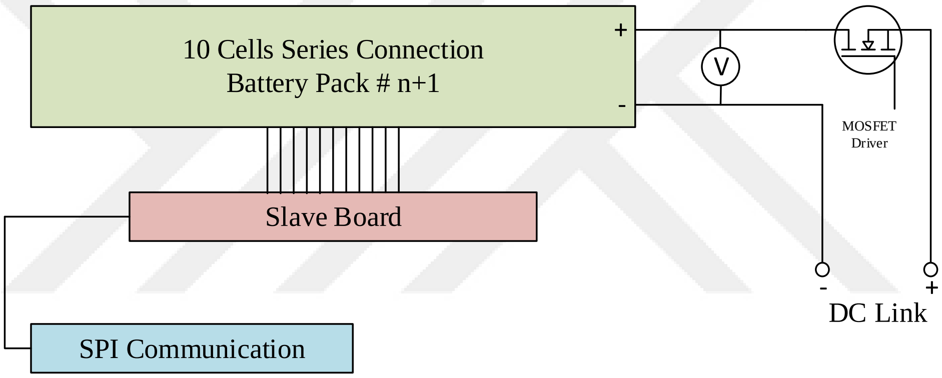

Figure III.28. Slave board block schema.

Processors that can monitor and control battery cells are provided by various electronic component manufacturers. Products of Texas, Atmel, Analog Devices, Intersil and Microchip firms were analysed and processor for target system was selected from ATMEL.

ATA6870N processor can simultaneously control 6 battery cells. 2 x ATA6870N were used in slave control cards and 12 battery cells can be controlled on same card. Each slave card communicates with each other and with main control card over SPI port and transmit necessary control signals. Additionally, with 4 temperature sensors on slave control card, 12 battery cells can be positioned to adequate places and temperatures of these cells can be monitored. To balance battery cells on slave control card, balancing can be conducted separately by using semi-conducted connected to each cell battery.

Slave Board Hardware Features;

- 12-bit cell voltage measurement
- Cell temperature measurement
- Charge balancing capability
- Integrated power supply for MCU
- Low cell imbalance current (< 10μA)
- Auto assignment ID capable
- Hardware interrupt for MCU wake-ups
- Each slave board monitors 10 battery cells
- No limit on number of strings
- Undervoltage detection
- Overvoltage detection

3.2.1. Design of the Master Control Board

Sematic design was completed based on battery management system requirements. Electronic components are selected for operating functions of the system and designs were implemented based on reference documents of related components. Details were given as blocks respectively.

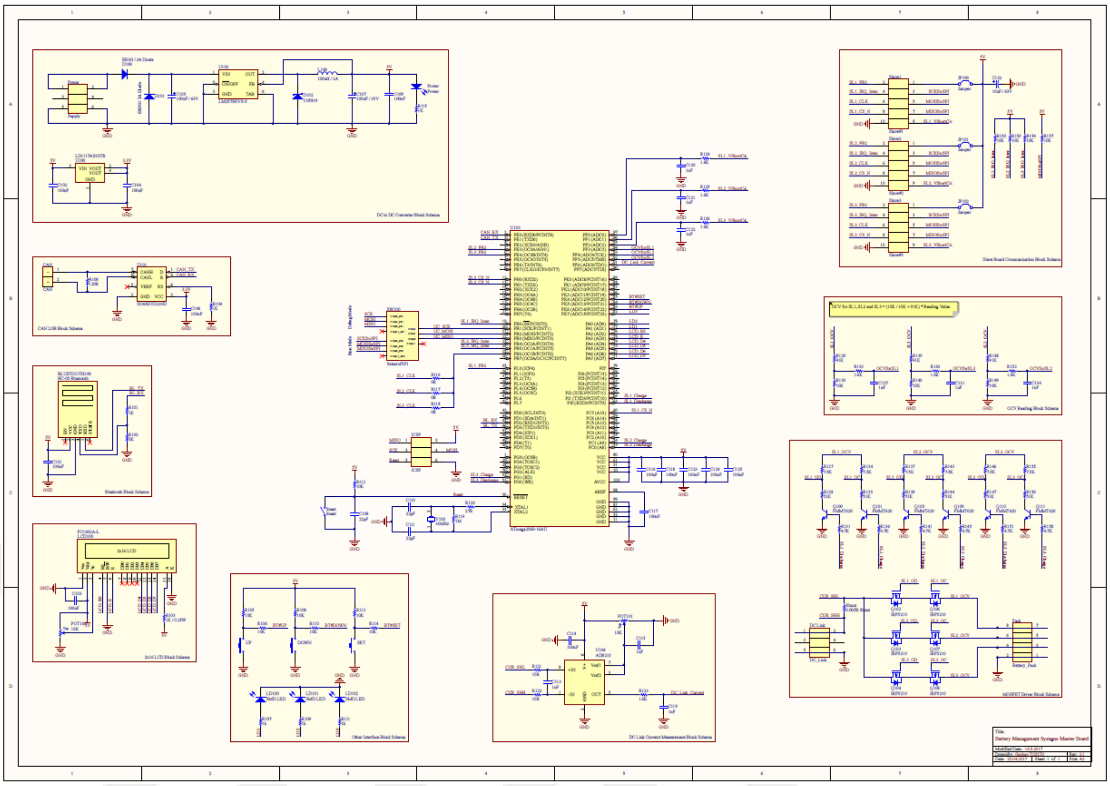

Figure III.29. Schematic design of master board.

- **Main Control Block Design**

To convert developed algorithms to control signals, 8-bit ATmega2560-16AU coded main control processor of ATMEL was selected.

ATmega2560-16AU Features;

- High performance, 8-bit microcontroller
- Advanced RISC architecture
- High endurance non-volatile memory segments
- JTAG Interface, peripheral features
- Special microcontroller features
- I/O and packages: 54/86 programmable I/O lines
- Temperature range: -40°C to 85°C industrial
- ATmega2560V: 0 - 8MHz @ 2.7V - 5.5V

Based on technical document of the processor, supply voltages were created and 16MHz crystals were used. Low – pass filter design for related input and output ports were completed and precautions to prevent noise disturbance was taken.

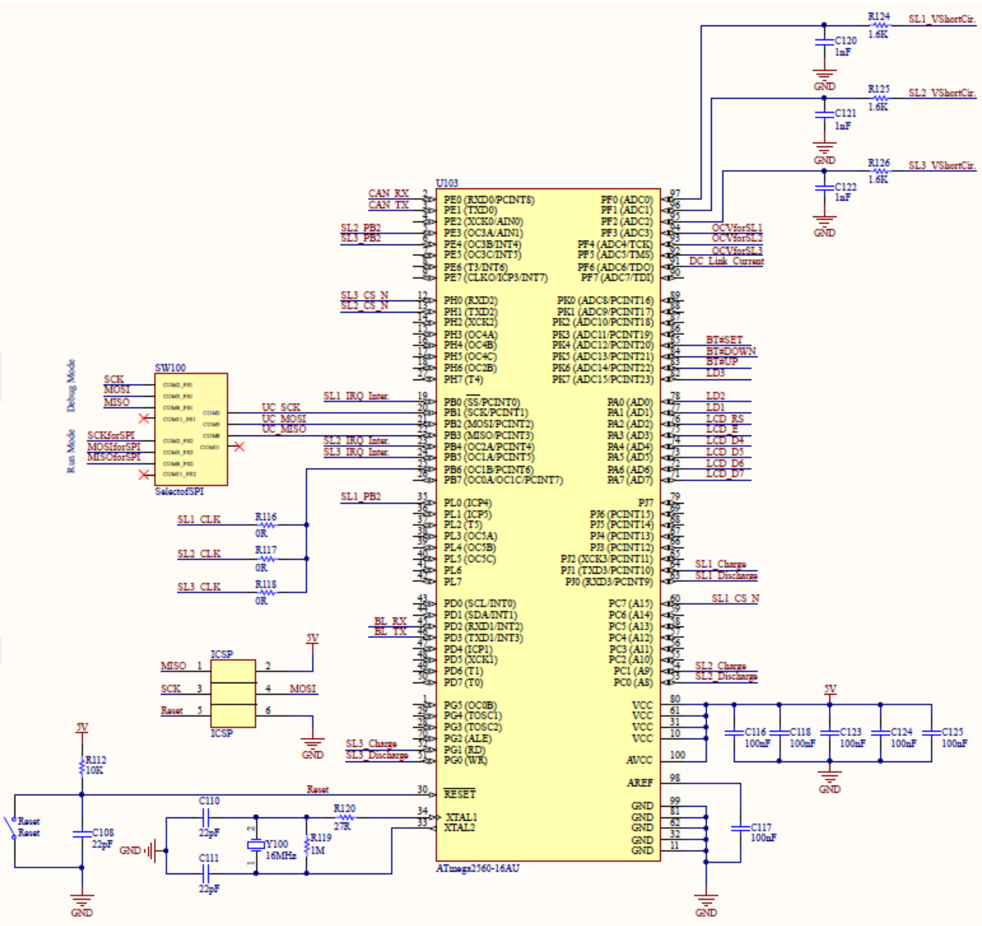

Figure III.30. ATmega2560-16AU main control schematic.

- **DC-DC Converter Block Design**

To create 5V voltage level required by the system, LM2575 Step-Down Switching Regulator of ON SEMICONDUCTOR was used. Passive components in the design were selected based on LM2575 reference design document.

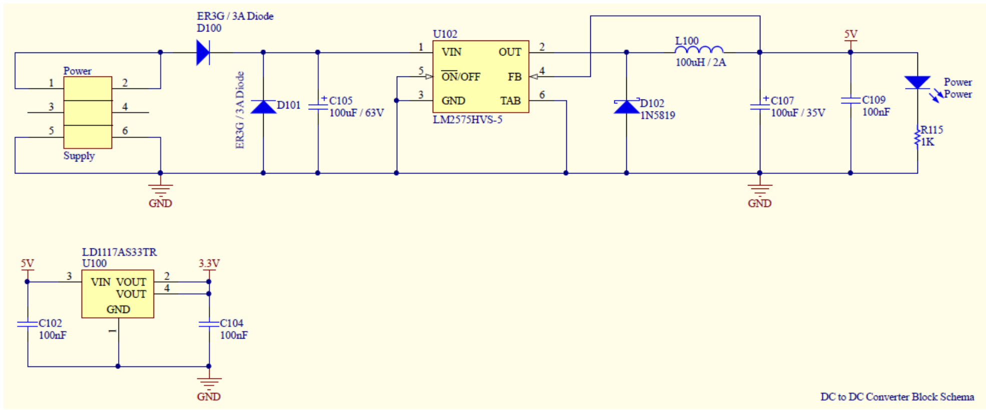

Figure III.31. DC-DC converter schematic.

- **CAN Communication Block Design**

CAN 2.0 communication protocol was applied to communicate related control signals and notification message of master control unit. UART communication hardware of main control processor was used to convert to CAN protocol with SN65HVD230D.

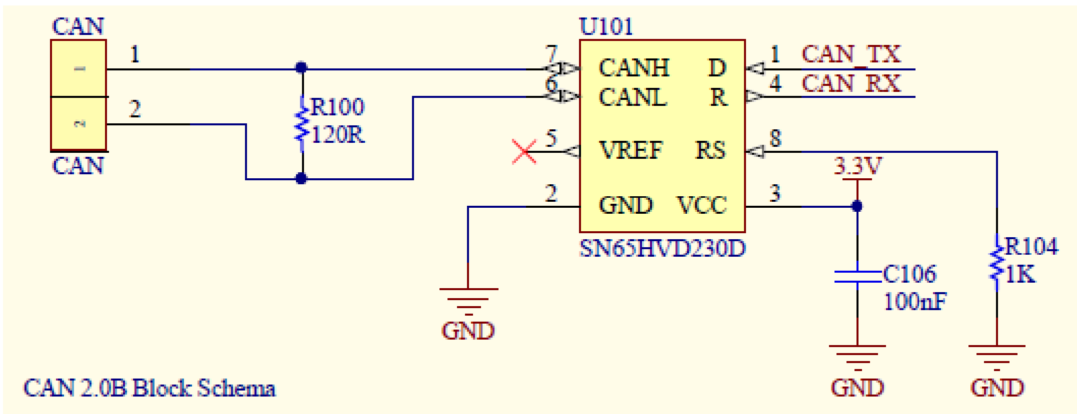

Figure III.32. CAN communication block schematic

- **Bluetooth Module and LCD Block Design**

In this thesis, optional communication protocol and LCD design was applied for users to monitor notifications on mobile device.

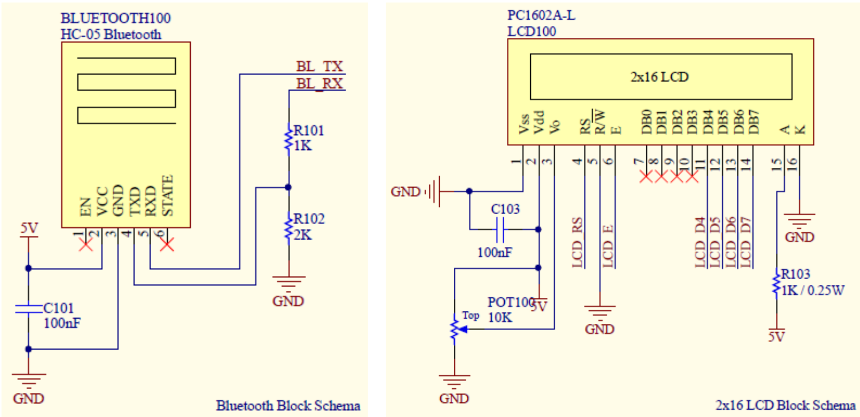

Figure III.33. Bluetooth module and LCD block schematic.

- **Other Interface Block Design**

3 button and LED design were added to adjust related parameters on master control unit and notification.

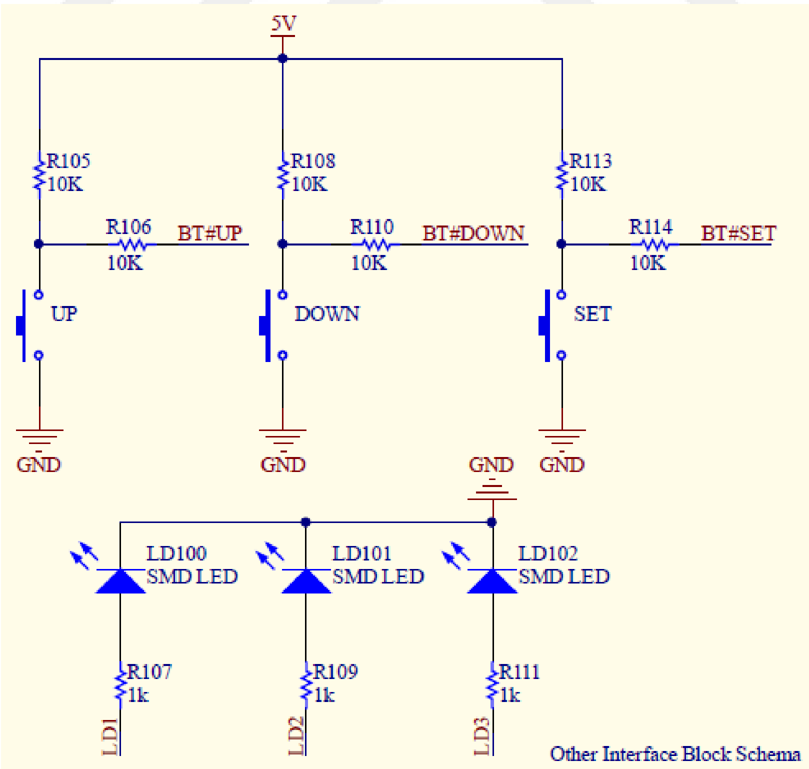

Figure III.34. Interface block schematic.

- **Current Measurement Block Design**

To measure main line current of battery package, AD8210 high voltage bidirectional current shunt monitoring IC of ANALOG DEVICES firm was used. Measured voltage over shunt resistor connected to battery package is converted to current data.

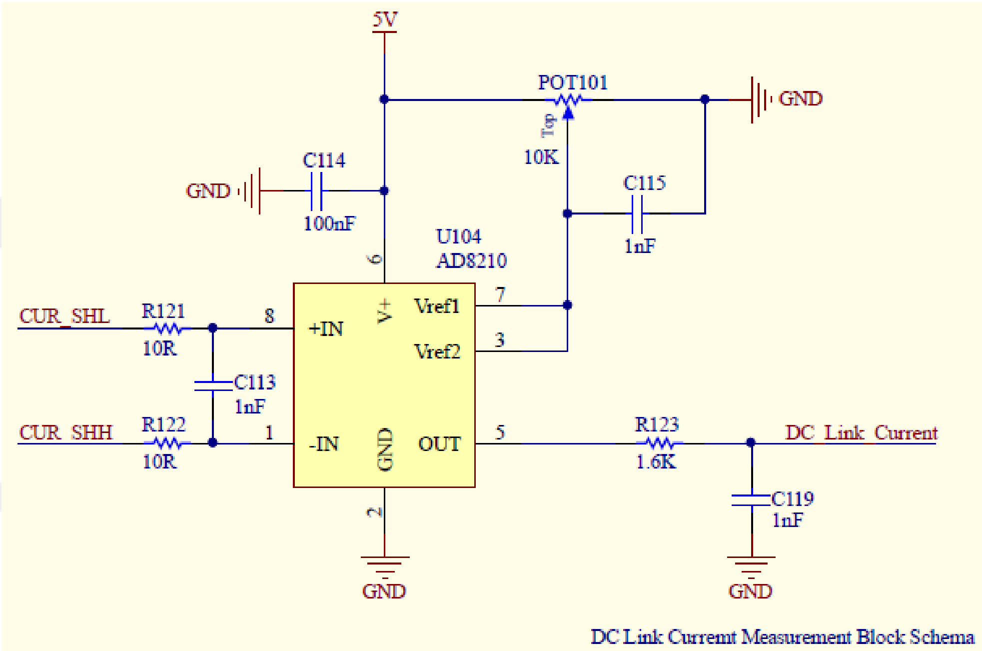

Figure III.35. Current measurement block schematic.

- **MOSFET Driver Block Design**

MOSFET was used to control main line of parallel cells in battery package. To control MOSFET by main control processor, passive components were adopted in driver design.

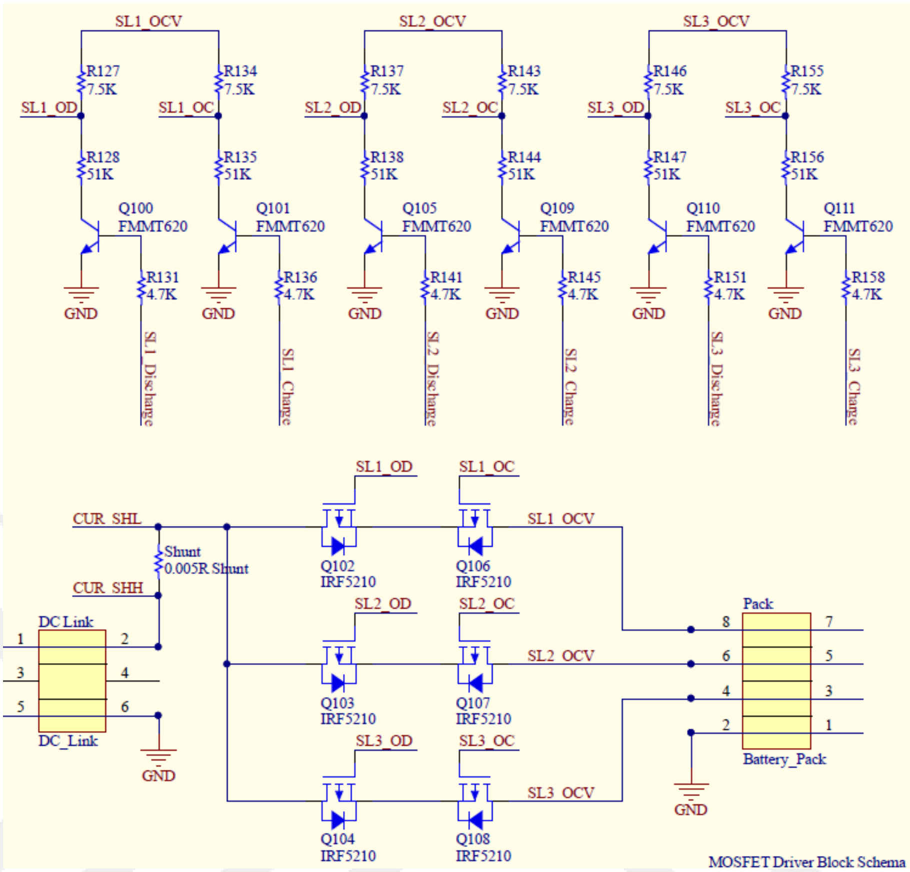

Figure III.36. MOSFET driver block schematic.

- **Open Circuit Voltage Measurement Block Design**

To measure voltage of battery package, voltage divider resistance was used and maximum voltage was designed for 0-5V range.

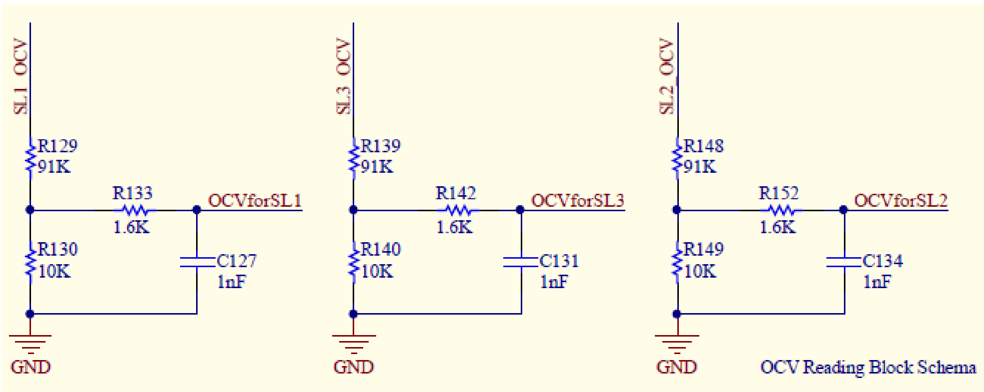

Figure III.37. OCV measurement block schematic.

- **Slave Board Connection Block Design**

To communicate master control unit with slave board, connector design was applied for connection of necessary control signals.

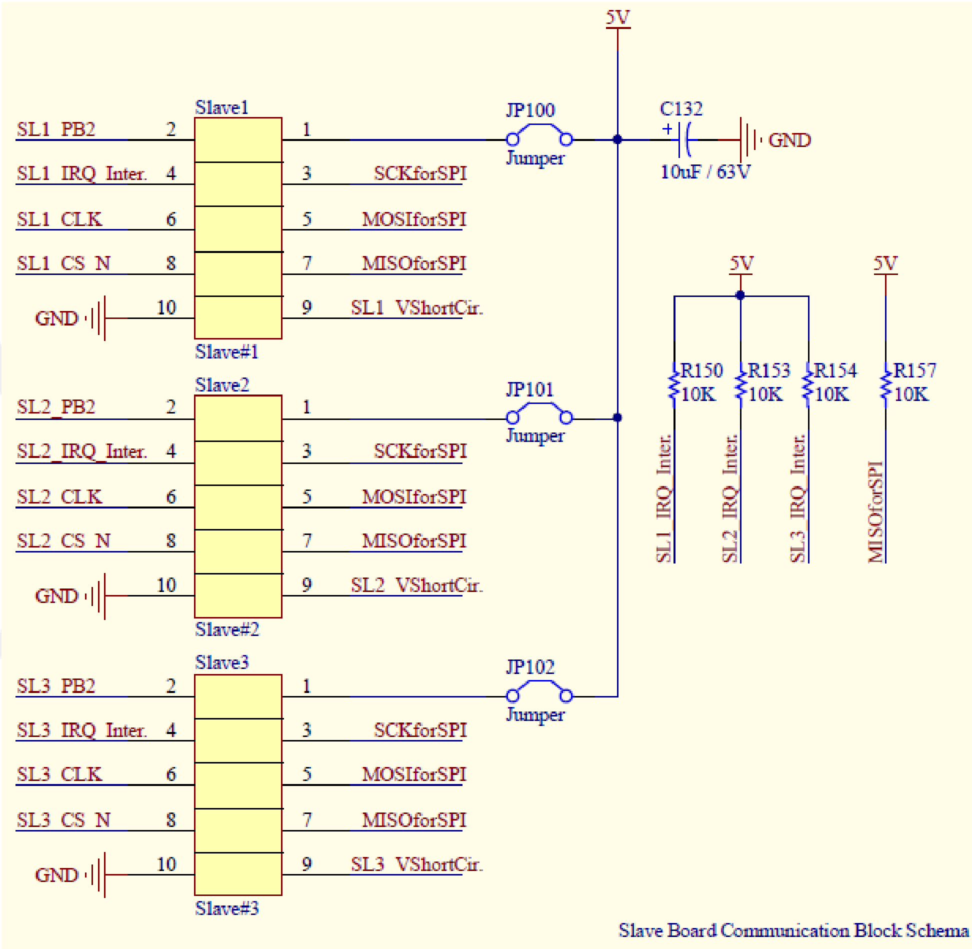

Figure III.38. Slave board connection block schematic.

3.2.2. Design of the Slave Board

To measure cell voltage and temperature, ATA6870 Lithium-ion cell measuring, passive balancing and external power-supply circuit IC's of ATMEL firm was used.

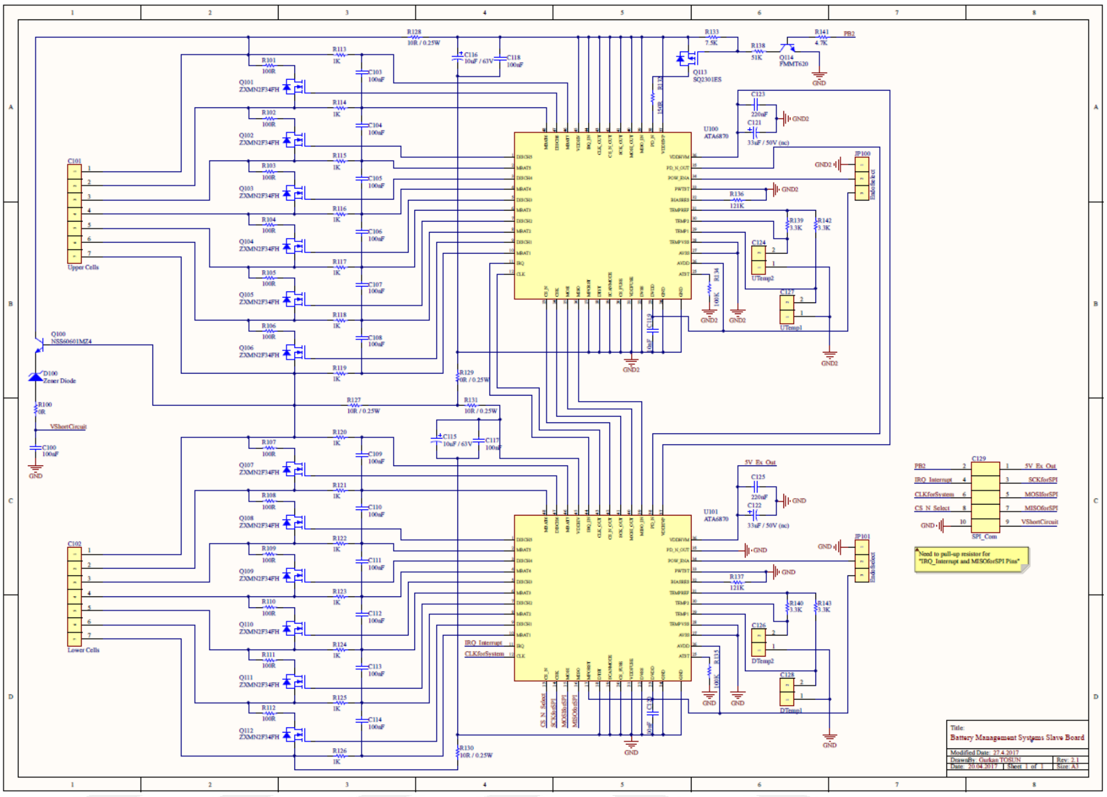

Figure III.39. Slave board block schematic.

ATA6870 Features;

- 12-bit cell voltage measurement
- Simultaneous battery cells measurement in parallel
- Cell temperature measurement and active and passive balancing capability
- Parallel balancing of cells possible
- Integrated power supply for MCU
- Undervoltage detection
- Less than 10µA standby current
- Interrupt timer for cycling MCU wake-ups
- Daisy-chainable
- Each IC monitors up to 6 battery cells
- 16 ICs (96 cells) per string
- No limit on number of strings

2 x ATA6870 were used in each slave board. Voltage of total of 12 cells were measured separately and passive balancing was achieved. Additionally, each slave board has 4 temperature sensor input. Based on cell configuration on battery package, average of temperature sensor information was used. Based on parameters set in control algorithm, balance resistance of related cell was connected and passive balancing was achieved.

3.2.3. PCB Design and Assembly

Altium Designer program was used in PCB design and design consisted of 2 layers. After completing schematic design, appropriate PCB sizes were determined, suitable material placement was completed and connections based on schematic design were made. Materials on master control were placed only on upper layer. Materials were placed on bottom and upper layer on slave board. Transitions between layers were set at appropriate sizes based on current limits. In each PCB design, bottom layer was set as ground and this layer was divided appropriately to distribute heat during operation. PCB images are presented below.

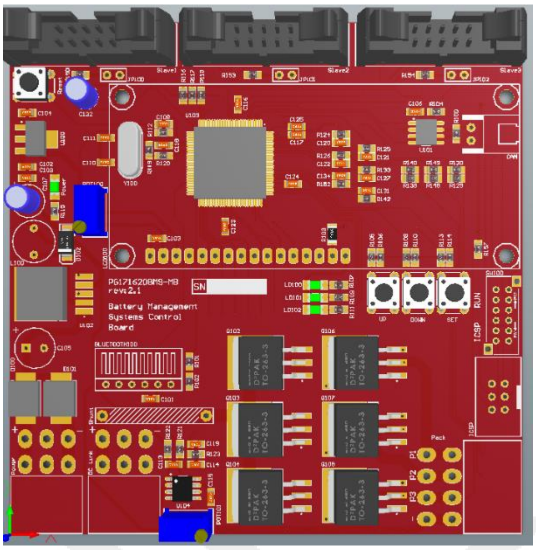

Figure III.40. Master board 3D view.

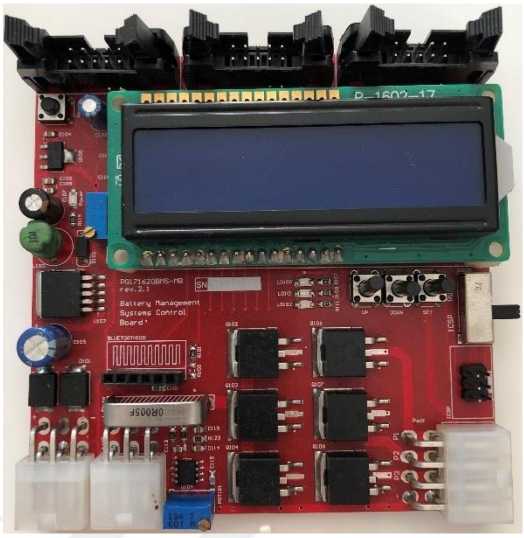

Figure III.41. Master board overall view.

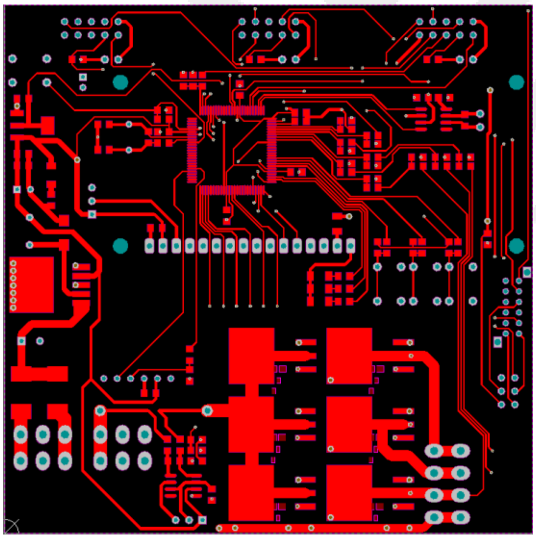

Figure III.42. Master board top layer.

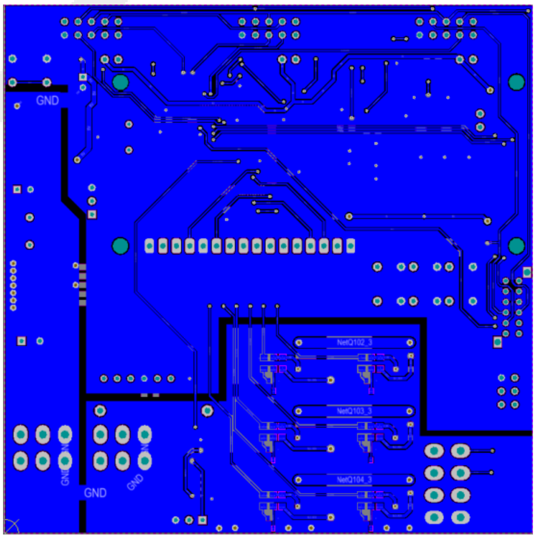

Figure III.43. Master board bottom layer.

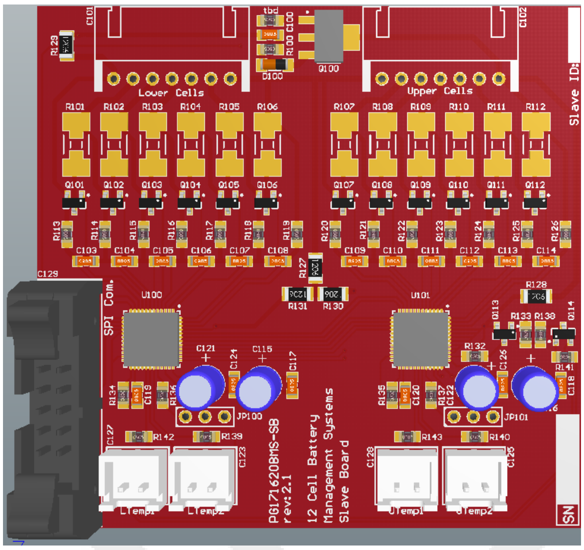

Figure III.44. Slave board 3D view.

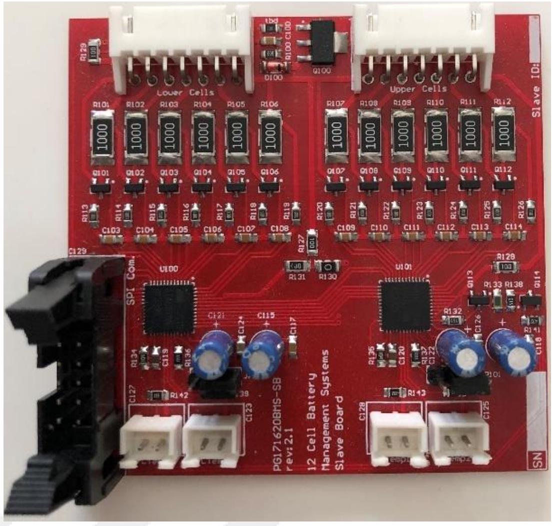

Figure III.45. Slave board overall view.

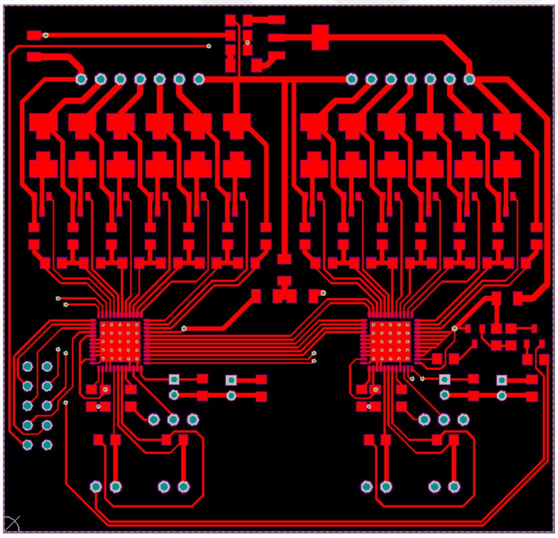

Figure III.46. Slave board top layer.

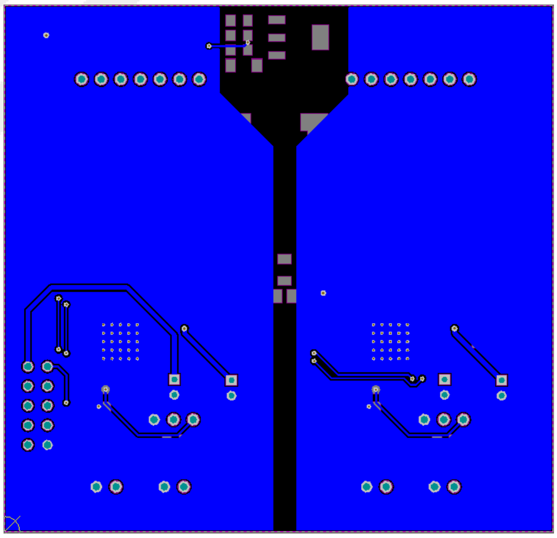

Figure III.47. Slave board bottom layer.

3.3. Implementation and Experimental Performance of BMS

After PCB mounting, functional tests of electronic cards are completed and operation of all input output ports were tested and validated. According to system requirements, tests were setup and functional tests were completed. Test setup details are given in the graph below.

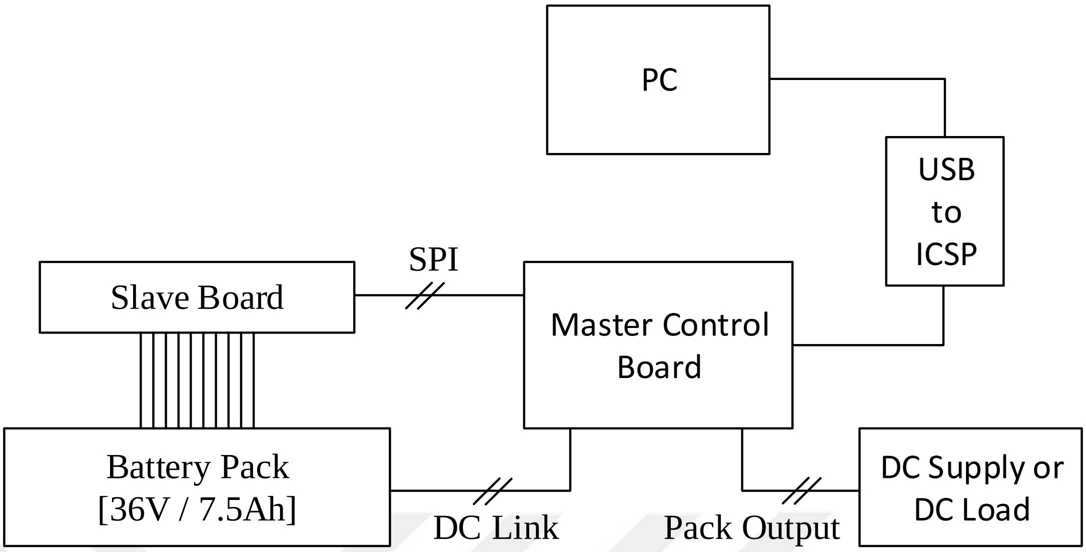

Figure III.48. A schematic of the experimental setup.

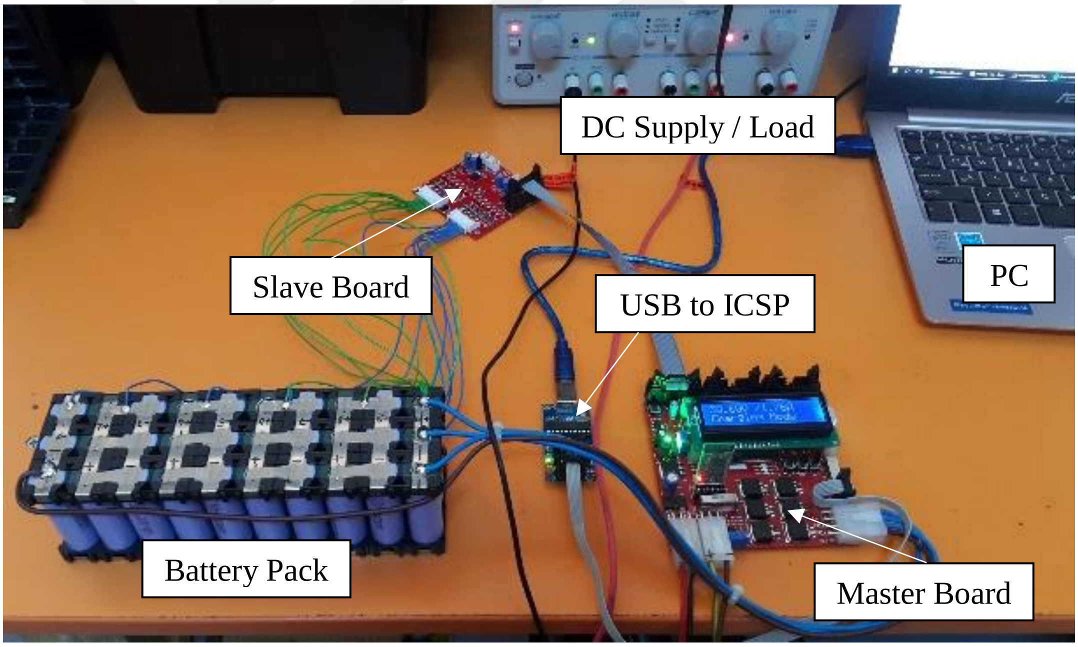

Figure III.49. Experimental test setup.

According to values given in cell technical documents, cell package was charged to 100% SoC value. Afterwards, cells were discharged until cut-off voltage under constant current, cell voltages were measured and capacities were calculated. After keeping battery package at ambient temperature for 3 hours, this package was charged at constant current up to 40V and cell voltages were measured. Cell capacity for each cell were calculated and values are given in the graph below.

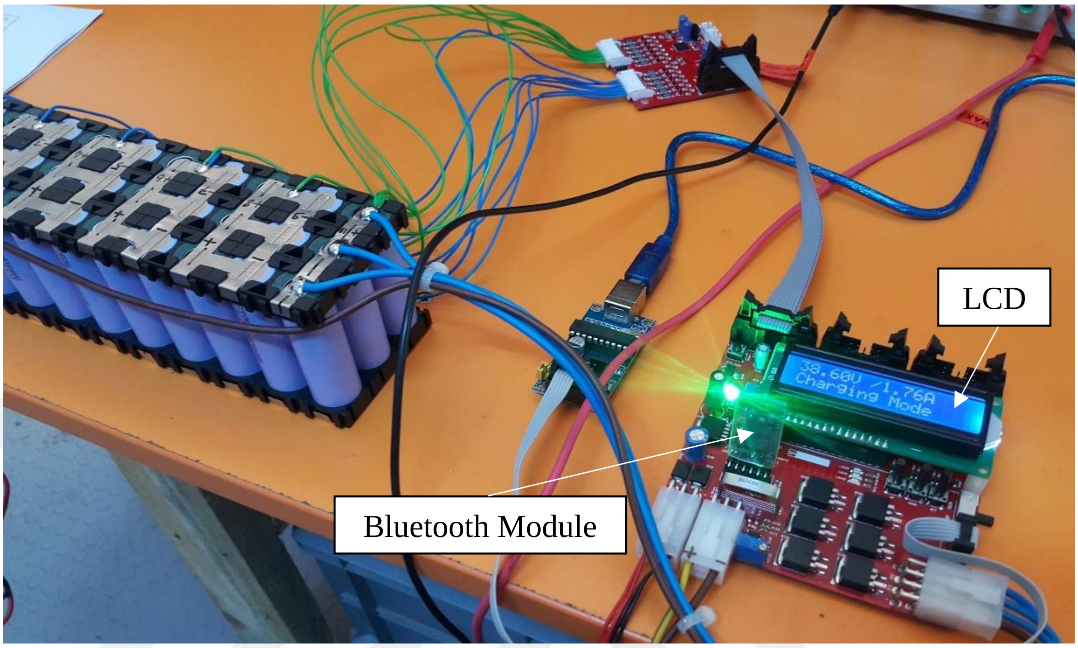

Figure III.50. Experimental test setup with bluetooth module.

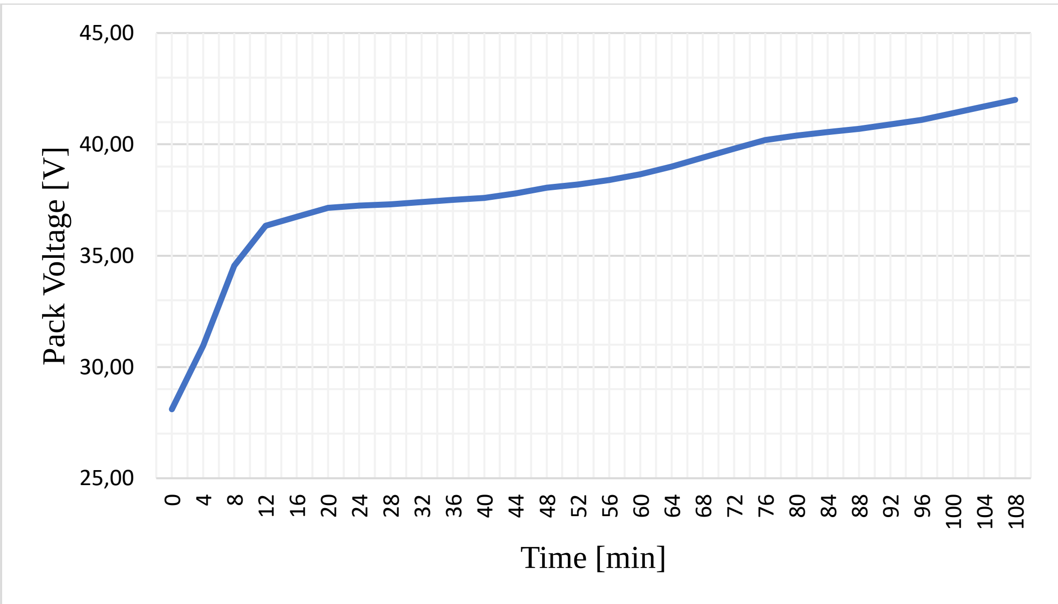

Figure III.51. Pack voltage.

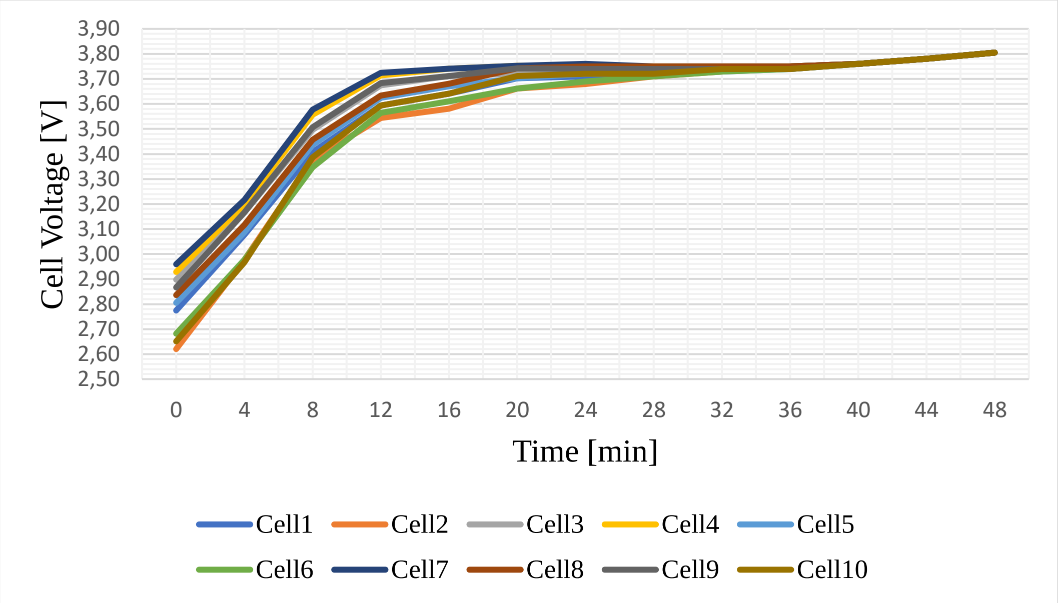

Figure III.52. Cell voltages (10 series cell).

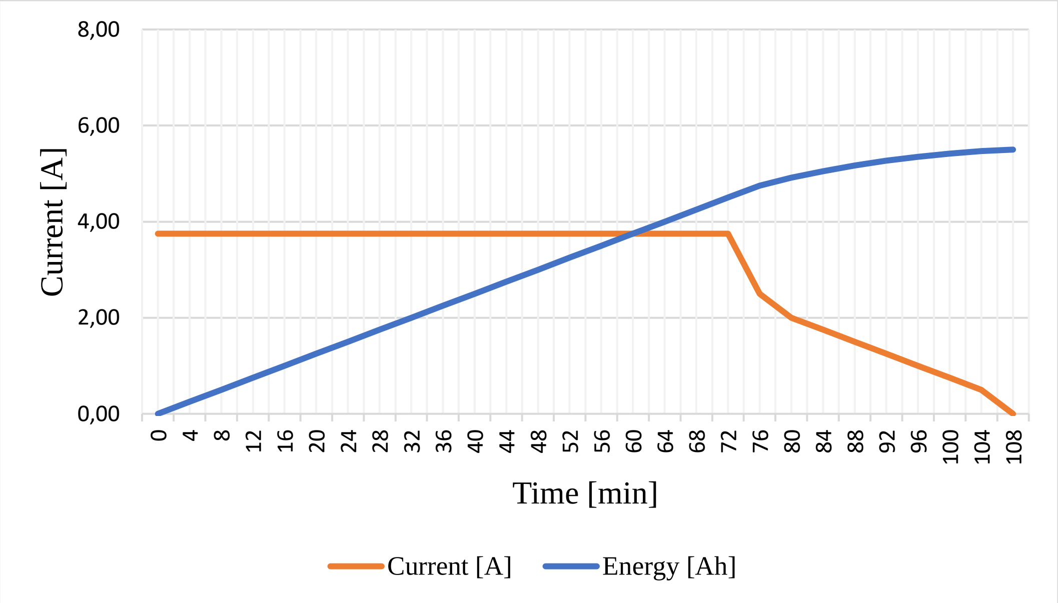

Figure III.53. Charge current and used energy.

IV. CONCLUSIONS AND FUTURE WORK

4.1. Conclusions

Within the scope of this thesis, a literature review on electric vehicles was conducted. Battery types and capacities in electric vehicles were identified and battery management system properties were analyzed. Based on electric vehicle cell types, battery management system requirements were analyzed and information was gathered.

Cell simulation models on electrical vehicles were presented and different simulation models were studied. The Thevenin equivalent circuit is adopted and the parameters necessary for the li-ion type cell were established.

To identify parameters necessary for li-ion type cell modeling, detailed academic research was conducted.

The charge-discharge performances of each cell for different currents were analysed. After that, battery package simulation models were created and analysed. Lastly, a balance simulation model was created for the battery management system. Simulations were run on cells with different initial SoC values and the balance performances were analysed.

In this study, battery management systems with completed design and prototype production were charged-discharged with different currents under laboratory conditions and system performance was analysed. The cell balancing algorithm was formed with Simulink state-flow blocks. The voltage of each cell is applied as input to each state-flow block and control signals of MOSFETs that control parallel balance resistance of each cell. The Cell balancing simulation model was tested for different charge current and system performance was evaluated.

As far as the experimental study of this thesis, İnitially the performance measures of the battery management system was established. Later the Master-Slave type of a battery management system was designed and a laboratory prototype was built. A set of experiments were conducted on 42V battery bank and the performance values were measured. It has shown that this battery management system is properly operating to control the charging and discharging processes of the Li-Ion battery pack.

The experimental results yield that, designed prototype BMS system is functioning adequately to supply, control and protect them.

4.2. Future Work

Developed cell models were built at 1st degree and simulation study was completed. More realistic results can be obtained by creating cell models with more details. The algorithm developed in the battery management system can be developed with different control methods and system performance can be improved. Under experimental studies, tests could be conducted similar to the electrical vehicle battery and accuracy and performance can be analysed.

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