

**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL**

**BATTERY MANAGEMENT SYSTEM DESIGN WITH EMBEDDED  
ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY**



**M.Sc. THESIS**

**Medet Kerem BABACAN**

**Department of Mechatronics Engineering**

**Mechatronics Engineering Programme**

**APRIL 2023**



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**Medet Kerem BABACAN  
(518201019)**

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**Thesis Advisor: Doç. Dr. Osman Kaan EROL**

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**ELEKTROKİMYASAL EMPEDANS SPEKTROSKOPİSİ YÖNTEMİ  
ENTEĞRE EDİLMİŞ BATARYA YÖNETİM SİSTEMİ TASARIMI**

**YÜKSEK LİSANS TEZİ**

**Medet Kerem BABACAN  
(518201019)**

**Mekatronik Mühendisliği Anabilim Dalı**

**Mekatronik Mühendisliği Programı**

**Tez Danışmanı: Doç. Dr. Osman Kaan EROL**

**NİSAN 2023**



Medet Kerem BABACAN, a M.Sc. student of İTÜ Graduate School student ID 518201019, successfully defended the thesis/ entitled “BATTERY MANAGEMENT SYSTEM DESIGN WITH EMBEDDED ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

**Thesis Advisor :**     **Assoc. Prof. Dr. Osman Kaan EROL**     .....  
Istanbul Technical University

**Jury Members :**     **Prof. Dr. Müştak Erhan YALÇIN**     .....  
Istanbul Technical University

**Assoc. Prof. Dr. Atilla ÖZMEN**     .....  
Kadir Has University

**Date of Submission : 27 March 2023**

**Date of Defense : 27 April 2023**





*To my Family,*



## **FOREWORD**

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Medet Kerem BABACAN  
Mechatronics Engineer



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## ABBREVIATIONS

<b>BMS</b>	: Battery Management System
<b>Li-ion</b>	: Lithium Ion Battery
<b>NiMH</b>	: Nickel–Metal Hydride Battery
<b>IOT</b>	: Internet of Things
<b>SOC</b>	: State of Charge
<b>SOH</b>	: State of Health
<b>SOF</b>	: State of Function
<b>OCV</b>	: Open Circuit Voltage
<b>EIS</b>	: Electrochemical Impedance Spectroscopy
<b>AC</b>	: Alternating Current
<b>HPPC</b>	: High Power Pulse Current
<b>XPS</b>	: X-ray Photoelectron Spectroscopy
<b>SEM</b>	: Scanning Electron Microscopy
<b>FRA</b>	: Frequency Response Analyzer
<b>DUT</b>	: Device Under Test
<b>CAN</b>	: Control Area Network
<b>USB</b>	: Universal Serial Bus
<b>IC</b>	: Integrated Circuit
<b>I2C</b>	: Inter Integrated Circuit
<b>CRC</b>	: Cyclic Redundancy Check
<b>DAC</b>	: Digital to Analog Converter
<b>ADC</b>	: Analog to Digital Converter
<b>FFT</b>	: Fast Fourier Transform
<b>LDO</b>	: Low Dropout Regulator
<b>IDE</b>	: Integrated Development Environment
<b>PCB</b>	: Printed Circuit Board
<b>TVS</b>	: Transient Voltage Suppression
<b>ESD</b>	: Electrostatic Discharge
<b>PC</b>	: Personal Computer



## **SYMBOLS**

<b>V</b>	: Voltage
<b>A</b>	: Ampere
<b>F</b>	: Farad
<b>Ah</b>	: Amper-hour
<b><math>\Omega</math></b>	: Ohm
<b>Z</b>	: Impedance
<b>Hz</b>	: Herz



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# **BATTERY MANAGEMENT SYSTEM DESIGN WITH EMBEDDED ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY**

## **SUMMARY**

Humanity is developing day by day in engineering and technical fields. Engineers and scientists all over the world are trying to take humanity one step further. As a result of these studies, the technology provides comfort in our daily lives. One of the best examples of this are transportation, mobility and automotive. Each year, the studies progressing cumulatively in this field have pioneered the presentation of more developed cars than the previous years, and to populate different transportation methods and concepts in our lives. Each development has been formed as a result of some needs. One of the most important motivations in the field of automotive is user requests, the limited resources and the environmental sensitivity. The transition to electric vehicles, one of the biggest revolutions in transportation, has undoubtedly accelerated due to the depletion of fuel resources and the environmental sensitivity. Fuels used to operate internal combustion vehicles are obtained from petrol. While the formation of a petrol reserve takes for thousands of years, the current reserves are running out. Considering the demand that will rise in transportation due to the population and industrialization increase over time, it is predicted that the petrol reserves will be drained in the coming years. In addition, as a result of reactions inside the internal combustion engine, harmful gases are produced and released into world atmosphere. These gases, which are released from millions of vehicles, accumulate in the atmosphere and disrupt the balance of nature. Therefore, humanity has now become unable to lean on to petrol fuels and have been in search of new fuel sources. In this context, the most innovative transportation methods seem to be hydrogen and electrical based. While the comparison of these two methods with each other is the subject of a separate study, this study will focus on the electrical transportation method and the batteries to be used in these means of transportation.

Transportation has been mainly provided by internal combustion vehicles until today. This naturally allowed many engineers working on this field to accumulate a lot of knowledge cumulatively. Over the years, engineers have solved the problems in the designs one by one and have reached the present knowledge level by pushing the limits of the existing technology. There have been many developments in internal combustion engines and vehicles in areas such as safety, efficiency, practicality and comfort. However, electric vehicles that have just started to become widespread have opened a new page. Compared to internal combustion propulsion systems, studies on electric propulsion systems are still in their infancy. Engineers and scientists are conducting a lot of work to fill the gap in this field.

One of the most basic components of electric vehicles are batteries. When we compare one to one with internal combustion vehicle, the battery group corresponds to the fuel tank of the vehicle. The first factors for the user, such as the range of the electric vehicle, the charge time and the performance at different temperatures, are completely related to the battery. When these factors are examined, they are all disadvantaged

compared to internal combustion vehicles. This offers a negative effect for the market share of electric vehicles. While the criterias mentioned are the factors that the user will experience directly, there is also a factor that the user cannot experience, but in fact, which is even more important than all of them, which is safety. As can be seen from time to time, electric vehicles may caught fire while charging or in a traffic accident. It is not possible to extinguish it when a battery flames. Therefore, this is a great danger for both the vehicle's user and for those around. These situations show that there are many more things to develop in terms of both safety and user experience in the batteries of electric vehicles.

Today, Li-ion type cells are widely used in the batteries of electric vehicles. These cells are preferred because they are one of the cell types that give the highest energy per kilogram. As a result of chemical reactions in these cells, electrical energy is generated, which provides power to traction. Battery cells have safe operating ranges. In particular, the voltage and temperature values of the cells should be within some ranges. Otherwise, chemical reactions in the cells come to an uncontrollable point and undesirable fires, explosions or structural deformations may occur. In addition, since these cells are non linear systems, it is not easy to predict the changes in their internal structures as a result of their use. For this reason, it is a research area in itself to predict the energy remaining in the battery of an electric vehicle and therefore the range it can go to. In order to overcome such difficulties, there is a control unit that manages the battery and this module is called the battery management system.

In this study, a battery management system will be developed to ensure the safety of the electric vehicle battery and has a new method to estimate the chemical structure of the batteries. The developed battery management system will measure voltage, current and temperature values in the battery and check whether the battery is at safe ranges. It will take the necessary actions to prevent these values get dangerous. In addition, the battery will drive auxiliary elements in battery pack such as contactors. It will send the measurements and calculations taken over the battery over the communication channels and work in harmony with the other components in the vehicle. The designed battery management system will be scalable and the big battery packets will be able to managed with different number of battery management system modules.

There are many methods to analyze the chemical structures of batteries. The most important of these is electrochemical impedance spectroscopy. In this method, an alternative current is sent to a battery cell in the laboratory environment and the voltage change in the cell terminals is monitored. This voltage change analyzed in the frequency domain and an idea is obtained about the chemical internal structure of the cell. In spite of obtaining valuable information as a result of this method, the devices that do this analysis are expensive, heavy and stationary devices that can be used only in the laboratory environment. Within the scope of this study, it is aimed to integrate such an analysis method into designed battery management system. Thus, the tests performed in the laboratory will be able to performed on the vehicle also, and the accuracy will increase for battery management system calculations.

Within the scope of this study, the hardware of a battery management system will be developed. After circuit schematic and printing circuit board design completed, circuit board will be produced and prototyping work will be done. Low level drivers, battery management system algorithms and electrochemical impedance analysis algorithms will be developed on this board. The developed product will be tested on a battery pack and measurements will be taken. Taken measurements will be used to express cell

structure as an equivalent circuit model. Application areas that product can be used and future studies will be discussed.





# ELEKTROKİMYASAL EMPEDANS SPEKTROSKOPİSİ YÖNTEMİ ENTEĞRE EDİLMİŞ BATARYA YÖNETİM SİSTEMİ TASARIMI

## ÖZET

İnsanlık mühendislik ve teknik alanlarından her geçen gün daha da gelişmektedir. Dünyanın her tarafındaki mühendisler ve bilim adamları, insanlığı bir adım daha ileri götürmek için çalışmaktadır. Bu çalışmaların sonucunda ortaya çıkan teknolojiler günlük hayatımızda bizlere kolaylık sağlamaktadır. Buna en iyi örnek verilebilecek alanlardan biri de ulaşım, taşımacılık ve otomotivdir. Bu alanda kümülatif bir şekilde ilerleyen çalışmalar her sene, öncekilerden daha gelişmiş otomobillerin piyasa sunulmasına, farklı ulaşım metotlarının ve konseptlerin hayatımıza nüfus etmesine öncü olmuştur. Her bir gelişme durduk yere olmayıp bazı ihtiyaçlar sonucunda oluşmuştur. Otomotiv alanındaki gelişim motivasyonlarının başında kullanıcı istekleri, kaynakların sınırlı olması ve çevreye duyarlılık gelmektedir. Ulaşımındaki en büyük devrimlerden biri olan elektrikli araçlara geçiş şüphesiz ki yakıt kaynaklarının tükenmesi ve çevreye duyarlılık sebebiyle hızlanmıştır. İçten yanmalı araçları çalıştırmak için kullanılan yakıtlar petrolden elde edilmektedir. Yer altında bir petrol rezervinin oluşması binlerce yıl sürerken, şu an halihazırda dünyada bulunan rezervler hızla tükenmektedir. Zaman içinde artacak olan nüfus ve sanayileşme etkisiyle ulaşımında yükselecek olan talebi de düşününce sahip olduğumuz petrol rezervlerinin önümüzdeki senelerde tükeneceği öngörülmektedir. Ayrıca içten yanmalı motorun içindeki yanma reaksiyonları sonucunda dünya atmosferi için zararlı gazlar üretilmektedir. Milyonlarca araçtan her an boyunca salınan bu gazlar atmosferde birikmekte ve doğanın dengesini bozmaktadır. Dolayısıyla, insanlık şu anda dünyayı kirletmekte olan, gelecekte ise tükenme tehlikesi olan petrol yakıtlarına sırtına dayayamamak duruma gelmiştir ve yeni yakıt arayışlarına girmiştir. Bu bağlamda günümüz teknolojisinde en umut veren yenilikçi ulaşım yöntemleri hidrojen ve elektrik tabanlı gözükmektedir. Bu iki yöntemin birbiriyle karşılaştırılması ayrı bir çalışmanın konusu iken, bu çalışma elektrikli ulaşım yöntemine ve bu ulaşım araçlarında kullanılacak olan bataryalara yoğunlaşacaktır.

Ulaşım günümüze kadar ağırlıklı olarak içten yanmalı araçlar ile sağlanmıştır. Bu da haliyle bu alan üstünde çalışan bir çok mühendis olmasına ve kümülatif olarak bir çok bilgi biriktirilmesine olanak sağlamıştır. Seneler içinde mühendisler tasarımlardaki sorunları tek tek çözmüş ve var olan teknolojinin sınırlarını zorlayarak günümüze ulaşmışlardır. İçten yanmalı motorlar ve taşıtlar konusunda güvenlik, verimlilik, kullanılabilirlik ve konfor gibi alanlarda bir çok gelişme yaşanmıştır. Fakat yeni yeni yaygınlaşmaya başlayan elektrikli araçlar yeni bir sayfa açmıştır. İçten yanmalı tahrik sistemleriyle karşılaştırıldığında elektrikli tahrik sistemleri üstüne yapılan çalışmalar henüz başlangıç aşamasındadır. Mühendisler ve bilim adamları bu alandaki açığı doldurmak amacıyla bir çok çalışma yürütmektedir.

Elektrikli araçların en temel bileşenlerinden biri bataryalardır. İçten yanmalı araçla bire bir karşılaştığımızda batarya grubu aracın yakıt deposuna denk gelmektedir. Elektrikli aracın menzili, şarj olma hızı ve farklı sıcaklıklardaki performansı gibi kullanıcı için ilk sırada gelen etmenler tamamen batarya ile ilgilidir. Bu etmenleri incelediğimizde hepsi de günümüzdeki içten yanmalı araçlara göre daha geride kalmış durumdadır. Bu da elektrikli araçların tercih edilmesi için negatif bir etki sunmaktadır. Bahsedilen kriterler kullanıcının direkt olarak deneyimleyeceği etmenler iken bir de kullanıcının deneyimleyemeyeceği fakat aslında hepsinden daha da önemli olan bir etmen vardır ki bu da güvenlidir. Zaman zaman görüldüğü üzere elektrikli araçlar şarj olurken ya da trafik kazası esnasında bataryaları alev alabilmektedir. Bir batarya alev aldığı anda bunu söndürmek geleneksel yöntemlerle mümkün değildir. Dolayısıyla bu durum hem aracın kullanıcısı için hem de çevredekiler için çok büyük tehlike arz etmektedir. Bu durumlar göstermektedir ki elektrikli araçların bataryaları konusunda hem güvenlik hem de kullanıcı deneyimi konusunda daha geliştirilecek bir çok şey vardır.

Günümüzde elektrikli araçların bataryalarında Li-ion tipi hücreler yaygın olarak kullanılmaktadır. Bu hücreler kilogram başına en yüksek enerjiyi veren hücre tiplerinden biri olduğu için günümüzde tercih edilir. Bu hücrelerin içinde gerçekleşen kimyasal tepkimeler sonucunda elektrik enerjisi elde edilir ve bu da araca tahrik sağlar. Batarya hücrelerinin güvenli çalışma aralıkları vardır. Özellikle hücrelerin gerilim ve sıcaklık değerleri bazı aralıklar içinde olmalıdır. Aksi halde hücrelerin içindeki kimyasal reaksiyonlar kontrol edilemez bir noktaya gelir ve istenmeyen yangınlar, patlamalar ya da yapısal deformasyonlar gözlenebilir. Ayrıca bu hücreler doğrusal olmayan sistemler olduklarından kullanımları sonucunda oluşacak iç yapılarındaki değişimleri tahmin etmek kolay değildir. Bu sebeple bir elektrikli aracın bataryasında kalan enerjiyi ve dolayısıyla gidebileceği menzili tahmin etmek başlı başına bir araştırma alanıdır. İşte bu gibi zorlukların üstesinden gelmek için batarya içindeki hücrelerin yanında bir de bataryayı yönetecek olan bir kontrol ünitesi bulunur ve bu modül batarya yönetim sistemi olarak adlandırılır.

Bu çalışmada elektrikli araç bataryasının güvenliği sağlayacak ve bataryaların durumunu kestirmek için yeni bir yöntem barındıran bir batarya yönetim sistemi geliştirilecektir. Geliştirilen batarya yönetim sistemi batarya içinden gerilim, akım ve sıcaklık değerlerini ölçerek bataryanın güvenli aralıklarda olup olmadığını kontrol edecektir. Bu değerlerin tehlike yaratabilecek bölgelere girmesini engellemek için gerekli aksiyonları alacaktır. Ayrıca batarya içindeki kontaktör gibi yardımcı elemanları sürerek bataryanın komple bir paket olarak yönetimini sağlayacaktır. Batarya üstünden aldığı ölçümleri ve hesaplamaları ölçüm kanalları ile dışarıyla paylaşacak ve araç içindeki komponentlerle uyum içinde çalışacaktır. Tasarlanan batarya yönetim sistemi ölçeklendirilebilir yapıda olacak ve batarya grubu büyüdüğünde, çok sayıda aynı modülün paralel çalışması sağlanarak her türlü ihtiyacın tek bir tasarım ile giderilmesi sağlanacaktır.

Bataryaların kimyasal yapılarını analiz etmek için bir çok yöntem bulunmaktadır. Bunlardan en önemlisi elektrokimyasal empedans analizidir. Bu yöntemde laboratuvar ortamında bir batarya hücresine alternatif akım gönderilir ve bu uyarı akımı sonucunda hücre terminallerinde oluşan gerilim değişimi izlenir. Bu gerilim değişiminin frekans alanında analizi yapılır ve hücrenin kimyasal iç yapısı hakkında fikir edinilir. Bu yöntem sonucunda çok değerli bilgiler elde edilmesine karşılık, bu analizi yapan cihazlar sadece laboratuvar ortamına kullanılacak pahalı, ağır ve hareketsiz cihazlardır.

Özgün ve literatüre faydalı bir çalışma gerçekleştirilmesi amacıyla böyle bir analiz cihazının daha küçük boyutlara indirgenerek, tasarlanan batarya yönetim sisteminin içine entegre edilmesi hedeflenmektedir. Böylece laboratuvar ortamında yapılan testleri araç üstünde de her zaman yapabilmek mümkün olacak ve batarya ile ilgili parametreler tahmin edilirken doğruluk oranı artacaktır.

Bu çalışma kapsamında bahsedilen özelliklerde bir batarya yönetim sisteminin donanımı geliştirilecektir. Devre şemaları ve baskı devre tasarımı tamamlanan devre kartı üretilecek ve prototip çalışması yapılacaktır. Bu devre kartı üstünde batarya yönetim sistemi algoritmaları ve elektrokimyasal empedans analizi algoritmaları geliştirilecektir. Geliştirilen ürün bir batarya grubu üstünde test edilecek ve ölçümler alınacaktır. Ürünün günümüz teknolojisinde hangi alanlarda kullanılabileceği ve gelecek çalışmalar tartışılacaktır.





## 1. INTRODUCTION

Batteries are devices that store chemical energy and release this energy out as electrical energy through various reactions. They have deeply penetrated our lives, especially by enabling devices such as phones and laptops to work cordless. Batteries have many use areas; portable devices, toys, military equipment, medical equipment, hardware tools are just some of them. Another area where the use of batteries has become widespread in recent years is automotive. In fact, batteries have always been used in vehicles. But this use consisted only of a small battery supplying the first impulse to start the internal combustion engine. However, the development of batteries has made it possible to make the propulsion systems of vehicles completely electric and to supply them with batteries. With the development of batteries, electric vehicles have become more suitable for daily use and their popularity has increased. With this increasing popularity, the engineering world has done even more research and development on batteries, resulting in a spiral development cycle.

As the batteries developed, the control systems around the batteries that allowed the batteries to work in harmony also developed rapidly. Battery packs contain a battery management system (BMS) that ensures these batteries operate within safe and optimal ranges. BMS is generally a hardware and software assembly. The hardware part contains sensors to take measurements from the battery, a platform for the software to run, the actuators to perform the actions decided as a result of algorithms, and communication channels for the battery to communicate with the outside. Above this hardware layer, a software layer is placed and many decisions regarding battery pack management are made here. The software checks if the battery is within safe ranges. Calculates important parameters such as the battery's state of charge, state of health, and instantaneous power. When we think about an electric vehicle, these parameters correspond to very basic and critical features such as the vehicle's range or acceleration capacity. Since batteries are nonlinear and complex systems, it is very difficult to estimate the mentioned values. In order to estimate the mentioned values as accurately as possible, manufacturers usually make measurements on the batteries

in the lab environment before the vehicle is released to the market and embed these base measurements in the BMS and use these values as the core in the calculations to be made throughout the life of the battery. Expensive, heavy, large and non-portable devices in lab environments are used to perform these measurements. However, over time, the internal parameters change as the batteries age. Even more if all cells are at the same aging level, but if they are used under different charge and discharge profiles, their internal structures can show some variations. Therefore, the beginning of life measurements taken on the batteries are no longer valid and estimation errors are seen in the estimated parameters related to the battery. Even if manufacturers take both beginning of life and end of life measurements in the lab and add them to the BMS algorithms, there will still be problems with consistency, since not every cell will age the same in all conditions of use. The correct estimations of the important parameters we mentioned is one of the most studied subjects in the field of BMS technologies today.

Reducing the environmental impact of battery manufacturing as much as possible, and the repeated use of same batteries at different applications is a growing and popular topic. Batteries that are too old to no longer meet the requirements for one application can be reused in a different application. This process named as second life application. For example, cells can be used at the beginning of their life in a demanding application such as an electric vehicle and can be reused in an application such as a vacuum cleaner when they are aged enough to affect the performance of the vehicle. However, in order to provide a standard in this process, measurements should be taken in the lab environment before the batteries are swapped. Then, cells with appropriate characters should be selected and transferred. This adds extra effort, cost and time loss to the process.

## **1.1 Purpose of Thesis**

In this thesis, a BMS hardware and software will be designed for use in electric vehicles. This BMS will perform all the control, calculation and safety processes that are currently required on a battery pack. In addition, the hardware and software required to perform the electrochemical impedance spectroscopy (EIS) method will be implemented on the BMS by reducing its size and cost. Onboard EIS hardware and software will be used to measure cell parameters, not only in the lab, but also anytime

and anywhere during the lifetime of the electric vehicle, In this way, estimations will be made with maximum consistency throughout the life of the battery. In addition, it is aimed to support the second life process of cells by EIS measurements taken on battery. By this way, suitable second life application will be determined based on the cell performances and parameters. Thus, damage to the environment and the losses in the process will be reduced.





## 2. BATTERIES

There are many chemistry types among the developing battery technologies day by day. There are many manufacturers and models in every battery chemistry. Many battery parameters are taken into consideration when deciding which battery is most suitable for an application. The main factors for battery selection are as follows:

- Cell capacity
- Nominal and maximum charge current
- Nominal and maximum discharge current
- Cell nominal, maximum and minimum voltages
- Weight
- Volume
- Cost
- Cyclic life
- Cyclic efficiency
- Optimal temperature range
- Environmental impact

In addition, the following parameters derived from above parameters are also very important in battery selection:

- Capacity or instantaneous power per unit mass
- Capacity or instantaneous power per unit volume
- Capacity or instantaneous power per unit cost

As a result of the classification and election made with the help of these parameters, the most suitable battery can be selected for the desired application. For example, in an electric family vehicle, a long-range, long-lasting and cost-effective battery can be built considering the capacity and cyclic life per unit cost. When designing an electric

racing vehicle, a high performance vehicle can be made by choosing a cell with a high instantaneous power value per unit mass and a wide operating temperature range. Or, for an IOT sensor that needs to work for a long time without being charged, an efficient cell with a high cell capacity can be selected.

## **2.1 The Most Used Battery Types**

Lithium Ion (Li-ion) is the most widely used battery type today. Although it is an expensive type of battery when compared to other battery types, it is widely used in mobile phones, laptops and electric vehicles due to its high energy density and high cyclic life [1].

Another commonly used battery type is lead acid. Although this battery chemistry is one of the oldest, it is used quite often today. The fact that these batteries are cheap and simple has been effective in this. These batteries are mostly used in internal combustion engine vehicles to start the engine by giving the engine the first move. It is also used as a backup battery against power cuts in buildings.

One more common type of battery is nickel-metal hydride (NiMH). Although these batteries lost their popularity especially after Li-ion batteries became widespread, they are still used to supply many handheld devices today.

## **2.2 Battery Types Under Development**

Nowadays, it is aimed to produce more advanced batteries at a cheaper cost by carrying out many research and development on batteries.

One of the most promising battery types for future use is solid state batteries. These batteries contain solid instead of liquid as electrolyte. Since they offer safer use compared to the Li-ion batteries used today, they are especially interesting for industries that prioritize safety such as automotive and aviation. They also promise longer life and better performance at low temperatures [2].

Another development area is graphene aluminum batteries. These batteries use graphene as the anode layer and aluminum as the cathode layer. Since these materials are cheap and easily available, it is a battery that is expected to be cost effective. In addition, since graphene is a highly conductive material, these cells can reach very high charge and discharge currents. This allows very short charging times [3].

Another developed battery type is Sodium-ion batteries. These batteries use sodium in the cathode layer. Although the performance is expected to be lower than Li-ion batteries due to the characteristic features of sodium, it is expected to be much more advantageous in terms of cost. For this reason, it can be a strong alternative in applications where low currents and low capacities are needed [4].

Flow batteries produce electricity by pumping an electrolyte across a membrane. This type of battery is expected to have a much longer life and high capacity compared to today's technologies. However, due to its cost disadvantage, it is a good alternative for high engineering and cutting-edge applications in the future [5].

### **2.3 Battery Characterization Techniques**

Cells to be used in an electric vehicle battery must be subjected to many tests before production. Cell characteristics should be examined with the help of these tests. In this way, it is predicted how the cells will behave throughout the life of the battery. In addition, in the light of the data obtained from these tests, BMS can predict values such as SOC, SOH and SOF with higher accuracy. Many test protocols have been established to characterize cells.

The most common among these tests is the open circuit voltage (OCV) test. During this test, the battery is kept for a while without being charged or discharged, and its internal chemistry is stabilized. Then, open circuit voltage of the cell is measured. This process is repeated at different temperatures and charge levels and results are recorded for further use [6].

Another method is the cyclic test. In this test, it is observed how the battery performance changes after a certain charge and discharge cycle. A series of charge and discharge cycles are applied to the battery. In each cycle, the capacity, efficiency and charge/discharge rate of the battery are measured. As a result of this test, researchers observe the effects of aging on the battery.

The electrochemical impedance spectroscopy (EIS) method is a non-destructive method that provides a lot of information about the cell. EIS gives information about the internal chemistry of the cell without damaging the cell. In the EIS test, a small AC current is applied to the cell. As a result of the impedance of the internal chemistry of the cell, this AC signal causes a voltage change at the cell poles. This voltage change

depends on the internal structure of the cell and the frequency of the applied excitation signal. By monitoring this current and voltage change, the impedance of the cell at different frequencies is calculated. By looking at this feedback, an electrical circuit model is proposed that will best represent the chemical structure of the cell. It can be examined how the internal chemistry and proposed electrical circuit model change by repeating the test at different temperatures, different charge levels and different aging levels.

The high-power pulse current (HPPC) test shows how the battery behaves under sudden and high current loads. This test simulates situations such as the sudden acceleration of an electric vehicle and presents the researchers how the battery responds to sudden loads [7].

X-ray photoelectron spectroscopy (XPS) is a different way to study the internal chemistry of the cell. In this method, X-Ray rays are sent to the cell from one side. The kinetic energy of the photoelectrons emitted from the other side is measured. The kinetic energy of the photoelectrons passing through the cell depends on the chemical structure they encounter inside the cell. As a result of the measurements, the chemical composition of the cell is determined. This method is particularly useful for understanding the chemical reactions that take place during charging and discharging [8].

Scanning electron microscopy (SEM) is used to take high resolution photographs of surfaces. In this method, an electron beam is sent to the area to be scanned and the electrons reflected from the surface are examined. Thanks to this method, surface morphology and micro structure of the materials in the cell are examined [9].

## **2.4 Battery Modelling**

Battery cells are not linear systems and some phenomena in them prevent the cell from being a perfect voltage source. Due to the chemical structure of the cell, there are some resistance, capacitance and inductance effects. Expressing battery cell chemical structure as an equivalent electrical circuit is an effective way to imagine and understand cell behaviour under different usage scenarios for engineers and it is easier to model it. Some electrical circuits have been proposed to model this chemical structure.

### 2.4.1 Randles equivalent circuit

Randles equivalent circuit is developed by William H. Randles in the 1940s and has been widely used for modeling batteries. Randles equivalent circuit includes Warburg impedance, double layer capacitance, charge transfer resistance and solution resistance circuit elements. Circuit model of this elements can be found in Figure 2.1 depicted in [10].

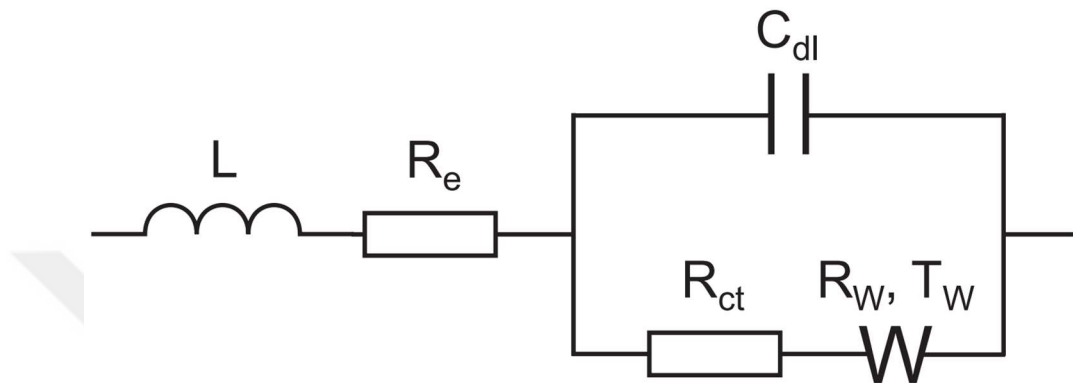


Figure 2.1 : Randles Equivalent Circuit Model [10].

#### 2.4.1.1 Warburg impedance

Warburg impedance is an equivalent circuit element used to model the diffusion process. Diffusion is the name given to the transition of ions from the high-density side to the low-density side in the cell. Thanks to this movement, the cell can be charged or discharged. However, there are some effects within the cell that resist this transitional movement. This resistance is caused by a number of factors, including the viscosity of the electrolyte solution, the ionic conductivity of the electrolyte, and the surface area of the electrodes. Warburg impedance is used to simulate these effects. This element is an important criterion for the battery as it affects the instantaneous maximum charge and discharge current of the battery.

#### 2.4.1.2 Double layer capacitance

Capacitors consist of an insulating layer between 2 conductive layers. When this sandwich structure comes together, it can store charge on it. A similar structure is also seen in the electrodes of battery cells. The electrical double layer is a thin layer of charge that forms at the interface between an electrode and an electrolyte. It consists of a layer of ions in the electrolyte that are attracted to the electrode, and a layer of electrons on the surface of the electrode that are attracted to the ions. These layers of

charge are separated by a thin layer of electrolyte, and they act as a capacitor, storing electrical charge. This element affects the instantaneous maximum charge and discharge current of the battery.

### 2.4.1.3 Charge transfer resistance

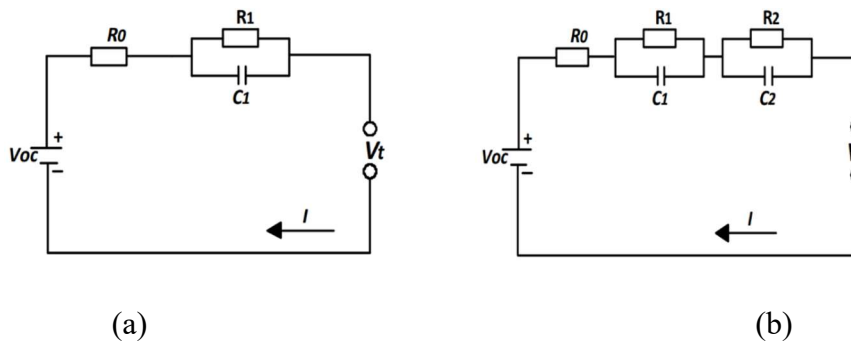
Charge transfer resistance simulates faradaic reactions resulting from the double layer capacitance effect. Since faradaic reactions are controlled by diffusion, the charge transfer resistance is modeled in series with the warburg resistance.

### 2.4.1.4 Solution resistance

The Solution Resistance simulates ionic resistance and electrodes immersed in the electrolyte.

## 2.4.2 RC model

The RC Model is another proposed circuit structure for modeling the battery. The RC model is a simplified version of Randles equivalent circuit which include additional electrical elements to represent other aspects of the battery's behavior. In the circuit, element R is used to model the internal resistance of the battery and element C is used to model the internal capacitances. While modeling the battery, these R and C values are chosen to reflect the characteristics of the real battery the most. For this, EIS tests are performed on the cell under test, and the impedances of the cell are found at different frequencies. The obtained findings are displayed on a nyquist table and the parameters in the RC model are selected to mimic the closest output to this nyquist response. After this stage, the RC circuit model can be used to simulate the behavior of the battery at different temperatures, loads and charge states. Different RC model representations can be found in Figure 2.2 depicted in [11].



**Figure 2.2 :** (a) RC Model. (b) 2RC Model [11].

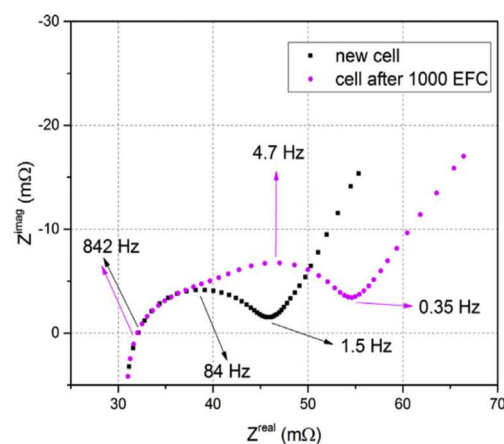
## 2.5 Cell Aging

Some chemical changes happen on battery cells over time. These changes cause the performance degradation on the battery and this is called cell aging. Effects such as the using conditions of the cell, the number and patterns of charge-discharge cycles, ambient temperature and storage conditions affect the aging of the cell.

As the cell ages, a series of changes occur in its internal chemistry. The biggest cause of aging is the separation of the anode and cathode materials inside the cell. Because of the mechanical and chemical stress during charge and discharge cycles, these materials can breakdown. Suboptimal temperature and humidity conditions can accelerate this degradation. As a result, the capacity of the cell gradually decreases because of aging.

Another effect that causes aging is lithium plating. During non-optimal charge and discharge patterns, lithium ions may not be able to fully intercalate into the anode. As a result, a coating of Lithium metal forms on the anode electrode. This causes an increase in the internal resistance of the electrode and thus the cell. As a result, a decrease in the instantaneous maximum charge and discharge currents of the cell and loss of capacity are observed.

Another factor is the physical stresses on the cell. Changes in the temperature of the cell during charge cycles and discharge cycles cause the cell to expand and contract. Because of this reason, micro cracks and voids are created in the cell, resulting in a decrease in the performance of the cell [12]. To better explain the topic, a EIS spectra which compares new and old cell can be found in Figure 2.3 depicted in [13].



**Figure 2.3 :** Comparison of EIS spectra of a new cell and a cell after 1000 equivalent full cycles [13].

## 2.6 Cell Second Life

Second life refers to the reuse of battery cells that have reached the end of their lives in a specific application, in a less demanding application. In this way, the lifetime of the batteries is increased, less waste is produced and the overall cost is reduced [14].

To determine whether a battery is suitable for second life, some parameters are considered. The most important of these are the remaining capacity and performance of the battery. If these values are at a level that can meet the requirements, they can be used for the second life. Another important issue is what the second life application is. If the new application requires lower energy density, lower capacity or a less demanding application compared to previous one, the cells may be suitable for second life. After preliminary examination with these considerations, the final decision can be made after characterization tests are performed on the cells to be used for the second life. For this purpose, the usable capacity of the battery can be determined by performing a charge-discharge test on the cell. Furthermore, by interpreting the spectra obtained by applying the EIS test, it can be decided that if cell is suitable for second life and, if appropriate, in which applications it can be used.

### 3. ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY

Electrochemical Impedance Spectroscopy (EIS) is a powerful technique for characterizing the electrochemical behavior of lithium-ion (Li-ion) cells. Its principle is based on measuring the impedance of the cell for a range of frequencies. Resulting impedance data can be used by engineers to better understand internal dynamics of the cell.

During EIS measurement, A small alternating current is applied to the cell and meantime a voltage sensor measures the voltage response of the cell against the applied current which is directly related to impedance of the cell. Measurement system must be very sensitive for small voltage variations, because applied small current to the cell also creates small voltage difference between cell terminals. Applying bigger currents to the cell can disrupt the stable state of the cell. The frequency of the AC signal is swept across a range of values, typically from low frequencies (mHz) to high frequencies (kHz). The resulting impedance data is then plotted as a Nyquist plot, which shows the real ( $Z'$ ) and imaginary ( $Z''$ ) components of impedance as a function of frequency [15].

To perform EIS measurement, various measurement devices are used. One of the most common device is a frequency response analyzer (FRA) which is a specialized electronic test equipment that applies a known frequency and amplitude to a device under test (DUT) and measures the resulting amplitude and phase at the DUT output. Another device is Impedance analyzer, it is an electronic instrument that measures the impedance of the DUT in a specified frequency range.

The raw data obtained from the EIS measurement is in the time domain, but to examine the underlying physics, it is important to convert it to the frequency domain. Fourier transform is used to convert time-domain signal into the frequency-domain signal, providing a frequency-domain representation of the EIS data. This allows for the

identification of different phenomena in the cell and the quantification of their relative contributions.

EIS is also useful method to study aging of Li-ion cells. As a cell ages, its internal parameters change. This can be observed through EIS diagram. By comparing the EIS diagram of the cell at different ages, engineers can comment on how cell is responding to aging.

EIS is a non-destructive analyzing method, it means it is not harmful for cell and it doesn't break up the internal structure of the cell. It can be applied several times to observe cells internal parameters during cells lifetime. This especially useful for areas like electric vehicles where the performance of the battery is crucial throughout the lifetime.



#### **4. TASKS OF BATTERY MANAGEMENT SYSTEM**

The nominal voltage of a Li-Ion cell is 3.7 volts, the minimum voltage is 2.8 volts and the maximum voltage is 4.3 volts. Temperature limits of Li-Ion cell is generally between 0 degree and 50 degree.

In order to ensure that the battery is in safe and optimal conditions, BMS constantly monitors the battery and take the necessary precautions. BMS should be able to detect the following conditions by simply measuring the voltage, temperature and current of the battery:

- Cell over voltage limit
- Cell under voltage limit
- Cell over temperature limit
- Cell under temperature limit
- Cell over current limit
- Battery short circuit
- Cell voltage imbalance limit

Exceeding the cell over voltage limit is one of the most dangerous situations for the cell. If the cell's voltage rises above the recommended voltage, risks may occur, including fire, explosion and gas release. In all of these situations, the cell can permanently damage itself and the surrounding objects and become unusable. To prevent this, BMS monitor cell voltages and if the maximum cell voltage exceeds the threshold, BMS shall limit charging.

Exceeding the cell under voltage limit occurs when the cell is over-discharged and the voltage drops below the recommended voltage value. In this case, an irreversible loss of cell capacity may occur. To prevent this, BMS shall limit discharging.

Exceeding the cell over temperature limit is the most dangerous situation for the cell. If the cell exceeds safe temperature range, an unstoppable thermal reaction may begin in the cell. This condition is known as thermal runaway. In this case, the temperature of the cells increases continuously due to the reaction in them, and as a result, it can get fire or explode. To prevent this, BMS should constantly monitor cell temperatures. If an increase in cell temperatures is detected, the cooling equipment in the vehicle should be operated and current flow from or to battery shall be limited to prevent heating.

Exceeding the cell under temperature limit will cause poor battery performance. If the cell temperature drops below the recommended temperature, all of the energy inside the cell can't be used. The maximum charge and discharge currents that the cell can handle at very low temperatures are very small. In this case, the vehicle charges very slowly or its performance decreases while driving. To prevent this, the BMS should send a signal to the heating equipment inside the vehicle to operate.

Exceeding the cell over current limit occurs when the instantaneous current exceeds the manufacturer's recommendation. In this case, the batteries are put under overload. In addition, excessive current withdrawal from the cell may decrease the cell voltage due to the cell's internal resistance, causing the cell to exceed the under voltage limit. In such a case, BMS shall limit consumers current demands.

Battery short circuit is another dangerous situation for the cell. Electric vehicle batteries can give very high currents instantly. If battery output is short-circuited, very high current can pass through the system. This may cause the vehicle's electrical system to be damaged in such a way that it cannot be used again. To prevent this, BMS shall detect short circuit and open the contactors immediately.

Exceeding the cell voltage imbalance limit is one of the key effects that decrease the performance of the battery. Even if the cells are the same brand and the same model, there may be minor differences in their internal parameters. Thus, In the long run, voltage differences can be seen between cells. In this case, not all battery capacity can be used effectively. It may be necessary to finish charging or discharging earlier than expected due to voltage differences between cells. In order to use energy the most efficient way, the voltages of the cells should be as equal as possible. If a voltage

difference occurs between cells over time, the BMS shall be able to detect this and have a balancing mechanism to eliminate this difference.

Today, there are many sensors that detect accidents on vehicles. These are usually detected by acceleration and vibration sensors. With the data from these sensors, equipment such as airbags are triggered. Vehicle crashing is one of the most dangerous scenarios for an electric vehicle battery. When the accident deteriorates the structural shape of the vehicle, battery cables can be short circuited to chassis and create dangerous situations. These situations may cause the victims to be shocked. To prevent such a situation, the battery management system should work synchronously with the equipment that detects the accident in the vehicle and ensures the safety of those around by ensuring that the battery and vehicle are disconnected from the vehicle in the event of an accident.

The battery management system carries out the control processes for charging the battery. As soon as the user comes to the charging station and plugs the charging cable into the vehicle, communication begins between the BMS and the charging station. BMS calculates the current and voltage values required for charging and reports it to the charging station.

The battery management system manages the precharge process. In electric vehicles, due to system has a high capacitance, if the battery is connected to the system directly, very high current is drawn. This will cause the battery to be overloaded momentarily. To prevent this, the battery is connected to the system via a resistor before the operation.

The battery management system is responsible for driving the contactors inside the battery. BMS decides which contactor will be driven in which order and for how long.

The battery management system measures many data in the battery and makes some calculations based on them. These data obtained by BMS can be very important for other control units in the vehicle. For example, the maximum deliverable power value calculated by BMS can be very important for the traction control unit of the vehicle. Battery management system should be able to communicate with other control units in the vehicle in order to deliver such data to the relevant places in the vehicle.



## **5. BATTERY MANAGEMENT SYSTEM DESIGN WITH EMBEDDED EIS FUNCTIONALITY**

### **5.1 Conceptual Design**

It is decided to design a BMS with electrochemical impedance spectroscopy in it so that the battery of an electric vehicle always works in the safe and efficient conditions. The process started with conceptual design. At this stage, the requirements of the BMS, the basic features, the characteristics of the hardware, software elements and the topics which extra care should be taken in the design are determined.

First of all, it is decided how many cells the BMS should measure. When the batteries of electric and hybrid vehicles in the market are searched, it is seen that battery packs ranging from 36v to 900 volts are used. Proposed BMS can also be used in a smaller electric vehicle such as an electric scooter or electric bike. In such vehicles, lower battery voltages are observed. The BMS to be designed should be capable of controlling all kinds of platforms. But it is not possible for a single system to control both a small scooter battery and a huge electric truck battery. To solve this problem, it is decided to design a small BMS board and to control large packages by parallel working BMS's. 10 cells measurements availability is decided for per BMS. In this case, one module will be used for a small scooter battery, while tens of this module will be used to control a truck battery and entire battery will be covered. A communication channel is needed for these BMS modules to work together. In order to achieve this, the BMS will be designed to communicate through the CAN Bus. Since CAN Bus is a very common communication method in automotive, while BMS modules communicate with each other, it will also be possible to send battery parameters to the outside by communicating with other control modules in the vehicle. In the scenario where, large battery packs are controlled by using multiple BMS together, each BMS will take measurements from a different part of the battery. In this case, when the BMS's are connected to each other via the communication channel, a

short circuit may occur between the cards due to voltage differences. In order to prevent this, it has been decided to designing battery measurement circuits galvanically isolated from the rest of the circuit. Thus, dangerous short circuits will not occur between the synchronous BMS's and the low voltage electrical system of the electric vehicle will be completely isolated from the high battery voltage. Thus, when a problem occurs in the battery measuring circuits, the rest of the vehicle will continue to operate safely.

During the life of the battery, voltage differences may occur between cells, which may prevent optimal use of battery capacity. As a solution to this situation, a balancing mechanism will be added to the BMS and the voltages of the cells will be equalized to each other. It is decided to use 5 NTC temperature sensors for temperature measurement from cells. BMS will take measurements from all of these temperature sensors and will ensure that the battery stays within safe ranges and the battery parameters are calculated correctly. The current drawn from the battery pack, which has a very important data for battery calculations, should be detected by the BMS. An external shunt resistor will be use for this and BMS has differential voltage measurement inputs connected to shunt resistor. The parameters calculated by the BMS should be delivered to the user and at the same time the user should be able to calibrate the BMS. The CAN Bus port currently in the system will serve for this purpose. However, in case of user does not have enough equipment to monitor the CAN Bus, there must be a USB port on the BMS to connect to the system.

It is decided to have EIS hardware and software integrated on BMS. In this way, EIS measurements can be taken from the cells throughout the life of the battery, and thus the state of charge and aging of the battery can be predicted with high accuracy. For this system to be functional, the BMS must be able to generate an excitation signal to the battery. The amplitude, frequency and waveform of this warning signal must be adjustable. In addition, the BMS should be able to calculate the impedances of the cells by monitoring the voltage changes that will occur as a result of this excitation signal. As a result of the calculations to be made on the BMS, the real and imaginary impedances of the cells should be found.

There may be loads such as pumps or contactors connected to the BMS board from the outside. BMS should have digital outputs to drive these loads. It should also have the necessary interfaces for analog sensors that can be connected from outside.

After determining the requirements for the BMS to be designed, the key components selection phase is started. While selecting the components, A few things in particular are given extra attention; the all requirements specified above will be satisfied, the stock status of the components will be checked and the components will be selected cost-effectively.

The requirements specified above have been determined by considering the industry and platform needs in general for an electric vehicle traveling on road. Therefore, when selecting the components, they should be selected to meet these requirements and never compromise the requirements related to safety, especially.

As seen in the preliminary stage when choosing components, it has been observed that there are major problems in the production and distribution of electronic components today. Therefore, many components appear as non-stocked. It should be aimed that the selected components are common and easy to find in order to avoid problems related to this situation throughout the project.

Therefore, due to the problems in the component production process, it has been observed that there is an upward trend in the prices of the components. When the designed BMS will be started to mass production, the unit product cost becomes very important. For this reason, while choosing the components, care will be taken to ensure that their price and performance are efficient.

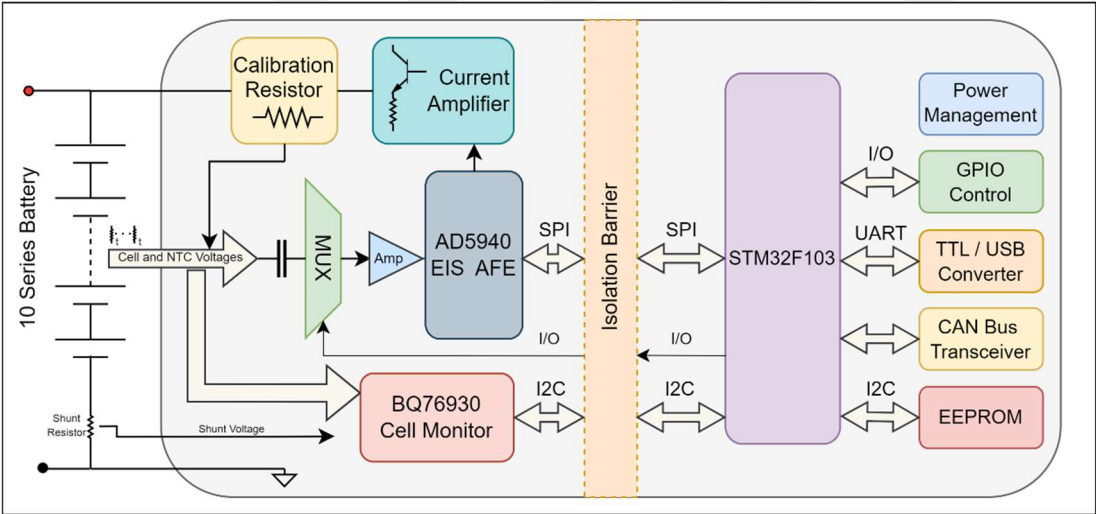
## **5.2 Choosing Key Components**

Component selection is started with the battery monitor, which has a very important part for BMS. The battery monitor is the component that will take voltage measurement from the cells. Also, most of the safety functions that will be integrated into the BMS will use the information from the cell monitor. Therefore, the cell monitor is a key element both for the safety of the system and for its performance. BQ76930 integrated circuit is chosen to be used in this project. This integrated circuit can take measurements from 10 cells with an accuracy of 386  $\mu\text{V}$ . In addition, there are differential inputs for shunt resistor for current measurement. It communicates using I2C communication method. In addition, it provides a safe communication via the CRC method. It is aimed to keep the performance of the system at the maximum level with the cell balancing allowed within itself.

Another important component is the integrated circuit that will perform the EIS measurements. AD5940 product is deemed suitable for this part. This IC has many DAC, ADC, calculation blocks and filter subsystems. This IC can generate excitation signals in configured waveform, frequency and amplitude. It is possible to measure the impedance by monitoring the voltage changes that occur as a result of this excitation signal. In addition, the measured impedance can pass through the filter and FFT accelerator in the IC, giving the user the real and imaginary resistance values of the test subject directly.

Algorithms designed for BMS will run on a microcontroller. The microcontroller to be used should be powerful enough to run the algorithms together and have enough interfaces to control all other subsystems on the BMS. It is decided to use the STM32F103C8 microcontroller to fulfill this task. This microcontroller has 48 pins and 72 MHz processing power.

After all key components are selected, an hardware architecture draw is created to understand project sub-elements better and it is expressed in Figure 5.1.



**Figure 5.1 : BMS hardware structure.**

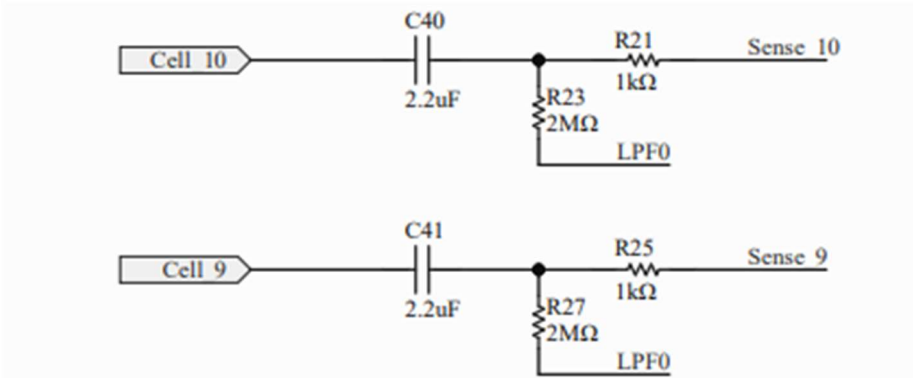
**5.3 Schematic Design**

After the conceptual design phase, the schematic design is started. Since designing schematic in only single page would be difficult to understand and inefficient, the schematic design is divided into certain parts and all of them are studied separately. After all sub-schematic designs are completed, the inputs and outputs of all sub-

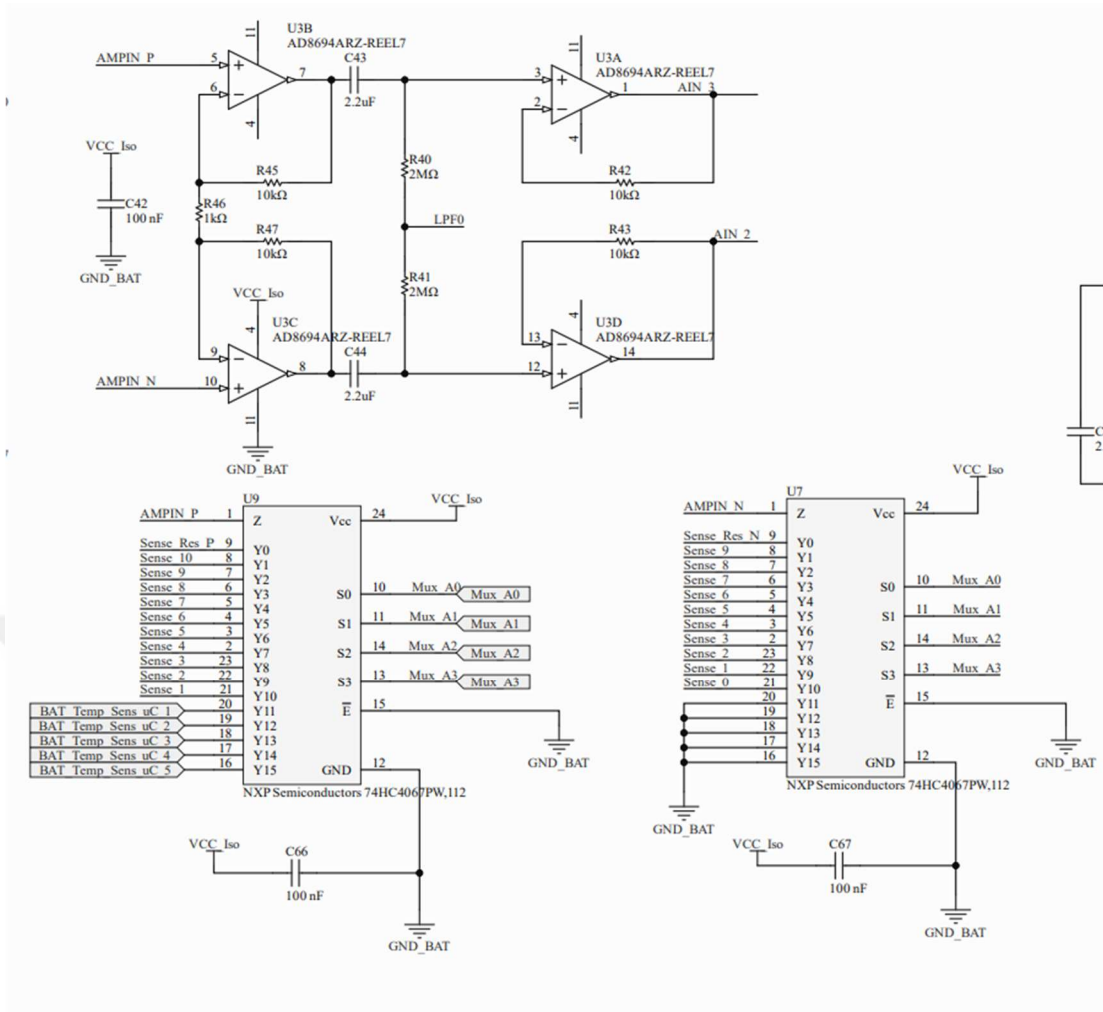


with a value of 5 mΩ is placed on the circuit in order to detect the effects that may cause errors such as cable resistance, connector impedance while taking impedance measurement from the cells. Before measuring the cells, it is decided to measure this resistance whose value is already known, then to measure real cells and to find the cell impedances by comparing the both measurements with each other. Ratio of known calibration impedance and cell impedance, will be equal to ratio of terminal voltages of calibration resistor and terminal voltages of cell.

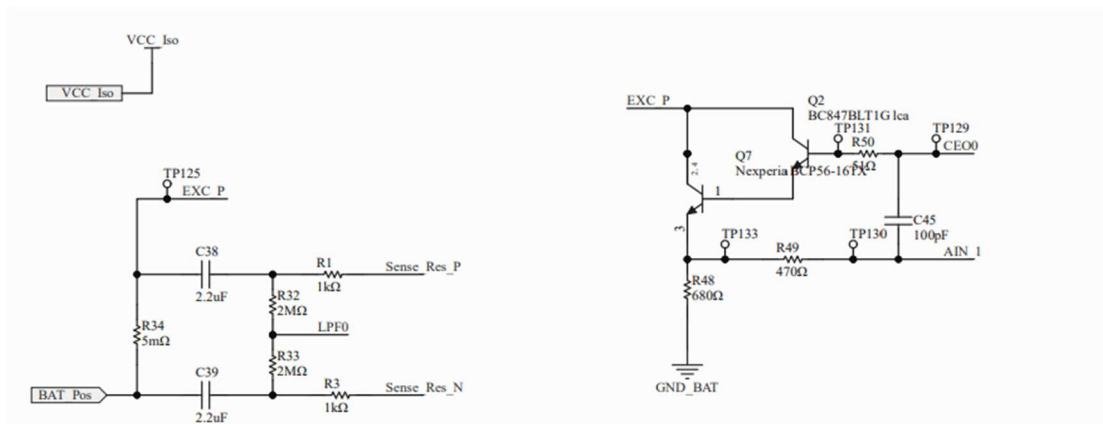
AD5940 integrated circuit has 5 analog inputs. However, BMS needs to take measurements from 10 cells, 1 reference calibration resistor and 5 temperature sensors. In order to use the available resources efficiently, it is decided to use a multiplexer in order to switch the signals through measurement channels. When the measurement will be taken, the multiplexer will be controlled via the digital signals coming from the microcontroller and the correct channel will be directed to the AD5940 analog pin from whichever channel the measurement is desired. It is expected that the impedances of the cells to be measured will be in the mΩ range. As a result of the applied excitation current, a voltage change will be appeared depending on the impedance. In order not to disturb the steady state of the cell, the excitation current must be small. A small excitation current applied to a cell, with a small impedance, will create a small voltage change. In this case, in order to use the measurement range of the electrical circuits efficiently and to perform the best possible measurement, the measurement signals to be used for EIS are amplified with an opamp after the multiplexer. Gain for this amplifier calculated as 21. This part of design can be found in Figure 5.4. An SPI connection is added between the EIS measurement circuit and the microcontroller to transfer the obtained measurements to the microcontroller.



**Figure 5.3** : DC block capacitors for EIS circuit.



**Figure 5.4 :** Amplifiers and multiplexers for EIS circuit.



**Figure 5.5 :** Current amplifier and calibration resistor EIS circuit.

In order to create EIS excitation current mosfet and resistor pair is used. Resistor is selected as 680Ω. As battery voltage is expected to 37 volts nominal, maximum excitation current is calculated as 54.4 mA.

AD5940 chip has an 16 bit ADC. As analog part of chip supplied with 3.3 V, minimum voltage change can be measured on chip pin is 0.05 mV. As gain of the differential amplifier at input of BMs is 21, minimum measurable voltage calculated as 2.39  $\mu$ V.

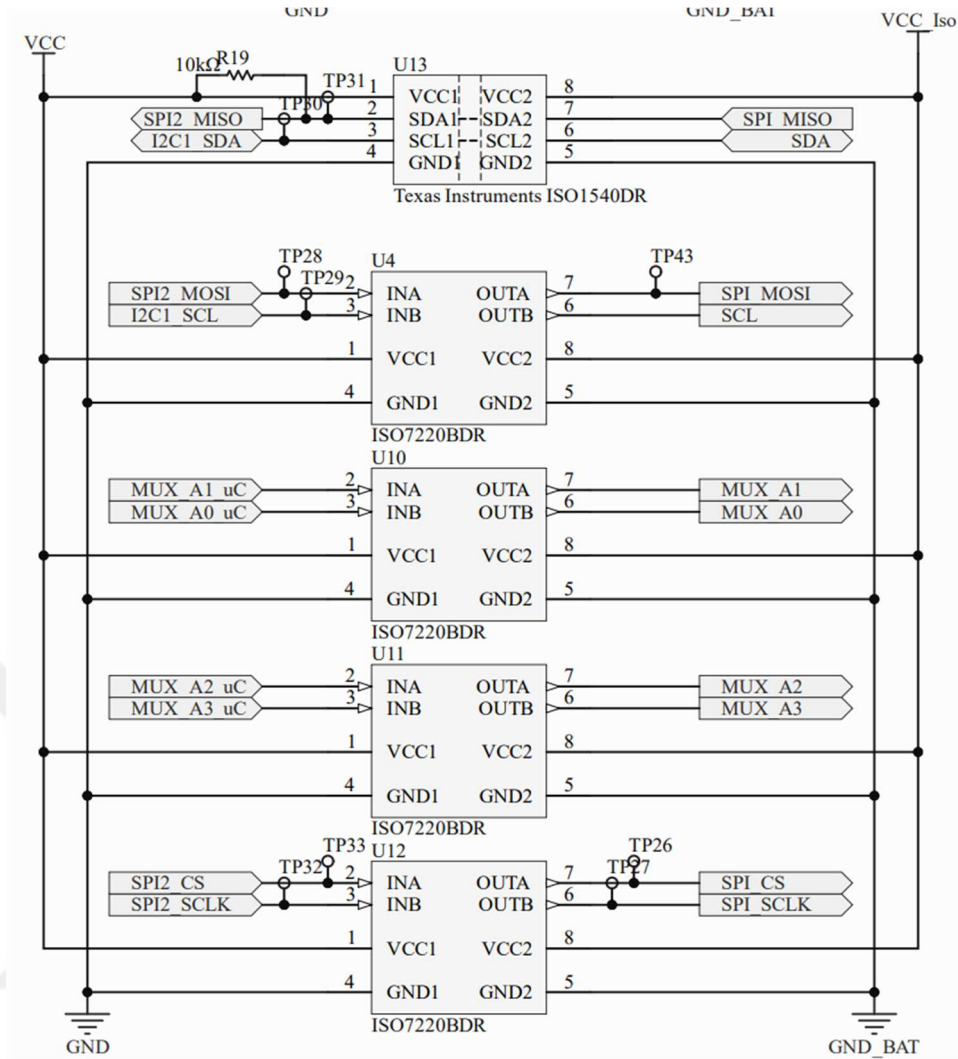
The smallest impedance that measurable by this design is achieved when the biggest excitation current is applied and smallest measurable voltage change is achieved across the measurement pins. So smallest impedance that measurable is calculated as 0.043 mOhm.

### **5.3.3 Galvanic isolation circuit**

The battery measurement circuit on the board and the rest of the parts are designed to be electrically isolated from each other in order for the BMS to work in the safest way and to avoid short circuits when running parallel to each other in large systems. However, it is necessary to provide data flow between the two subcircuits without breaking this isolation. For this, digital isolators are used. During designing, the signals that need to be transmitted between the two regions are determined as follows.

- SPI MISO signal for EIS measurement circuit
- SPI MOSI signal for EIS measurement circuit
- SPI SCLK signal for EIS measurement circuit
- SPI CS signal for EIS measurement circuit
- I2C SDA signal for cell monitor circuit
- I2C SDL signal for cell monitor circuit
- 4 digital signals for multiplexer channel selection.

In order to transmit these signals, 5 of the dual channel digital isolators are used. Since there will be data transfer in both directions over the I2C SDA connection, a bidirectional digital isolator is chosen accordingly for this channel. Schematic representation of isolators can be found in Figure 5.6.

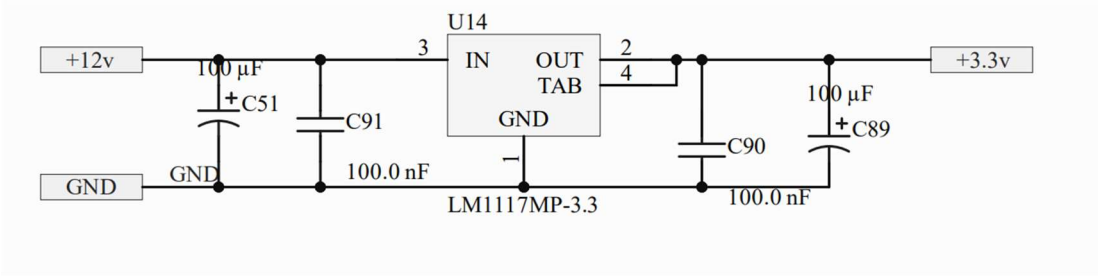


**Figure 5.6 :** Isolation circuit.

### 5.3.4 Power supply section

When the electrical architecture in a car is examined, it is seen that the voltage levels are between 12 and 24 volts. However, many components on the BMS are powered by 3.3 volts. In this case, there is a need for a circuit that will reduce the voltage in a wide range of input values to 3.3 volts. LDO or buck converter can be used for this situation. LDO's can create a noiseless and clean voltage supply at their output, but they are inefficient. Buck converter, on the other hand, can operate efficiently in wide voltage ranges and can transfer high currents, however, its dimensions and output ripple are larger than LDO. A cascade of buck converter and LDO can be used in succession to eliminate the handicaps of these two structures [16]. When all the loads to on the BMS are examined, it is expected that a maximum of 40 mA will flow through the 3.3 volt line. Since the power requirement is low, even if only LDO is used, it will be sufficient.

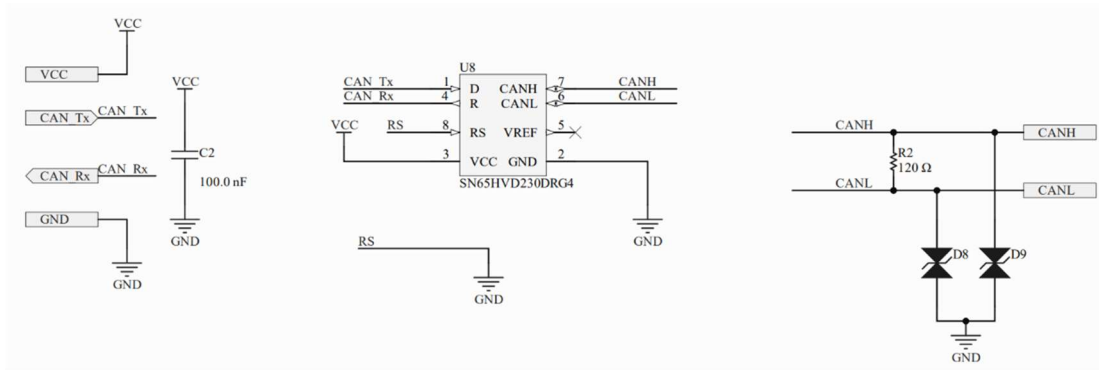
Therefore, the LM1117 integrated circuit is used to supply the circuit. Power supply can be found in Figure 5.7.



**Figure 5.7 :** Power supply section.

**5.3.5 CAN Bus section**

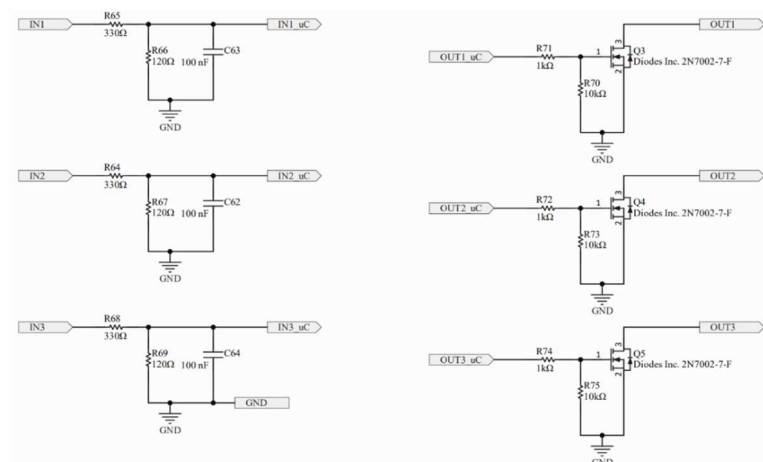
CAN Bus is a communication method that is widely used in automotive and is designed to transfer data safely in harsh environments. CAN Bus contains 2 cables and these cables carry inverted data according to each other. While the cables are routing in the environment, the noise is injected into the both cables in the same way. When CAN bus cables enter a node, the node inverts the data from one cable and superimposes it on the other. In this way, while the noise signals mixed in the cables dampen each other, meaningful data signals strengthen each other, thus eliminating the negative effects in harsh environments. In order to add the signals sent and received by the microcontroller to the CAN Bus network in this way, specially designed transceiver integrated circuits are required. In the BMS project, the SN65HVD230 integrated circuit is used as CAN Bus transceiver. TVS type diodes have been found that beneficial to filter the electrical shocks from external environment so a pair is added to the CAN Low and CAN High lines on the circuit board [17]. In this way, if applied discharge shock has higher voltage than the tresholds of these TVS diodes, these diodes will be conductive and will allow this shock to flow to the ground before it reaches the circuit. In addition, one of the 2 termination resistors of the CAN Bus line is integrated on the BMS. Another 120Ω resistor must be added to another control unit at the end of the CAN Bus communication network. CAN Bus communication stack is showed at Figure 5.8.



**Figure 5.8 : CAN Bus section.**

### 5.3.6 GPIO Section

A battery pack may contain other electrical equipment besides the BMS. These can be contactors which are mechanical switching elements of the battery pack, or actuators such as fans, compressors or valves to be used to air conditioning of the battery. Furthermore, it could be a sensor used to measure a parameter inside the battery pack. In order for the BMS to drive external sensors and actuators, it is decided to add 3 general purpose analog inputs and 3 general purpose digital outputs on the BMS. Since a 12 volt signal is expected from the analog inputs, this signal is passed through a voltage divider before connecting to the microcontroller. In addition, a low pass filter has been added to suppress electrical noise from outside. A low side driver circuit is used to drive the electrical loads. In this architecture, the positive supply of the external load will be connected directly to the supply and the negative supply will be switched over the BMS. For this purpose, an N channel mosfet is driven by microcontroller. GPIO section is showed at Figure 5.9.

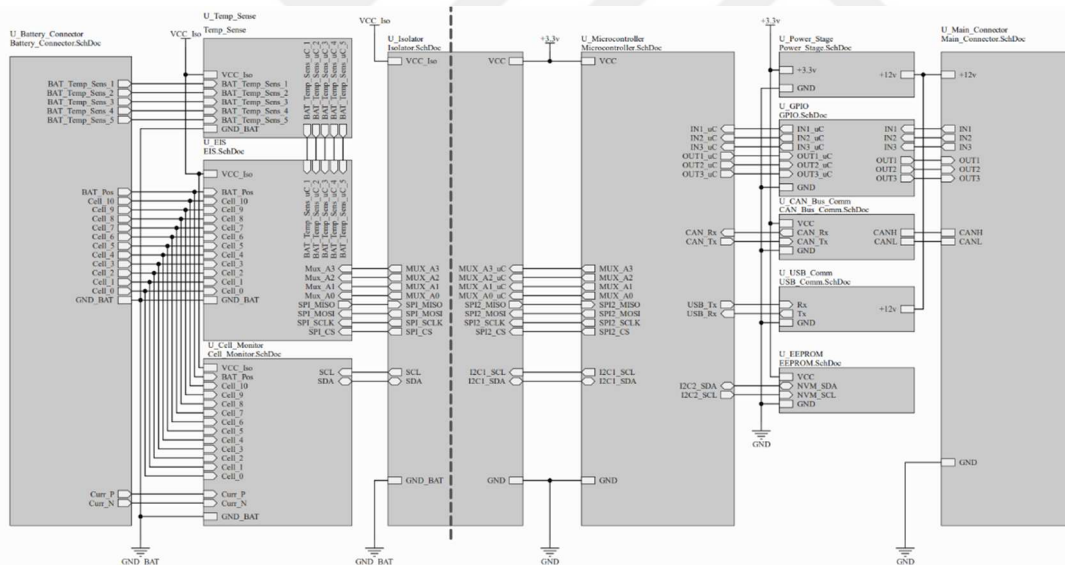


**Figure 5.9 : GPIO section.**

### 5.3.7 Connectors

In order for the designed BMS to be modular and easy to assemble, connectors are used in all interfaces. Molex microfit type connectors are used to make these connections suitable and durable for the size of the BMS board. Three connectors are used on the circuit board. The first of these connectors is used for battery temperature sensors. The second connector is used to capture voltage measurements from the battery cells. In the third connector, there will be main supply and general purpose inputs and outputs. Each connector has a different number of pins to prevent any connector from being connected incorrectly. For this reason, a plug cannot be inserted into any other connector than it should be, and unwanted electronic damage will be prevented. In addition, 10 nF capacitors are connected to each pin of the connectors in order to absorb electrical discharges that may come from the circuit board.

Finally all sub-circuits connected each other to complete the schematic design as showed at Figure 5.10.

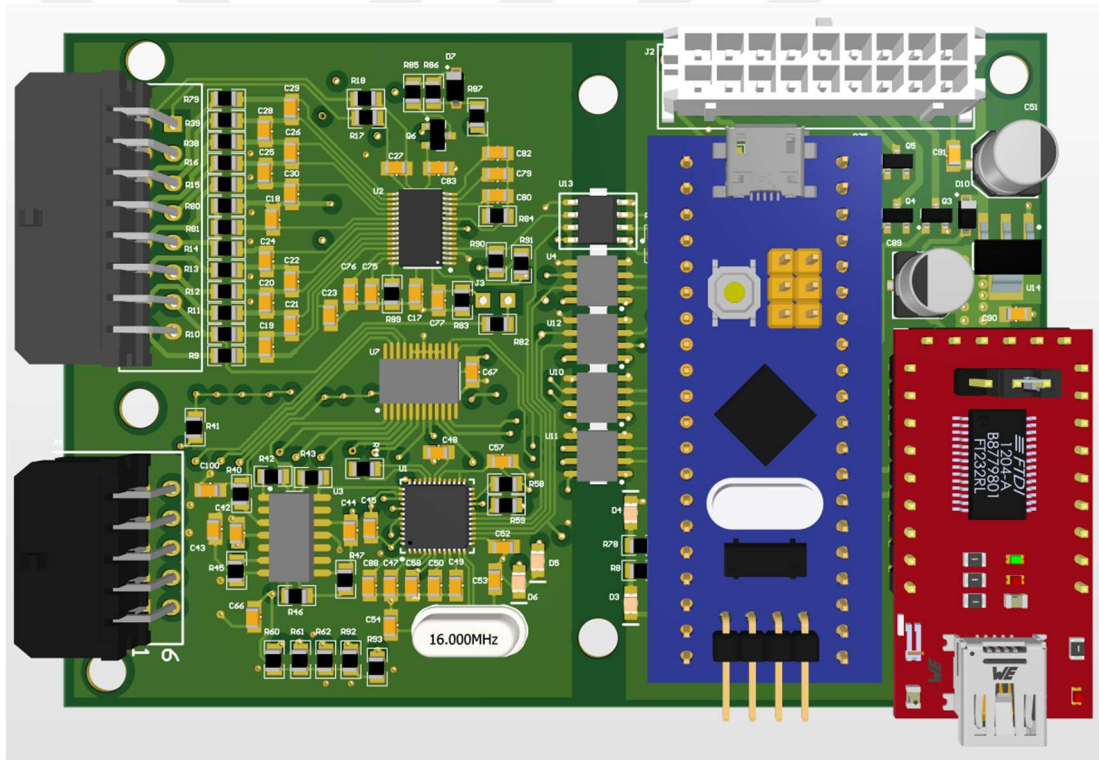


**Figure 5.10 :** Top level schematic of all sub-circuits.

### 5.4 PCB Design

After the schematic design of the BMS project is completed, it continued with the PCB design. PCB is the circuit board where all circuit components will be physically located and electrical connections between each other will be provided.

The design is started by placing the components on the board and positioning them relative to each other. Related components are placed close to each other. The more effectively the components are placed at this stage, routing can be done easier. In addition, the creation of signal lines with shorter length will increase performance. In order to achieve this, it is necessary to plan well during the placement of the components. Since the battery measurement circuits will be electrically isolated from other parts on the circuit board, all of these components are placed on left side of the board and the other components are placed on the right side of the circuit board. During the placement, attention is paid to ensure that the capacitance and TVS type diodes used for ESD protection are as close as possible to the connectors. Capacitors used to filter analog signals in battery measurement circuits are positioned as close to ADC measurement pins as possible. Final component placement is shown at Figure 5.11.



**Figure 5.11 :** Board component placement.

After the components are placed on the board according to their purpose, the routing process is started in order to create the electrical connections between components. Since the number of signals in the circuit is high and it is aimed to keep the circuit board size small, it is decided to design a 4-layer PCB. This will also provide extra protection against noise for high frequency signals. There will be components in the top and bottom layers, and it has been decided to carry signals in these layers. In the

middle 2 layers, it is aimed to place power planes and carry power. The routing width and via hole diameters to be used are selected according to the PCB manufacturer's specifications. Lines carrying differential signals, such as cell voltage measurement, are aligned very close to each other, and it is aimed that the resistances of the paths carrying these signals will be the same and the ambient electrical noise will affect these signals in an identical way. At the end of the process, one of the middle layers is used as the ground plane, so that the signal return paths are aimed to reach the ground as easily and quickly as possible. The other middle layer is used for power delivering. Thus, it is aimed to provide power to the energy-consuming components in the circuit over a path with as low resistance as possible. In addition, these power plane and ground plane layers, which are adjacent to each other, create a capacitive effect, making the board more resistant to noise. After all electrical connections in the circuit board are completed, mounting holes are placed in the corners and middle part of the board in order to make possible to mechanical assembly. Cross sections for each layers of PCB showed at Figure 5.12.

After the completion of the PCB design, the hardware design process has been completed. After that, production process is started for PCB and the necessary circuit components are also supplied. Components are soldered on the produced PCB by hand and prototyping work is started. After all the components are soldered, the circuit board is gradually powered and simple hardware checks are made. Voltage measurements are taken from the points on the board and compared with the required values. It has been checked whether there are hot spots on the circuit board and no problem has been found. The hardware platform has been successfully designed, produced, prototyped and made ready for the next stages. Soldered hardware is showed at Figure 5.13.

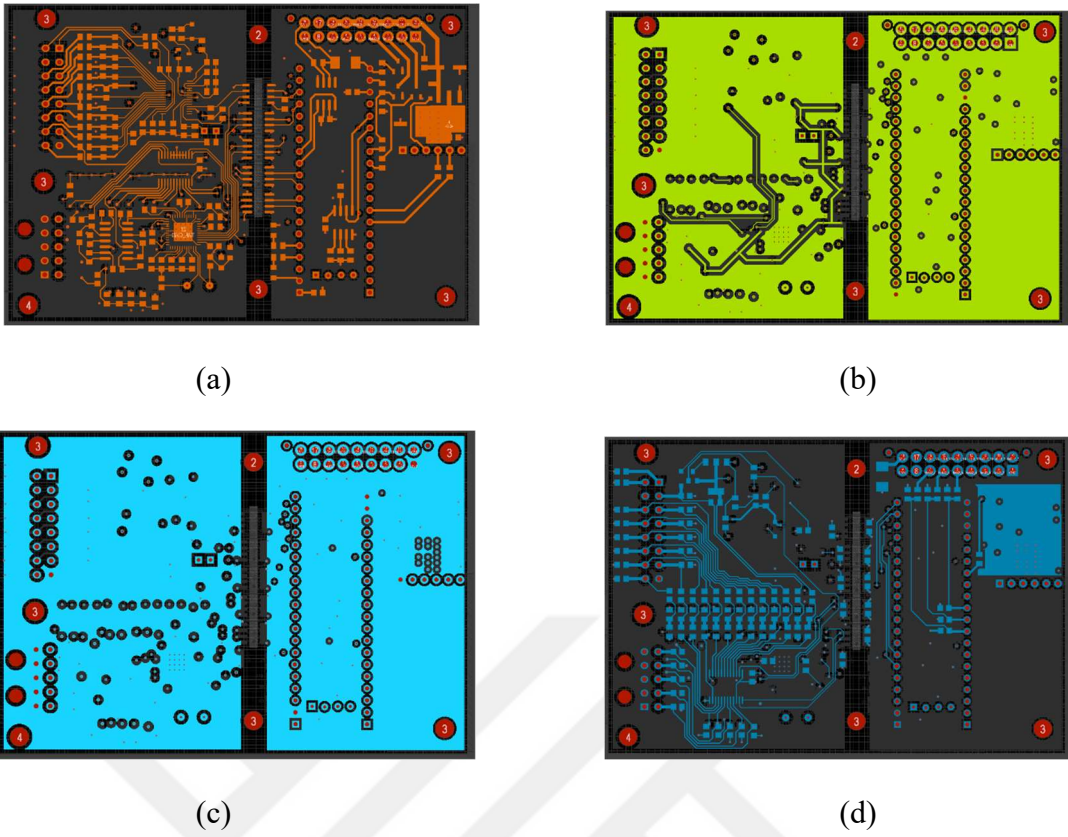


Figure 5.12 : (a) PCB top layer. (b) PCB second layer. (c) PCB third layer. (d) PCB bottom layer.

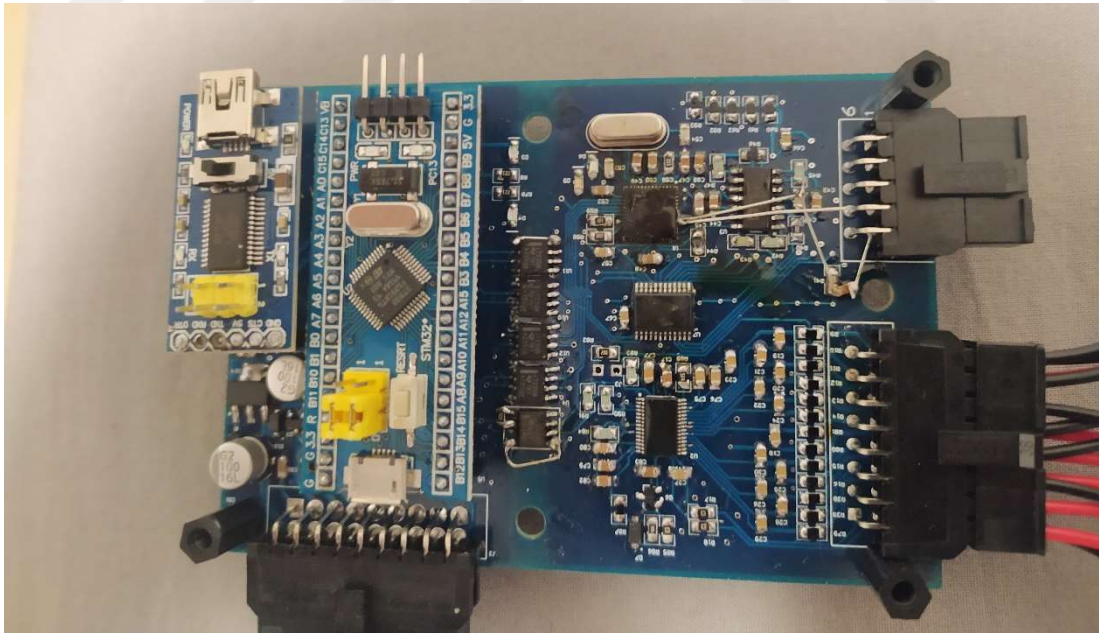
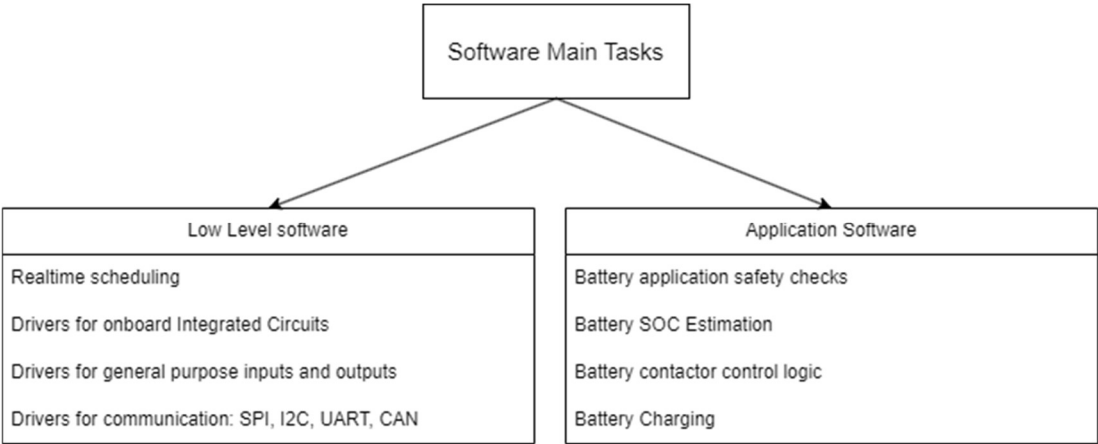


Figure 5.13 : Prototyped board.

### 5.5 Software Development

The hardware design completed in the previous stage, serves as a platform on which the software we will design at this stage will run. Embedded systems are combination of hardware and software. The designed hardware is useless without software. The software that will run on this hardware should make it possible to take measurements from the battery, make calculations based on these measurements, and take some actions as a result. The hardware will provide the interface for the inputs required by this software. In addition, software output signals will trigger the actuators on hardware.

The hardware design process is generally divided into 2 parts; low level software and application software. The reason for following this approach is that the most efficient methods are different for different tasks within the software that will run in the BMS. The low level software controls the integrated circuits on the BMS circuit board, provides communication. It is hardware dependent and will be programmed in C language. The application software, which is hardware-independent and includes battery control algorithms, is model-based and will be developed in the MATLAB/Simulink environment. Figure 5.14 is a table that shows software sub-parts and tasks.



**Figure 5.14 :** Main BMS software tasks.

#### 5.5.1 Low level software design with C language

Low level software is the software that depends on the hardware of the system. This software enables communication with the integrated circuits around the circuit board. It contains a real time operating system so that BMS algorithms can work safely and

stably. It contains the necessary bidirectional interfaces for the application software to control the hardware.

C language and STM32 Cube IDE development environment are used for the development of this software layer. Development is started with GPIO drivers first. These drivers control the digital inputs and outputs of the microcontroller. Thanks to these drivers, BMS has gained the ability to drive external loads, capture external inputs and drive LEDs and other digital signals on the circuit board.

In the next step, communication modules are developed. SPI driver has been integrated firstly. This driver will enable the microcontroller to communicate with the EIS measurement circuit. The I2C driver has been developed and thus the microcontroller has become able to communicate with the cell monitor and EEPROM. By developing the UART driver, it is possible to exchange data with circuit board and USB port. By developing the CAN Bus driver, communication between BMS's and other electric vehicle components has been ensured. For the validation of all the designed drivers, the communication lines are physically accessed with a logic analyzer. The data packets coming out of the microcontroller and the responses of the integrated circuits on the board are examined and the data flow is validated by comparing measurements with the datasheets of the integrated circuits.

ADC driver has been developed and it is used to get measurements from analog sensors that connected to the BMS from outside.

All drivers are called within the integrated real time operating system and the scheduler running in it. In this way, priority ordering has been made in communication and timeout errors have been prevented. In addition, the scheduler is enabled that the BMS algorithms can also work in real time safely.

Finally, necessary API interface functions are developed to link application software and low level software.

### **5.5.2 Application software design with MATLAB/Simulink**

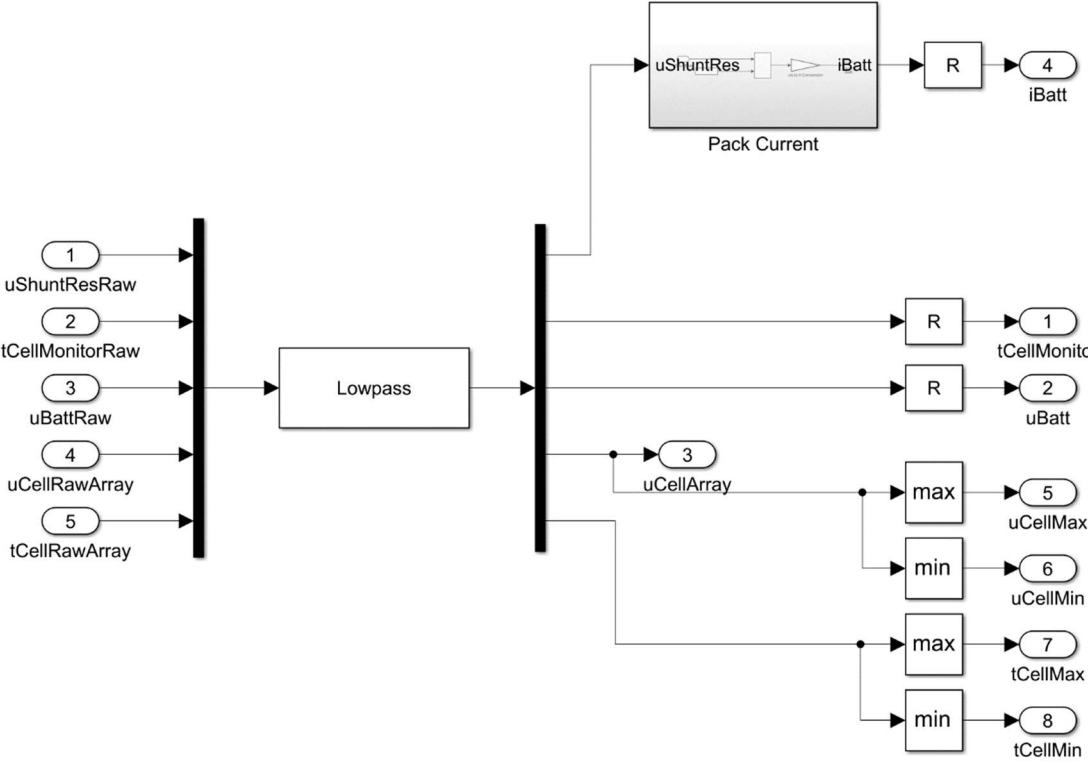
Application software is a model-based software layer that includes BMS algorithms. In this layer, controllers, decisions and calculations are made. Development environment is based on MATLAB/Simulink. After the development is completed, code generation tool inside Simulink is used and C codes are produced. These

generated codes are integrated and compiled with the low-level software completed in the previous stages, and then flashed into microcontroller.

In the application software layer, filtering of signals, BMS main state machine, SOC Calculation, contactor control, charging, cell balancing and safety checks functions have been developed.

**5.5.2.1 Input filters**

Many values such as measured cell voltages and cell temperatures are used as inputs in critical functions for BMS. Therefore, noise should be extracted from these signals as much as possible. These signals are filtered using the low pass filter block before entering any other function. In this part of the software, the battery pack current is also calculated using the shunt resistor voltage. In addition, maximum-minimum cell voltage and maximum-minimum cell temperatures are obtained to be used in the next stages. Input filters are showed at Figure 5.15.



**Figure 5.15 :** Application software input filters.

**5.5.2.2 BMS state machine**

A stateflow block is used for the BMS main operating states. 5 states are defined in this block. Flow starts with the 'power down' state first. In this case all contactors are

open, so the battery is electrically isolated from the rest of the electric vehicle. In this case, no charge or discharge takes place on the battery. When a power up request comes from outside, the 'precharge' state is entered. Here, the main contactor on battery negative side and precharge contactor are triggered and the main contactor on the positive side is left open. Such capacitive loads inside the vehicle are charged through precharge contactor and precharge resistor and inrush current is prevented. After this stage, according to the direction of the current flowing from the battery, one of the separately defined 'power up' states for charge or discharge is switched. Here the main contactor in the positive side is triggered and the precharge contactor is not triggered. Thus, the battery is fully connected to the electric vehicle's system and is now operational. After this stage, if the power up request is interrupted or if powerdown is requested due to other effects, the 'power down' state can be returned. The condition here is that the battery current should be below a certain level. Because if the contactors are opened while current flows through the contactors, this may cause premature aging or welding of the contactors. There is also an 'emergency power down' state. If the BMS algorithms detect a dangerous situation, main state machine enters into this state. Since it is urgent to disconnect the battery from the vehicle here, the switch is made without waiting for the current to drop below a certain value. BMS state machine can be found in Figure 5.16.

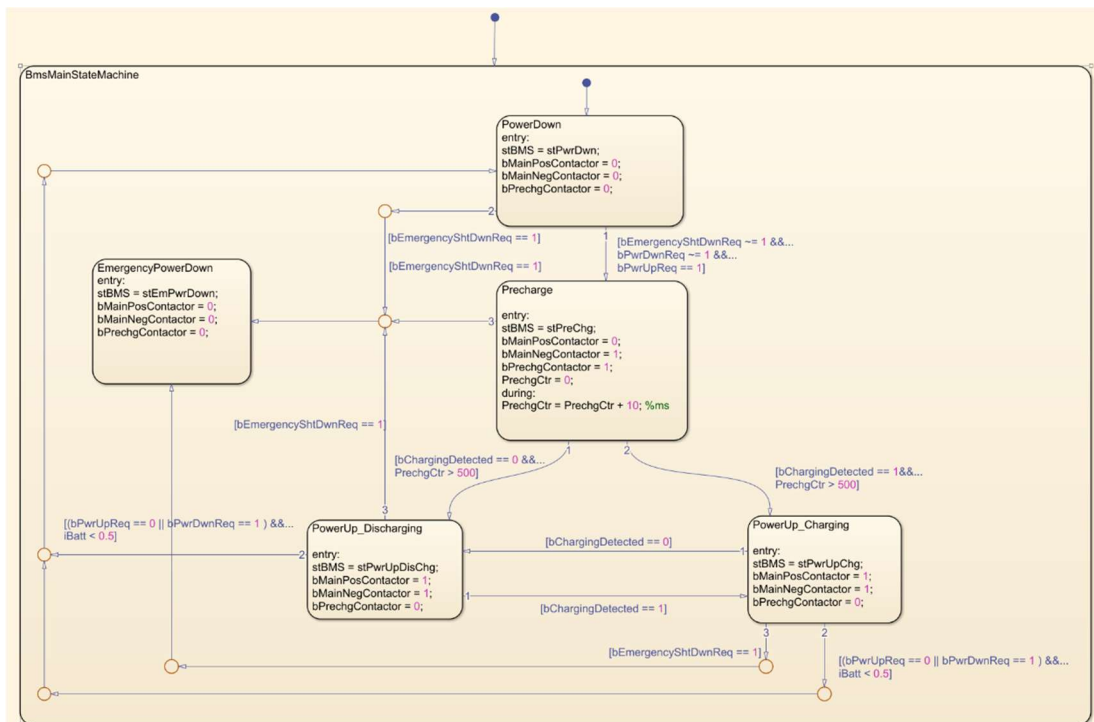


Figure 5.16 : BMS state machine.

### 5.5.2.3 BMS safety tracker

In order for the battery to work safely, some parameters must be within certain ranges. In order to validate that the battery is in safe ranges, cell voltages and temperatures, battery current, voltage difference between cells are checked with comparators. 2 levels of error are determined for signals that are not in the safe range. At the first level, the values have slightly exceeded the limit and power down is requested to keep the battery safe. Since the urgency is low here, it is expected that the battery current will decrease in order for the contactors to open. If it is a second level fault, it represents a definite urgency for the battery, and in this case, emergency shutdown is requested and the battery contacts are opened as soon as possible. The software part which checks the critical values can be found in Figure 5.17.

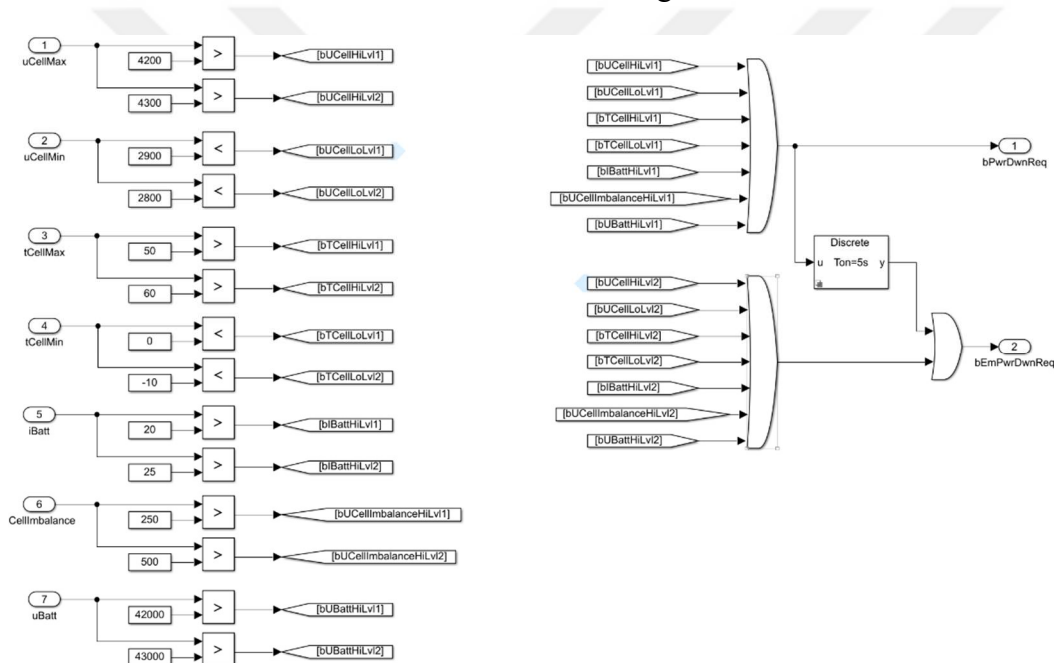
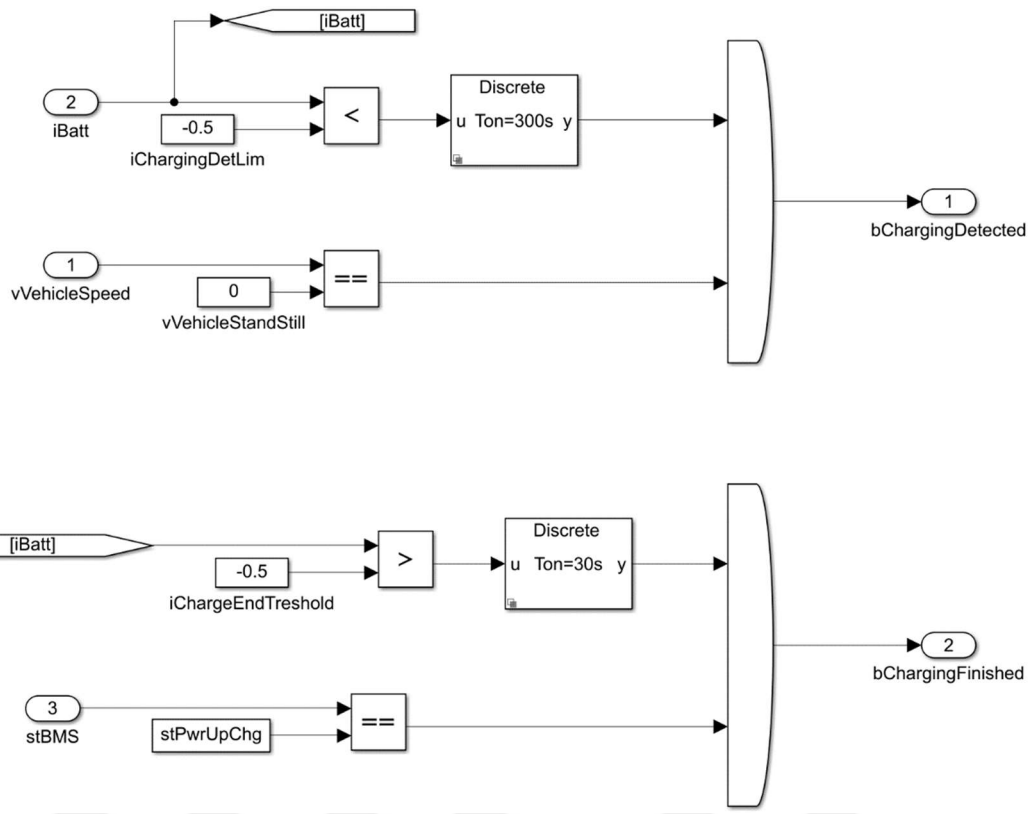


Figure 5.17 : BMS safety limits checks.

### 5.5.2.4 BMS charging detection logic

While controlling the battery, different algorithms can be applied during charging and discharging processes. First of all, it should be determined whether the battery is charging or discharging. Here it is judged that the battery is charged if the vehicle is at a standstill and the battery current is negative for a certain period of time. The battery current is also monitored to understand that the charge is over. If the main state machine is in the charge power up state and the current has fallen below a certain value

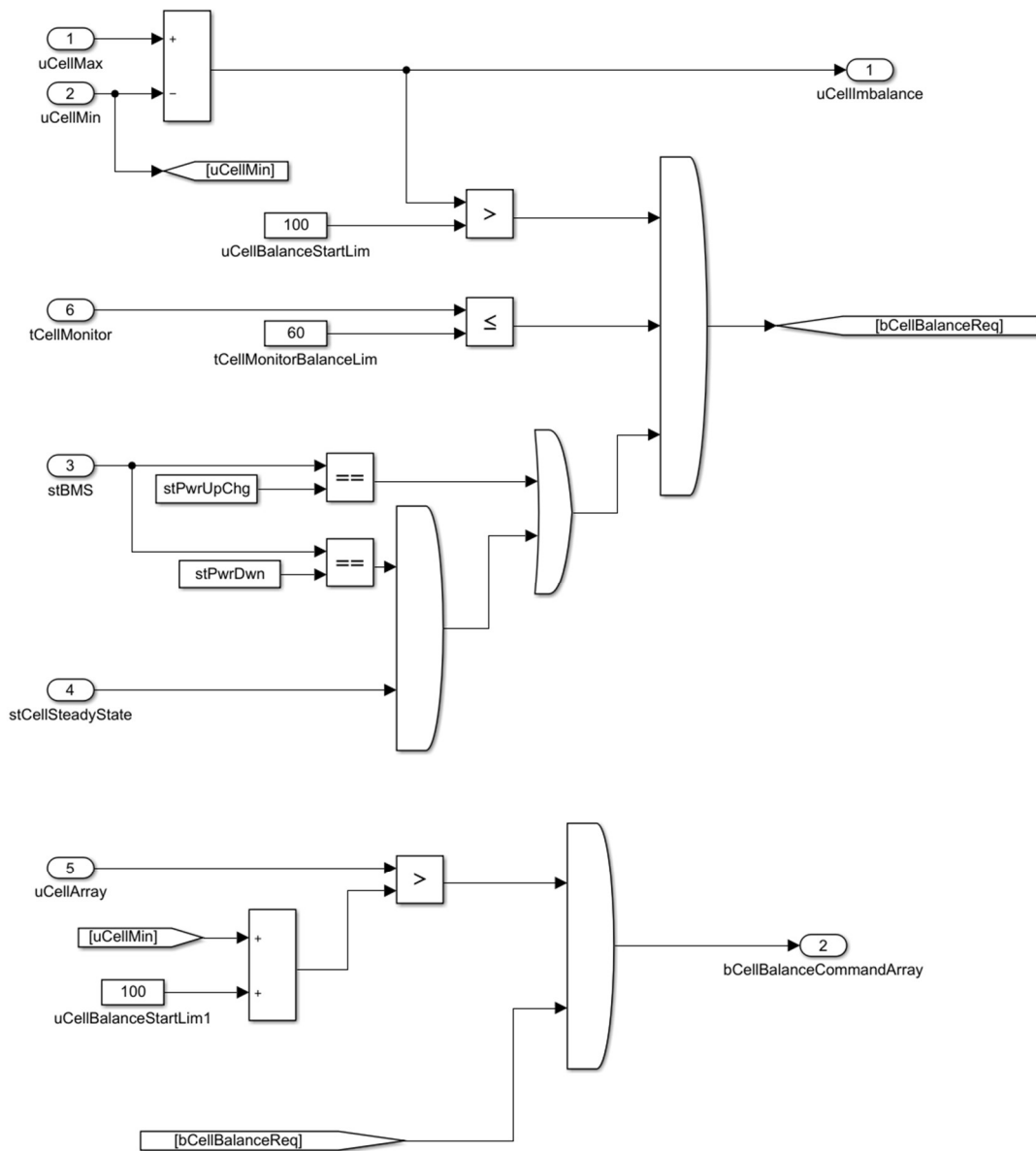
for a certain period of time, it is judged that the charge is finished. Charging detection logic can be found in Figure 5.18.



**Figure 5.18 : BMS charging detection logic.**

### 5.5.2.5 BMS cell balancing logic

In order to use the capacity of the battery most effectively, the voltage levels of the cells connected in series should be as equal as possible to each other. For this, a balancing algorithm has been developed. It is decided that the balancing should be done while the battery is charging or idle and the cells are in a stable state. If the battery current does not flow for a certain period of time, it is decided that the cells are stable. In addition, for the balancing algorithm to work, it is decided that the difference between the cell voltages should exceed a limit and the temperature of the balancing circuit should be below a certain limit. If these conditions are met, the balancing command for each cell is calculated as on or off according to the voltage difference between the cells. Cell balancing algorithm can be found in Figure 5.19.

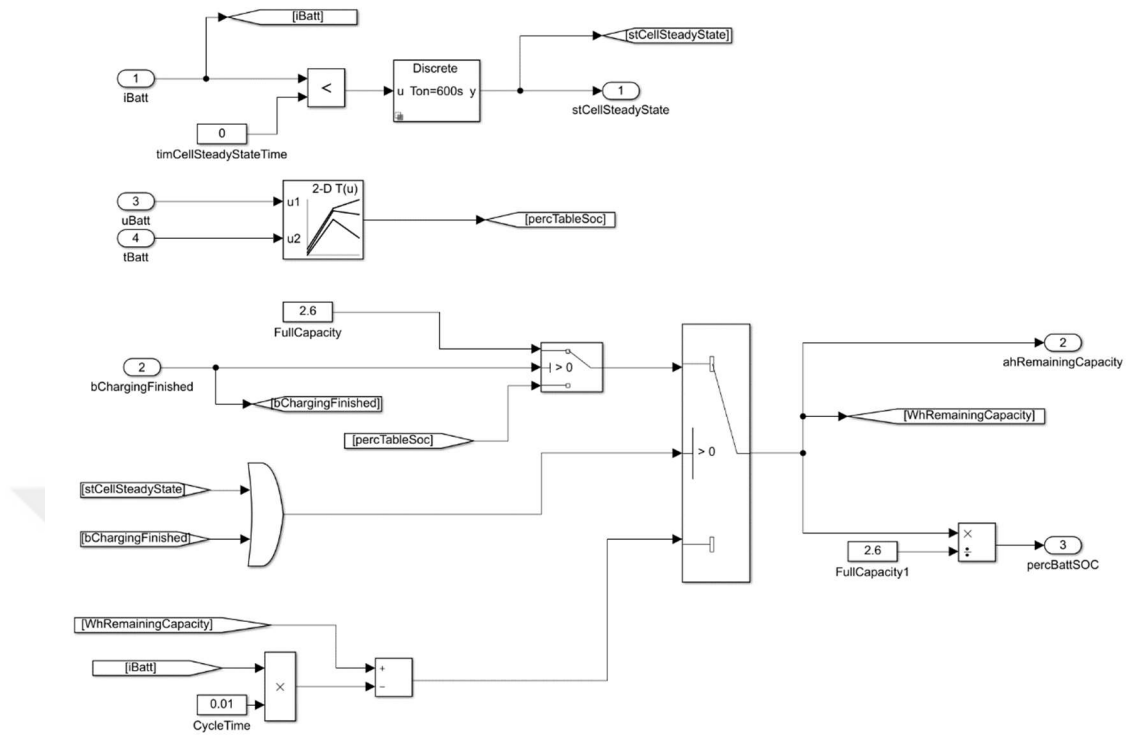


**Figure 5.19 : BMS cell balancing logic.**

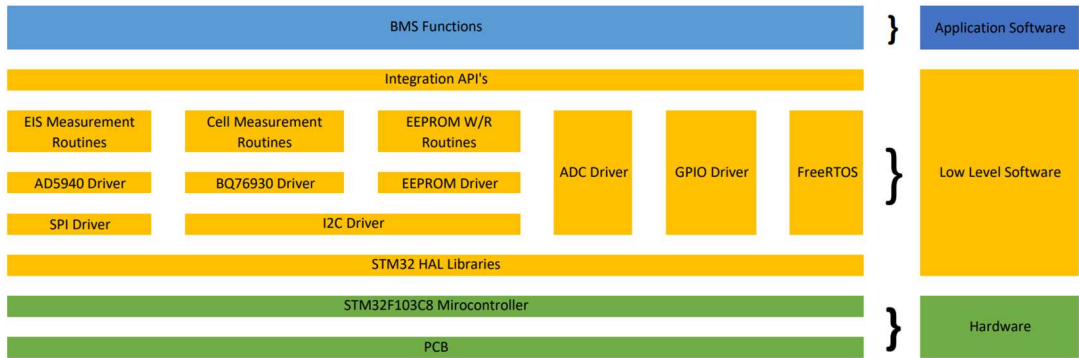
### 5.5.2.6 BMS SOC estimation logic

In order to accurately calculate the range of the electric vehicle, the SOC value must be accurately estimated. Three different methods are used for SOC Estimation in BMS software. The main method here is coulomb counting. In order to support this method, 2 more methods have been integrated. The SOC increases while the vehicle is charging. The algorithm is designed to set the SOC to 100% as soon as the charge is finished. In addition, if the cells are at steady state, the SOC is estimated using a look-up table by looking at the cell voltage and cell temperature. If the conditions are not suitable for these 2 methods, the BMS calculates the residual capacity by integrating the instantaneous flowing current. The remaining capacity is divided by the total

capacity of the battery and the SOC is estimated. BMS SOC estimation logic can be found in Figure 5.20. Also finished software architecture can be found in Figure 5.21.



**Figure 5.20 : BMS SOC estimation logic.**



**Figure 5.21 : Final BMS software architecture.**



## 6. SYSTEM TEST AND VERIFICATION

It is necessary to collect data on a sample battery pack in order to conduct tests of the designed BMS hardware and software and validate the designs. But since the battery of an electric vehicle would be too large and dangerous for such an experiment, it is decided to make a small demonstration battery pack instead. A miniature electric vehicle battery is obtained by connecting 10 cells in series on a test setup. Electrical connections are established between the cells and the BMS in order to take voltage measurement from the cells. Voltage sensing connections and power supply connections from battery pack to BMS are separated due to current flow on cables that carrying power may cause to voltage drop because of the cable resistance and it can may distort the measurements. Samsung ICR18650-26J 2600 mAh cells are selected to be used in the demonstration. Cell voltages has been measured on this battery and EIS measurements are carried out. The data measured by the BMS is sent to PC environment via USB connection and the data is observed on the terminal software. Test setup can be found in Figure 6.1.

First, the voltage levels of the cells are measured on the BMS. The measured results are also compared with the measurements taken by the multimeter to confirm their accuracy. The cells are charged and discharged to different charge levels and the stable operation of the system is tested throughout the measurement range. After every measurement cycle, cell voltages are sent to computer via USB connection. Cell voltage measurements taken by BMS can be found in Figure 6.2.

EIS measurement has been taken on a cell at 6 different SOC values. These SOC values determined as 0%, 20%, 40%, 60%, 80% and 100%. In this way, it is aimed to observe how the EIS graphs of cells are changing at different charge levels and examine the characteristics of cell throughout usable range. Captured EIS measurement data is decided to be used for further equivalent circuit model estimation. EIS measurements that executed at different charge levels can be found in Figure 6.3.

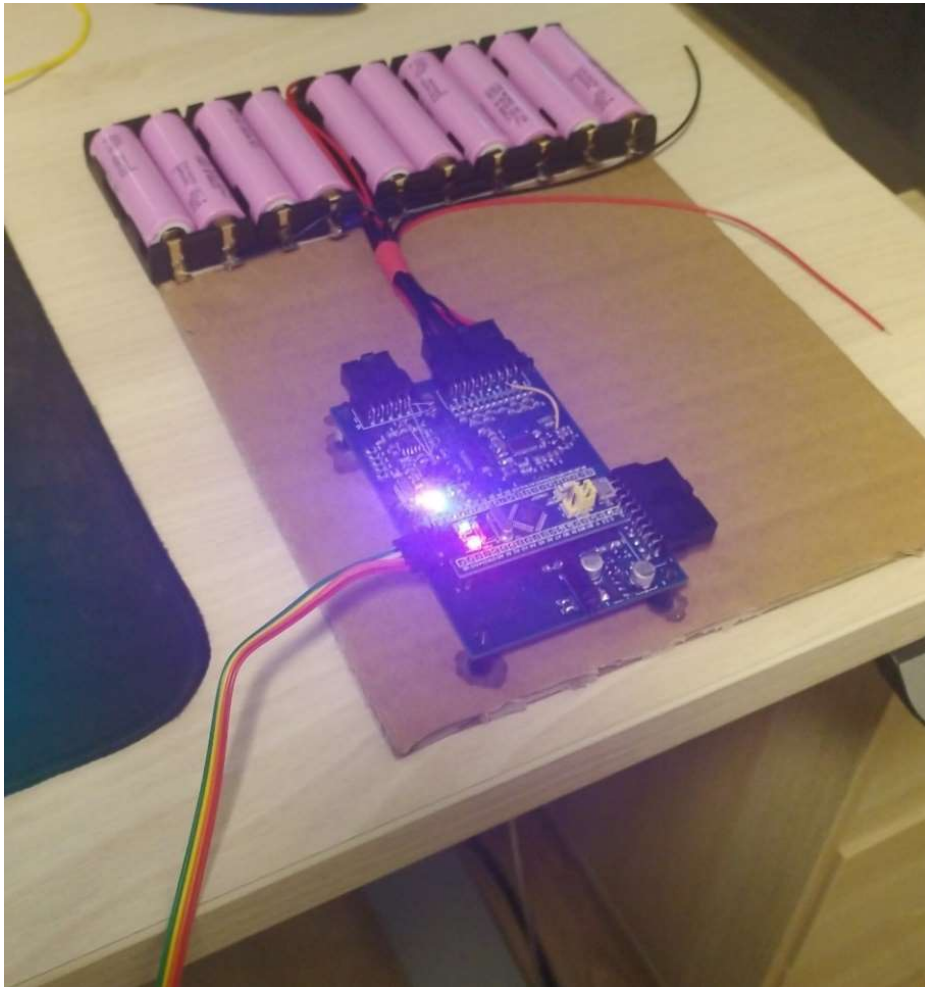


Figure 6.1 : BMS test setup.

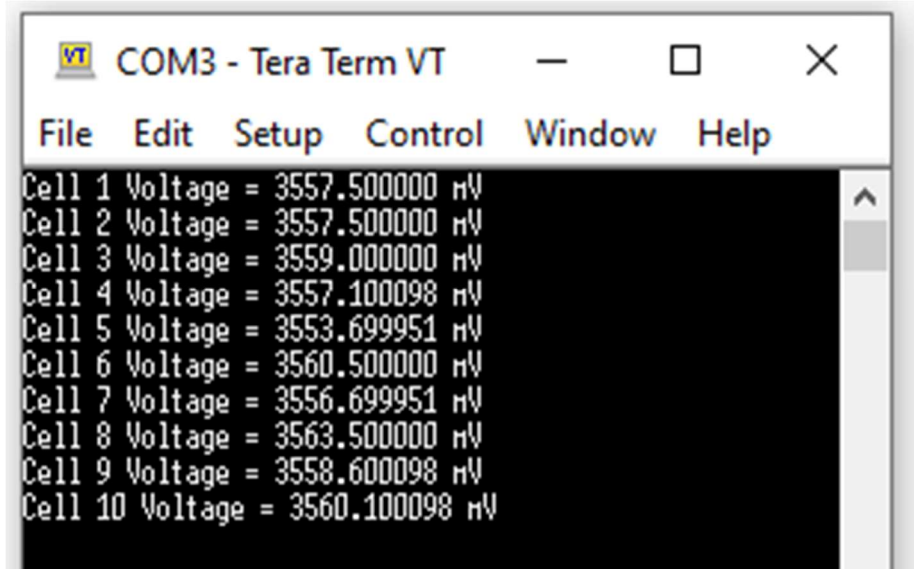
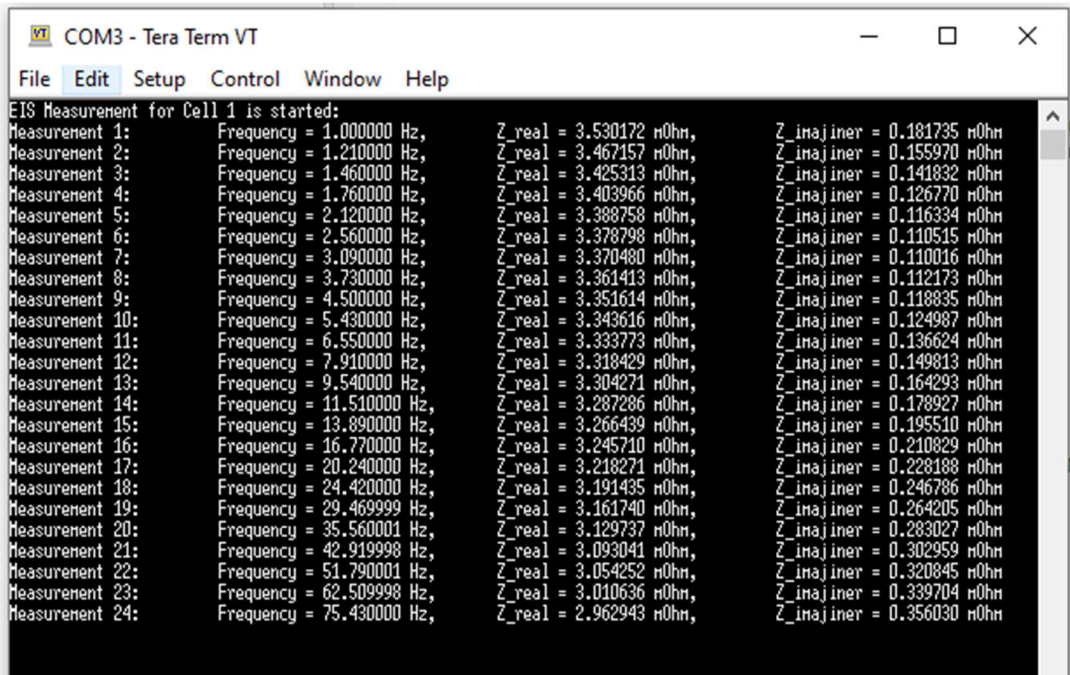


Figure 6.2 : Cell voltage measurements via BMS.

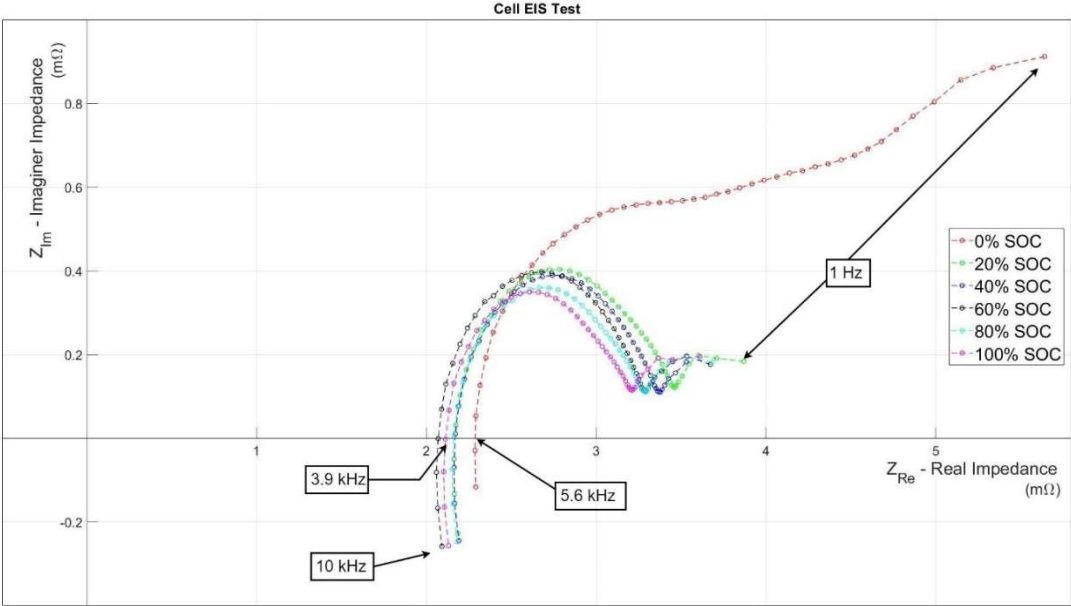


**Figure 6.3** : EIS measurement at different frequencies via BMS.

As a preparation for test, the cell is first discharged to 0% SOC. For this, the discharge process is started with 1C discharge current. When the cell voltage reaches 2.8 volts, the discharge current is reduced and the energy in the battery is completely discharged. When the discharge current reaches down to 50 mA, the discharge process is terminated. While the cell is being charged, it is charged with 0.5 C and the charging process is finished when the charging current reaches down to 50 mA. After each charging and discharging process, it has been waited for 2 hours for the cell chemistry to stabilize and then EIS measurement is taken. EIS measurement from a cell took almost 8 minutes. This time depends on the points where the measurement range starts and ends and how many points will be measured in this interval. It is seen that, when measurement frequency range goes lower, measurement time increases as completing one cycle takes more time. In addition, multiple samples are taken at each measurement point and the measurements are passed through digital filters. This is another factor in the long measurement time. After the measurements are transferred to the PC via USB connection, they are graphed in the MATLAB Simulink environment. EIS spectra compares different SOC levels can be found in Figure 6.4.

As seen in the figure, the EIS graph shifts to the right and up as the SOC of the cell decreases. This means that the internal resistance of the cell increases. It is observed

that the graph drastically shifted to the right and up, when 0% SOC, the energy in the cell is about to run out.



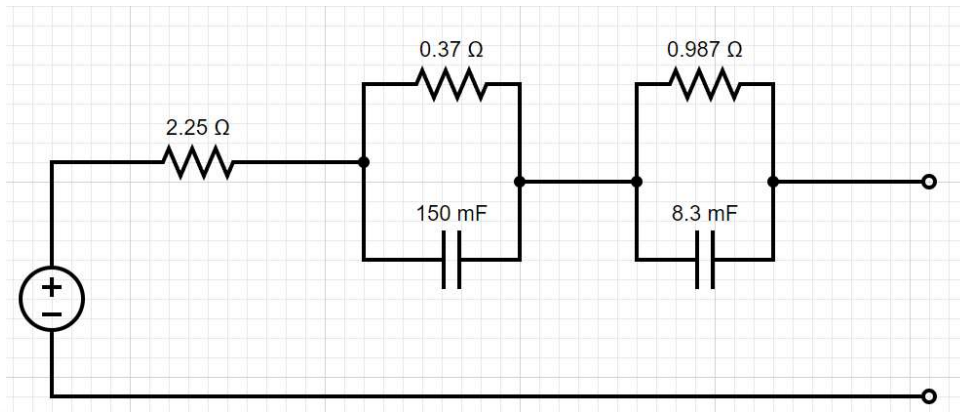
**Figure 6.4 :** EIS graph for different SOC levels.

In this case, the internal chemistry of the cell is more resistant to current and it is harder to transfer the ions through solution and other materials. This explains why the maximum charge and discharge currents of the cell decrease as the cell charge decreases. After testing, it is decided to program the BMS algorithm to prevent overdischarging since it is observed how cell character changes when it is overdischarged. The findings from the experiment are consistent with the experimental results in previous studies [17,18]. It also shows why the difference between the cell voltage under load and the open circuit voltage increases as the SOC decreases in the case of a constant discharge current. Because increasing internal resistance causes more voltage drop under the same current.

After EIS responses investigated, an equivalent circuit model is suggested in order to understand the cells internal structure. Also, expressing the cell structure as an electrical circuit, will make it easier to model the cell during application In order to model cell electrical behaviour. In order to model to cell structure, a 2RC circuit model is used. This model contains 2 sets of resistors and capacitances connected in series. Also, includes one series connected resistor and one series connected voltage source. Zfit library on MATLAB is used to estimate the circuit model. The EIS measurement

test at %100 SOC is used as a data source for optimization. Zfit tool optimizes circuit parameters to minimize error between real EIS measurement and given circuit model.

Calculated circuit parameter and circuit structure is given at Figure 6.5.



**Figure 6.5 :** Estimated Cell Equivalent Circuit Model.



## **7. CONCLUSION AND RECOMMENDATIONS**

In this thesis, a battery management system is designed from scratch. The main contribution of this study is to integrating the electrochemical impedance spectroscopy method into both BMS hardware and software. Thus, the estimations about the internal structure of the battery can be carried out better. The project is started with requirement analysis. Needs and problems in electric mobility field are identified and requirements are determined accordingly. A concept design of a hardware that will meet these requirements is made and the main structure is determined. Schematic design and printing circuit board design have been completed by following this concept design. Designed equipment is produced and prototyping work is performed. Drivers in C language are developed and board bring up activity is completed. The model based application software has been designed on MATLAB/Simulink and integrated to platform. After that, design and development process has been completed. In order to test the designed BMS, a demonstration battery consisting of 10 serial cells is builded. On the battery, Electrochemical Impedance Spectroscopy is performed via the designed BMS and the internal structure of the cells have been compared at different SOC values. It is seen that battery internal structure is very dependent to SOC level and as SOC level decreases, internal resistance of the battery increases.

The finished system is a complete solution to ensure safe control of the batteries used in electric vehicles, electric scooters and even electric aircrafts.

### **7.1 Recommendations and Future Work**

Electrochemical impedance spectroscopy process is performed on cells at different SOC levels, with the designed BMS. In order to better examine the internal structures of the cells and the effect of environmental conditions on this structure, more measurement at different aging levels and different temperatures will be useful. To perform these tests, the cells should be charged and discharged a few hundred cycle

and measurements should be taken in a controlled climate cabin. Since these facilities were not available, these processes could not be performed in this thesis study.

In addition, an algorithm that uses EIS data for SOC and SOH estimation can be designed. Furthermore, validating this algorithm on the test bench may fill a gap in the literature.



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## **CURRICULUM VITAE**

**Name Surname** : **Medet Kerem Babacan**

**EDUCATION** :

- **B.Sc.** : 2020, Istanbul Technical University, Faculty of Electrical and Electronic Engineering, Control and Automation Engineering
- **M.Sc.** : 2023, Istanbul Technical University, Graduate School of Science, Mechatronics Engineering

**PROFESSIONAL EXPERIENCE AND REWARDS:**

- (2022 - ...) DAF Trucks N.V. - Embedded Software Engineer
- (2018 - 2022) FEV Türkiye - Electric Vehicle Systems Engineer