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ACTIVE AND PASSIVE BALANCING BATTERY CONTROL FOR ELECTRIC VEHICLE

PHD Thesis

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We have read the thesis entitled **"Active and Passive Balancing Battery Control for Electric Vehicle"** completed by **Tolga Özer** under the supervision of **Assoc. Prof. Dr. Sinan KIVRAK** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of PHD.

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ACTIVE AND PASSIVE BALANCING BATTERY CONTROL FOR ELECTRIC VEHICLE

ABSTRACT

Battery technology is developing every day and usage rate is increasing day by day. Particularly with the spread of electric vehicles, battery usage will also increase. In this way, the work done in the battery field will become more important. Generally, battery-based systems consist of many battery cells. In systems consisting of several battery cells, it is important to ensure that the batteries can be charged and discharged in the same amount, in terms of the effective use of the total energy and the prolongation of the battery life. This system is called battery management system.

Two different battery management systems based on passive and active methods have been designed and implemented for use in electric vehicles in the proposed thesis. The first of these battery management systems includes both active and passive balancing, and the second includes only passive balancing. Resistance based passive control method was used in both battery management systems. metal oxide semiconductor field effect transistor switching elements have been used as a load instead of resistance. For this purpose, an original digital analog converter circuit was designed and used in passive balancing systems. In the first battery management system, active balancing method was applied in addition to passive balancing method. A circuit topology was designed in which both control methods could be applied. The application for two methods was successfully performed. A circuit design in which active and passive balancing methods can be applied in the same circuit topology was made for the first time in the literature. In this respect, a new circuit topology has been introduced to the literature. The applicability of these methods has been tested with two different experimental systems. The successful operation of these systems has been proved by the obtained experimental results.

Keywords: Battery, battery control, battery management system, active-passive balancing.

ELEKTRİKLİ ARAÇLAR İÇİN AKTİF VE PASİF BATARYA KONTROLÜ

ÖZ

Batarya teknolojisi her gün gelişmekte olup kullanım oranı da gün geçtikçe artmaktadır. Özellikle elektrikli araçların yaygınlaşması ile batarya kullanımı da artacaktır. Böylelikle batarya alanında yapılan çalışmalar daha önemi hale gelecektir.

Genellikle batarya tabanlı sistemler birçok batarya hücresinden oluşmaktadır. Birden çok batarya hücresinden oluşan sistemlerde, bataryaların aynı oranda şarj ve deşarj olabilmelerini sağlamak, toplam enerjinin efektif kullanılması ve batarya ömrünün arttırılması açısından önemlidir. Bu işlemi yapan sistemlere batarya yönetim sistemleri denilmektedir.

Önerilen tez çalışmasında elektrikli araçlarda kullanılmak üzere pasif ve aktif yöntem tabanlı iki farklı batarya yönetim sistemi tasarlanmış ve uygulaması gerçekleştirilmiştir. Bu batarya yönetim sistemlerinden birincisi hem aktif hem de pasif balanslama yöntemini, ikincisi de sadece pasif balanslama yöntemini içermektedir. İki batarya yönetim sisteminde de direnç tabanlı pasif kontrol yöntemi kullanılmıştır. Direnç yerine metal oksit yarı iletken anahtarlama elemanları yük olarak kullanılmıştır. Bu amaçla özgün bir dijital analog dönüştürme devresi tasarlanmış ve pasif balanslama sistemlerinde kullanılmıştır. Birinci batarya yönetim sisteminde, pasif balanslama yönteminin yanısıra, aktif balanslama yöntemi de uygulanmıştır. Her iki kontrol yönteminin uygulanabileceği bir devre topolojisi tasarımı yapılmıştır. İki yöntemin uygulaması başarılı bir şekilde gerçekleştirilmiştir. Aktif ve pasif balanslama yönteminin aynı devre topolojisinde uygulanabileceği bir devre tasarımı literatürde ilk defa yapılmıştır. Bu açıdan da literatüre yeni bir devre topolojisi kazandırılmıştır. Bu yöntemlerin uygulanabilirliği oluşturulan iki farklı deneysel sistemle test edilmiştir. Bu sistemlerin başarılı bir şekilde çalıştığı elde edilen deneysel sonuçlar aracılığı ile kanıtlanmıştır.

Anahtar Kelimeler: Batarya, batarya kontrol, batarya yönetim sistemi, aktif-pasif dengeleme.

CONTENTS

NOMENCLATURE

Acronyms

°C	Centigrade
µA	Microampere
A	Ampere
AC	Alternative Current
ADC	Analog Digital Converter
ASCII	American Standard Code for Information Interchange
C	Capacitance
DC	Direct Current
DMA	Direct Memory Access
DNS	Domain Name System
EBCDIC	Extended Binary Coded Decimal Interchange
FTP	File Transfer Protocol
Gb/s	Gigabit/Second
GIF	Graphics Interchange Format
HTTP	Hyper Text Transfer Protocol
I2C	Inter-Integrated Circuit
IC	Integrated Circuit
ID	Identification Number
JPEG	Joint Photographic Experts Group
Kb/s	Kilobit/Second
kHz	Kilohertz
km	Kilometer
kV	Kilovolt

L	Inductance
LED	Light Emitting Diod
m	Meter
Mbps	Megabit Per Second
MHz	Megahertz
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
mV	Milivolt
mΩ	Miliohm
PC	Personal Computer
PLC	Programmable Logic Controller
PWM	Pulse Width Modulation
R	Resistor
RPC	Remote Procedure Call
RTU	Remote Terminal Unit
SMTP	Simple Mail Transfer Protocol
SNMP	Simple Network Management Protocol
SPI	Serial Peripheral Interface
SPX	Sequenced Packet Exchange
TCP / IP	Transmission Control Protocol/ Internet Protocol
TFTP	Trivial File Transfer Protocol
TIFF	Tagged-image File Format
UDP	User Datagram Protocol
USB	Universal Serial Bus
V	Voltage
Wh	Watt-Hour

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CHAPTER 1

INTRODUCTION

Battery technology has a wide range of uses from simple electronic devices to electric vehicles area. Charging batteries uses every day by almost everyone The global revenue from batteries reached $33 billion in 2018. According to estimates, the global lithium ion battery market will surpass $60 billion by 2025, as reported in the latest study by European Commission [1].

Proper management of batteries is essential because of batteries sensitive structure. Therefore, proper use of batteries is very important in terms of their performance and life along with the performance of the system. This situation indicates that the batteries must be controlled. These control systems named as a battery management system (BMS) which monitors and manages batteries. The BMS keeps each cell within a desired voltage range through cell balancing. The cells need protection from cell overvoltage (COV) and cell undervoltage (CUV) by alerting the user if these conditions exist. This system also needs to prevent gas leakage or fires by shutting the system down if thermal excursions occur beyond the set temperature limits.

Battery packs can be used in series and parallel. Voltage, current and capacity values of the battery pack are determined according to serial and parallel connected cell numbers. A battery management system is used to ensure coordination between these series and parallel connected cells and to establish the safe working area of the battery packs. The battery management system consists of three main parts: data monitoring, calculation and protection. The data monitoring function observes instantaneous conditions such as voltage, current and temperature of each cell in the battery pack. The calculation function calculates values such as battery charge rate, battery health status, maximum and minimum charge/discharge current, maximum and minimum voltage, run time and number of cycles using the instantaneous values observed from the data monitoring function. With the values obtained from the calculation function, it is possible to obtain high-low voltages during charging discharging from the cells and the battery pack in the protection function, high current draw, leakage current and high / low preventing the formation of heat. One of the important tasks of the battery management system determining the battery charge ratio to ensure that the battery cells in the battery pack are balanced in case of charge and discharge. Different methods are used for this balancing process [2].

1.1 Battery Technologies Used in Electric Vehicles

Today, various battery technologies with different nominal voltage and energy density are available and are being developed. Battery technologies and characteristics that are commonly used in electric vehicles and yet in research are given in Table 1.1 [3].

Table 1.1 Battery technologies used in electric vehicles

Battery Types	Nominal Voltage (V)	Energy (Wh / kg)	Cycle Life	Memory Effect	Operating Temperature (°C)
Pb-acid	2	35	1000	No	-15, +50
NiCd	1.2	50-80	2000	Yes	-20, +50
NiMH	1.2	70-95	<3000	Rarely	-20, +60
Zebra	26	90-120	>l200	No	+245, +350
Li-ion	3.6	118-250	2000	No	-20, +60
LiPo	3.7	130-225	>l200	No	-20,+60
Zn-air	1.65	460	200	No	-10, +55
Li-S	2.5	350-650	300	No	-60,+60
Li-air	29	1300-2000	100	No	-10, +70

1.1.1 Lead-Acid (Pb-Acid) Battery

Lead acid batteries are an old type battery technology that is frequently used in many applications. Batteries consist of structurally positive, negative electrodes and electrolyte fluids. In this type of battery, lead is used in negative electrode, lead dioxide is used in positive electrode (PbO_2) and sulfuric acid (H_2SO_4) is used as electrolyte liquid. The main advantages of lead acid batteries are their cheapness, high discharge current and no memory effect. In addition to these advantages, it has some disadvantages. The main disadvantages is that battery life is reduced when not in use. In addition, low output voltage and low energy density are some of the other disadvantages.

1.1.2 Nickel Cadmium (NiCd) Battery

Nickel cadmium batteries are a safe and inexpensive technology. Nickel cadmium batteries use cadmium/cadmium hydroxide (Cd /$Cd(OH)_2$) on the negatively charged electrode, nickel hydroxide/nickel oxyhydroxide ($Ni(OH)_2$/NiOOH) on the positively charged electrode and potassium hydroxide (KOH) materials as the electrolyte. Ni-Cad batteries can be charged up to 1000 times. However, the batteries must be fully discharged before charging. When the battery is charged before it is fully discharged, the charge capacity drops and this will shorten the life of the battery. This is called a memory effect. This battery, which provides a high discharge current, has a higher energy density than lead-acid batteries. However, this battery technology has significant disadvantages. These are high discharge current value, low charging efficiency and bad memory effect.

1.1.3 Nickel Metal Hydride (NiMH) Battery

Ni-MH batteries contain many different compounds such as titanium, nickel, manganese, cobalt, aluminum, vanadium, zirconium, iron and chromium. These batteries are durable and can be recharged repeatedly. Ni-MH batteries produce 1.2V potential in a battery unit. Ni-MH batteries have high energy capacities. Like Ni-Cad batteries, Ni-MH batteries should not be fully charged without discharging, as the memory effect also applies to these batteries. Although Ni-MH batteries seem advantageous in many respects, the only drawback is that the discharge times are quite short when not in use.

1.1.4 Lithium Ion (Li-ion) Battery

Lithium metal oxides are used as positive electrodes in lithium ion batteries with the advantage of low toxicity, high capacity and cheapness compared to other materials. Commonly used oxides: Lithium cobalt oxide ($LiCoO_2$), Lithium nickel oxide ($LiNiO_2$), Lithium manganese oxide ($LiMn_2O_2$). Lithium ion battery technology has different characteristics than nickel based battery technology. It has higher nominal voltage and higher energy density than nickel-based battery packs.

1.1.5 Lithium Ion Polymer (LiPo) Battery

Lithium-ion batteries have almost the same characteristics. The only difference between them is the use of polymer material as the electrolyte in lithium ion polymer batteries. The electrical conductivity of polymer electrolyte material is higher than other organic liquid electrolytes. In addition, the use of this material allows lithium polymer batteries to be produced more easily, faster and with different shapes.

1.2 Battery Cell Balancing

Balancing the battery cells is one of the main tasks of the battery management system. The purpose of the balancing process is to ensure that all the battery cells in the battery packs are balanced during the charge process. The balancing process is active and passive balancing [4]. The balancing topology of the battery cells is given in Figure 1.1.

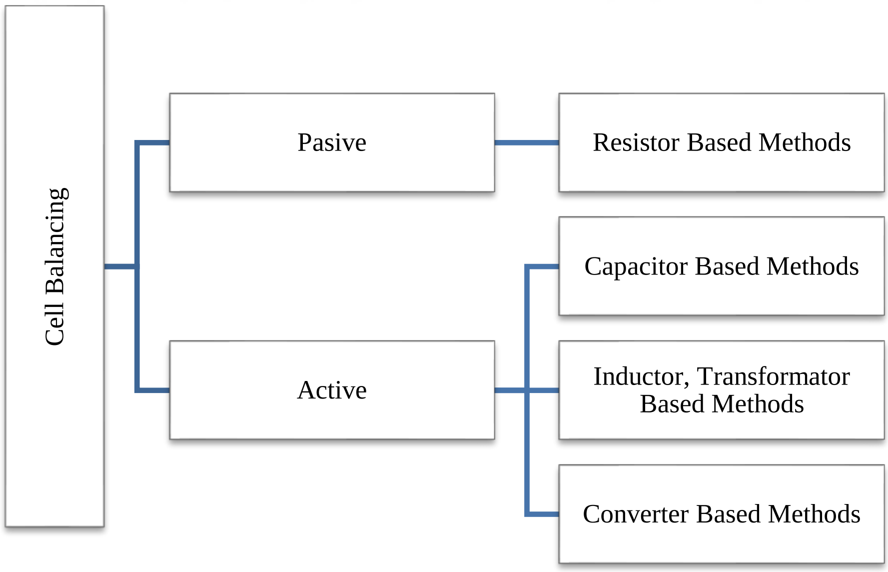


Figure 1.1 Passive and active cell balancing topologies

1.2.1 Active Balancing

Another method of balancing the battery cells is actively balancing. The active compensation circuit balances the battery cells at an average level by performing voltage transfer according to the voltage levels of the battery cells. Thus, the energy that is spent in passive balancing is transferred to the other battery cells in the active balance, resulting in more efficient balancing.

1.2.2 Passive balancing

Passive balancing of battery cells is simple and easy to apply. The passive compensation circuit detects the lowest voltage level of the battery cells and reduces the voltage levels of the other battery cells to the voltage level they reference by spanning across parallel resistors.

1.3 Resistor Based Methods

Resistor based balancing methods are classified under the pasive control method topic. This method is removing the excess energy from the higher voltage cell by means of heat on the resistors. So highest voltage cell charge level is decreased at same level of lower voltage cell. The resistor based methods can be divided into two main different categories.

The first method is using fixed shunt resistor for spending excess energy [5]. In this method, current is used continuously for all cells by bypass method. The resistance in the circuit is used to limit and adjust the cell voltage. This techniques can be only used for Lead-acid and Nickel based batteries. Because these kinds of batteries are durabe for overcharge conditions [6]. The main advantege of this method is balancing circuit simplicity and low cost. But it has continuous energy dissipated as a heat for all cells.

The second method is based on controlling the switch which is using for connected shunting resistor [7]. The energy from the higher cell is sent to lower cells using switches/relays. When the voltage imbalance is detected between the cells, the controller decides which resistance should be activated. This method is more effective, simple, reliable and can be used for Li-ion batteries when comparing to the fixed resistance method. The disadvantage of this method is the loss of excess energy as a heat. So this balancing method can decrease the battery run time. The circuit diagrams of the shunting resistor based cell balancing methods are shown in Figure 1.2 respectively.

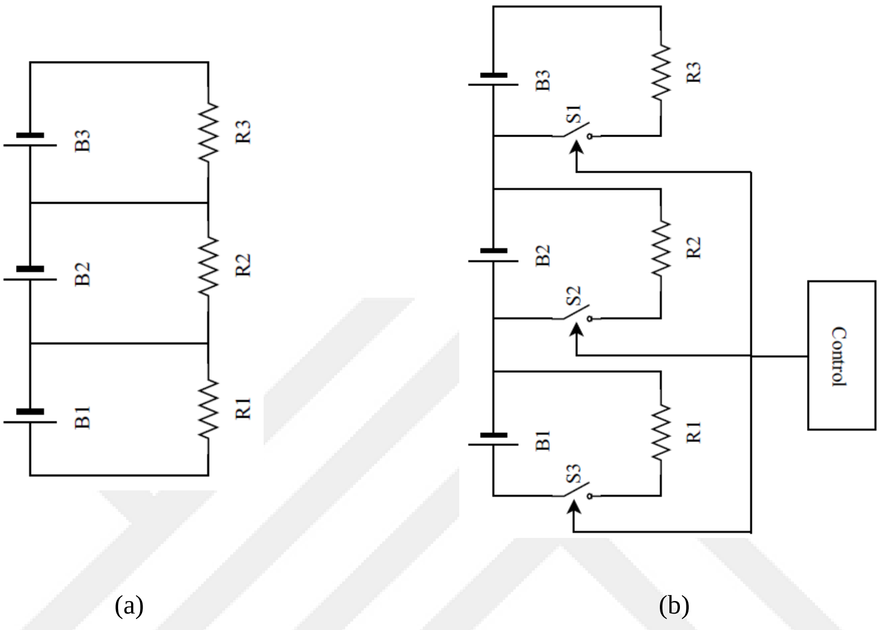
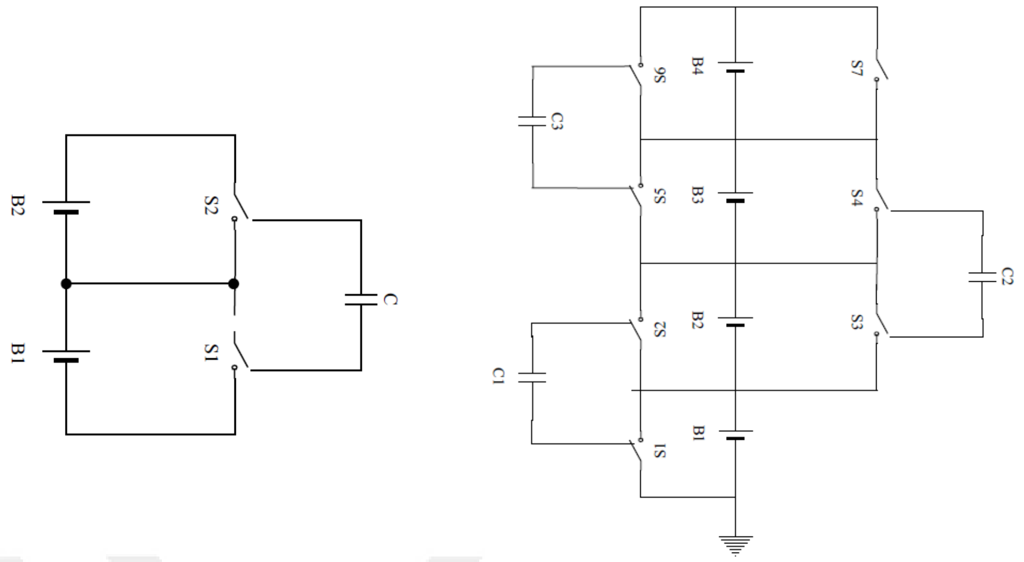


Figure 1.2 Shunting resistor a) Fixed resistor b) Control shunting resistor

1.4 Capacitor Based Methods

It is the method by which the voltage values of the battery cells are balanced by using capacitive elements. It is also known as "Charge Shuttling" in the literature [9-11]. The excess energy in the high energy battery cell is first transferred to the capacitor and this energy is directed to another cell having a lower energy value. Capacitors are used in this method for energy storage. The circuit diagram of the simple capacitor-based balancing method is shown in Figure 1.3 (a). In this way, the working logic of the method is understood. In more complex structures, there are not only two cells, so more cells need to be balanced. As a circuit diagram for these structures, Figure 1.3 (b) can be shown as an example.



(a) (b)

Figure 1.3 (a) One capacitor connected battery cells balancing circuit. (b) Capacitor based cell balancing circuit diagram of multiple cells

The charge can be easily transferred from one cell to another by means of capacitors connected to battery cells connected in more than one series. Each cell shares the capacitor with the adjacent cell. The charge can be easily transferred from one end of the cell array to the other with capacitors at the series connected battery cells. Each cell shares the capacitor with the adjacent cell. In this approach, it takes a lot of time to transfer the energy from the high cell to the low cell on the opposite sides of the cell with excess energy and the cell with low energy. Because the energy will have to pass through every cell. Also this situation will create a disadvantage in terms of time and efficiency. Therefore, an efficient result cannot be achieved. In the capacitors, energy losses during charging can be as high as 50 percent. There are also losses due to the heating of the transistors used for switching purposes. These losses should be considered in terms of the efficiency of the system. However, there is no loss in the energy transferred in this process. The energy of the battery cells decreases only due to its use. In this method, the compensation rate is proportional to the voltage differences of the cells. It is effective in the process of full charge of the cells or in the stage of full discharge.

1.5 Inductor Based Methods

Inductor based balancing methods use inductors as energy storage elements and transformers as energy conversion elements. These elements are used to transfer energy between battery cells from one cell to another [12-15]. The time required to balance the batteries is less than in other methods. The disadvantage of this method is the high cost of transformers. The circuit diagram for the inductor-based cell equalization method is shown in Figure 1.4. The inductors in the circuit store the excess energy in the cells. The control system selects two cells based on the voltage values and transfers this excess energy to these cells.

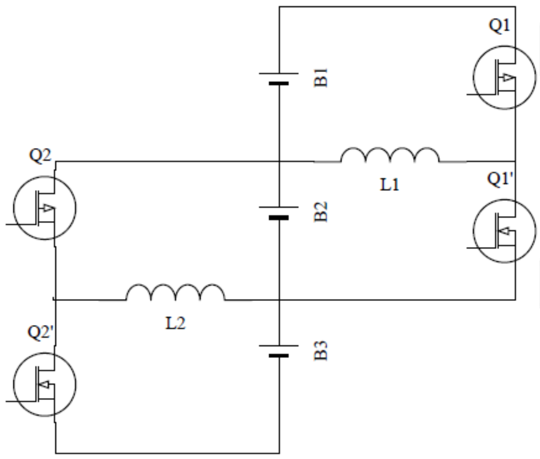


Figure 1.4 Multi Inductor based battery balancing topology

Transformer-based methods are also widely used in battery balancing systems, such as inductor-based methods. Transformer based systems are used as energy storage and conversion working principle in this method [15-16]. There are essentially two methods used at the transformer based methods. The first one is the system that works with the logic of the package to the cell. The second is the cell-to-package method. In the first method, the energy is transferred to the weak battery cells via the switched transformer. This energy is transferred to the battery cell by controlling the switching elements. In the second technique, excess energy is transferred from the high-energy cell to the low-energy cell through the transformer. The circuit diagram according to the first method, which is based on the operating principle from the package to the cell, is shown in Figure 1.5.

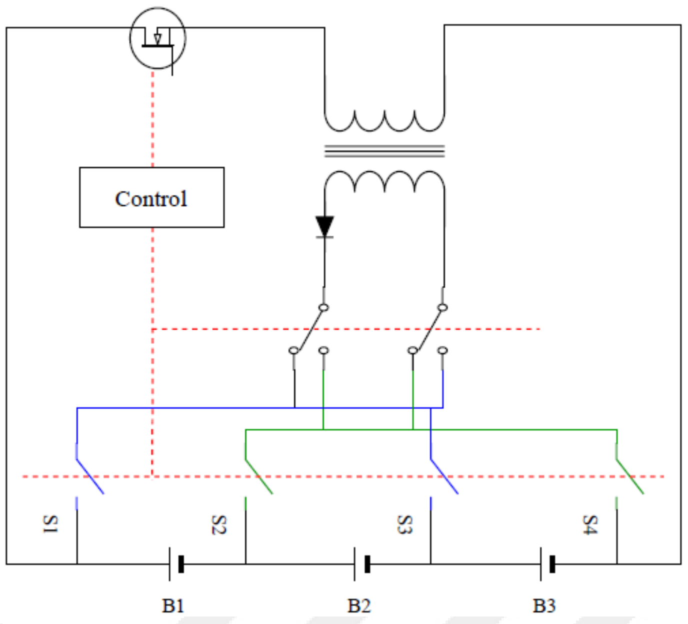


Figure 1.5 Single windings transformer balancing topology

1.6 Converter Based Methods

Different circuit topologies based on converters are used in the battery balancing control systems. Excess energy is transferred from one cell to another by means of converters in these methods. The energy converter performs the energy transfer between the two battery cells. Energy converters have different circuit topologies and features. The energy converters used for cell balancing and generally this systems include Buck, Boost, Flyback, Cuk, Ramp, full bridge and Quasi-Resonant type converters [17-19]. These types of converters are used continuously in the balancing process. The disadvantage of this method is high cost and complexity of the system.

A Cuk converter based battery balancing circuit topology is shown in Figure 1.6. Also this circuit topology can be referred to as individual circuit balancer. This system can be used to stabilize both neighboring battery cells. Each circuit has two inductors, two switches and a capacitor. The converter transfers energy between two adjacent cells. Therefore, the battery cell will have a very long charge and stabilization time for large battery packs [17,18].

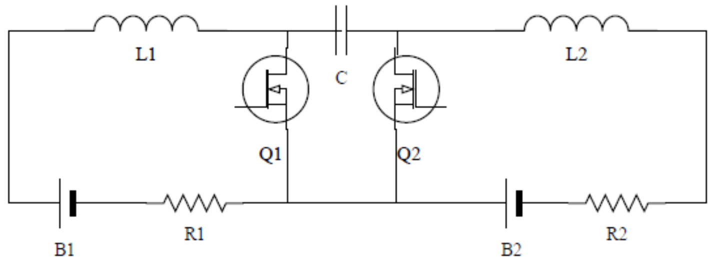


Figure 1.6 Cûk converter balancing topology

1.6.1 Buck or/and Boost converter

Buck, Boost and Buck-Boost type energy converters are commonly used circuit topologies [2]. These circuits can also be widely used in battery balancing systems [20-21]. Each circuit topology has its own specific use in balancing systems. Boost type converter is used to transfer the excess energy in the cell to the whole package. The buck-boost converter is used to transfer excess energy from the cell with the most energy to the DC line and the weakest cell. Battery balancing systems are required to detect accurately the voltage of the cells in order to perform the correct and sensetive control process. Converter-based systems are expensive and complex, but also suitable for a compact design. The Buck-Boost energy converters cell balancing topology as shown in Figure 1.7.

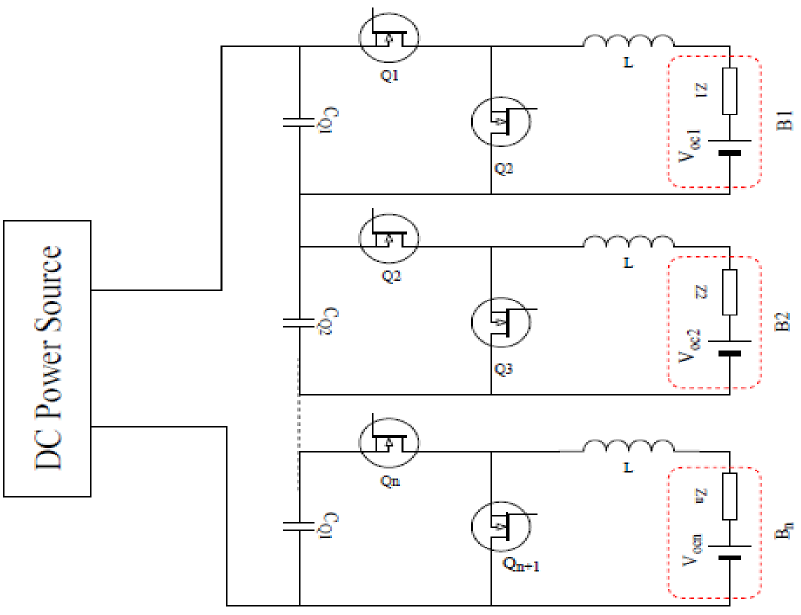


Figure 1.7 Buck-Boost energy converters cell balancing topology.

1.6.2 Flyback converter

One of the most important features of Flyback converters is that they are structurally insulated. Therefore, they have the ability to isolate both sides. Thanks to these features, they can be used as uni or bi-directional [16]. This circuit topology is shown in Figure 1.8. In the case of the converter operating in a bidirectional manner, the excess energy is stored in the transformer when the switching element is on, and when the switching element is off, this excess energy is transferred to the pack. The unidirectional Flyback converter is more flexible and convenient to transfer energy than bidirectional. The bidirectional converter can also transfer energy from the package to the cell. The disadvantage of this system is the difficulty in design and implementation. The Flyback converter should be well designed and the windings should be wounded properly. If it is not properly wounded, the balancing circut system may not work as desired due to magnetic losses [16].

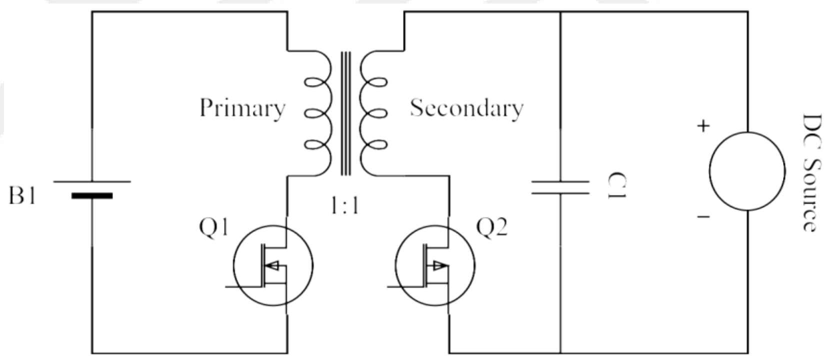


Figure 1.8 Flyback converter based battery balancing circuit schema

1.7 Review of Related Works

Although research and development on electric vehicles show themselves in the 20th century, the initial start is based on the 18th century [1]. The first electric vehicle was developed by Robert Anderson between 1832 and 1839 as a passenger vehicle. Christopher Becker who was assistant of Professor Stratingh manufactured the first electric vehicle developed by Professor Stratingh in 1835. In 1842, Thomas Davenport and Robert Davidson developed the first electric vehicle that could not be recharged.

Gaston Plante and Camille Faure then developed a rechargeable battery to be used in electric vehicles instead of non-rechargeable batteries [23].

In recent years, the trend towards electric vehicles has increased considerably throughout the world, and studies in this area have increased. The main reasons for this tendency are to aim to reduce environmental pollution and to increase efficiency. For these reasons, investments in electric vehicle technology are increasing day by day. Most of these investments are made for battery technology which is an indispensable part of electric vehicles. The distance that electric vehicles can travel depends directly on the energy stored in the battery. The work in the battery field continues in many branches and many studies are being done on different battery types. The main battery technologies commonly used in electric vehicles are; (Lead acid) [24], NiCd (Nickel Cadmium) [25], NiMH (Nickel Metal Hydrate) [26] and Li-ion (Lithium Ion) batteries. Li-ion type batteries are more preferred for electric vehicles. This is mainly due to the high output voltage, the high energy density that can be stored, and the longer service life compared to other battery types. However, they still do not have the desired useful life [27,10].

When the characteristics of the batteries are examined, it is seen that their service life is directly related to the charging process and usage. Charging is the most important factor affecting the use of batteries. Depending on the charging method and shape, the life of the battery cells can be reduced or increased for longer periods close to full capacity. Uncontrolled charging of batteries may result in serious damage, such as explosion of batteries, and fatal events. For this reason, battery management systems must be used to control and charge the batteries in a controlled manner [11,28].

The battery management system is the unit in which the batteries are inspected and managed by using the battery charge rate [29]. The BMS performs several tasks such as measuring the system voltage, current and temperature, the cells state of charge (SoC), determined the state of health (SoH) and monitoring and storing measured data. The BMS most important task is the cell balancing and it can affects the battery health and efficient negatively.

In this field lots of studies were performed and different methods applied battery cells to decrease the balancing effect on the system [1-29]. The cell balancing methods can be seperated two main topic as passive and active balancing [8]. Resistive, capacitive and inductive components use for active and pasive charge balancing systems [8]. The resistive method is called passive, capacitive and inductive methods are called active charge balancing systems. Also active balancing systems include converter and transformer based balancing techniques.

In the literature, passive balancing-based methods can be applied in two different ways. One of these methods is fixed shunt resistance method and balancing process is performed continuously [5]. In this method, a resistor is connected to each battery cell. The balancing current varies according to the value of this resistance. In [5] was presented, discussed and evaluated the different techniques proposed to achieve individual cell equalization for series battery stacks.

The second method is based on controlling the balancing resistance. This method is referred to as controlled shunt resistance [7]. Semiconductor-based switching elements or mechanically switching relays can be used for this control technique. The excess energy of the battery cell is spent on this resistance with this method. In [7], one of the passive balancing methods, a controlled shunt resistor method was used. In this system, switching operations are carried out by using relays for control operation. As a result of using this technique, higher efficiency is obtained compared to other systems. At the same time, the balancing process was performed faster than different systems. Different studies have been conducted on Li-Ion batteries including balancing techniques. In these studies, different control chips and software applications are used for balancing control [30].

Active balancing methods use external circuits to actively transport the energy among cells in order to balance them. Active balancing methods can be diveded under three main topics. It can be grouped as capacitor, inductor-transformator or converter based [8].

In [9-10] capacitor based balancing methods illustrated. It was expressed that control strategy was simple and did not need intelligent control. Because these systems were had only two states. Designed system could work in both recharging and discharging operation. And this system disadvantege was relatively long equalization time.

In [13], used one inductor for transferring energy between the whole pack. Firstly the control system sensed the voltage of the cells and selected the other cells according the charge conditions.

In [12,14], the multiinductor system was used for balancing system. This method uses n-1 inductor for balancing n cells. PWM signal was used switching for balancing system and complex control was needed. It is determined that equalization time of the system too long.

In [15-16], single windings transformer method was used. The applied method of these studies advantages were determined as fast equalization speed and low magnetic losses but disadvantages were observed as control of the system was difficult and system implementation was expensive.

Energy converters can be used for active cell balancing methods. A buck-boost converter method was proposed in [14]. Here, all the cells were connected in parallel with a converter. This method can strongly balance all the cells on a charge cycle. The end result of this method shows that balancing has excellent spreading and minimal circuit losses compared to other methods. Similarly, in [31] an isolated DC-DC converter with a multiwinding transformer was used in charging and charge equalization functions. In [32], a two-way DC-DC converter was used to balance the cells during both charging and discharging. It is not difficult to build this circuit, but some electrical components required in the circuit increase the total cost of the system.

Full-bridge PWM converter based technique was proposed in [33]. These kinds of converters can be used as AC/DC or DC/DC converters. The topological structure of the circuit is suitable for this purpose. In such an application, the energy in the battery pack can be transferred to the weak cell. The main advantages of this circuit topology are its high efficiency and suitable for high power applications. The only drawback is the difficulty and complexity of the control stage.

CHAPTER 2

DATA TRANSMISSION AND COMMUNICATION PROTOCOLS

Nowadays, with the development of technology, the place and importance of electronic and digital based systems in our lives are increasing. Electronic and control based systems are basically two parts. One of these units is a communication unit that enables the transmission of data with a software controllable processor unit. Communication units enable the transfer of digital information from one point to another. This event is called data transmission. Data transmission systems perform data transmission between computers, computers and terminals or between computers and receivers.

The data is transferred to the processor via the communication unit to receive, transmit and interpret the data. With the data collected and interpreted by the processor, electronic based systems continue to work according to the algorithm logic. The control process is carried out according to the data received within the framework of the desired program logic. In this respect, it is very important that the data is received and sent to the system in order to control the systems. There are different methods depending on the environment and communication method used in the transmission and collection of data.

To classify the communication systems according to the environment used:

- Transmission in radio frequency waves (in free space)
- Optical transmission in the atmosphere
- Cable transmission
- Optical transmission from fiber optic transmission line

Each transmission medium has its own advantages and disadvantages. Although transmission with radio frequency waves in the atmosphere is cheap and flexible, it is not used in wide bandwidths (10 Gb/s) and requires high power in long distance transmission. Optical transmission in the atmosphere is quite flexible. However, the quality of the signal depends on the transmission distance and the ambient conditions. Dust particles and density homogeneity can cause scattering.

Cable types used in data transmission over cable are usually grouped into four main groups. The two-wire open cable is a parallel two-wire conductor and is the simplest communication medium. Each wire is insulated from the other and the distance between the two conductors is usually between 5 cm and 15 cm. In order to form support and keep the distance between the conductors constant, non-conductive spacers are periodically spaced. Such cables are sufficient for systems that are approximately 50 m away from each other and with bit rate transmissions at medium speed (19.2 kb/s).

The double-screw cable consists of a pair of copper wires wound on top of each other. Winding of the wires is to reduce the effect of the electromagnetic field against each other. Therefore, double-twisted cables are more resistant to artificial noise signals. It is the most common and easy method for local area networks, providing data transmission rates of 1-128 Mbps. In the case of four twisted pair cables, data can be transmitted at a speed of 1 Gb/s.

Coaxial cable is a type of cable that is easy to use and reduces the effects of artificial noise, such as double-twisted cables. It is designed to carry high frequency signals.

Fiber optic cables are the ideal type of cable for data and voice transmission. Fiber optic cables have more transmission capacity than copper coaxial cables. They are also lighter and occupy less space. They are also unaffected by electromagnetic influences and are highly reliable since no signal leakage occurs.

The data transmission medium to be used may vary according to the system to be realized and designed. Communication methods used in data transmission are also classified under two headings as parallel and serial [34].

2.1 Parallel Transmission

Parallel transmission of 8 bits of digital data is transmitted simultaneously on 8 separate transmission lines. If the data to be sent is a 64-bit data and 1 bit is transmitted in 1 second, all data will be transmitted in 8 seconds. The block diagram of the parallel transmission technique is shown in Figure 2.1 at the bottom.

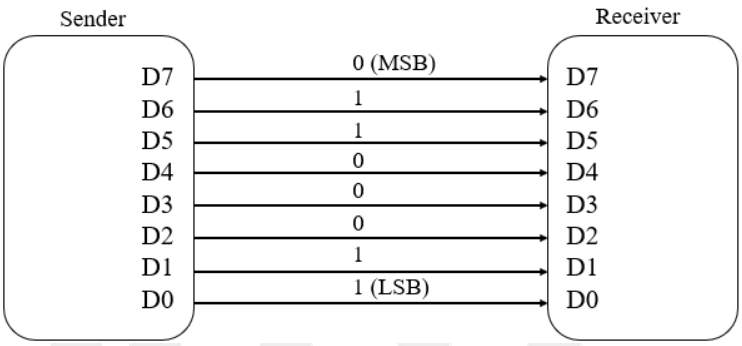


Figure 2.1 Parallel transmission block schema [35]

2.2 Serial Transmission

The sequential transmission of digital data over a single data transmission line is called serial transmission. The transmission on computer networks is serial transmission. If the data to be sent is 64-bit data and 1 bit is transmitted in 1 second, the entire data will be transmitted in 64 seconds. The block diagram of the serial transmission technique can be seen in Figure 2.2 at the bottom. Figure 2.3 shows the components of the communication medium as a block schema.

Figure 2.2 Serial transmission block schema [35]

The data communication system consists of five elements [36]:

Message: The information transmitted in a variety of ways, such as audio, images, numbers, text, images.

Sender: It is a device that sends data such as PC, workstation, video camera.

Receiver: Receiving data such as PC, workstation, television.

Transmission Medium: A physical way of transmitting data such as fiber optic cables and radio waves between devices.

Protocol: It is the element that initiates, manages and terminates data communication.

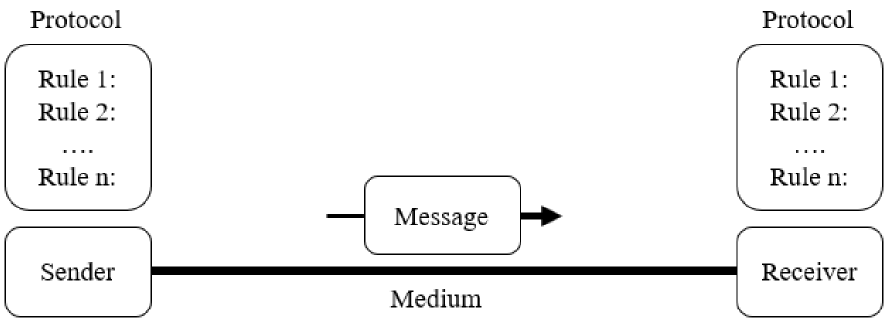


Figure 2.3 Five components of data communication [34]

2.3 Communication Protocols

The protocol is the common language in which all elements in a system communicate with each other. The infrastructure of the communication system should be determined according to the used software and hardware for fast, secure and clear data communication between the transceiver. Receivers and transmitters are produced to communicate over a specific protocol [35]. "Fieldbus", which has a market share of around 80% in the world's automation systems, is the general name of all protocols used in and out of the factory. This protocol consists of the physical layer, the communication framework and the user layer [35]. There are two types of communication protocols: open and closed system communication protocols. These are shown in Table 2.1:

Table 2.1 Communication protocols

Protocol	Identification	Manufacturer
Open Architecture	Interbus-S, Profibus, Canopen, Devicenet, As-Interface, FIP, CAN, LON	Phoenix, Pno/Siemens, CIA, Allen-Bradley, AS, Verein/Siemens, AEG-Schneider Automation, Intel/Motorolla/Phillips, Echelon/Motorolla
Specific Architecture	Beckhoff I/O, Melsec, Suconet K, ET 100, CS 31, Remote I/O, Modnet	Beckhoff, Mitshubishi, Klockner Moeller, Siemens, ABB, Alen Bradley, AEG

2.3.1 Open System Communication Protocols

The devices used for the same purpose can communicate with each other regardless of brand, called open system communication. For example, Profibus products from Omron and Profibus products from Phonix can communicate with each other. Open system communication protocols are as follows [35]:

Interbus-S Protocol: This bus system was developed by Phoenix Contact and is very common in Germany. This system is open architecture and standardized according to German Institute for Standardization (DIN) norms. The data communication is bidirectional and the system communicates with the closed loop topology [35]. Error detection in the network can be done to a limited extent.

Profibus Protocol: Profibus, whose opening is a otomobil Process Field Bus Field, is designed to be used in automobile technology for extensive production automation. It was first developed by the German Department of Education and Research in 1989 and later used by Siemens. It is based on EN 50170, EN 50254 and IEC 61158 standards. They are widely used in high-speed applications or in complex communication systems by providing communication between different manufacturers' devices without requiring a special interface [35]. Faulty devices can be disconnected from the line and the system can be checked without affecting other devices at any time [37].

Modbus Protocol: It is a serial communication protocol developed by Modicon in 1979 with master/slave relationship. Communication starts on a master device and can communicate up to 247 slaves on the same network [35]. The most common types are Modbus RTU and TCP / IP.

CAN-Bus Protocol: It is a serial communication protocol developed by Bosch company which is generally used in automotive and medical field [19]. This protocol allows multimaster operation. In other words, all CAN points can transmit data and some of them can request at the same time. Operates according to message priority [35]. It is a reliable protocol that reduces the weight of the vehicle by reducing the number of cables used in vehicles, and is fast, easy to detect. In this section, the CAN-Bus protocol will be explained in detail.

DeviceNet Protocol: A protocol developed by the American company Allen-Bradley, which is part of the CAN application layer. This protocol is designed for intelligent sensors and actuators. By this, it can be connected to devices such as limit switches, photoelectric sensors, barcode readers and motor starters to communicate with devices such as PC or PLC [35]. It is also a low cost and robust communication system.

AS-i Interface (Actuator Sensor): The AS-i interface was developed by a research group formed by 11 different companies. It is a simple, reliable and inexpensive system. Consists of 1 master and a maximum of 31 slaves. With special data converters, the Profibus DP signals can be converted to AS-i format and the signals that control the actuators can be controlled by processing the signals from the sensors [35].

2.3.2 Closed System Communication Protocols

Closed System Communication Protocols are protocols that allow each manufacturer, such as Mitsubishi, Melsec, Omron Phoenix Contact Interbus-S Compobus, to communicate only with their products [35].

2.3.3 Serial Communication Protocol Systems

There are many serial communication protocols such as SPI, I2C, Universal Asynchronous Receiver/Transmitter (UART), CAN, USB [38]. UART protocol is the most widely used protocol except CAN protocol. The most commonly used are RS232 and RS485. The UART protocol makes point-to-point communication and is widely used because of its low cost. It creates a standard serial channel interface between the card and the computer [39]. The negative feature of this protocol is; Byte based communication cannot send more than one byte at the same time. In addition, there is no error control, so a different software is used. As a result of this process, the system becomes slower. [39].

The UART protocol performs point-to-point communication. Cable usage increased with the increase in the number of units to communicate with each other. This has led to an increase in the weight and cost of the vehicle. Therefore, CAN protocol has been developed to eliminate these problems. The CAN protocol is especially preferred for connecting electronic control modules, sensors and actuators in automotive and industrial applications with the multi-master feature. Serial communication protocols are shown in Table 2.2 comparatively [39]

Table 2.2 Serial communication protocols [39]

BUS	Positive aspects	Negative aspects
UART	They are well known. Cost is low and simple.	Limited functionality, point-to-point communication.
CAN	Safe and fast.	It is complex and used for onlu automotive and some of industrial applications.
USB	Fast, simple and low cost.	Requires strong master and special drivers.
SPI	It is fast, universally accepted and low cost.	There is no determined standard.
I2C	It is simple, well-known, universally accepted, cost-effective.	It has limited speed.

When the BMS applications are examined, it is seen that the data is transferred using CAN bus protocol. The CAN protocol is generally preferred in BMS applications due to its high security structure, flexible design, ability to configure according to master-slave logic, fast and communication with only two wires [40]. Therefore, the following sections provide information on the CAN bus protocol and CAN bus protocol structural features are mentioned.

2.4 Investigation of CAN Communication Protocol

The Controller Area Network (CAN) protocol was developed in 1983 by Bosch company for use in the automotive industry and was officially used in 1986. This communication protocol aims to reduce the cable network in the vehicles. Thanks to this protocol, data from many sensors in the vehicle can be controlled using only two wires. Although CAN protocol is used mainly in automotive sector, it is used in many systems including microprocessor due to the reasons such as data transmission rate, low error rate and ease of application. It also provides reliable data transfer with high accuracy in noisy environments. The communication speed is 1M bit/sec at 40m and 40K bit/s at 1km distance. The CAN communication protocol is message-based. Each message has an ID number. Messages are transmitted through frames and are divided into data and request messages. Request messages do not contain data. In data messages, up to 8 bytes of data are transmitted. Two different versions of the CAN communication protocol are available in world standards. The first version is the CAN 2.0A low-speed version and is called the basic CAN or standard CAN. This standard is specified in the ISO11519 standard of ISO. The other version, CAN 2.0B, is the high-speed version, also called full CAN or extended CAN. This standard is also defined in ISO11898. The difference is that the message lengths are different. CAN communication protocol is determined by the standards all over the world [41].

- CAN 2.0A: ISO 11519 - low speed
- CAN 2.0B: ISO 11898 - high speed

The main objective of the CAN communication protocol is to provide high capacity data exchange between network elements in real-time applications and to provide as much economic solutions as possible.

The use of the CAN communication protocol has reached 600 million nodes after 2007 and this market is growing by 30% each year. CAN is used in many industry applications. The two most important of these are automotive and industrial machinery [42].

2.4.1 CAN-BUS Protocol Information

The process of providing data consists of sending, receiving, checking and accepting. The information sent by the electronic control units from the CAN line is called bus information. Each bus user has the unit for sending and receiving information. When sending data, all units receive the information, only one bus user transmits the information.

In the CAN communication system, the controls determine the incoming data by looking at the potential difference between the two wires. There are two levels on the bus. These are dominant and recessive levels, and these two levels can also be on the bus. The sending controller sends its message to the recipient by changing these bus levels. Figure 2.4 shows a typical CAN connection. All nodes connected on the bus can send messages to the bus. If two nodes send a message to the bus at the same time, the message of the priority node is sent and the other nodes are in the receiving state [43].

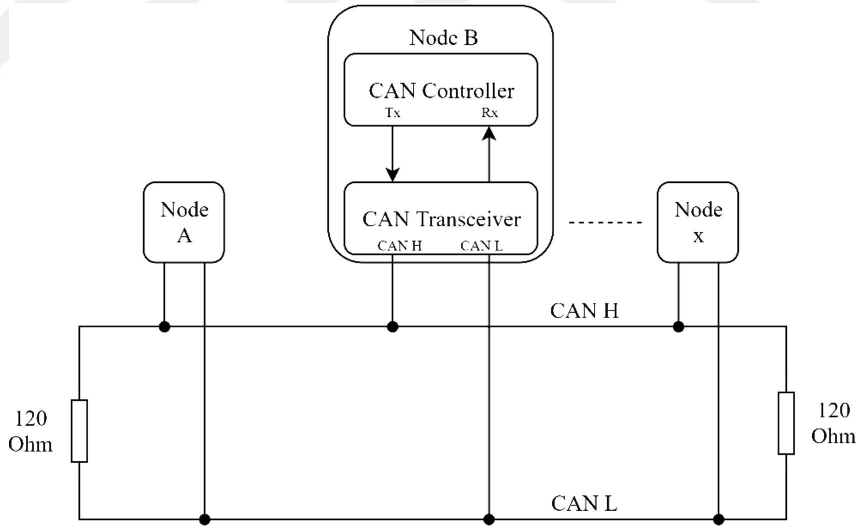


Figure 2.4 Typical CAN-Bus connection schema [44]

In general, a CAN port is shown above. The ports are called nodes and consist of a microcontroller, CAN controller and CAN transceiver. To obtain the dominant level in the physical interface shown in Figure 2.5, the electrical signal is applied simultaneously, with the C_H line at high level and the C_L line at the low level. This results in a potential difference between the two line ends dynamically. In the recessed state, the C_H and C_L lines are in the high impedance state. This is always the case if no data is sent to the bus. To obtain the recessive state here, the bus must be composed of two wires and terminated on both sides with 120 Ohm terminating resistors. The purpose of using this resistor is to prevent the return of information. This does not interfere with bus information.

In the CAN structure, the receiver and transmitter are physically independent of each other. However, due to the nature of the nodes, the sent message can be listened to from the receiver. In this way, the processor that sends the data compares the sent and read data. Error and messages are allowed to be transmitted according to their priority level [43].

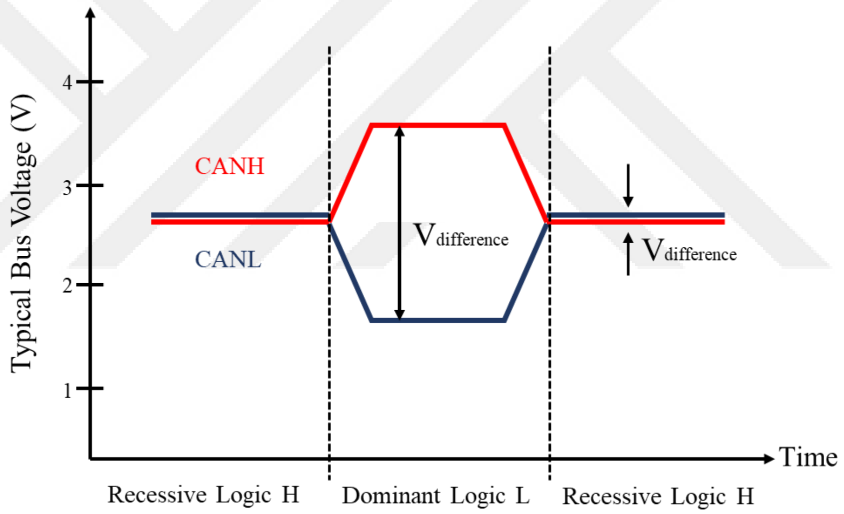


Figure 2.5 CAN-Bus electrical signal waveform [45]

As shown in the Figure 2.5 above, the logic level of the line can take two different values and the level of these values appears. Logic 1 is called recessive, logic 0 is dominant. This is because if 0 and 1 are written simultaneously from different nodes, 0 overrides 1.

When logic 0 overrides logic 1, the message priority belongs to the node with a low ID number. When it is decided to send a message by a node, the message is waited until the bus is empty. Each node follows the bus continuously. The message reaches each node and the associated nodes read and process the message. If more than one node starts writing a message on the bus, the low ID node captures the bus and the other nodes withdraw from the bus and wait for the bus to empty. Every written bit was read at the same time. If a node reads 0 when writing 1 on the bus, it will recognize that it is writing a message on another node [44].

Since the priority of the node that writes the message is high so it leaves the bus to higher priority of the node. When the bus is clear, it tries to send it again. For example, we have three nodes named A, B, and C that try to write data to the bus at the same time. Let node A write path 36 (100100), node B 47 (101111), and node C 37 (100101). This situation can be understood in Figure 2.6 signal shape at the bottom [45].

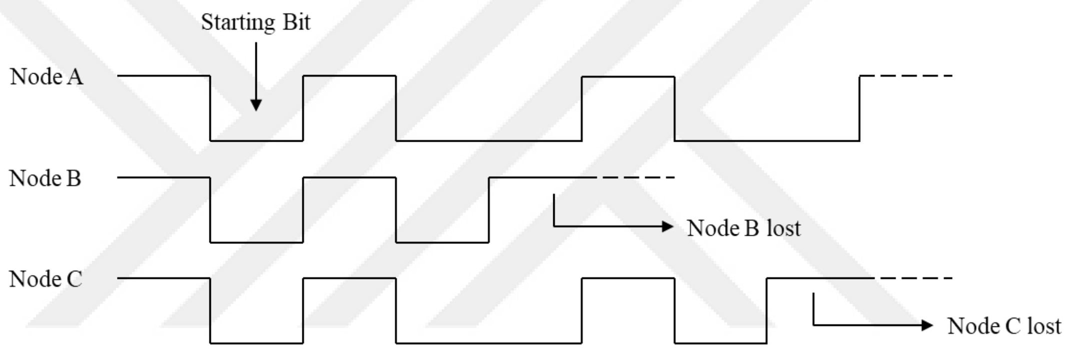


Figure 2.6 CAN-Bus electrical signal determining priority of the node [45]

Nowadays, the transfer of data is usually between computers or with computer architecture based devices. Therefore, it is very important to understand what are the communication techniques of computer based systems and how the communication process takes place. Thus, the position of the CAN protocol within the communication layers is determined and the working logic of the CAN protocol can be understood easily. In the early days of sharing information through computers, each company used its own method of sharing information. Therefore, there was no communication between different firms or manufacturers. Here is the Open Systems Interconnection (OSI) Model was developed to eliminate this problem. The OSI Model makes it easy to communicate between networks of different companies. It is not mandatory to reference this model, but it will be very difficult to communicate with other networks.

The OSI Model is divided into seven layers and can be seen in Figure 2.7. The task of each layer is different and each layer serves the next layer [46].

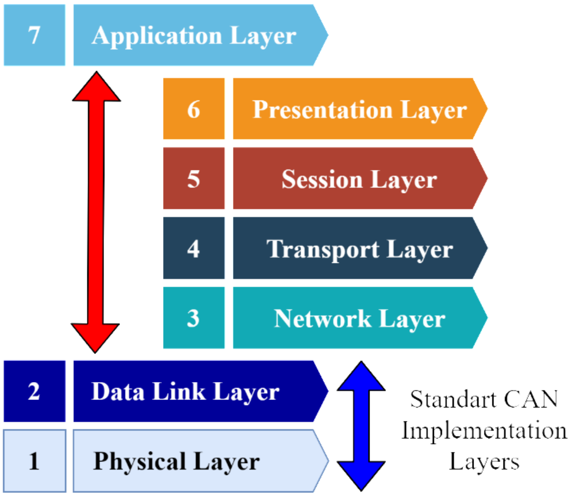


Figure 2.7 CAN protocol based OSI model schema [46]

2.4.1.1 Physical Layer

This layer defines how data is converted and transferred to electricity. The sending data converts the bits into electrical signals and transfers them to the cables, while the receiving data converts the electrical signals back into the bits.

2.4.1.2 Data Link Layer (Data Transmission Layer)

The data transmission layer provides data transfer from node to node. Identifies errors due to physical layer. Specifies the protocols for establishing and closing connections between two physically connected devices.

IEEE 802 standart divides the data layer into two sub-layers:

• Media Access Control (MAC) Layer: The error control code (CRC) adds the recipient and sender's Mac addresses to the data to be sent.

• Logical Link Control (LLC) Layer: Responsible for setting network layer protocols. One of its most important tasks is to ensure that corrupted outgoing or unreachable data packets are resent to the receiving unit.

2.4.1.3 Network Layer

The network layer is the layer to which information for routers is added when the data packet needs to be sent to a different network. IP, ICMP, ARP protocols work in this layer. In this layer, the data is transported as a packet. In this layer, the transmission of data in the most convenient way between the two stations is controlled. In the network phase, the messages are addressed, and the logical addresses are translated into physical addresses. At this stage, operations such as network traffic and routing are also performed.

2.4.1.4 Transport Layer

The transport layer divides the data from the top layer into network packet size segments. Responsible for sending data to the other party without corruption. TCP, UDP, SPX protocols work in this layer.

2.4.1.5 Session Layer

The session layer is responsible for establishing, using, and ending the connection between computers. The applications we run do not interfere with the session layer. NetBIOS, RPC, Named Pipes and Socket protocols work in this layer.

2.4.1.6 Presentation Layer

The data must be converted into a common format in order to the shared data to be read and understood by computers. This layer makes the necessary transformations to make the data meaningful by computers. This layer also deals with the encryption of the data and it is generally related to software. GIF, JPEG, TIFF, EBCDIC, ASCII etc. works in this layer.

2.4.1.7 Application Layer

This layer provides an interface between the user and the network. Applications are allowed to run on the network. Telnet, FTP, TFTP, SMTP, SNMP, HTTP, DNS work in this layer. The CAN protocol is not an address-based protocol, but a message-based protocol. All messages sent are propagated to all other network nodes in the network as broadcast [46]. CAN bus defines the Data Link Layer and a part of the Physical Layer of the OSI model. Since the data structure used in Data Link Layer is based on frame data type same as CAN bus protocol. The data is also sent and received in frames in the CAN network. The location of the CAN protocol in the OSI model is shown in Figure 2.7. As can be seen from the Figure 2.7, the CAN protocol does not follow all layers. It passes directly from the second Data Link layer to the seventh Application Layer [47].

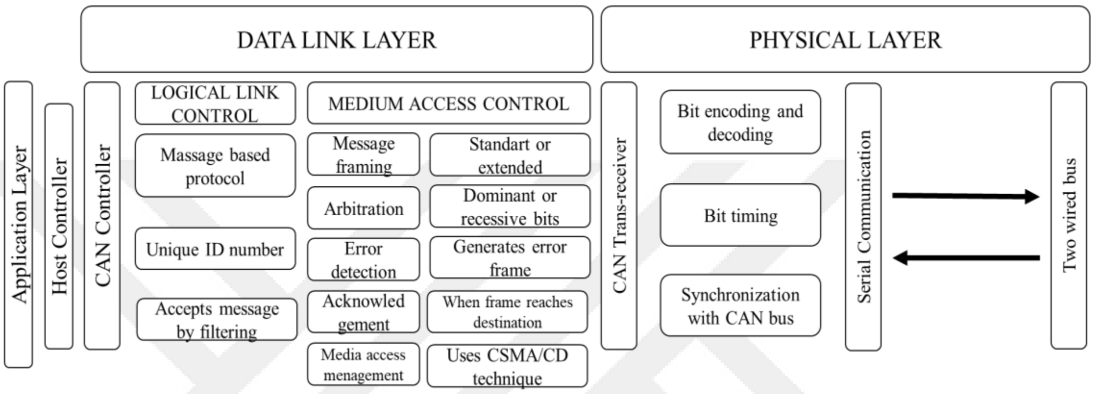


Figure 2.8 OSI model layers of CAN bus protocol defined

The operating architecture and logic of the CAN communication protocol is explained by the diagram in Figure 2.8. Many microprocessor-based nodes can be connected to the CAN line. Microprocessor-based systems in these nodes can also be called Host controllers. The application layer of the OSI model is realized through this unit. The CAN protocol basically includes the Data Link layer (DLL) and the Physical layers. The CAN controller is located in the DLL layer. The microprocessors in the nodes connected to the CAN line collect the necessary sensor data and transmit them to the CAN controller. This unit includes Logical Link Control (LLC) and Medium Access Control (MAC). The LLC unit functions to filter incoming messages by ID information. In the MAC layer, the messages are framed. After framing, this process is followed by arbitration, error detection and acknowledgement. The prepared frame is transferred to the CAN transreciever unit. At this stage, encoding and decoding operations are performed. After all these operations, the CAN transceiver communicates with the CAN bus line and sends the message to different nodes. [47].

2.4.2 CAN Messages Structure

Messages are transmitted by dividing them into frames on the bus. There are two different message types. These are the data frame (Message Frame) and the request frame (Remote Transmit Request Frame). The difference is that data frames can carry data up to 8 bytes long. Data of a particular message is also requested through the request framework. There are also two types of CAN standards. These are CAN 2.0A and CAN 2.0B. The CAN 2.0A standard is called a Base Frame and CAN 2.0B standard is called a Extended CAN frame. Standart CAN data frame and extended CAN data frame can be seen in Figure 2.9 and Figure 2.10 respectively.

Start of Frame(SOF) SOF (1 bit)	11 bit Identifier (ID)	RTR	IDE	R0	DLC	Data Field 1-8 byte	CRC 16 bit	ACK 2 bit	End of Frame (EOF) 7 bit	Idle 3 bit

Arbitration Field Control Field

Figure 2.9 Standart CAN frame (CAN 2.0A) fields

SOF 1 bit	11 bit ID	SRR	IDE	18 bit ID	RTR	R1	R0	DLC	Data Field 1-8 byte	CRC 16 bit	ACK 2 bit	EOF 7 bit	Idle 3 bit

Arbitration Field Control Field

Figure 2.10 Extended CAN frame (CAN 2.0B) fields

Table 2.3 CAN data frame fields and bits

SOF: The Start of Frame is a 'dominant 0' to tell the other ECUs that a message is coming	CAN-ID: Contains the message identifier- lower values have higher priority (e.g. RPM, wheel speed, ...)	RTR: The Remote Transmission Request allows ECUs to "request" messages from other ECUs	Control: Informs the length of the Data in bytes (0 to 8 bytes)
Data: Contains the actual data values, which need to be "scaled" or converted to be readable and ready for analysis	CRC: The Cyclic Redundancy Check is used to ensure data integrity	ACK: The ACK slot indicates if the CRC process is OK	EOF: Marks the end of the CAN message

The tasks of the bits in the CAN data frame are shown in Table 2.3. Each CAN data packet has a SOF (Start of Frame) bit at the beginning. This area is a one bit area and is structurally dominant. After this bit, there is a control field with a size of 12 bits. The first 11 bits of this 12-bit field contain the ID information. Bit 12 of the control field is an important bit called RTR. Depending on the value of this 12th bit, it is understood whether the frame is a data packet or a request packet. If the value of this bit is 0, it indicates that it is a data packet and if it is 1, it indicates that it is a request packet. When this frame is sent, it is understood from which node this data comes from according to the ID information. When the receiver, receives this frame, it reads the value in the ID field and understands which data to sends it when the path is empty. In this way, CAN protocol can work as master and slave [48].

In the CAN data frame, the arbitration field and the control field are respectively. The first bit of the arbitration field is defined as the RTR bit. The IDE bit is dominant, indicating that the data frame is in the 2.0A version and the ID capacity is 11 bits. The IDE bit is followed by an unused bit, expressed as a reserved bit. There is a 4-bit DLC field after the reserved bit. This field provides information about the size of the data sent. The DLC field is followed by the data field. The maximum data size in the CAN data frame is 8 bytes. The data field is followed by a 16-bit CRC field. 15 bits of this field are referred to as CRC (Cyclic Redundancy Check) information and the remaining bit is expressed as CRC Delimiter bit. The CRC field checks the accuracy of the data frame up to the beginning of the CRC field. This check is performed on both sides. First, the node that sends the data calculates a value using the 15-bit portion in the CRC field and sends it in the data frame. If the node that receives this data frame calculates the same CRC value as a result of its calculation, it understands that the data arrives without error. If the data is received incorrectly by the nodes receiving the data, the data is sent again. There is a 2-bit ACK field after the CRC field. This field specifies whether the sent data is received correctly by at least one node. If data is received by a node, it sends 0 (dominant) data to the CAN line. Thus, the sender understands that the data has reached at least one node correctly. If the sender cannot read the dominant data, it sends the data again. The second bit of this field is called ACK delimiter and is recessive. Then comes the 7-bit EOF field indicating that the frame is finished. The bits in this area are recessive. Then a 3-bit Idle field comes up to leave a space between the frames and the bits are recessive.

The operating logic and frame characteristics of the system are similar in CAN 2.0B as with the standard CAN 2.0A. The difference from CAN 2.0B is that the message ID field is 29 bits and this frame is called Extended Frame. So more messages can be received from 229 different nodes in the CAN 2.0B protocol. The CAN 2.0B was developed with compatibility in mind with 2.0A. Both protocols can work in the same path, but messages with a 29-bit ID should not be sent to 2.0A nodes [48].

CHAPTER 3

METHODOLOGY

Today, the need for energy is increasing day by day. With the digitalization of life and the increase of electronic systems, electrical energy has become one of our indispensable priorities. It is also very important to store and use energy [49]. As is known, batteries are used to store and use energy in DC form. With the digitalization of our daily lives, batteries are the energy storage elements that we encounter quite a lot. Batteries have many different applications. In recent years, with the increase of electric vehicles, they are widely used in these areas. In addition to electric vehicles, batteries are used for energy storage in renewable energy production facilities. In this respect, batteries are used in many different applications and the usage of batteries is increasing day by day. However, there are two main factors that limit the use of batteries. The first one is the high cost of the batteries and the second one the service life. The life of the batteries varies depending on their usage, charge and discharge, and temperature. Therefore, the long-term healthy use of the batteries is very important in terms of the high cost of the batteries. For this purpose, the batteries are used and charged by the control cards in order to avoid any possible negativity. These control systems are generally referred to as Battery Management Systems (BMS). The battery or battery cells are properly charged via these systems [50].

Although batteries are used in many areas, it is clear that they will be used more intensively in the applications for electric vehicles in the future. Therefore, BMS-based studies are often described or shaped according to electric vehicles. For this reason, the designed and implemented BMS system is explained through electric vehicles. However, the designed BMS system can be used in different battery-based applications together with electric vehicles.

The positions of the BMS system and battery pack on an electric vehicle are shown in Figure 3.1 for a better understanding the location of BMS systems on electric vehicles. The position of the BMS system and battery pack in the vehicle may vary depending on the mechanical and electrical design of the electric vehicles.

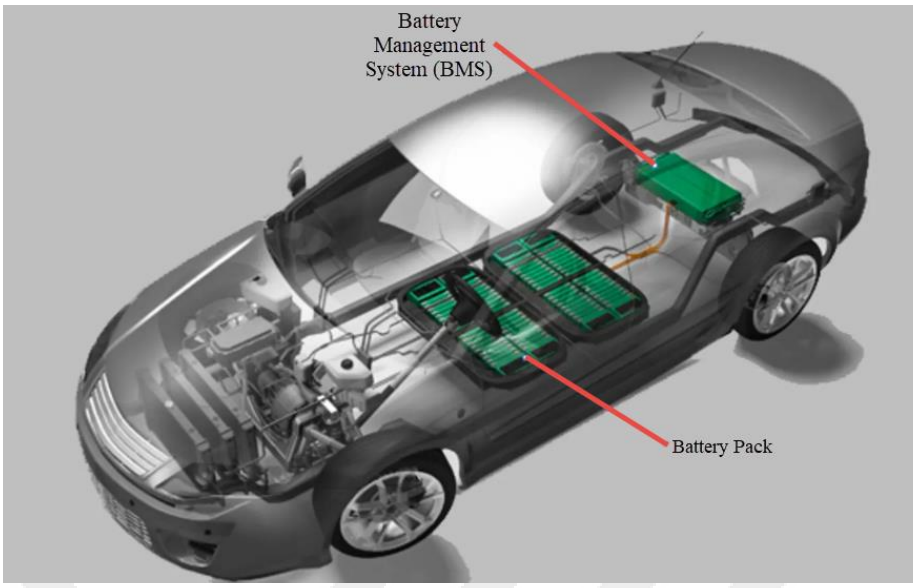


Figure 3.1 Position of BMS system and battery pack on electric vehicle [51]

BMS systems are one of the most important control units of electric vehicles. The number and importance of electric vehicles are increased also the studies in this field are progressed. Thus, many studies have been conducted in the literature related on BMS systems. Different circuit topologies or different charging methods are used in these studies. The most important of these methods are based on balancing techniques.

Because of these reasons this thesis study was conducted on the BMS balancing techniques due to the increasing importance of the BMS studies with the development of electric vehicles. This thesis study has been carried out for the BMS system that can be used in electric vehicles. Unique charging circuit topology has been developed by applying active and passive balancing methods in this study.

In this part of the thesis, theoretical analysis of proposed active and passive based methods performed. The working logic of the circuit discussed in this section. After the theoretical analysis of the BMS control cards, the applications of the designed systems explained in detail.

3.1 Passive Balancing Method Based Circuit Theoretical Analysis

MOSFET switching element is used as a resistance in the passive balancing based method. Stone resistance is used in the passive charging circuit. The purpose of using this resistor is to limit the balancing current. MOSFET is controlled in linear mode. Thus, MOSFET is used as a resistor, not as a switching element. In this control method, excess energy is consumed as heat energy on MOSFET according to the value of the balancing current. Thus, a method has been established in which the battery cells can be charged in a stable manner. A Digital Analog Converter (DAC) circuit is designed and implemented to control the MOSFET in linear mode. A PWM signal is applied to the input of this DAC circuit and a constant voltage value is obtained from its output. The resistance value of the MOSFET can be adjusted as desired by means of this constant voltage.

3.1.1 MOSFET Linear Mode Operation

MOSFET semiconductor elements are used for switching purposes in many converter, motor driver and control based electronic system applications. MOSFETs can be controlled in linear, cut off and saturation regions according to the voltage applied to the gate pin [49]. Mathematical equations of these regions can be seen at equations (1), (2), and (3).

$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t \quad \text{cutoff region} & (1) \\ \beta\left(V_{gs} - V_t - \frac{V_{ds}}{2}\right)V_{ds} & V_{ds} < V_{dsat} \quad \text{ohmic (linear) region} & (2) \\ \frac{\beta}{2}\left(V_{gs} - V_t\right)^2 & V_{ds} > V_{dsat} \quad \text{saturation region(linear mode)} & (3) \end{cases}$$

Figure 3.1 illustrates in detail the different operating modes and operating regions of an N-channel MOSFET. The N-channel Power MOSFET can operate in three different regions. These regions are referred to as Ohmic, Saturation and Cut-Off regions respectively. In the cut-off region, the system is open circuit since gate source voltage (V_{GS}) is smaller than the gate threshold voltage ($V_{GS(th)}$). This means that no load current is flowing. In the ohmic working area, the semiconductor element acts as a constant resistance ($R_{DS(on)}$). The resistance value increases or decreases linearly due to the proportional variation of the V_{ds} and I_{ds} variables. If the I_{ds} current remains constant despite the increase of the V_{ds} voltage, this indicates that the device is operating in the Saturation region. In this operating mode, the drain current (I_{ds})value is a function of the gate-source voltage (V_{gs}) value [52].

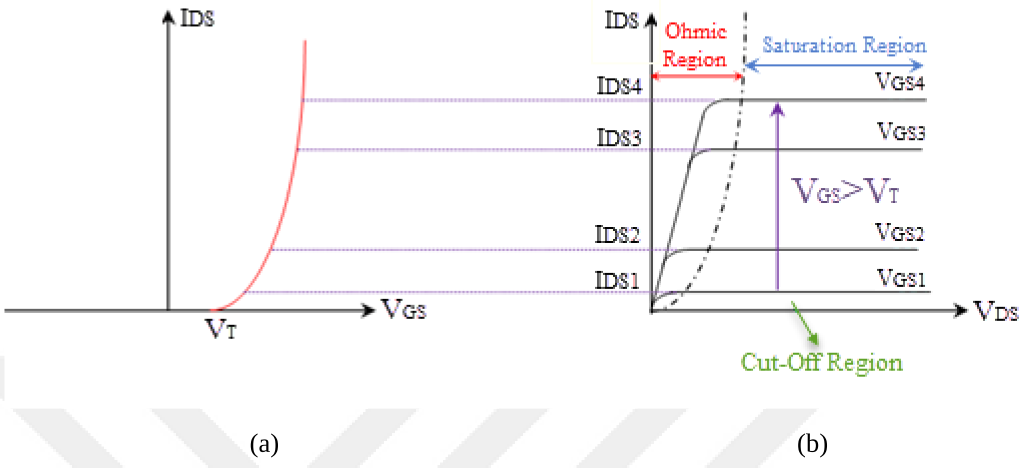


Figure 3.2 (a) Transfer characteristics of n-channel Enhancement-type MOSFETs, (b) MOSFETs opeation regions [53]

Figure 3.2 (a) shows the transfer characteristics of N-Channel Enhancement-type MOSFETs. It is seen that the I_{DS} (Drain to Source current) current varies inversely proportional to the V_{GS} (Gate-to-Source voltage) voltage. As can be seen from this graph, the I_{DS} current does not flow until the V_{GS} voltage exceeds the V_T threshold voltage. Under this condition, even an increase in V_{DS} current will not flow as shown by Figure 3.2(b). As a result, this state represents cut-off region of the MOSFET's operation.

MOSFET's operating in linear mode should not be confused with its operation in the linear region. Although these statements are conceptually similar, there are significant differences between the two working situations. In the case of linear zone operation, the drain current changes proportionally to the drain voltage value. In linear mode, an I_{DS} current flows at a higher value in spite of the change of a small V_{GS} value. Thus, the I_{DS} current passing through the MOSFET can be controlled directly with the V_{GS} value. In linear mode operation, MOSFET can be used as a gate controlled current source. This means that high magnitude voltages and currents are apply simultaneously to the MOSFET. So, this situation leads to significant power dissipation.

Many applications can be found about Power-MOSFET operated in linear mode. There are different types of applications based on the use of MOSFETs in linear mode. Fan control, buck converter and general switching applications are some of these types of applications. Although MOSFETs are used in such applications, there are not many applications where they are used as load. In cases where MOSFETs are used as load, the SOA (Safe Operating Area) graph should be examined. According to this graph, it is determined whether MOSFET is suitable for use as a load and maximum load capacity can be determined by means of SOA graph [54].

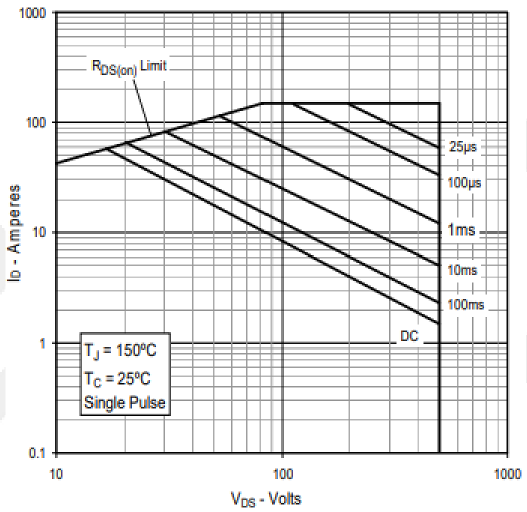


Figure 3.3 IXTK60N50L2 Safe operating area [55**]**

Figure 3.3 shows the SOA graph of MOSFET. The DC operating limits are shown and expressed as "DC" in the given graph. According to the values in the graph, while the V_{DS} voltage of the MOSFET is 100V for 100 ms, approximately 8A current can flow over the MOSFET. Under these conditions, the power value that MOSFET can dissipate is 800W. When MOSFET is used as a load, the area below the DC limits must be considered. The MOSFET's $R_{DS(on)}$ and dynamic parameters are irrelevant to judge power dissipation in case of continuous operation in linear mode. This situation is the simplest condition where the MOSFETs are fully enhanced (switched ON). Higher current flows through MOSFETs with low R_{DSon} value. As more current passes through the MOSFETs, it emits more heat energy. (power dissipation $P = V_{DS} \times I_{DS}$).

3.1.2 Passive Control Circuit

One of the important parts of the BMS system is the charge controller unit. Passive balancing technique based charcing method is used in this unit. Batteries were charged using passive balancing method. In this method, the amount of energy that causes excess voltage is spent as a heat energy on the stone resistance. The passive balancing control circuit diagram and circuit elements are shown in Figure 3.4. In this circuit logic, the PWM signal was applied to the Buck converter output filter topology. This output filter is also a DAC circuit. The PWM signal applied to the input of the circuit is converted to a constant voltage through this circuit. Thus, constant and low voltage value can be obtained output of the designed DAC circuit. This circuit consists of inductance (L1), diode (D1) and capacitance (C10) components. The circuit structure is similar to the Buck converter output circuit. The current value was calculated by taking the voltage differences between of the using stone resistance legs. Current value can be measured with this method in the BMS circuit without using the current sensor. The MOSFET was used as a regulated resistor by applying the constant voltage value from the buck converter to the gate of the MOSFET. So, the excess voltage was spent on the MOSFET.

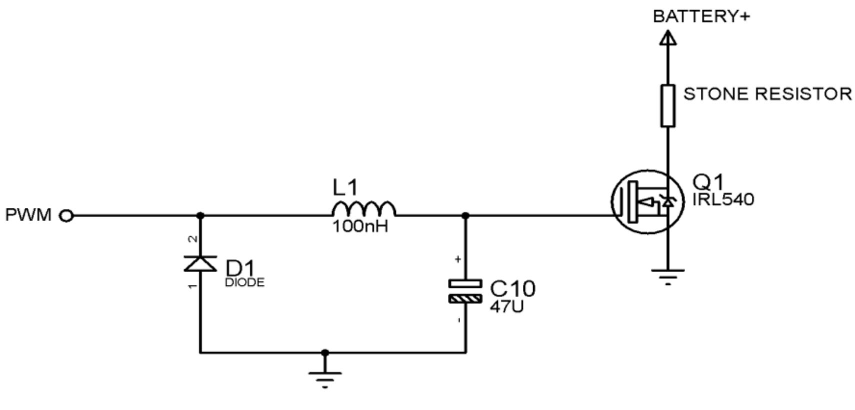


Figure 3.4 Passive control circuit

3.2 Active Balancing Method Based Circuit Theoretical Analysis

The simplified version of the proposed method is shown in Figure 3.5. The method is based on the logic of bypassing the battery cell and consists of two switching elements.

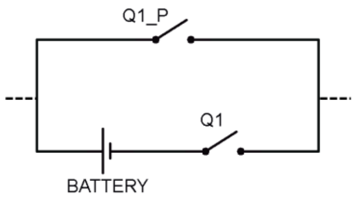


Figure 3.5 Simplified version of the proposed method

The detailed method of the proposed method is shown in Figure 3.6. In this proposed BMS method, while the Q1 MOSFET is connected in series for battery charging, the parallel connected Q1_P MOSFET is driven in the linear mode. So the charging current and voltage of the battery can be controlled by means of Q1_P.

In the control circuit which is shown in Figure 3.6, U1 represents the current sensor, while U2 and U3 represent the optocouplers to be used. The voltage value of the battery cell is measured by R1 and R2 voltage divider resistors. The signal from the output of the DAC (Digital Analog Converter) circuit is applied to the Q1_P Gate control pin of the MOSFET switching element. A constant voltage value is applied to the gate pin. Hence the Q1_P MOSFET switching element can be operated in the linear mode. Thus Q1_P MOSFET can be used as a set resistance. With this method, the charge current and voltage of the battery can be controlled via Q1_P MOSFET switching element. The control card will be isolated using U2 and U3 optocouplers to protect the BMS from high voltages and currents. The voltage value of the cell is read by the microprocessor in this system. The MOSFET is controlled according to the values of read parameters. The system is realized consists of battery and control card. The control card shall have microprocessor block, balance block and DC/DC converter voltage regulator. Using the voltage of the battery, the DC/DC booster conversion circuit provides a constant voltage of 5 volts. Hence the current sensor in the circuit is supplied via 5 volts. At the same time, the voltage regulator provide the 3.3 volt voltage required for the microprocessor on the control board. If the system has not reached the desired voltage by reading and evaluating the voltage on the battery, the current will continue to flow to the battery. If the desired voltage is reached, the MOSFET is switched off by driving in the linear mode and open the other MOSFET. The voltage on the battery continues to be read by the microprocessor. Charging of the battery will be ensured by switching the MOSFETs according to the determined limits. The most important feature of the system is that it can be used as active and passive control circuit.

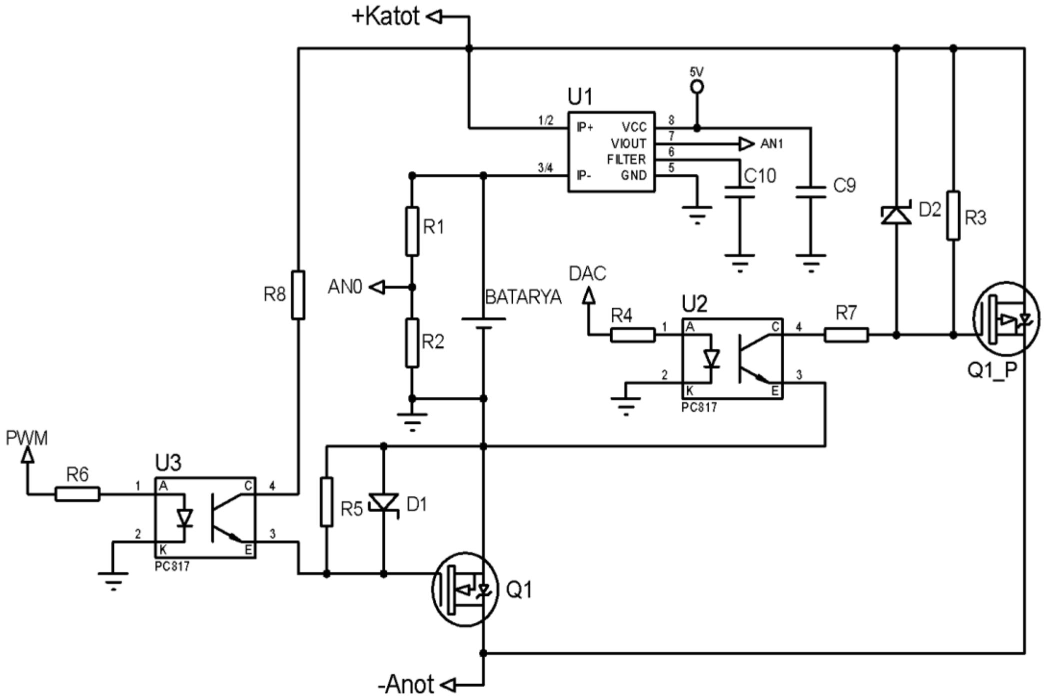


Figure 3.6 Active balancing method circuit schema

3.2.1 Active Balancing Method Based Circuit Simulation Analysis

In order to test the active balancing control method, active charge balancing control circuit was established in Proteus program and the logic of operation was examined. In the simulated circuit, first of all, N-channel and P-channel type MOSFETs which are suitable for the logic of the circuit are selected and the circuit is formed. LED lamps in the circuit are left to represent the battery. The main purpose of using LED D1 is to visually see that the charging current has passed. In the case of active charging of the circuit, if the battery is to be charged, Q1 must be in transmission and Q1_P should be in cut. If the battery is charged Q1 is opened and Q1_P is transmitted. The current flowing through this region is also visualized using the D2 LED. The main purpose in this simulation is to test whether the circuit is operating in the active charge compensation logic. Firstly, serial and parallel arms can be switched to transmission and cutting when requested. Buttons representing the switching signal are used in the simulation circuit. When the buttons are pressed, it has been observed that all of the series and parallel arms are seperately conducted. Thus, the electronic circuit based on the theory of active balancing has been practically operated. The active balancing method based circuit simulation schema which is shown in Figure 3.7

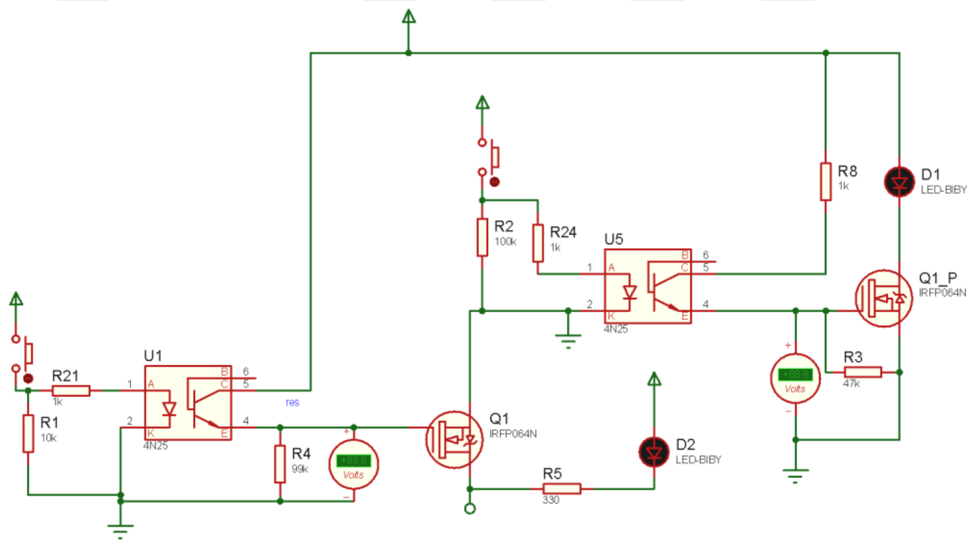


Figure 3.7 Active balancing method circuit simulation schema

After simulating the BMS circuit in the Proteus simulation program, the circuit must be tested in real time. The circuit was designed in Proteus ARES program for testing process. The designed BMS control card is composed of more than one electronic part, it is divided into subsections and drawn in this way in the circuit card desinging program.

3.3 BMS Control Card Implementation

There are several points that are important in design. These are the communication protocol, the control method to be used, the microprocessor type and the design of the

BMS control circuit board. The communication system is particularly important in these parts. In electric vehicles and battery energy storage systems, the system is generally used by CAN bus or UART based communication techniques [56-59]. The CAN system is reliable and it is possible to add and remove different units easily also UART is preferred frequently because of its simplicity and widespread use. These features are important reasons for choosing CAN and UART based communication systems [60-61].

In this study, an industrial BMS charge control circuits are designed for four battery cells. Two different BMS systems were designed in the form of different circuit and control systems. The first BMS system is designed to implement both passive and active cell balancing. The circuit is located separately from the battery cells. In this unit, CAN bus type communication method is preffered. The second system was created and designed for only passive-based control. In this unit, UART type communication method is preffered. Also, a different mechanical design is realized and cells control cards are designed to be mounted on top of the cells. Although it looks like two different systems, in fact both of them have the same passive based technique and circuit model. The microprocessor types and communication protocols are different. In this BMS card, the circuit design was carried out by selecting the circuit elements in order to use UART and CAN-Bus communication protocol. The control circuits for the BMS system are created with active and passive balancing method as two different system. Also two different systems have been established in the passive control based BMS system. In the first system, include passive and active circuit together but second system control card is composed only based on passive balancing method. Although there is no difference in terms of basic operating principles, there are differences in terms of hardware and used communication techniques. The active-based control method only available in the first system.

The first system is created with active and passive balancing method based charge control circuit and sensors for controlling the charge of the batteries. A compact card design was made using the STM32f103C8 as a microcontroller in order to perform the control operations. All cells are composed of STM based microprocessors. Data was transferred to the computer interface using the designed BMS circuit. The data values are taken by three different sensors. There are three data in each cell and 12 data are collected at four different cells. Three sensors are used for each cell in the designed card. These are current, voltage and temperature sensors. First, the data must be received correctly through the used communication protocol. When this process is passed, arrangements are made for correct reading from the sensors. For this reason, the used sensors, their characteristics and circuit models in the designed system are explained in details. These are important for reading correct data value. Also these kinds of sensors used in designed second system for BMS slave control circuits. In the second system, STM32f103C8 microprocessor is used only for master cell and PIC18f4520 type microprocessor is used for slave cells.

3.3.1 Current Sensor

ACS712T ELC-5A model current sensor is used in BMS control circuit. There are four current sensors used in the BMS control card. Allegro brand ACS712T ELC-5A given in Figure 3.13, are in the range of -5A to +5A. The current sensor operating according to the Hall effect principle allows two-way current input up to 5 ampers. It provides an analog voltage output of 185 mV/A and provides a measurement rate of less than 5%. SMD type current sensor is used in the card design. The view of this current sensor is shown in Figure 3.8. Also the current sensor circuit used in the designed BMS card is given in Figure 3.9.

The characteristics of the current sensor are given below [62].

• Designed for bidirectional input current from -5A to +5A (stable sensor IC can withstand overcurrent up to five times).

• The internal resistance of the conductor track is typically 1.2mΩ.

• The use of a Hall effect sensor means that the IC can electrically isolate the current line from the electronics of the sensor (up to 2.1kV RMS) so that the sensor can be installed anywhere on the current line and used in applications requiring electrical isolation.

• By adding a capacitor to the pins defined as the filter on the card, the bandwidth of 80 kHz can be optionally reduced.

• Operating temperature is between -40 °C and 85 °C.

Figure 3.8 SMD type ACS712 current sensor IC [62]

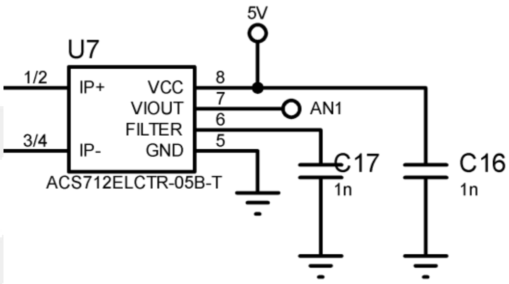


Figure 3.9 Designed BMS card current sensor circuit

3.3.2 Temprature Sensor

The electronic measurement of the temperature variable and its availability as a data is very important from industrial life to daily life. In electronic thermometers and temperature control applications, we obtain the temperature information numerically through these sensors. One of these sensors is the semiconductor LM35 temperature sensor which can measure the ambient temperature from -55 degrees to 150 degrees. The LM35 temperature sensor is a semiconductor analog heat sensor with a sensitivity of 0.5 degrees. The output voltages of the LM35 temperature sensors change proportionally to the temperature. The measuring range is between -55 and 150 degrees. It provides 0.5 degree accuracy with a supply voltage in the range of 4-30 V and a current of less than 60µA. The output voltage increases by 10mV with each degree increment. Thus, the mathematical ratio is established and the temperature of the outdoor environment is converted from analog to digital. In this way, the temperature value is obtained numerically [63]. The view of temperature sensor and its pins feature are shown in Figure 3.10. Also the temperature sensor circuit used in the designed BMS card is given in Figure 3.11.

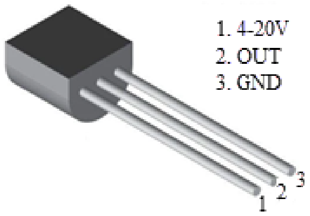


Figure 3.10 LM35 temperature sensor IC

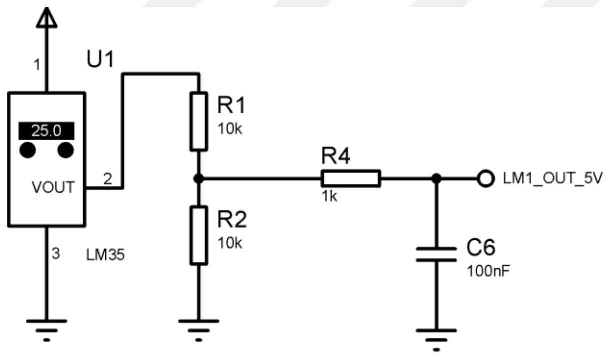


Figure 3.11 Designed BMS card temperature sensor circuit

3.3.3 Voltage Sensor

The voltage divider method with two resistors is one of the commonly used circuits in electronic measuring systems. The main purpose of this circuit is to reduce the input voltage to a lower value depending on the ratio of the two resistors. This calculation helps determine the output voltage of the divider circuit with input (or source) voltage and resistance values. When determining these values, the power to be lost on the resistors should be taken into account. In addition, if the impedance of the circuit to which the output voltage is to be connected is small, measurement errors will occur. In order to reduce these errors, resistance values should be selected high. The logical circuit schema of this voltage divider system and mathematical equation can be seen in Figure 3.12 and Equation 4 consequently. Also the voltage divider circuit used in the designed BMS card is given in Figure 3.13.

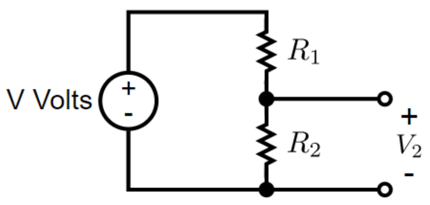


Figure 3.12 Voltage divider method circuit schema

$$V_2 = V * \frac{R_2}{R_1+R_2} \tag{4}$$

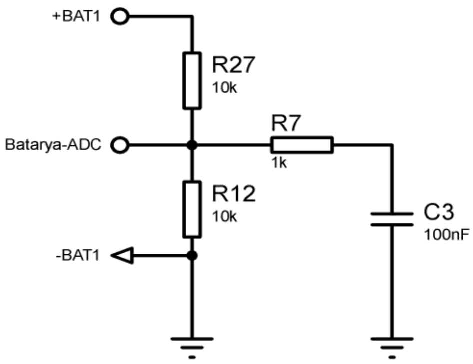


Figure 3.13 Designed BMS card voltage divider circuit

3.3.4 STM32f103C8T6 Microprocessor

The STM32f103C8T6 type microprocessor is a mid-segment microprocessor manufactured by ST company with RISC architecture. It uses the Cortex-M3 core in the processor. It can be operated at 72 Mhz frequency. It is powered by a 2.0-3.6V power supply. The STM32f103C8T6 microprocessor offers two 12-bit ADCs, three general-purpose 16-bit timers, and a PWM timer with standard and advanced communication interfaces. These communication protocols consist of two I2C and SPI, three USART, one USB and one CAN protocols. This processor can be used in a wide range of applications such as motor drives, application control, medical devices, PC and gaming tools, GPS platforms, industrial applications, PLCs, inverters, printers, scanners. The technical characteristics of the microprocessor are shown in Table 3.1 at the below.

Table 3.1 STM32f103C8T6 microprocessor features [64]

Main	System	Connectivity	Analog	Control
48 MHz ARM Cortex-M3 CPU	Power Supply 1.8V internal regulator	3 USART	Up to 16x 12Bit ADC	3x 16 Bit Timer
64-Kbyte Flash Memory	Xtal Oscillators 40 kHz+ 8 MHz	2 SPI	Temperature Sensor	12 Channel DMA
10-Kbyte SRAM	Internal multispeed ULP RC Oscillator 64 kHz to 4 MHz	2 I2C		
84-byte Backup Data	SysTick Timer	1 USB		
Nested Vector Interrupt Controlller (NVIC)	Clock Control, 2 Watchdogs			
JTAG/SW Debug	37/51 Input/Output			

In Figure 3.14, the pins of the microprocessor board and the features of the pins are illustrated in detail. This is a circuit board of the STM32f103C8T6 type microprocessor. It is also known on the market as Blue-Pill. One of the most important reasons for choosing this microprocessor module is that it is quite cheap compared to other microprocessors in the market and its speed is high. In this study, also it was preferred because of its low price, high speed and popularity of ARM based microcontroller in recent years. In this thesis, microprocessor was used as a module in the designed BMS circuit card and it was designed to be mounted directly to the BMS circuit card.

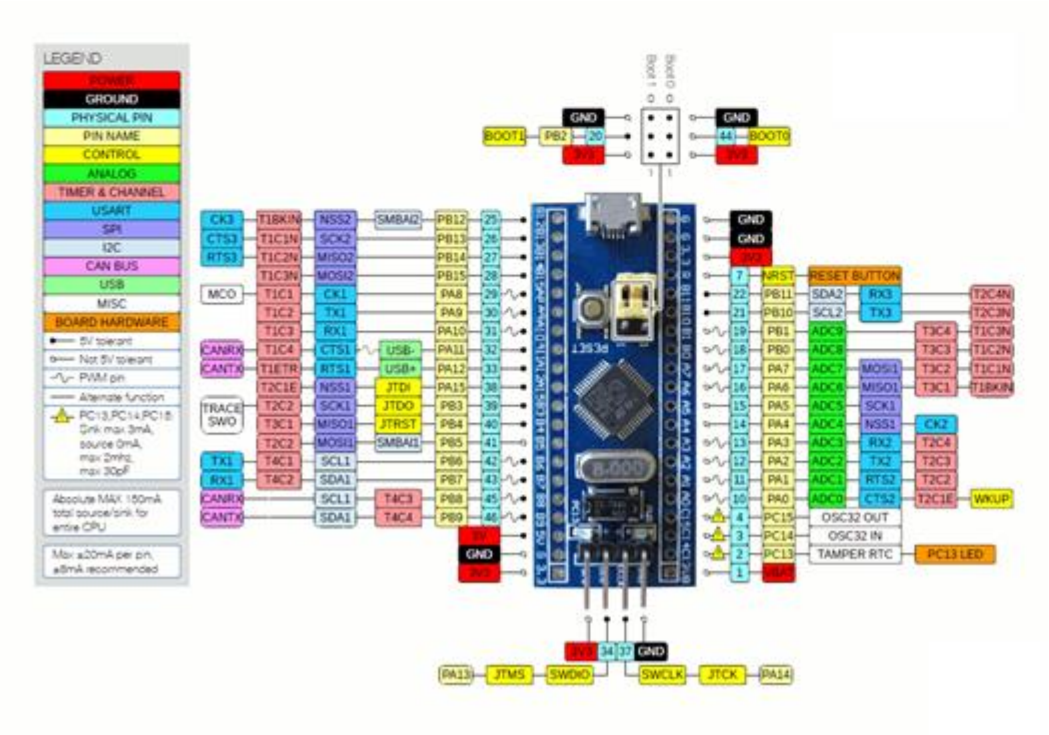


Figure 3.14 STM32f103C8T6 microprocessor pinout diagram [65]

3.3.5 PIC18f4520 Microprocessor

The microprocessor IC is shown in Figure 3.15 at the bottom. The PIC18F4520 microprocessor is produced from Microchip company. It is 8-Bit and has a 40 MHz working frequency. Microcontroller product can be found in market as mounted and Smd package type. This microcontroller's 36 of the 40 pins are can be used as I / O pins. Its memory type is Flash type and the supply voltage range can be changed between 4.2V to 5.5V. Also this microcontroller can be operated between -40 °C and +85 °C degree temperature conditions [66].

Figure 3.15 PIC18f4520 SMD type microprocessor

3.3.6 Overview of Designed BMS Circuit Cards

The overviews of the desined BMS systems are examined under two sub-headings. Since two different BMS systems created so the design of BMS cards hardware change.

3.3.6.1 Overview of Designed First System BMS Circuit Cards

The designed BMS control card consists of five parts. These are the power circuit, the charge control circuit, the CAN-Bus based communication circuit, the microprocessor circuit and the sensor circuits. These units are arranged to fit on one card in the circuit design. The size of the circuit is reduced to a minimum size and is designed to be as small as possible.

The power circuit is where the supply voltage is applied to the BMS card. In this section, a booster circuit of type which increases from 0.9V voltage to 5V voltage is used. The supply voltage of the BMS circuit will be supplied from the adjacent battery cell in the battery pack. Therefore, a boost circuit is used to increase the battery voltage to 5V. Thus, the external feeding problem of BMS control cards was desired to be eliminated.

The charge control circuit of the BMS system consists of a circuit based on active and passive control method. Depending on the control of the MOSFETs used as the switching element, the control circuit can operate in two different topologies. MOSFET is used as resistance in passive-based control method. In active-based control method, the circuit continues to operate according to the bypass method.

CAN-Bus communication protocol is used for the communication of the battery cells. ISO1050 IC chip is used for CAN bus communication. The reason for the use of isolated CAN Transceiver is to protect the BMS card in case of a possible short circuit.

In the BMS system, a control method was created according to the Master-Slave logic. Therefore, one of the four cells is determined as master controller, while the other three control cards operate as slave. The cells communicate with the CAN bus based to each others. Data from the cells are transmitted to the computer interface via the serial communication unit. STM32f103C8 was used as a microprocessor module. In the BMS control circuit, the circuit design has been carried out so that the microprocessor module can be easily removed and installed. Thus, a flexible usage possibility has been created. Due to its low cost and high speed, this type of microprocessor module has been selected.

There are three main types of sensors on the BMS control board. These are current, voltage and temperature sensors. Sensors are very important for the BMS system since the control process will be performed according to the information from the sensors. ACS712 IC circuit is used as current sensor. In the charging process, the current sensor is very important for controlling the current flow. LM35 is used as a temperature sensor. It is intended to be used measuring temperature information of the cells. In this way, overheating conditions will be determined in advance and the cells will not be overcharged. Possible explosion and combustion conditions due to overheating of the batteries will be prevented. In this respect, the temperature sensor is essential for the safe operation of the batteries under proper conditions. Designed BMS control card and parts of this card can be seen at Figure 3.16.

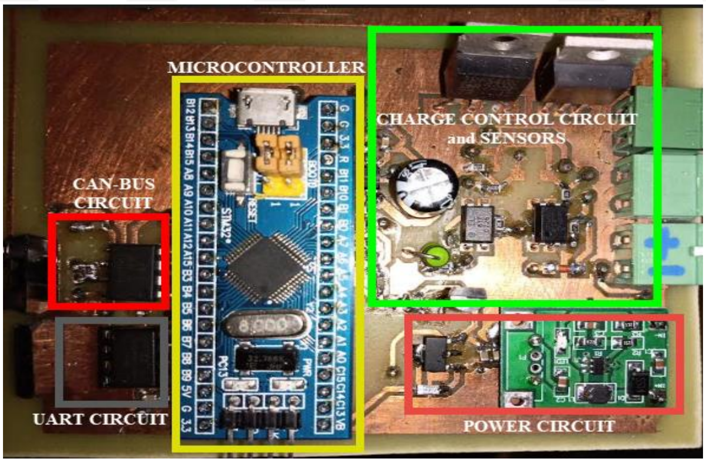


Figure 3.16 Designed BMS control card

3.3.6.2 Overview of Designed Second System BMS Circuit Cards

Battery management system circuits consist of two main parts. These are master and slave circuits. In this system main design process especially applied to slave control cards. There are PIC based four slave controllers used for passive balancing process. Also, one STM based microcontroller module used as master controller. This module used directly so there is not any circuit design for master controller part. So only slave controller card design process is mentioned in this section. The designed slave control card consists of serial communication circuit, charge control circuit, voltage boost circuit and measuring circuit with sensors. PIC18f4520 microprocessor is used in the slave control system to perform the control operations. The operating voltage of this microprocessor is 5V. Therefore, the voltage value obtained from the batteries in the range of 3-3.5V has been increased to 5V by using boost circuit. Also, other circuit elements such as optocoupler and UART IC that need 5V supply voltage in the control board are supplied with this boosted voltage.

The charge control circuit is constructed according to the passive cell balancing topology. For this purpose, N-channel type MOSFET was used in the balancing circuit. 4.7Ω stone resistor which is limited the balancing current, and filtering elements that convert PWM signals to DC are used. Balancing is performed when the voltage difference between the two battery cells rises above the determined level. The duty cycle of the PWM signal varies in proportion to the voltage difference between the two cells. As a result of this process, excess energy was spent at the MOSFET by converting it to heat energy. Thus, balancing process was performed between the cells. The required data for the control process is obtained from the unit where the sensors are located and the measurement operations are performed. The system collects voltage, balancing current and temperature information for the control process. Charging process is performed according to the collected data. The balancing current is measured without the use of a current sensor. Firstly, the voltage difference between the pins of the stone resistance is obtained. In the next step, this voltage value is divided by stone resistance value and current value is found with this way. Temperature values of the batteries were measured using LM35 sensor.

A button is added for the reset process and the operating status is visualized by LED in the circuit design. The block schema of the slave system can be seen in Figure 3.17 at the bottom.

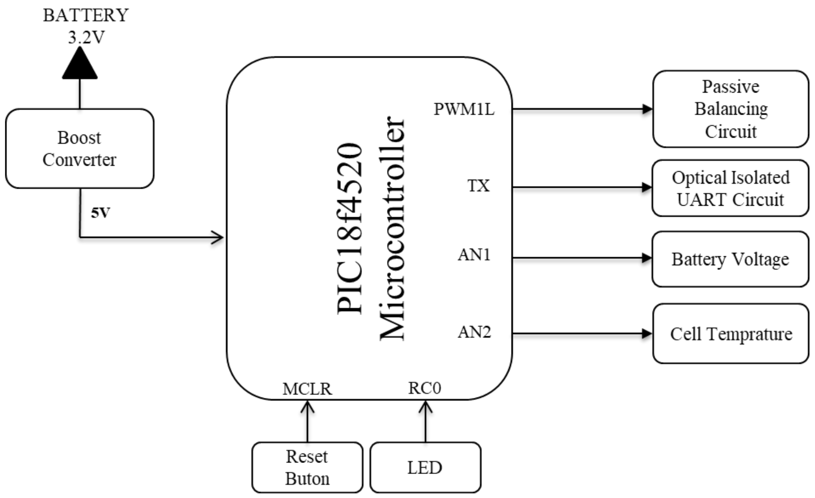


Figure 3.17 Designed second BMS System slave control card block schema

The passive method based balancing circuit is included in the slave controller. The master controller has two main tasks. Important tasks such as controlling the charge of the batteries and transferring the collected data to the computer are performed by the master controller. The data is sent to the master controller by the slave cells. Each slave cell reads its data via sensors and transmits it to the master cell via UART communication protocol. The general diagram of the master and slave-based BMS system is shown in Figure 3.18.

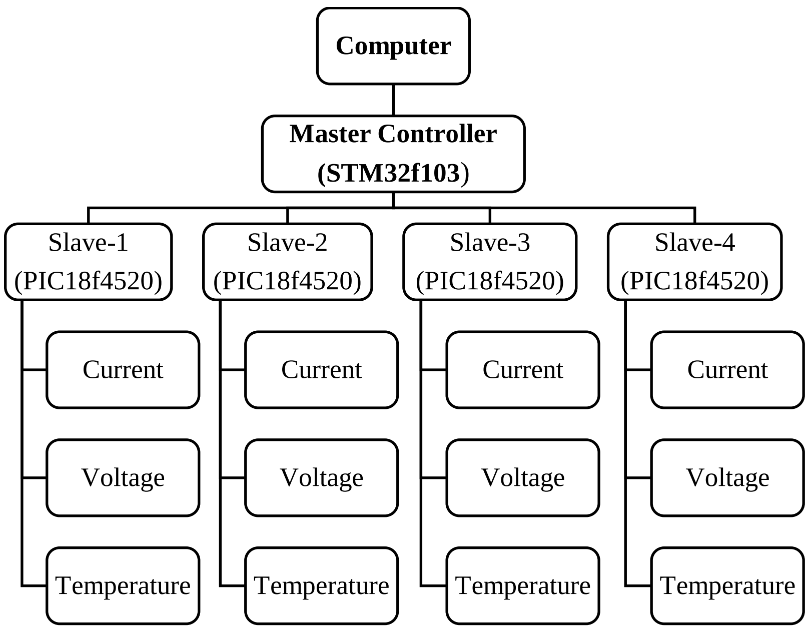


Figure 3.18 BMS control system block schema

3.3.7 PCB Design With Using SMT and Through Hole Technique

One of the most important things in circuit design is the proper operation of the designed system. In addition to this, it is also very important for industrial works that the designed circuit system works smoothly for a long time. Circuit components were classified based on their mounting style. There are two types mounting techniques at industrial designs for continuous and smoothly operation of electrical circuits. Through hole and surface mounting techniques are two important methods used frequently in circuit designs. SMT has helped significantly in solving the space problems that were commonly noticed with the Through Hole mounting. Also EMI (Electromagnetic Interference) effect can be decreased with using SMT. These techniques used for two BMS system controller cards design and implementation process. During this design phase, Proteus program was used. Top of the PCB was designed as +3.3V source layer and bottom of the BMS controller card was used as a ground layer for first type of BMS controller card. Also top of the PCB was designed as +5V source layer and bottom of the BMS controller card was used as a ground layer for second type of BMS slave controller cards. The card design has been realized by using SMD elements in slave control cards. Proteus circuit program was used for design process. Through hole and surface mounting techniques were used at these designed BMS control cards. Proteus program of one cell and four cell BMS control card design and 3D view can be seen at respectively Figure 3.19 and Figure 3.20. Real-time designed and implemented four cell BMS control card can be seen at Figure 3.21. Proteus program of one cell BMS slave controller card design and 3D view can be seen at Figure 3.22. Real-time designed and implemented slave cell BMS control card can be seen at Figure 3.23.

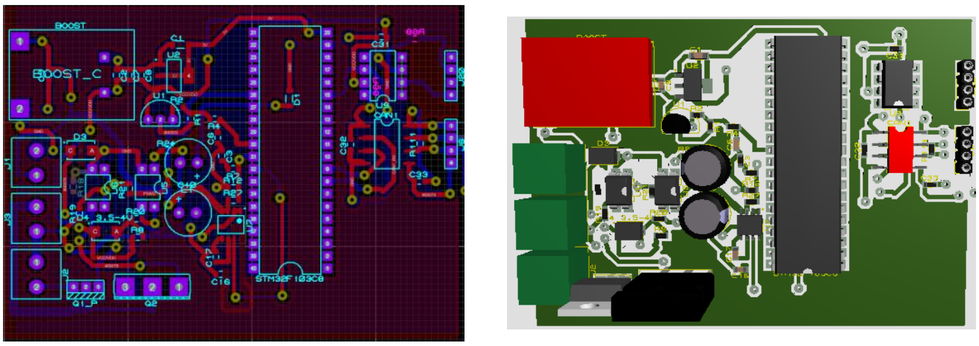


Figure 3.19 ARES program design of one cell BMS control card and 3D view

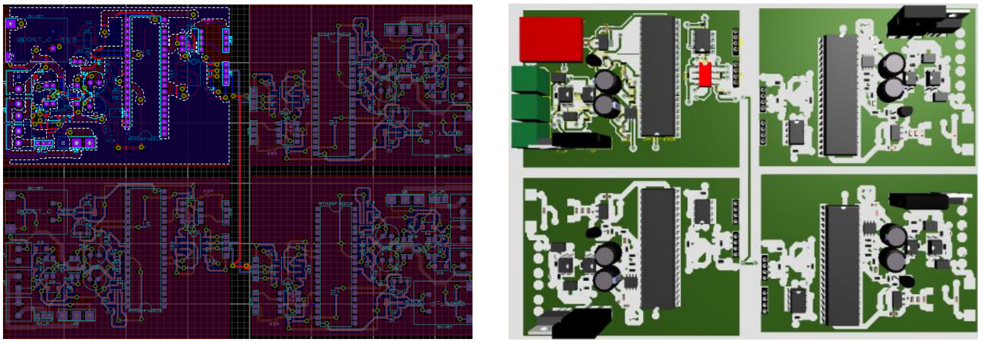


Figure 3.20 ARES program design of four cell BMS control card and 3D view

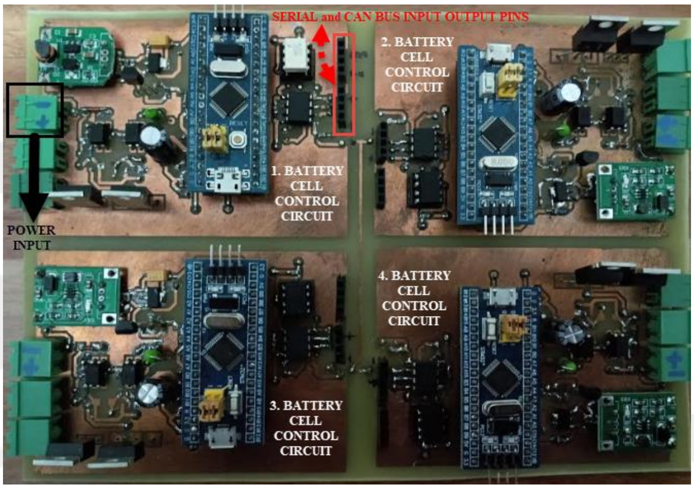


Figure 3.21 Real time implementation of designed four cell BMS control card

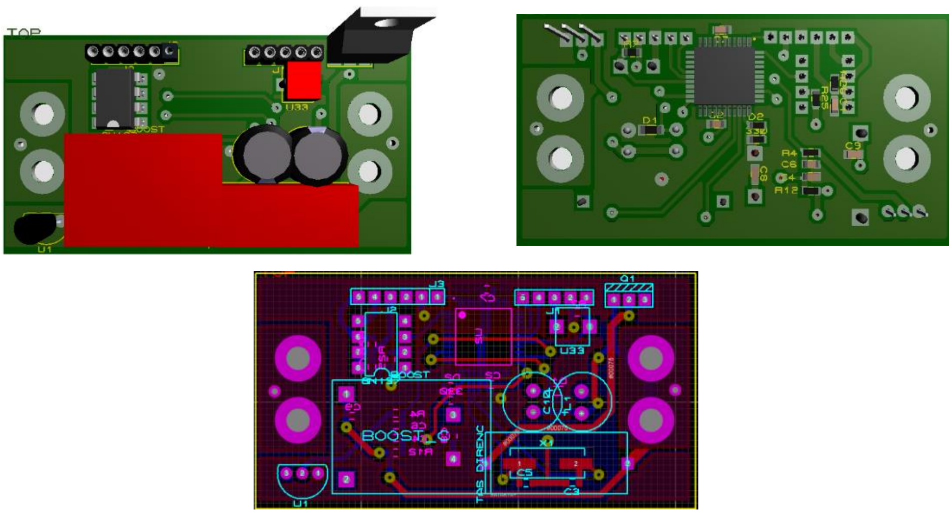


Figure 3.22 ARES program design of Second BMS system slave controller card 3D view

Figure 3.23 Real time implementation of designed Second BMS system slave controller card

3.3.8 CAN Bus Communication Method Based BMS Control Card Design for First BMS System

CAN communication method is used for first BMS system. Every slave controller cards are designed according to CAN bus technique. STM32f103C8 microprocessor is selectred for this aim. The CAN controller IC is directly connected to the CAN bus. CAN bus is a two-wire bus terminated with 120 ohm resistors on both sides. CAN bus based communication part of designed BMS control card can be seen at Figure 3.24.

It is stated in the previous sections that ISO1050 insulated integrated is used for CAN bus communication. The ISO1050 is a galvanically isolated CAN transceiver. This IC has the logic input and output buffers. These buffers are separated by a silicon oxide (SiO_2) insulation barrier. So this isolation barrier provides galvanic isolation up to 5000 V_{RMS}. ISO1050 CAN transceiver provides up to 1 megabit per second (Mbps) signaling rates transmit and receive capability. Input and output voltage range supports 3.3V and 5V microprocessors.

ISO1050 CAN transceiver can be used lots of different area applications. Such as these kinds of applications can be related with industrial automation, control, sensors, and drive systems, building and climate control (HVAC) automation, security systems, transportation, medical, telecom.

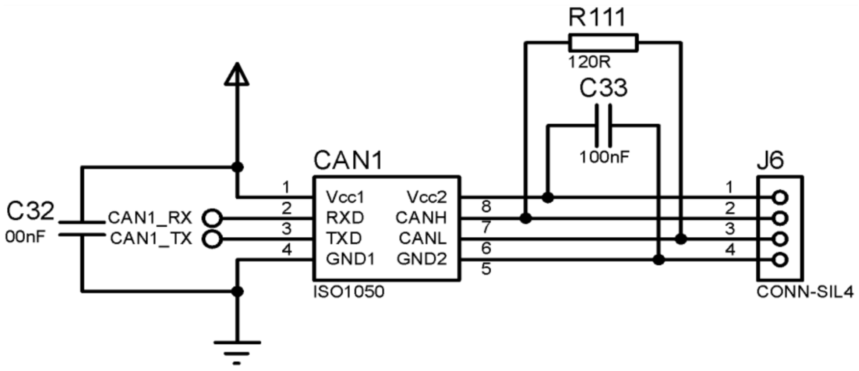


Figure 3.24 CAN-Bus communication part of designed BMS control card

3.3.9 UART Communication Method Based BMS Control Card Design for Second BMS System

UART protocol is used at second BMS system as a communication method. Four slave controller circuits are designed according to UART communication. PIC18f4520 microprocessor is selected as a microcontroller at slave circuit. These cards have isolated UART protocol with 6N137 optocoupler. Thus, each cell was isolated from each other and communication was established with this technique. UART communication part of designed BMS slave control card can be seen at Figure 3.25.

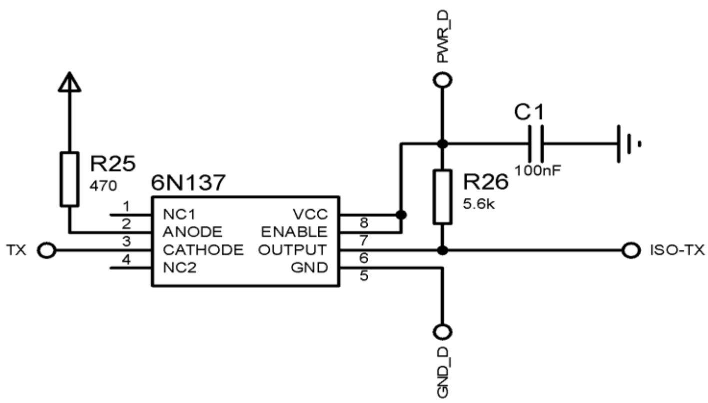


Figure 3.25 UART communication part of designed BMS slave control card

3.4 Working Principle of CAN-BUS Based Data Acquisition System for First BMS System

In the designed system, data were collected from the three cells by the CAN bus to the master processor. The collected data in the master processor is transferred to the computer via UART serial communication protocol. Each slave cell is assigned an ID number. The data to the master processor is read according to these ID numbers. The data is taken from the slave cells according to the request of the master cell. The master cell first requests current, voltage or temperature data from each slave cell. Upon this request, the slave cell reads the requested data and sends it to the master cell. This means that both the master and slave cells are not constantly busy. The data of the cells is read and stored in the database in every seven seconds in order to prevent excessive data stored in the database. Designed BMS system working block diagram of data acquisition process is given in Figure 3.26 at the bottom.

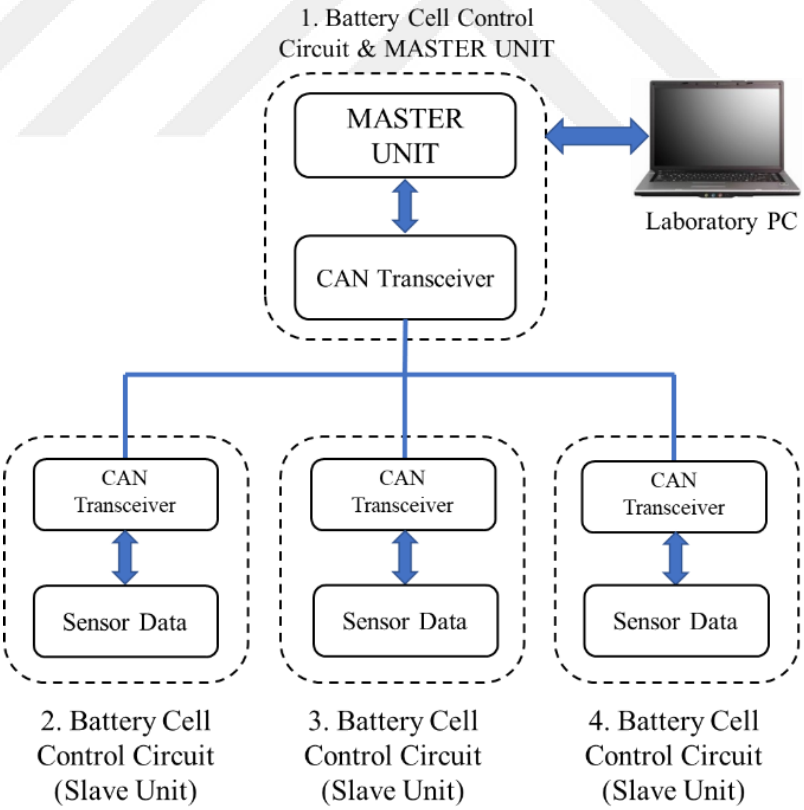


Figure 3.26 Designed BMS system general working schema

3.5 Working Principle of UART Based Data Acquisition System for Second BMS System

Data were collected from the four cells by the master processor with using UART communication protocol at the designed BMS system. The collected data in the master processor is sent to the computer via UART serial communication protocol. The data is taken from the slave cells according to the request of the master cell. The master cell requests sensor data from the slave cells respectively. The slave cells, which realize that the data is requested, read the data and send it to the master cell. Data can be transmitted to the master cell through all the cells in sequence, since this method uses the UART protocol. There is no bi-directional communication in the UART communication protocol. The data which is read from the RX pin of the master cell by pass the slave1, slave2, slave3 and slave4 respectively. The data read from the cells is transferred to the PC via the UART module. The master cell firstly requests current, voltage or temperature data from each slave cell. Upon this request, the slave cell reads the requested data and sends it to the next cell until this data reached to the master unit via RX1. The data of the cells are sent via TX3 to the PC and stored as txt extension file. So, two different UART lines are used for this BMS application. For example, when the master cell requests data from slave cell 1, it sends this request command to slave cell 1. The 1st slave cell that receives this command understands that the master cell requests data from it and writes the data to the array. This array is sent to the adjacent slave cell. The 2nd slave cell transmits the data to the 3rd cell and the 3rd slave cell to the 4th cell and the 4th slave cell transmits this data to the master cell. Thus, the data belonging to the first cell is transferred to the master cell. Designed second BMS system working block diagram of data acquisition process is given in Figure 3.27 at the bottom.

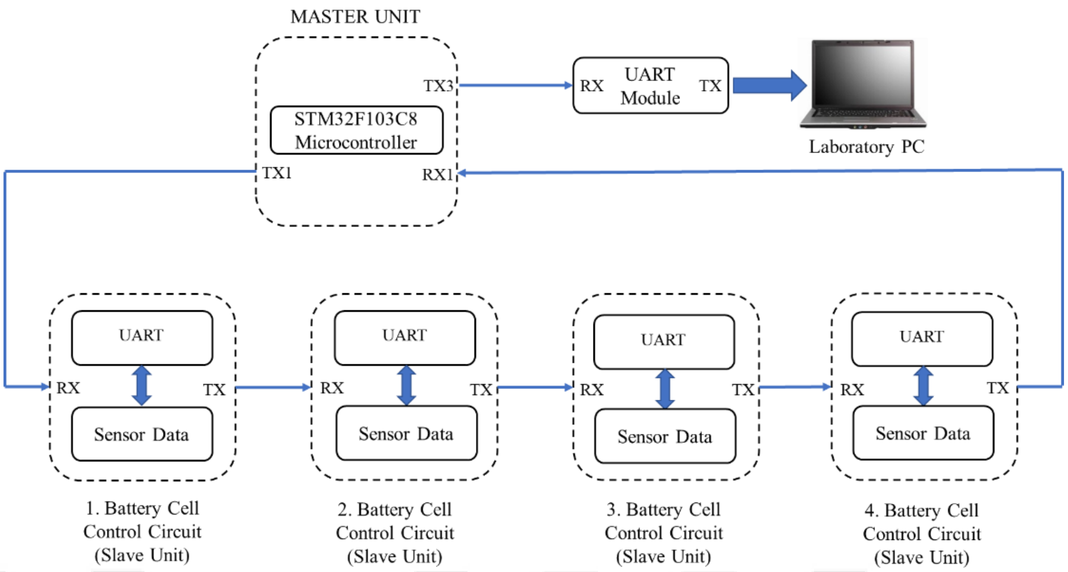


Figure 3.27 Designed second BMS system general working schema

3.6 Visualization and Saving of Data

Communication systems and protocols are very important in the designed all electronic and control based systems. Therefore, the accuracy and smooth operation of the communication process is essential for the intended system. It was mentioned in previous sections that the BMS system communicates with slave cells based on CAN and UART protocol. Also two systems are sent data to the computer with UART protocol. The sensor data from the cells are properly collected on the Master and then sent to the PC. These process are same for the first and second type of BMS systems. The correct reading of the data is very important for the correct control. However, visualizing and storing properly this data is just as important as other processes. In order for the system to make sense to the user, the changes measured by the sensors in the system must be controlled by the user. Therefore, in order to observe the change of data received from the BMS system, an interface was created on the PC side using the C# program. Thus, current, voltage and temperature changes in all cells can be easily monitored instantly for the two BMS systems. While the UART-based second BMS system does not have a professional data recording system, the CAN bus-based first system has created a more professional data saving system. For this purpose, the values of all cells are recorded by using SQLite data storage program at the designed first BMS system.

3.6.1 C# Program

It is possible to hear new things from day to day in the software industry, which started from the 1950s to the present. Because throughout history, humanity has been inclined to produce products to facilitate their work. Programming in the 20th and 21st century has been a tool used to produce products that make life easier for people.

Many programming languages have been developed to date. They are used in many fields in different platforms according to different language structure and characteristics. Among all languages, two programming languages are very important for humanity, especially in the field of objective programming. The first of these languages is Java, which can be run as a common platform. The second one is the C# (CSharp) programming language, which can be programmed in a common platform with all languages by integrating with the Net library and with an easy coding structure.

C# is derived from the two most commonly used software languages, C and C++, in the software industry. There are also similarities between C# and Java programming languages. The most striking feature of C# is that it is a completely object oriented software language for the .Net Framework platform. That is, objects are first written in classes. The programmer can use these objects in the software. The programmer writes lines of code that will execute the object it uses for its intended purpose and includes it in its software. Thus, a software can be created to control different units via an interface.

C# was first developed to improve the negative aspects of C++ and Visual Basic programming languages. However, in addition to this purpose, it has become an important language among object oriented languages in a short time. C# minimizes errors thanks to its advanced compiler infrastructure. Programmatic errors are indicated to the user via a different window in the program interface. Errors can be detected more easily by displaying them in different windows. In addition to these features, programmers can contact C# developers and get help. C# and .Net Framework structures are generally perceived as the same concept. But Net Framework and C# are different concepts. The two programs were developed for different purposes. As it is known, C# is an object oriented programming language. Net Framework is the working environment required for C# to work. All libraries in C# are based on the Net Framework.

General features of C# language:

- Simple and general purpose language
- Platform-independent language
- Easy to use modern language
- 100% Object oriented programming language
- A appropriate and robust language for future-based applications

Applications that can be done with C#:

- Console application development
- Windows application development
- NET application development
- Writing Web services
- Mobile application development (for PDA, mobile phones, etc.)
- Writing a DLL

Visual Studio is an IDE manufactured by Microsoft that is used to create consoles, graphical user interfaces, Windows forms, Web services, or Web applications. Only native code supported by Microsoft Windows is used within the Visual Studio program. Visual Studio program is can be used development environment for different programming languages (C, C++, C#, Visual Basic, .NET, F#, Fossil, M, Python, HTML/XHTML/CSS, JavaScript). At the same time Visual Studio generally preferred as development environment for C#. It can said that Visual Studio is software for producing some kinds of software. Visual Studio software doesn't coded itself, but thanks to its advanced features, it helps developers prepare their programs in less time. It can be prepared computer software, web applications and web services more quickly and easily. The Visual Studio user interface is shown in Figure 3.28 at the bottom. In the interface shown in the Figure 3.29, coding operations are performed to determine how the used objects will work in software.

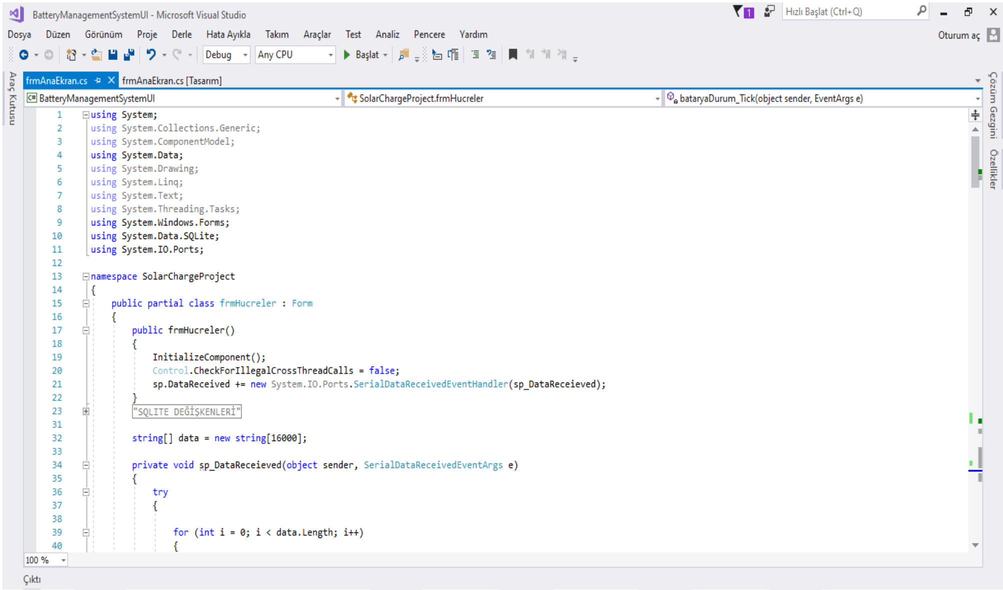


Figure 3.28 Visual Studio programming screen

Figure 3.29 shows the section where the visual interface is created by selecting the objects of the Visual Studio program. In this part of the program, the interface is designed by adding the objects and designed according to the user's request. As each new object is added, a new code writing area is inserted in the code section for the controlling added object. An interface can be designed and created as shown in the figure. Each text field and text here is considered an object.

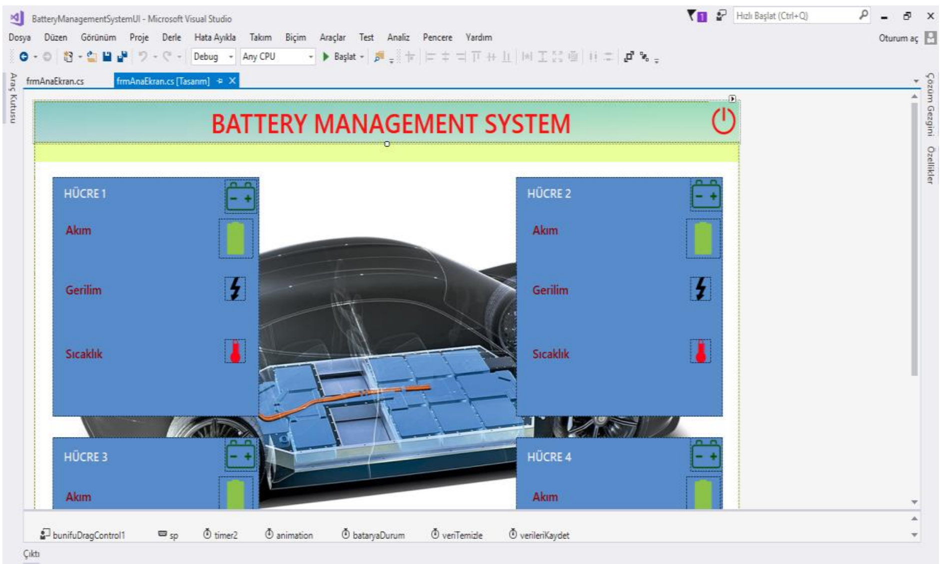


Figure 3.29 Visual Studio interface designing screen

3.6.2 SQLite Database Program

SQLite is an operational and relational SQL database engine that is widely distributed in the world and recommended for developers to use. It is fully open source, coded in C and C++ programming languages. SQLite is a self-contained, high-reliability storage solution that can run on all operating systems and is not dependent on external resources. Therefore, it is highly preferred. It is an embedded system, meaning that it does not need a server to write and read data. It is directly write and read data from the database file on the disk.

SQLite database can be used easily in dozens of programming languages. Such as ASP, BASIC, C#, C, C++, Delphi, Java, PHP, Python and Visual Basic widely known programming languages can be used with SQLite database.

SQLite database can be easily used in local applications. For example, preparing a application which is containing user information of the company. The texts and information to be written on this application have to be stored in a database so that the user can access them again at any time.

SQLite database was not known exactly in the past years. Therefore, generally different database systems were used. SQLite is often preferred in these days because it reacts faster and causes less problems than other database systems.

In addition to this, SQLite is the primary and permanent choice of developers for applications developed for Android and iOS. Because it is capable of working in 100% harmony with these systems.

The SQLite database program user interface is shown in Figure 3.30 at the bottom. Databases can be created, viewed and controlled in this interface. In Figure 3.31, the recorded data is classified according to the created database and can be displayed separately.

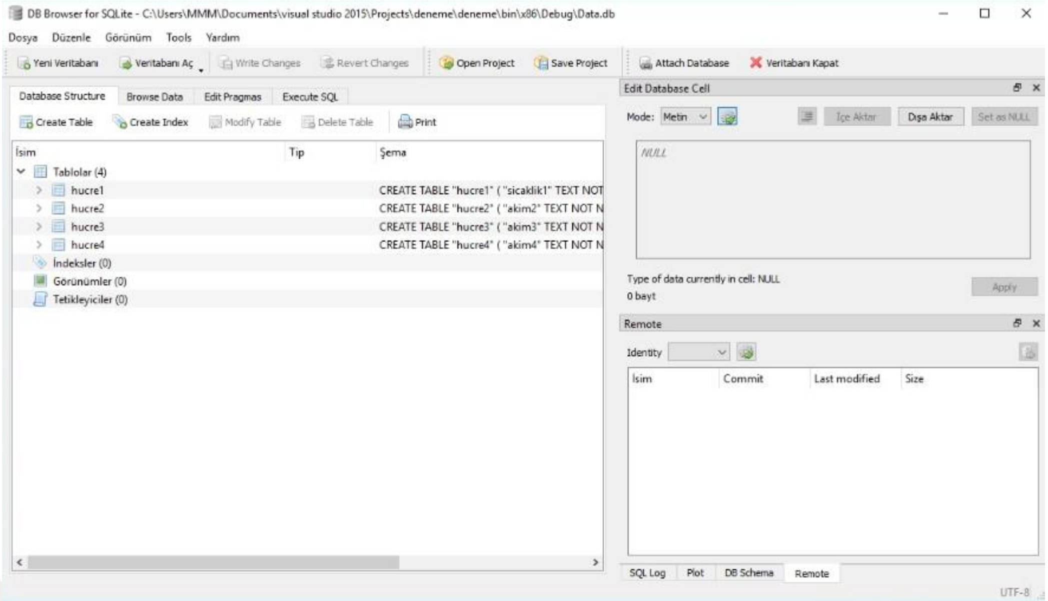


Figure 3.30 SQLite database program main screen

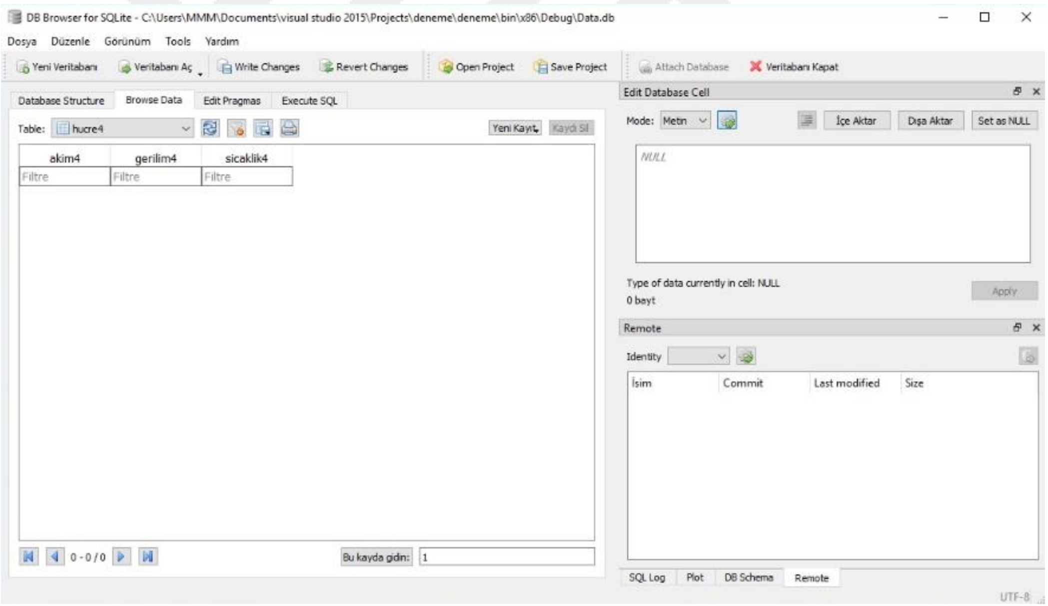


Figure 3.31 SQLite database program saved data screen

3.7 Created Algorithms for First and Second BMS Systems

When BMS-based systems are examined, it is seen that simpler methods are chosen to control these systems because of the complexity of the control process. The main reasons for the complexity of the system are the large amount of data, software-based and the necessity of continuous monitoring of each cell instantly. The more complex and difficult part of this work is the smooth flow of data. Once this step is performed, the other steps can be performed more easily. For this reason, the algorithms are divided and explained into groups.

As it is known, two different systems have been established based on UART and CAN communication protocols. Therefore, the algorithms will be classified under two main headings. Under these main headings, also the algorithms for master and slave cells will be explained.

3.7.1 First BMS System Algorithms

Firstly, the algorithms of the master and slave cells are given according to the basic process flow. After the basic process flow, the algorithm that controls the data flow of the system is mentioned. After this step, the software algorithm which is used C# and SQLite programs, related to visualizing and saving the collected data in PC side and finally the algorithms for battery charging are explained consequently.

According to the algorithm in Figure 3.32, initial adjustments for the master controller are performed. CAN and UART based communication operations are started after the necessary adjustments are made. The master cell requests the voltage, current and temperature data from the slave cells respectively and sends the data in the desired slave cell via CAN-Bus protocol. After obtaining the desired data, minimum and maximum voltage values of the cells are determined. The voltage difference between the cells is constantly controlled since voltage-based charging is performed. The control system between the cells is formed based on voltage information. When the voltage difference exceeds 50 mV, the balancing process is started for the battery cell with a high voltage value. If the system does not need balancing, it continues to read the data and checks the voltage values of the battery cells. The temperature conditions of the cells are also checked and charging is stopped in case of a temperature above the specified level.

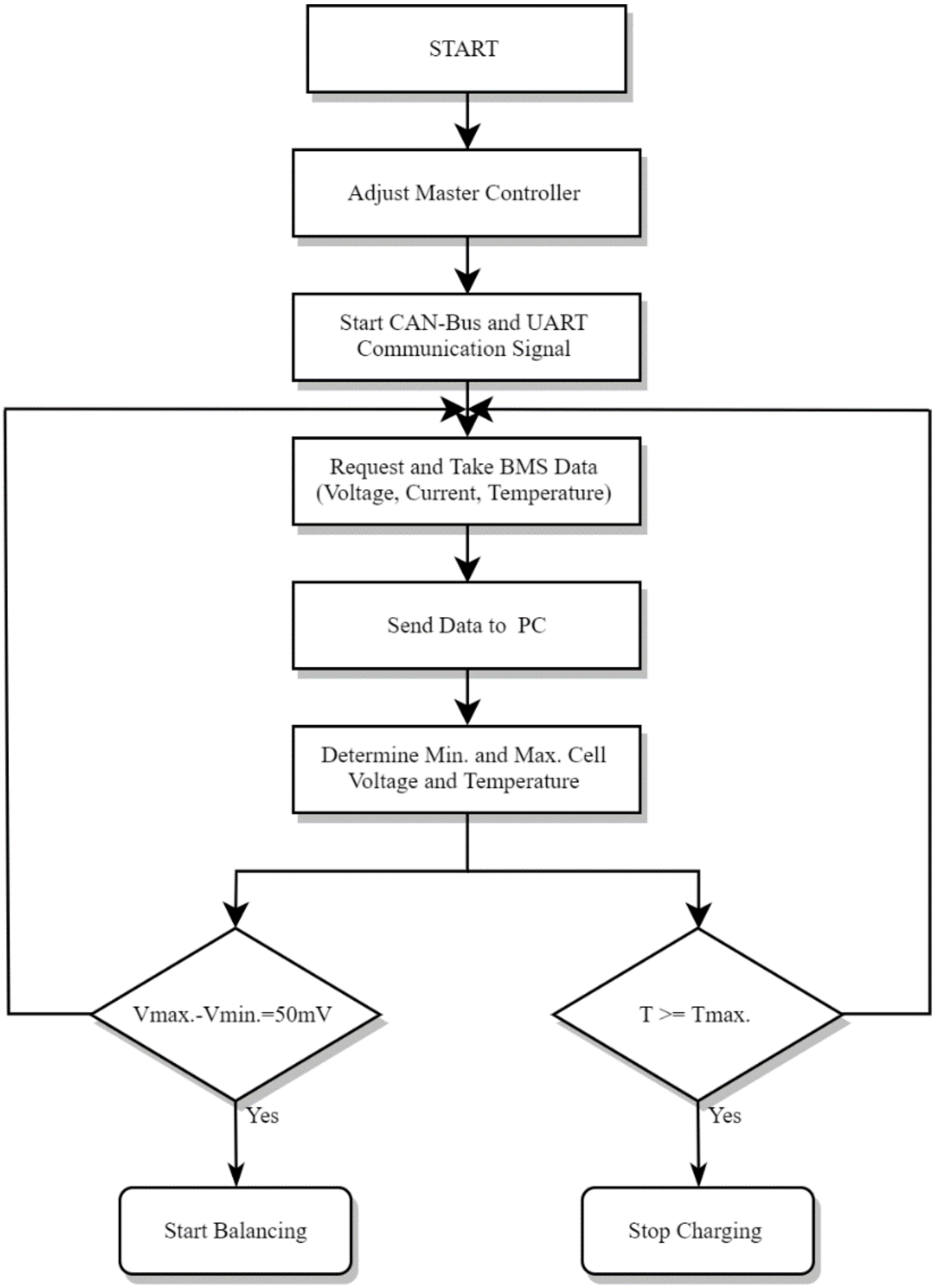


Figure 3.32 First BMS system master cell main control algorithm

Figure 3.33 shows the algorithm diagram of the slave control circuit. In the first step of this algorithm, initial settings are adjusted related to interrupt, timer, serial communication and CAN bus communication protocol.

It was stated that the master cell reads the data from the slave cells at any time. The reading of the data at any time is carried out in order to prevent the continuous unnecessary data transmission of the master and slave cells. Thus, the frequency of reading the data was tried to be adjusted. The current, voltage and temperature information is received from the cells as one data package with the CAN-Bus line. When the master cell requests data from the slave cell, master cell sends data packet is request command. According to this information wanted data package is sent to the master cell. When a command is sent by the master controller for balancing, the MOSFET in the slave cell is controlled by the PWM signal. Measured sensors data are read and send with ID number using CAN-Bus data protocol to the master controller.

Master cell data flow control process can be seen in detail at Figure 3.34 algorithm schema. Firstly, the settings of the timer, UART and CAN-Bus units used for reading and writing data are performed. After these operations, these units have the settings to work as desired. The functions used to receive the desired data from the slave cells are prepared. After these operations, the necessary timer settings are made to read the data packet from each slave cell according to determined time interval. This timer is set to count every 6 seconds in total. In the first second, the algorithm reads the values of the sensors in the master cell. It performs the necessary mathematical operations and sends the data to the interface created on the PC via UART. This data is sent to the PC side with some characters such as “s”, “g” and “a”. The purpose of this process is to make the sent data meaningful by the software on the PC side. These letters are left at the beginning of temperature, voltage and current data respectively. In this way, after reading these characters, the PC can understand which data is being read. This logic is applied in the same way for all read and write operations. Also “s”, “g” and “a” characters are used for the other slave cell data packages.

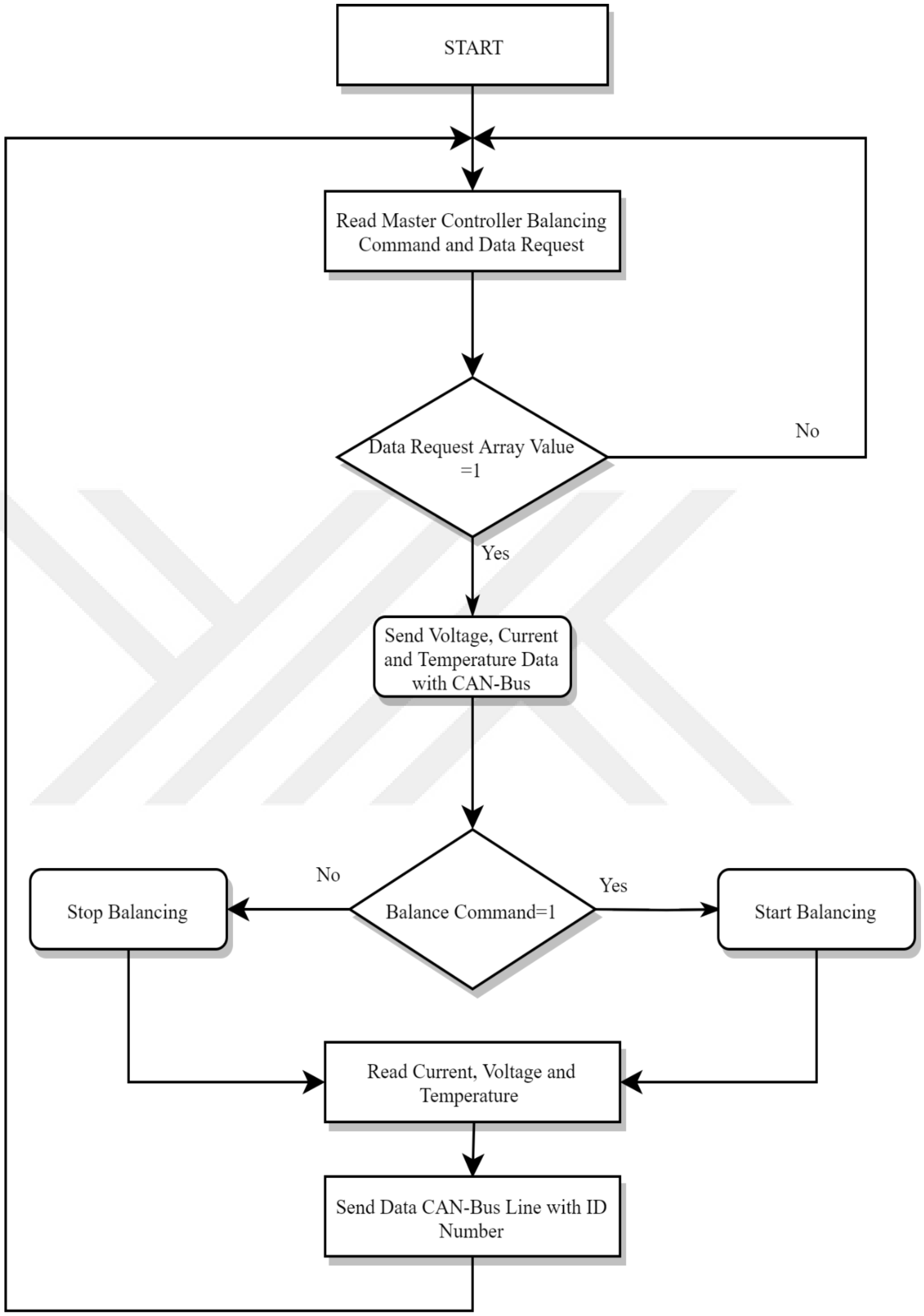


Figure 3.33 First BMS system slave cell data flow control algorithm

Data visualizing and saving control algorithm of BMS system can be seen in detail at Figure 3.35 algorithm schema. C# and SQLite programs are used for creating an interface for show reading data changing and saving data to database system. In order to make the data in the master cell understood by the PC, some letter characters were added and data packets were sent. In this algorithm, a software system is created based on these added characters. Data packets are interpreted according to the incoming characters and it is determined that these data are current, voltage or temperature information. The determined data has been read in such a way that it will be displayed in the relevant text field on the created interface. The data is saved to the created database with the SQLite program in every five seconds after the data of all cells are transferred to the relevant fields in the interface. For this process, firstly the connection to SQLite program is automatically established through C# program and the data is written to the specified columns. The read data from each cell is saved to the SQLite program in current, voltage and temperature columns.

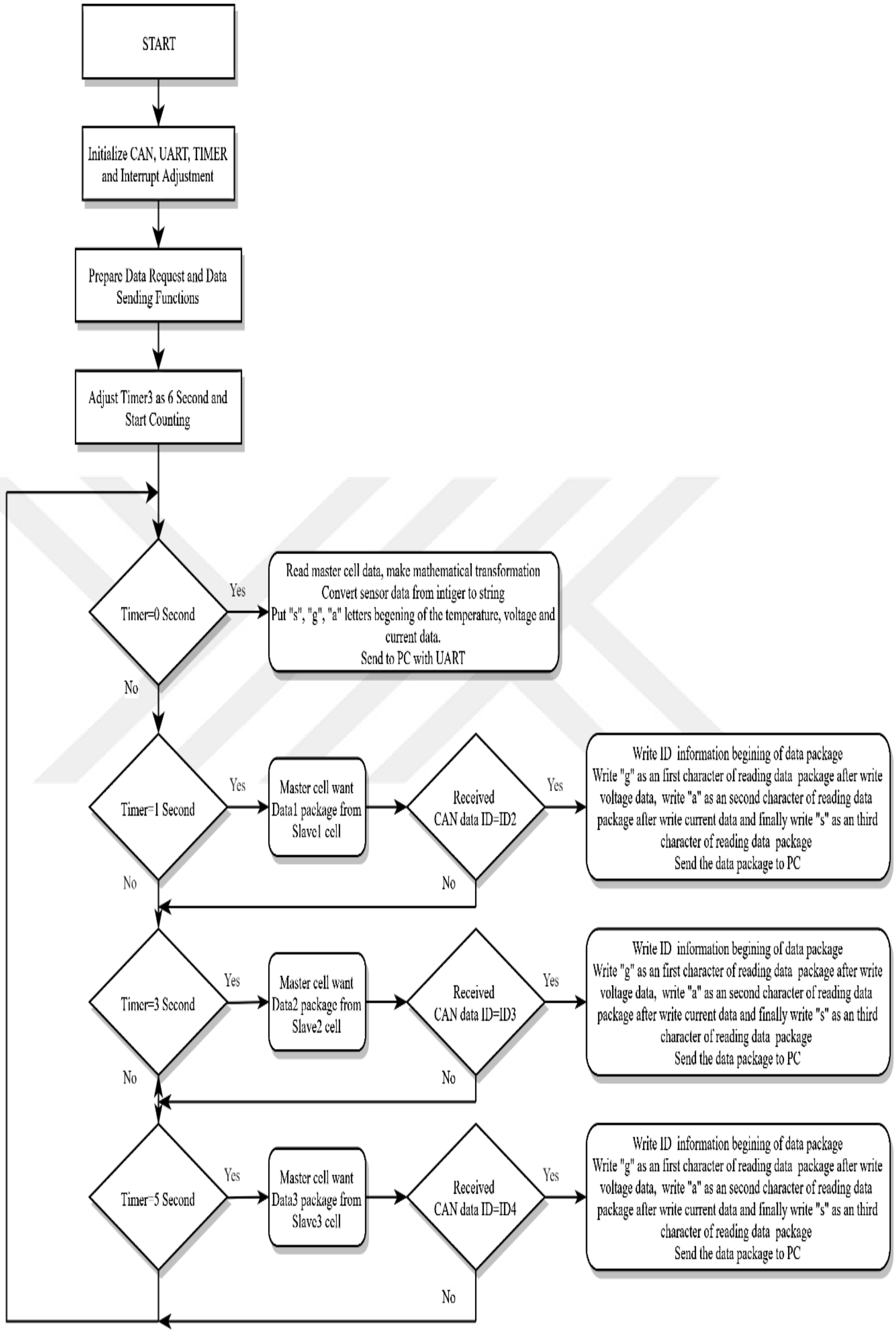


Figure 3.34 First BMS system master cell data flow control algorithm

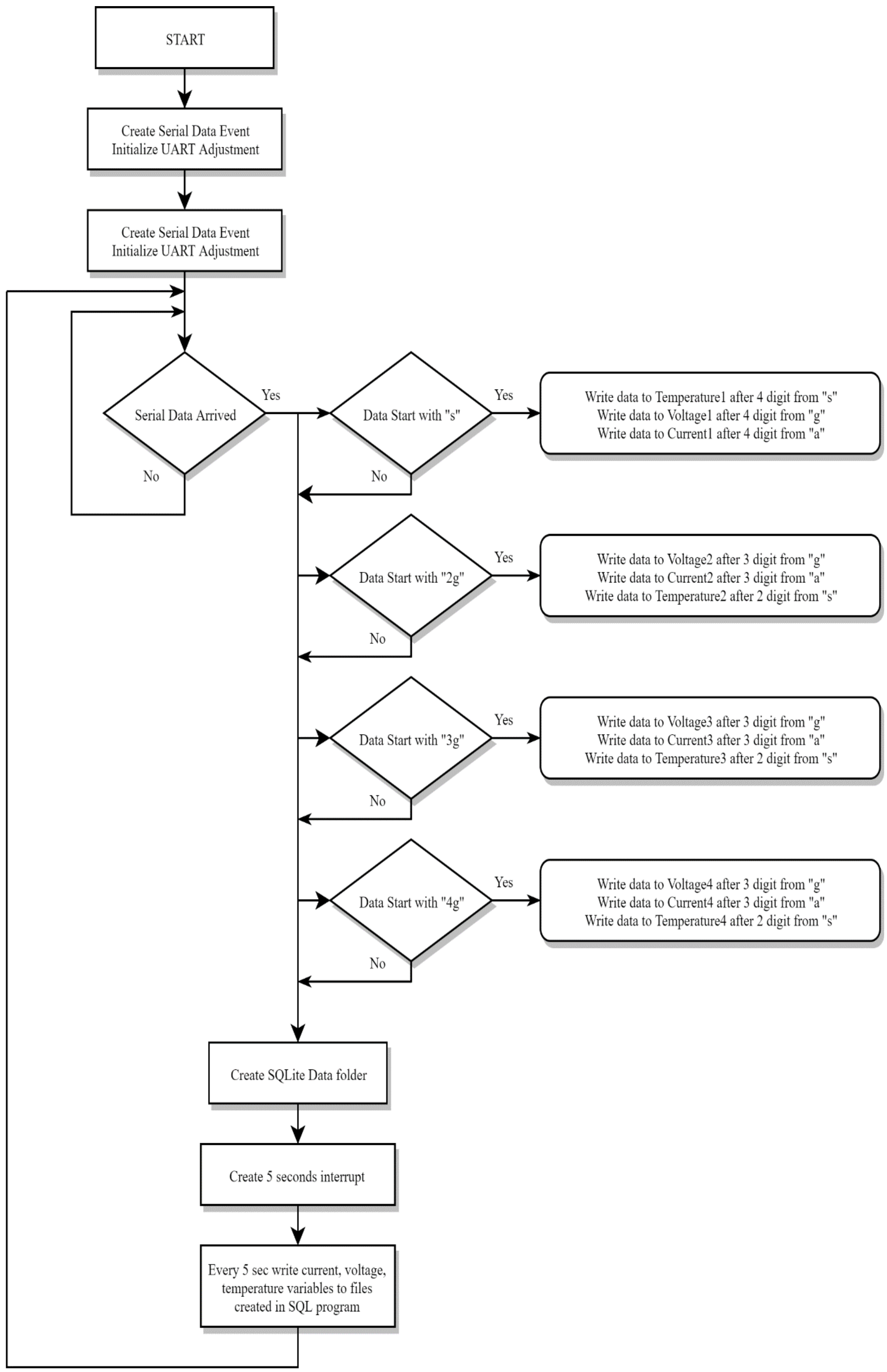


Figure 3.35 Data Visualizing and saving control algorithm of first BMS system (C# and SQLite)

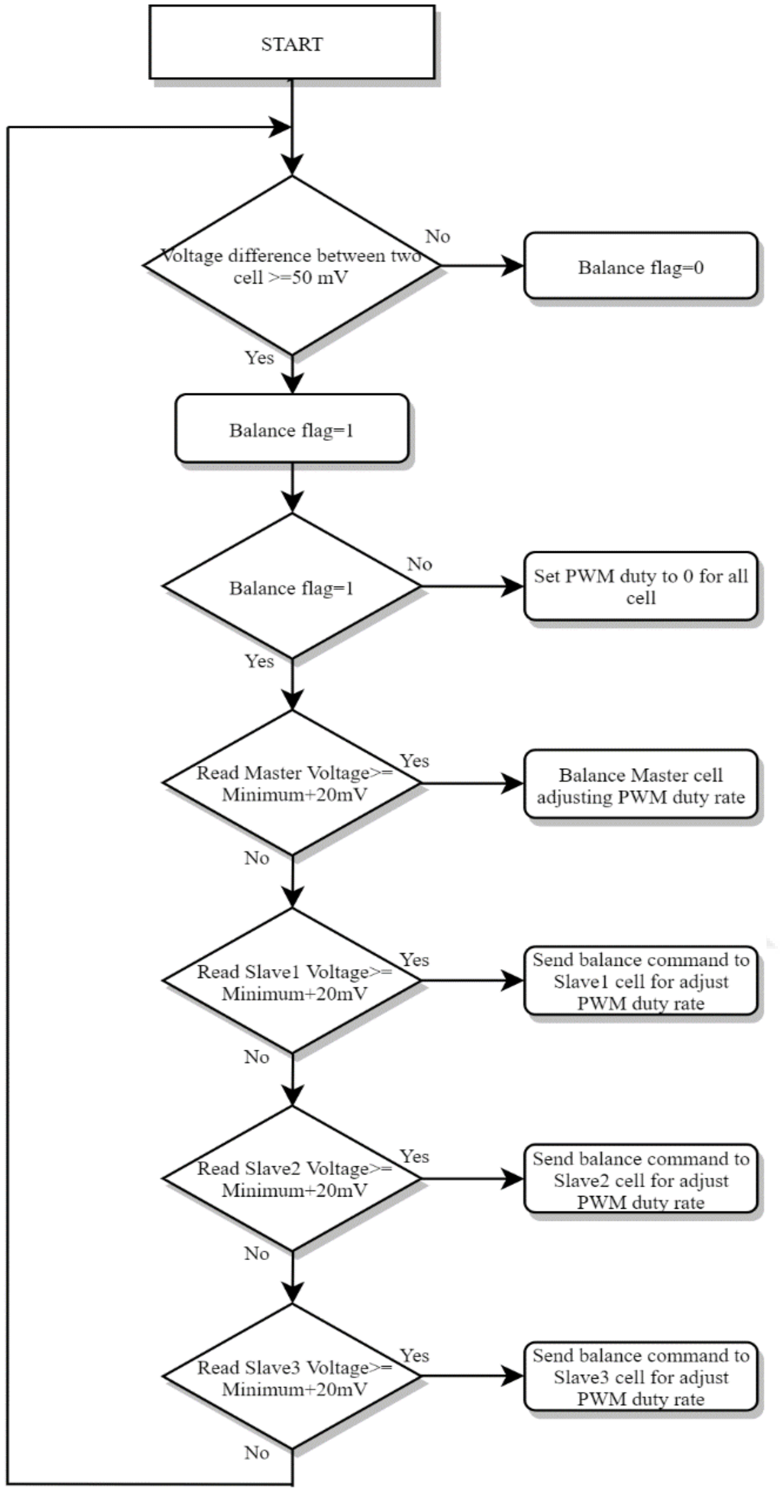


Figure 3.36 Passive BMS charging control algorithm of first BMS system

Figure 3.36 shows the algorithm scheme for passive balancing. Passive balancing algorithm is created by using voltage value information so the balancing technique is applied based on the voltage information of the cells. This algorithm is implemented by the master cell. Firstly, the voltage values of the cells are checked and if the voltage difference between any two cells is more than 50 mV, the system decides the balancing process. In order to increase the charge voltages of the cells in a balanced manner, it is provided to charge the cells together by referring to the more than 20 mV of the minimum cell voltage value. Thus, the difference between the voltage values of the cells can be kept at a certain level and charged until they all reach the same voltage value.

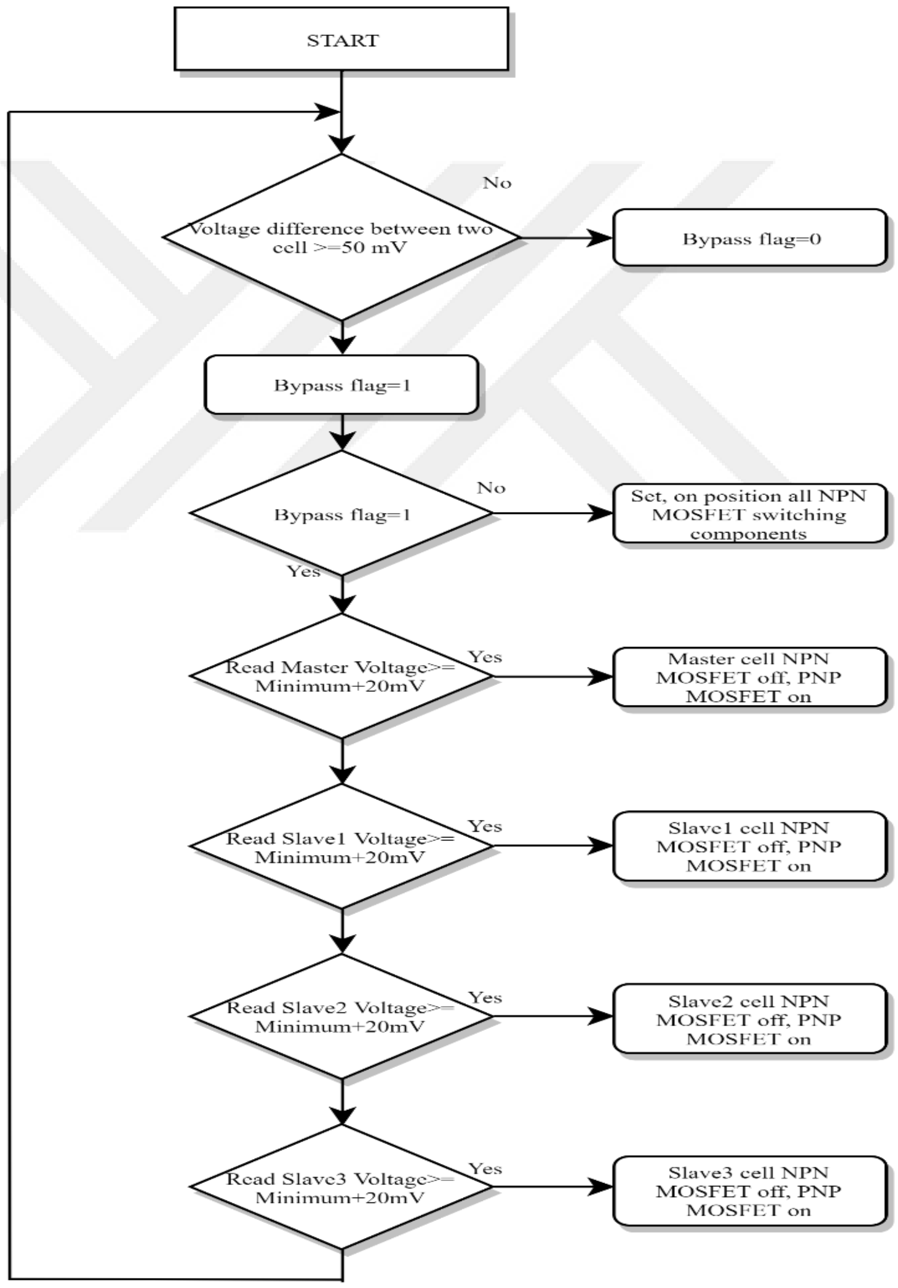


Figure 3.37 Active BMS charging control algorithm of first BMS system

Figure 3.37 shows the algorithm scheme for active balancing. Active balancing algorithm is created by using voltage value information so the technique is applied based on the voltage information of the cells. This algorithm is implemented by the master cell. Firstly, the voltage values of the cells are checked and if the voltage difference between any two cells is more than 50 mV, the system decides the bypass process. This method is provide to charge the cells together by referring to the more than 20 mV of the minimum cell voltage value. N-channel and P-channel type MOSFETs are switched after the cell to be bypassed is determined. As a result, the bypassed cell exit the charging process. The charging current continues through the P-channel MOSFET switching element of the respective cell and continues charging the other cells. Thus, the difference between the voltage values of the cells can be kept at a certain level and charged until they all reach the same voltage value.

3.7.2 Second BMS System Algorithms

Master and slave logic are also used in the second BMS system. In this respect, it has the same logical design as the first BMS system. However, there are significant differences in the number of used microprocessors and the used communication protocol type. The most important difference that separates the first system from the second system is that the communication infrastructure is based on complately UART protocol. Firstly, the algorithm structures of the master and slave cells are explained as in the algorithm layout of the first system. Then the algorithm of UART based data collection system is given. And finally, algorithms related to the transfer of data to the computer are given. In this system, the data is saved to a txt file only. That is, no database is used as in the first system. Two different algorithms are applied in the second BMS system. These are algorithms applied to master and slave cells. The algorithm applied to the master cell is shown in Figure 3.38. According to this algorithm, the necessary adjustments are made for interrupt and UART communication of the master processor. When the master processor is ready, control and communication operations are started. The master processor receives the sensor data of the slave cells. According to this data, control algorithms are operated. At the same time, this data is sent to the computer interface via serial communication. The maximum and minimum cell voltages are determined by the master cell for balancing.

If the difference between the battery voltages of the two cells is more than 50mV, the balancing process is started. If the difference is less than 50mv, the read data is sent to the computer and no balancing is performed. At the same time, the temperature of the cells is continuously controlled. If the temperature of the cells reaches above the specified critical value, charging is stopped. It has a similar structure with the passive based control algorithm used in the first BMS system. Also, voltage information is taken as reference at the second BMS system algorithm structure. Figure 3.39 shows the scheme of the algorithm applied to the slave control cards. According to this algorithm, firstly, necessary adjustments are made for interrupt and serial communication. The slave cells are balancing according to the command from the master processor. For this reason, the slave cell checks whether data related to the balancing information is received from the master cell. If there is information about balancing, PWM signal is applied to MOSFET. While performing these operations, the sensor data is read out to be sent to the master cell. Also, C# based interface is designed to visualize the data of the second BMS system as in the first BMS system. The processes of reading and transferring the data to PC interface are the same logic based as explained in the first system.

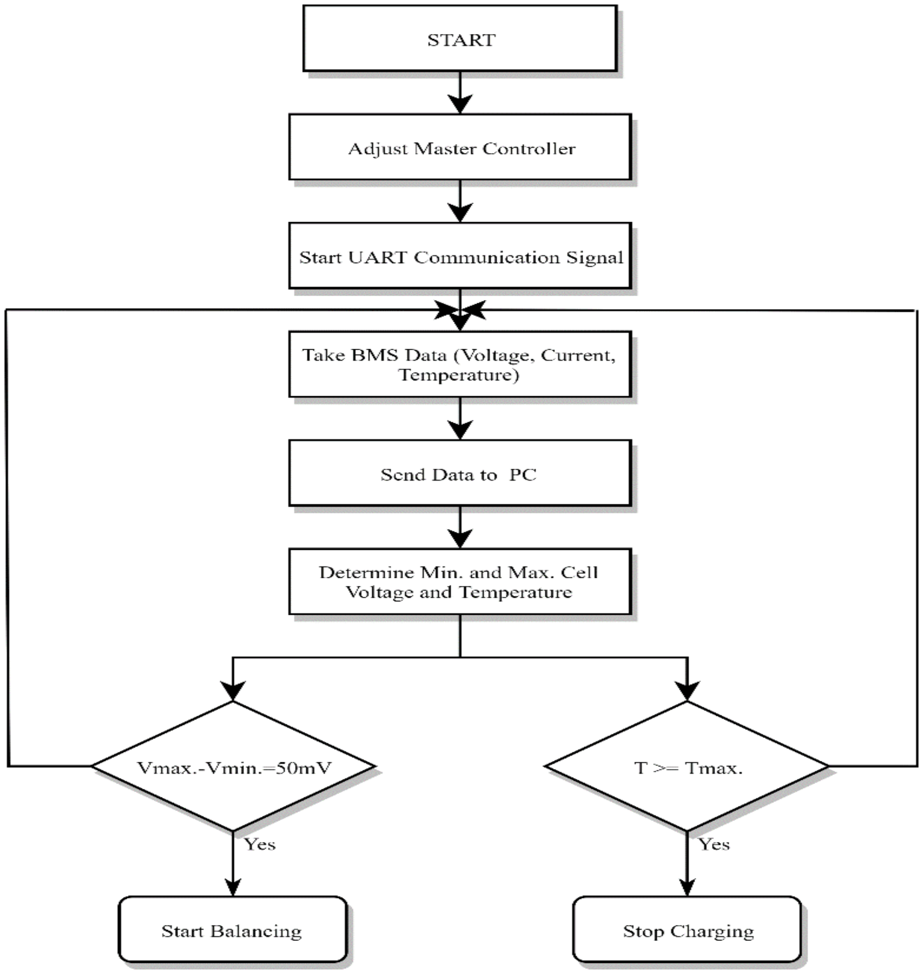


Figure 3.38 Second BMS system master controller algorithm schema

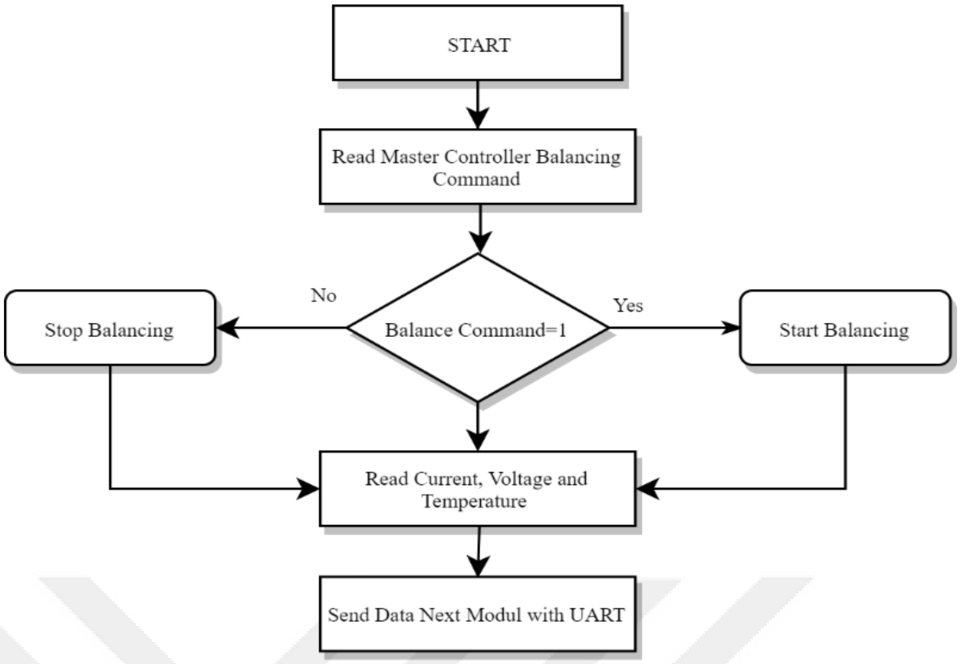


Figure 3.39 Second BMS system Slave controller algorithm schema

The data of any cell has to go through the entire UART line to the master cell since the data in the UART line can move only one direction. Firstly, the master cell sends the request information to the slave cells with using UART line. Master cell takes data from the slave cells at specified time intervals. When the slave cell receives data request command from the UART, writes the data in data array. This data array sends with the UART line after this process. Each slave cell sends the data array to the adjacent slave cell. The 4th slave cell then transmits the data to the master cell. Then the master cell receives the data of the slave cell. Second BMS system master cell data flow control algorithm can be seen in Figure 3.40.

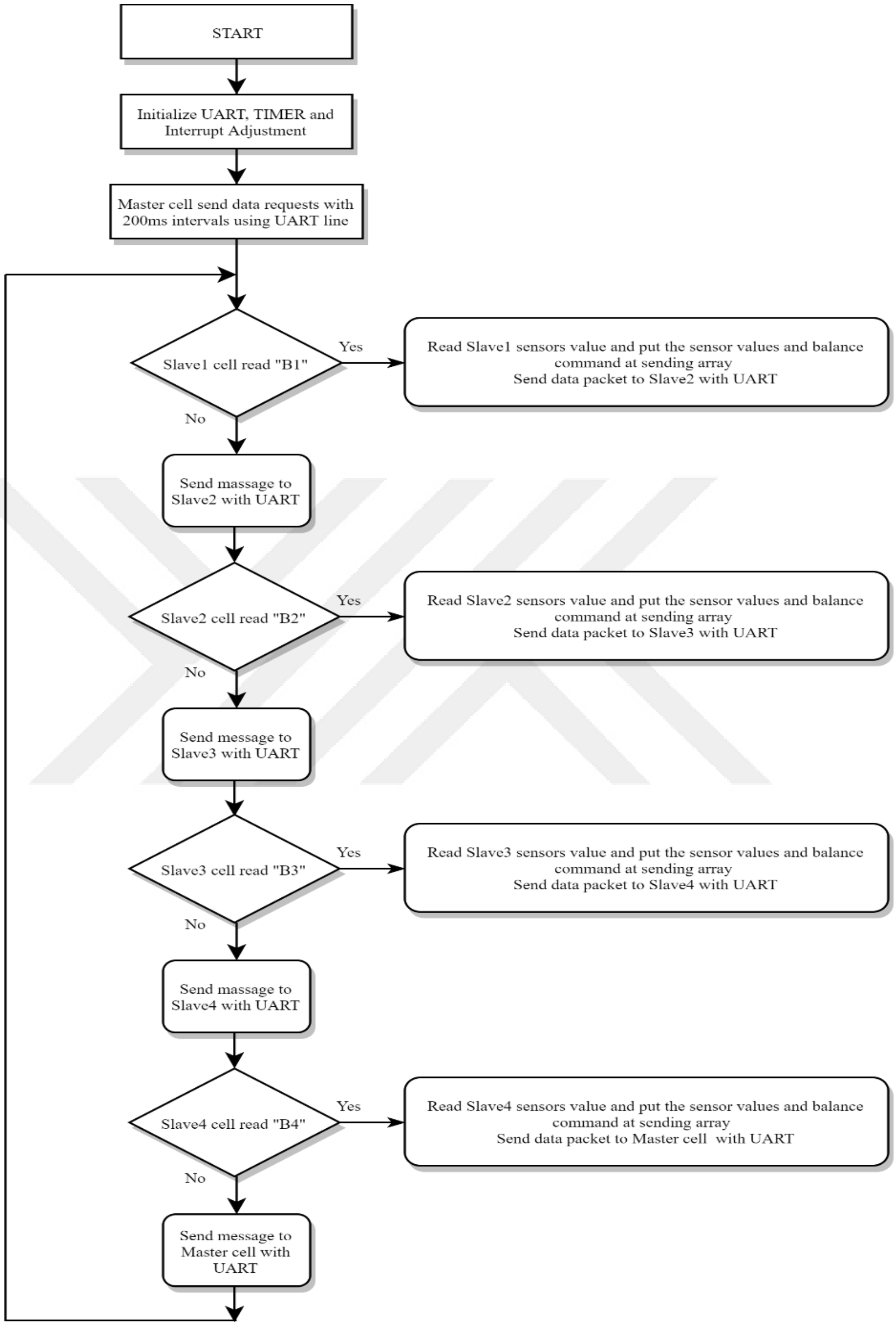


Figure 3.40 Second BMS system Master cell data flow control algorithm

CHAPTER 4

EXPERIMENTAL RESULTS & DISCUSSION

4.1 First BMS System Results

Firstly the system outputs related to data reading and writing to the interface events are mentioned in the begining of experimental results section. The working logic of the designed data acquisition system, sent and read data structure are explained with tables.

The data of the cells in the BMS system are transferred to the computer side via serial port. The data are read in sequence and sent to the PC in a controlled manner from the master and slave cells. Firstly the data of the master cell is taken, then the data of the 2nd, 3rd, and 4th slave cells are transferred to the PC, respectively while reading the data. The data read from the slave cells are taken as one data packet. In order to avoid confusion of these data packets, the letter characters are added to the data packets and sent to the PC.

The following tables show the data structures in detail for a better understanding of the data packets. The master cell reads the sensors directly on itself and sends these data to the PC with using serial communication. So master cell data can be sent as a one package. Also, slave cells send data as a single data packet respectively. A data packet can be up to 8 bytes in the CAN bus protocol. In each slave cell, the data of the three sensors is read and the read data firstly sent to the master cell. When master take the data is sent to the PC. The data package was formed by taking 3 digits of the voltage value, three digits of the current value and the first two digits of the temperature information in order to fit the data in the CAN package. Therefore, when these data are read or written, they are converted into numbers as an integer structure in software. And it is mathematically processed to obtain its true value. Table 4.1 shows the general structure of the data packet sent from the master cell to the PC. Also Table 4.2 show the general structure of the data package sent from the master cell to the PC. The values given in the tables are representative. It is written for a better understanding of the data structure.

Table 4.1 Read and sent Master cell data to the computer

	Identifier Character	Temperature Data	Identifier Character	Voltage Data	Identifier Character	Current Data
Master Cell Data Package	“s”	17.4	“g”	3.35	“a”	5.97

Table 4.2 Collected and sent data packages from Slave cells to the computer

	Identifier Character	Voltage Data	Identifier Character	Current Data	Identifier Character	Temperature Data
Slave1 Cell Data Package	“1g”	335	“a”	335	“s”	23
Slave2 Cell Data Package	“2g”	335	“a”	335	“s”	23
Slave3 Cell Data Package	“3g”	335	“a”	335	“s”	23

The communication infrastructure is based on the CAN bus and its software has been created within this scope. The communication unit and the power unit are isolated from each other using an isolated ISO1050 CAN bus IC. The charge control of four different battery cells can be performed with this design. In the experimental application, three cells are slave and one cell is set as master controller. Data from the slave cells were transferred to the Master cell via the CAN bus. The master cell correctly classified the incoming data according to the ID number. Thus, the collection of data from different points via the CAN bus using the STM32f103C8 microprocessor was accomplished successfully.

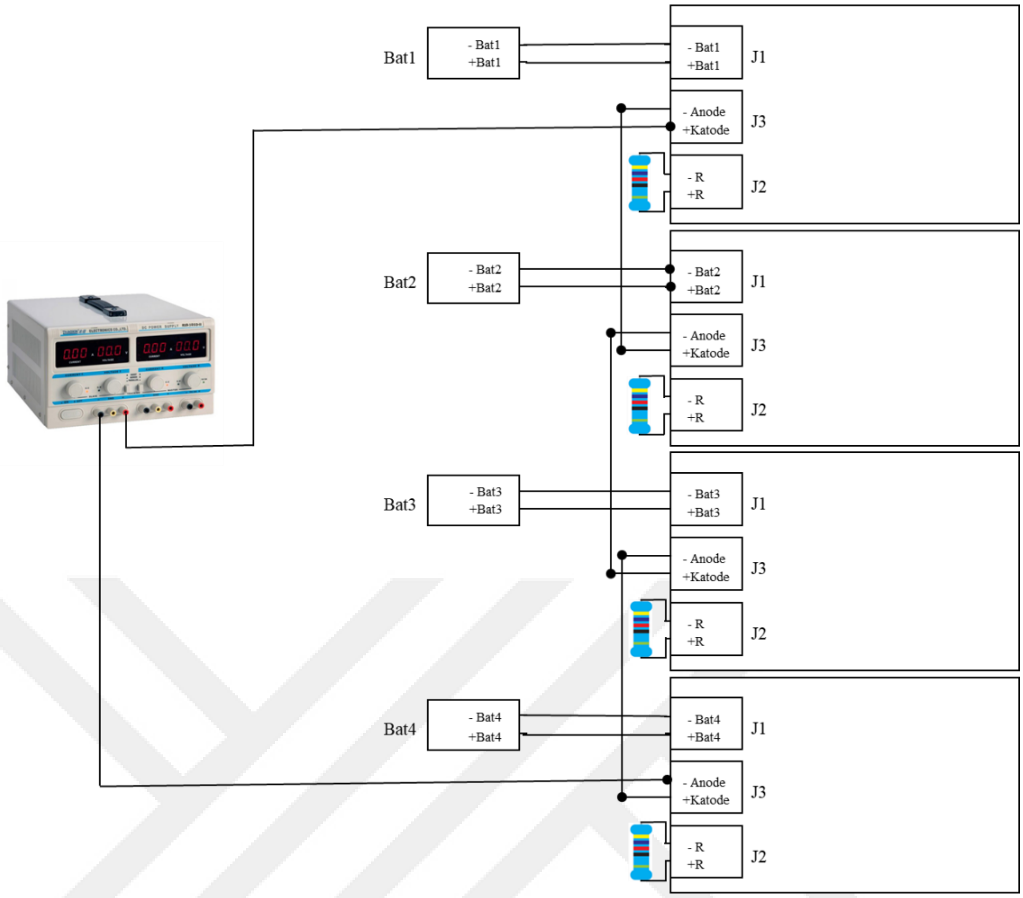


Figure 4.1 First BMS control system and batteries power flow line connection schema

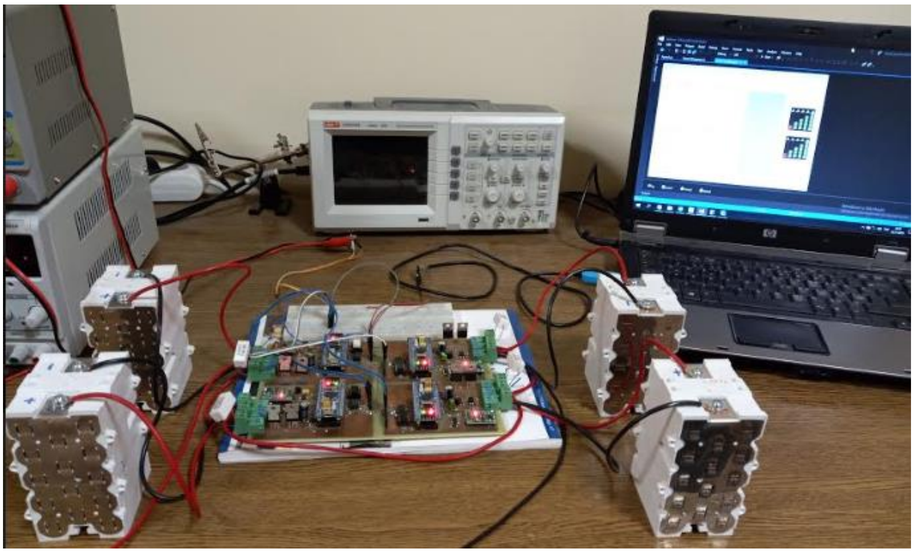


Figure 4.2 First BMS control system and batteries

The system is connected according to the connection diagram in Figure 4.1. Experimental results were also obtained when working in this connection scheme. The created and implemented BMS system is shown in Figure 4.2. Battery modules charging operation is controlled with slave and master controllers. Also master controller controls each of slave cells for charging process.

Table 4.3 Resistance value of P-channel MOSFET changing according to V_{GS} voltage

V_{GS} (V)	Balancing Current (A), I_B	MOSFET $R_{DS(on)}$ Resistance Value (Ω)
-3.6	0.70	0.08
-3.5	0.65	0.53
-3.4	0.58	1.2
-3.2	0.5	2.2
-3.1	0.41	3.7
-3	0.36	5
-2.9	0.28	7.85
-2.8	0.24	10
-2.7	0.21	12.1
-2.6	0.14	20.7
-2.5	0.08	40
-2.4	0.06	55
-2.2	0.02	High (Off State)

The battery system consists of four battery modules. These battery group was supplied from a DC source to provide charging. Battery modules charge value was close to each other at the begining. At this point, the designed BMS system started the charging process based on passive balancing technique for each cell. The cell with the lowest voltage value among the battery cells is determined by the master cell. The voltage levels of the other cells are equalized to the voltage value of the lowest cell. When balancing occurs, the voltage value of the cell with high voltage value is reduced to the lowest specified voltage level. The excess voltage in the cell is spent on the MOSFET and balancing is performed. Thus, the excess voltage value is reduced to the specified value. Table 4.3 shows the different V_{GS} voltages applied to a battery cell, respectively. As a result of these different voltages, it is seen that the balancing currents and MOSFET R_{DS} resistance values change. R_{DS} values are obtained when the battery voltage is 3.6V (V_{Bat}). When the values in the table are examined, it is seen that MOSFET is in cut-off region when V_{GS} voltage is -2.2V. In this case, MOSFET is not transmitting. Table 4.3 shows that the R_{DS} resistance value of MOSFET changes in direct proportion with the V_{GS} voltage. When the V_{GS} voltage is -3.6V, the value of the R_{DSon} is measured as 0.08Ω. NDP6020P type MOSFET is used as P-channel MOSFET in control cards in BMS system. When the datasheet files of this MOSFET are examined, it is understood that the resistance value of MOSFET at the time of transmission is 0.08Ω. As it can be seen from the values in the Table 4.3, it is seen that MOSFET is completely transmitting when -3.6V is applied to Gate pins of MOSFET. 5 Ohm stone resistor is used to limit the balancing current in the passive control system. Knowing this resistance value is important for determining the internal resistance of MOSFET. The R_{DSon} values in Table 4.3 were calculated using the formulation in Equation 5.

$$R_{DS(on)} = \frac{V_{Bat}}{I_B} - 5 \qquad (5)$$

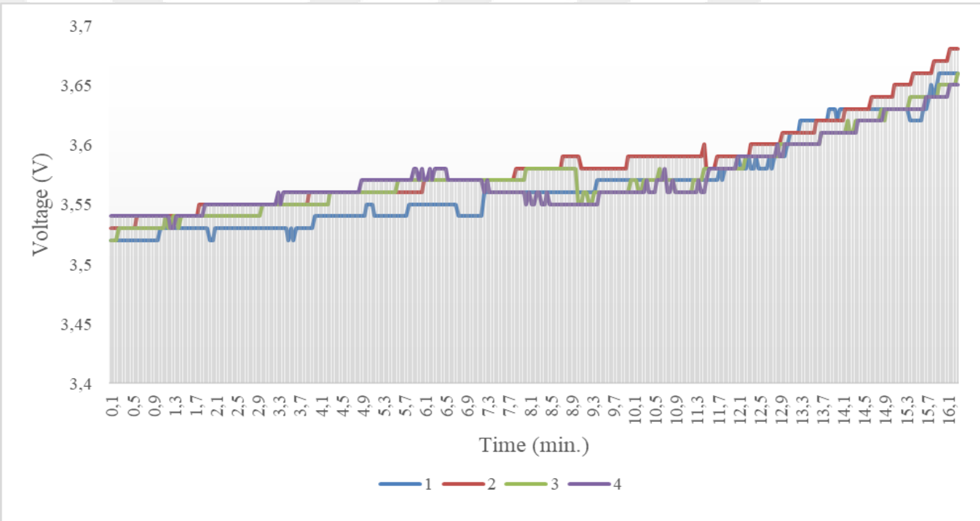


Figure 4.3 First BMS system batteries voltage values

The time-varying voltage graph of the four battery cells is shown in Figure 4.3 during the charging process. The battery cells are charged simultaneously using the BMS system. It is seen that the voltage values of the battery cells are around 3.52V before the charging process. After charging, the voltage of the battery cells increased to 3.67V. All the cells were charged in a passive balancing technique in this period.

First BMS system passive method based charging process took approximately 16 minutes. During this charging process, the charging source voltage is set to around 17.4V. The initial voltage values of the battery cells are close to each other. Charging process was performed without balancing current because between the cells of voltage difference value is not big enough to require balancing. According to the generated BMS software, a voltage difference of approximately 50mV is required between any two cells for balancing. However, there was no such difference in this experimental procedure. Therefore, the system was tested by connecting four different voltage sources to the system as a battery in order to test whether the balancing process works as desired. A 10 ohm stone resistor is connected to the system to limit the balancing current. Thus, the maximum balancing current is limited to 0.36A. The input voltage values of the connected voltage sources such as the battery were changed and the system's response to the balancing process was tested. As determined by the algorithm, a current flow of approximately 0.4A was observed in the cell that needs to be balanced when more than 50mV difference occurs. This test was performed separately for each cell, and the circuit and software were observed to work properly. Thus, the passive balancing method based new circuit model was successfully operated. In addition, the software and hardware features of the designed BMS system have been completed. A novel BMS system and BMS circuit topology has been created. Thus, an orginal BMS system has been added to the literature.

If the charge rate is above a certain level, these cells or cells exit the charging process in the active cell balancing method based applications. Thus, the low voltage value cells are charged. When the voltage level of the other cell is reached the higer voltage cells, the existing cell is re-included in the charging process. The charging cell is bypassed in this method, so this method is called as bypass method. The existing software algorithm was created according to the active cell balancing method and applied to the battery system in this experimental application. An important situation arises in the active cell balancing method. The voltage value of the charging source must be adjusted according to the removed number of battery modules from the BMS system because of bypass operation. If the source voltage value is not set according to number of battery modules, the battery cells may be exposed to much higher voltage than the required voltage value. This occurs very dangerous and unfavorable situation for the charging and use of batteries. The chemical properties of the batteries may deteriorate due to the applied high voltage values. In addition, combustion and explosion may ocur due to this wrong charging situation. Therefore, the voltage of the charging source device must be controllable when applying active based balancing method.

However, a controllable voltage source does not exist in our laboratory infrastructure. So, the BMS system has been tested controlling the voltage adjustment of the charger by manually. Firstly, the two battery cells charge voltage values are adjusted to have a lower voltage value than the other two cells. Two battery cells are bypassed in this case. The system charge only two lower voltage modules. Therefore, approximately 8.7V voltage value must be applied as the charging source voltage. When the low voltage battery modules voltage values reach the voltage values of the other cells, the charging source voltage is increased to 17.4V by manually. Because four cells are charged in this situation at the charging system.

The voltage values of the four battery modules are shown in Figure 4.4. The active balancing method based BMS charging system allows the two battery modules which are lower voltage than others charged together. Initially, two lower voltage battery cells start charging at nearly 3.40V and charging process continues to 3.55V until the voltage of the four battery modules is equal. After all the modules were charged together at 3.60V. The charging current is kept constant at 0.6A during the charging process.

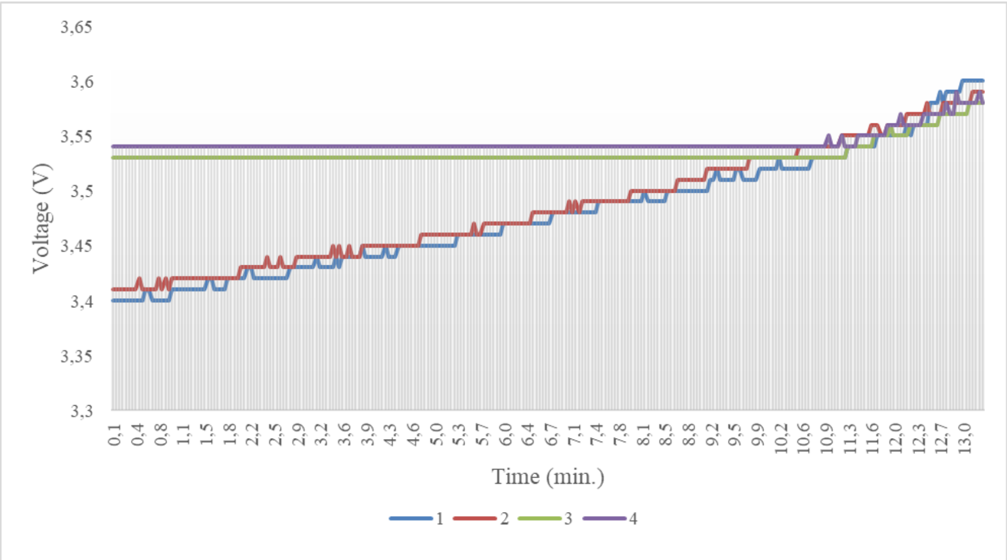


Figure 4.4 First BMS control system and batteries

4.2 Second BMS System Results

In this system, the master cell only receives the data and decides the balancing process. It was also used to send data from slave cells to the PC. The data structures of the slave cells sent from the master cell to the PC are given in the Table 4.4. The values given in the table are representative. It is written for a better understanding of the data structure.

Table 4.4 Collected and sent data packages from Master cells to the computer

	Identifier Character	Voltage Data	Current Data	Temperature Data
Slave1 Cell Data Package	“1”	335	335	23
Slave2 Cell Data Package	“2”	335	335	23
Slave3 Cell Data Package	“3”	335	335	23
Slave4 Cell Data Package	“4”	335	335	23

The communication infrastructure is based on the UART protocol and its software has been created within this scope. The communication unit and the power unit are isolated from each other using an isolated 6N137 optocoupler. The charge control of four different battery cells can be performed with this design. In the experimental application, four cells are slave and one cell is set as master controller. Data from the slave cells were transferred to the Master cell via the UART protocol. The master cell correctly classified the incoming data according to the given number. PIC18f4520 is used as slave and STM32f103C8 is used as master microcontroller. Thus, the collection of data from different slave cells via the UART was accomplished successfully.

The DC power supply is used to charge the battery pack. Initially, the voltage values of each battery module were at different levels. Therefore, the BMS control system has started balancing process in accordance with the written algorithm. The BMS system firstly determines the lowest and highest voltage values of the battery cells. The difference between the voltage levels of other cells was determined by reference to the lowest determined voltage value. When balancing is required during the charging process, the voltage level of the cell with high voltage value has been reduced to low voltage level. The excess energy is spent on MOSFET as a heat, thus the voltage difference between the cells is eliminated. The experimental BMS system was implemented according to the connection diagram in Figure 4.5. Also, the real time implemented BMS system is shown in Figure 4.6.

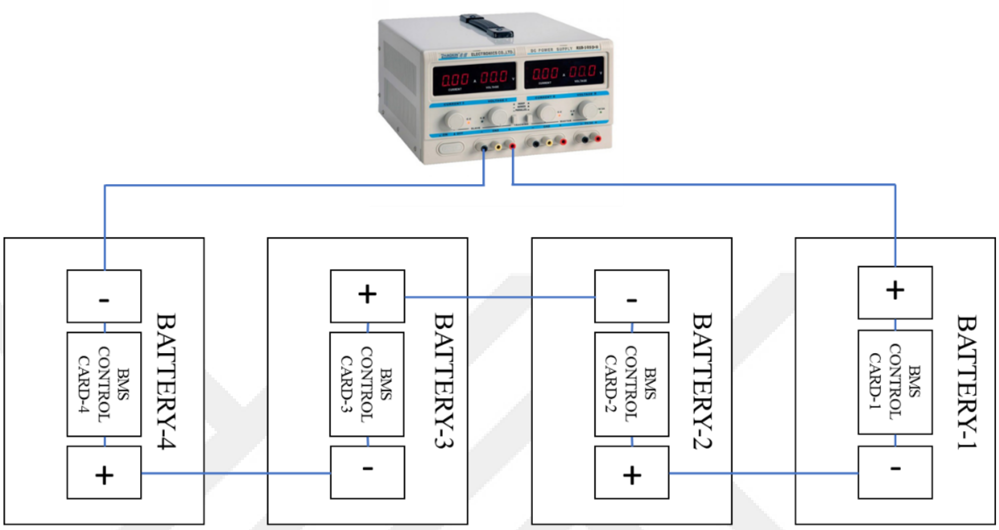


Figure 4.5 Second BMS control system and batteries power flow line connection schema

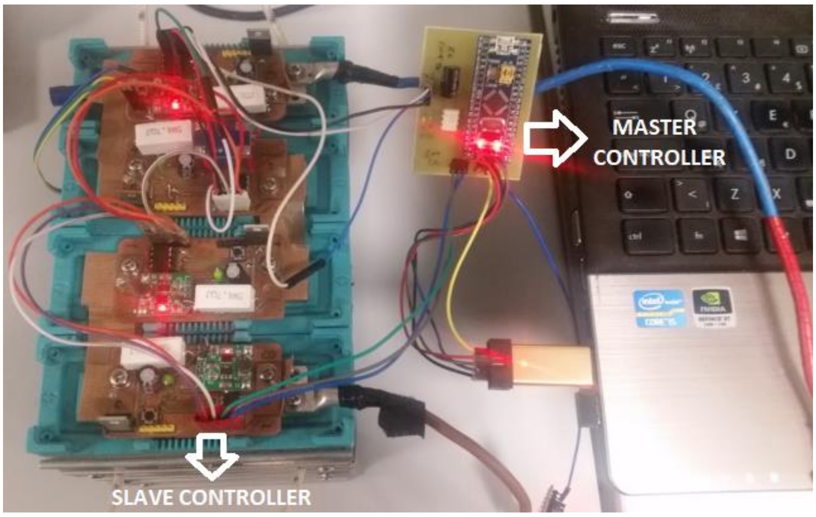


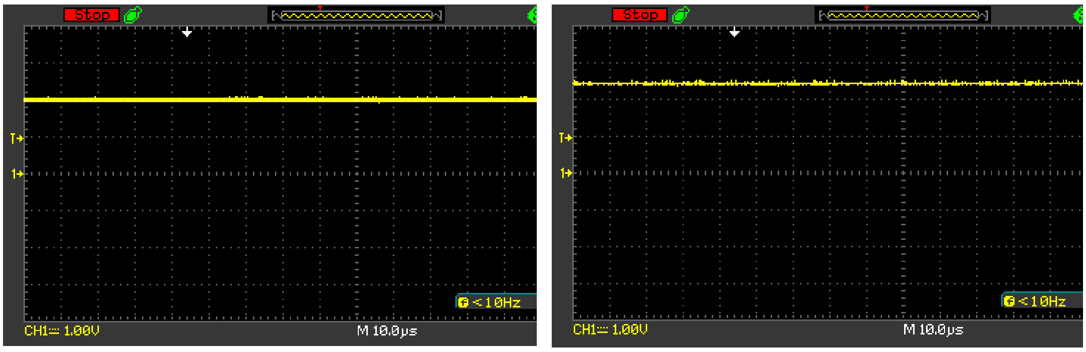
Figure 4.6 Second BMS control system and batteries

The battery modules are connected in series as shown in the Figure 4.5. Then, it is connected to DC source and necessary connections are made for charging process. The slave controller connected to each cell and the master controller controls all of the slave cells as shown in Figure 4.6. V_{GS} voltage, balancing current of the battery cell and obtained MOSFET R_{DS} values are given in the Table 4.4. The resistance values were determined according to the measured battery supply voltage.

Table 4.5 Resistance value of N-channel MOSFET changing according to V_{GS} voltage

V_{GS} (V)	Balancing Current (A), I_B	MOSFET $R_{DS(on)}$ Resistance Value (Ω)
1.52	0	High (Off State)
1.92	0.04	77.8
2.02	0.13	20.68
2.08	0.3	6.3
2.13	0.47	2.32
2.18	0.62	0.62
2.28	0.68	0.15
2.43	0.69	0.04

Table 4.5 shows the different V_{GS} voltages applied to a battery cell, respectively. As a result of these different voltages, it is seen that the balancing currents and MOSFET $R_{DS(on)}$ resistance values change. $R_{DS(on)}$ values are obtained when the battery voltage is 3.3V (V_{Bat}). When the values in the table are examined, it is seen that MOSFET is in cut-off region when V_{GS} voltage is 1.52V. In this case, MOSFET is not transmitting. Table 4.5 shows that the $R_{DS(on)}$ resistance value of MOSFET changes inversely proportion with the V_{GS} voltage. When the V_{GS} voltage is 1.52V, the value of the $R_{DS(on)}$ is measured as high. IRL540N type MOSFET is used as N-channel MOSFET in BMS system control cards. When the datasheet files of this MOSFET are examined, it is understood that the resistance value of MOSFET at the time of transmission is 0.04Ω. As it can be seen from the values in the Table 4.5, it is seen that MOSFET is completely transmitting when 2.43V is applied to Gate pins of MOSFET.



(a) V_{GS}=2.02V, Balancing Current=0.13A, R_{DS}=10.8Ω

(b) V_{GS}=2.43V, Balancing Current=0.69A, R_{DS}=0.04Ω

Figure 4.7 Signal from DAC filter output applied to MOSFET Gate terminal (a), (b)

4.7Ω stone resistor is used to limit the balancing current in the passive control system. This resistance value is important for determining the internal resistance of MOSFET. The R_{DSon} values in Table 4.5 were calculated using the formulation in Equation 6.

$$R_{DS(on)} = \frac{V_{Bat}}{I_B} - 4.7 \qquad (6)$$

Figure 4.7 shows the signals received from the DAC circuit output. These signals are taken when the voltage value is 2.02V and 2.43V respectively. These signals are applied to the MOSFET's Gate pins. When these voltage signals are applied, it is observed that the current flowing over the MOSFET is 0.13A and 0.69A, respectively. In these operating conditions, MOSFET resistance values were measured as 20.68Ω and 0.04Ω.

While charging the four battery cells, the charge graph is obtained in Figure 4.8. As shown in this graph, the battery cells perform the charging process together. The voltage value of the battery cells at the beginning of the charging process is approximately 3.4V. It is understood that this value increases to about 3.7V during a charging process of 20 minutes.

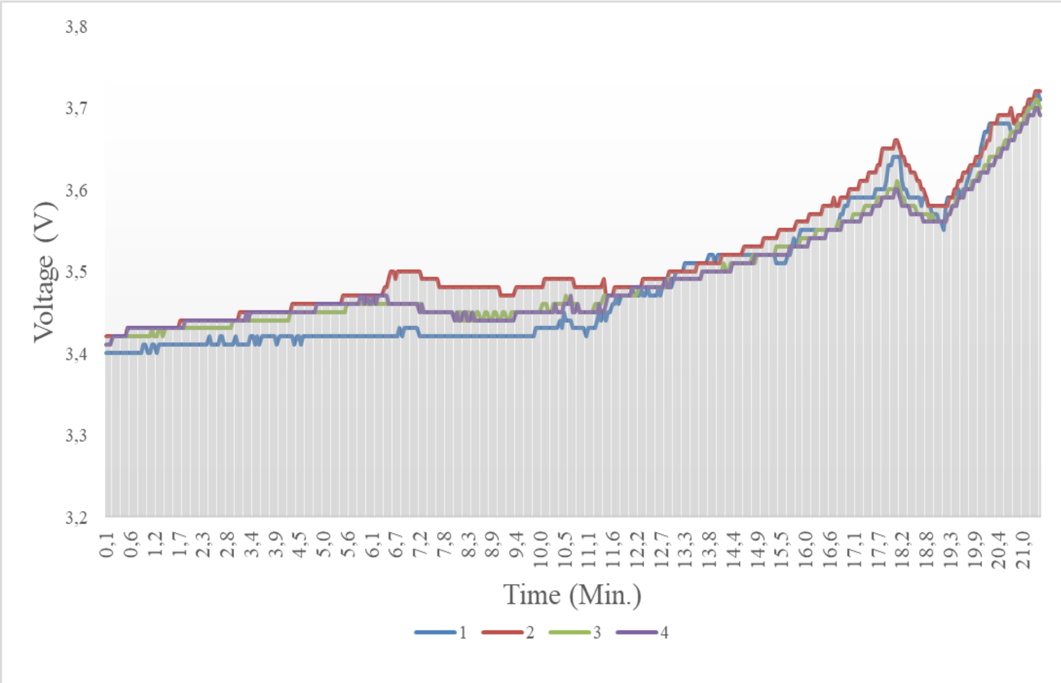


Figure 4.8 Second BMS system batteries voltage values

The balancing currents that occur during the charging process are shown in Figure 4.9. The balancing currents are limited to approximately 700mA by means of the using stone resistance. This balancing current flow and eliminate the voltage imbalance between the battery cells. As can be seen from the Figure 4.9, balancing current has occurred at different times. It is seen that the balancing currents of the second, third and fourth battery cells occur simultaneously at 6.5th minutes. The balancing currents are approximately 700mA. At this time, the balancing current value is at 0A level, since there is no balancing current flowing from the first cell. It is understood from the third and fourth battery cells signals on the Figure 4.9 that the balancing current occured between 8 and 11 minutes. It is seen that the balancing current passes through the first cell between 18 and 20 minutes. In this process, balancing current values are determined as 700mA. At the end of this charging period, the average temperature values were determined between 26-32 ° C.

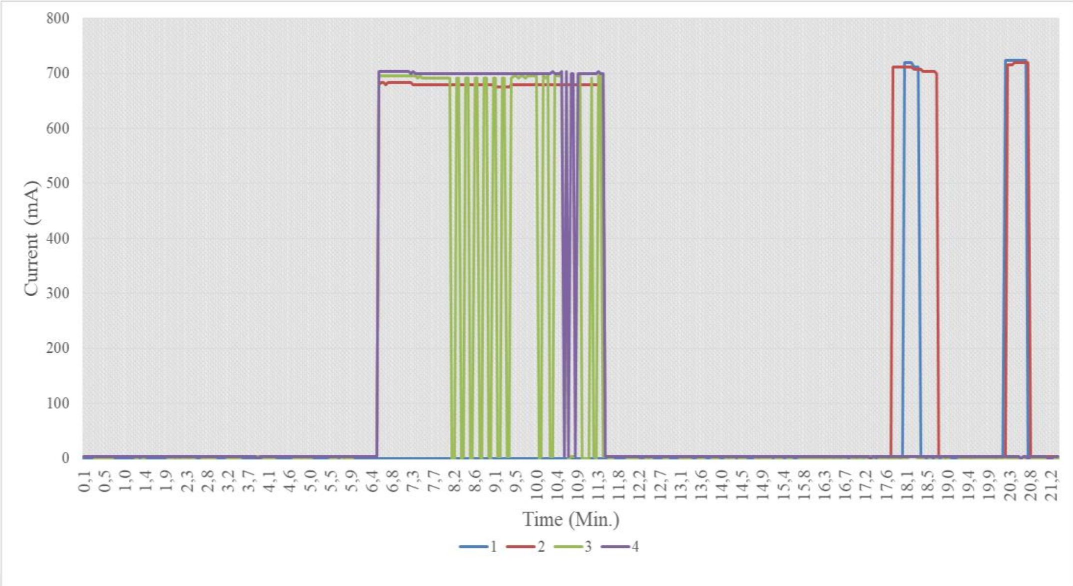


Figure 4.9 Batteries balancing currents

The interface created for the second BMS system is shown in Figure 4.10. In this interface, measured voltage values and balancing currents of the cells can be seen. The charging status of the batteries can be controlled from the interface and information about their general status can be obtained. There is a setting area where make the connection and baud rate adjustments at the upper right of corner.

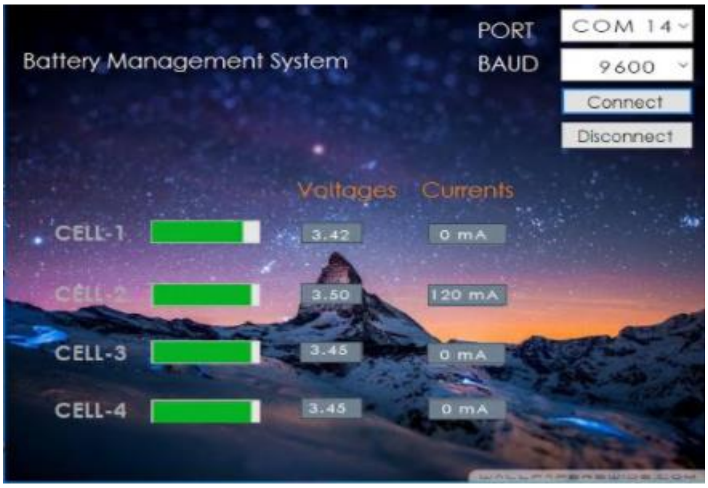


Figure 4.10 Second BMS system interface

4.3 Comparison of First and Second BMS Systems

The main features of the two BMS systems created in this thesis are shown in the following Table 4.6. The features of the two systems are given in a same table. It is aimed to be made more clearly the comparison of the BMS systems.

Table 4.6 Comparison of First and Second BMS systems

	First BMS System	Second BMS System
Used microprocessor type	STM32f103C8	STM32f103C8 & PIC18f4520
Number of used microprocessors	4(1 Master, 3 Slave)	5 (1 Master, 4 Slave)
Total number of modules	4	4
Used communication protocols	CAN-Bus, UART	UART
System flexibility	High	Low
System applicability and control complexity	Complex	Lower complexity than the first BMS system
Used battery balancing method	Active, Passive	Passive
MOSFET type used as load in passive balancing method	P-channel	N-channel
Data transfer to PC	UART	UART
Used PC interface program for data visualization	C#	C#
Database for data saving	Yes (SQLite database based)	No

Both systems are designed as microprocessor based. There are differences in the type of used microprocessor. In the first system, STM32f103 series microprocessor was used in all cells for control operations. In the second system, control operations were carried out using both STM and PIC series microprocessor type. It is better to use the same type of microprocessor in terms of system integrity. The use of the same type of microprocessor in all cells is a factor that reduces the problems that may arise in hardware and software. Therefore, it can be said that the first system has a more robust infrastructure than the second system.

In the first system, four control cards and microprocessors are used, whereas in the second system, this number increases to five. However, in both systems, four battery modules are controlled. Although the first system is more equipped in terms of control, it has been able to reduce the number of control cards. Because the master processor controls the battery cell in the first system while controlling the other cells. The master cell is used at full capacity, so no additional control card is required. This provide significant advantages in terms of low cost and simplicity at BMS systems which are consist of multiple modules in high-power systems.

Communication infrastructure and method is very important for BMS systems. There is an almost uninterrupted communication situation since the data received and sent from the cells continue the all charging time. In the first system, CAN bus and UART protocols are used together, in the second system only UART protocol is used. A more professional communication system has been established in the first system, since CAN bus protocol is used. At the same time, the use of CAN bus protocol provides the flexibility to the BMS system. In the first BMS system, a system infrastructure has been created which can increase the number of cells up to 127. Thus, higher power BMS systems can be created. The second system does not have an expandable infrastructure since only the UART is used in this BMS system. If this infrastructure is used in systems with a large number of cells, problems will arise due to late transmission of data. Therefore, the system cannot continue to operate stably.

The first system is more complex in software and hardware than the second system. In the first system, the data is transmitted at certain times by using two different communication protocols. This process is quite complicated and difficult compared to the second system. It may be appropriate to use the second system in applications where the number of cells is low and the control process is simple. Active and passive cell balancing method can be applied by the circuit topology used in the first system. Active and passive methods can be applied by changing the applied algorithm. Only passive-based method is applied in the second system. Both systems send data to the PC. This is done through the UART protocol. The data sent to the PC side is also visualized with C # based interfaces. The first system saves data to an SQLite based database, but the second system does not save data to a database.

When the first and second systems are examined, it is clear that the first BMS system is more professional, original. and more suitable for industrial systems. It is understood that the features of the first system are more advanced. However, the required system may vary depending on the situation. While the first system may be preferred in more professional and high-power battery structures, it may be logical to select the second system in terms of simplicity and ease of application of the BMS system in smaller power systems.

Different circuit topologies are applied for battery charging in the field of BMS [67]. Balancing technique differs according to the used circuit topology. Battery charging circuit topologies can be used in active or passive compensation method. Active or passive balancing circuit topologies can operate separately with different circuits [68-69]. In the circuit topology developed in this thesis, BMS system can be used as active or passive balancing circuit only by changing the software. This feature is one of the most important original aspects that distinguishes it from other studies. The second unique aspect is that the N-channel and P-channel type MOSFET switching element is used as a resistor circuit element. In the studies carried out in the field of passive balancing, excess energy that causes imbalance between cells is consumed by using resistance [70-71]. At the same time MOSFET has been used as resistance in some studies [72-73]. However, no study was performed in which both types of N-channel and P-channel type MOSFETs were used as resistance. The area covered by the high power stone resistors is large and the costs are high. With this proposed method, such disadvantageous situations can be eliminated. Because of these negative aspects, in this thesis, MOSFET switching element is used as resistance instead of stone resistance for these purposes.

In addition to these originalities, the control and communication systems created during the application stage of the thesis can be used in many industrial fields in terms of their software and hardware infrastructure. In some studies, simpler systems may be preferred to facilitate the control process [74-76]. ARM and PIC-based microprocessors which are commonly used in industry, prefered in control circuits. The applications of this thesis include ARM and PIC based microprocessor types, which increases the usability of this hardware and software infrastructure in many different fields and professional works.

CHAPTER 5

CONCLUSION

In this thesis, two different BMS systems consisting of lithium ion batteries which are widely used in electric vehicles, have been formed. Active and passive cell balancing based charging techniques are used in BMS systems. Balancing-based battery charge control operations are performed using a circuit topology that has not been previously used in the literature. In this respect, a new circuit topology has been introduced to the literature. In addition, MOSFET was used as a load in passive balancing charge control based processes of both BMS systems.

The control of the MOSFET is performed by changing the amplitude of the voltage applied to the gate pins. The amplitude value of this voltage, determines the resistance value of MOSFET. It is not possible to increase or decrease the amplitude of voltage to desired extent in electronic circuits. 0 or 5V values can be applied under normal operating conditions. A circuit design has been realized which allows the voltage value of the MOSFET gate control pin to be changed to the desired extent. For this purpose, a DAC circuit which converts the PWM signal to a DC signal has been designed and implemented successfully.

The first BMS system consists of three slaves and one master cell. It is designed to charge four different lithium-based battery modules. Two BMS systems were successfully applied and the battery modules were charged. In both systems, charging of the battery modules has been accomplished successfully. Control of the charging process is created based on voltage value information. Voltage value based control has been preferred in charge control operations of BMS systems in terms of its easy applicability. The first BMS system includes a unique circuit topology structure that can operate both active and passive balancing. The operation of the BMS system in active or passive mode can be adjusted according to the algorithm to be applied to the control circuit. If the balancing process is to be performed in passive mode according to the applied algorithm, charging is performed by using MOSFET as load. If it is to be operated in active mode, energy is transferred to the cells in the charging process by bypass method.

CAN bus based data acquisition system has been successfully established in the first BMS system. Data from all cells were collected by the master cell, respectively. The control procedures were carried out by obtaining the data correctly. The use of the CAN bus protocol has made a significant contribution to the system's control and proper operation. Therefore, the first system has a significant advantage over the second BMS system in terms of its communication infrastructure. At the same time, the first system contains the infrastructure and hardware features that can be commercialized and turned into an industrial based system.

The first system was operated separately with using active and passive balancing techniques. At this stage, different software algorithms have been applied according to used balancing technique. It has been proved that the proposed new circuit topology operates according to the active and passive balancing technique. The passive balancing method based charging process of the battery has been realized successfully in the second BMS system and the proposed circuit topology has been proved to work in the desired direction.

The second BMS system can be defined as the previous version of the first BMS system in terms of its hardware and features. Because this system includes only passive balancing technique and UART based communication system. The passive balancing circuit is the same as in the first system passive balancing circuit topology. Also, same topology used in second BMS system. Only the type of MOSFET used as a load in the passive control circuit varies. P-channel type MOSFET was used in the first BMS system and N-channel type MOSFET was used in the second BMS system.

During the passive charging process of the first BMS system, charging was carried out when the voltage levels of the battery cells were around 3.6V. During this charging process, the voltage at the gate end of P-channel type MOSFET was adjusted to -3.6V and operated in transmission mode. In this mode, the balancing current is limited to 0.36A levels using a 10 Ohm resistor. Balancing current values of 0.36A were observed during the balancing process. It has been determined that the resistance value of MOSFET used for balancing purposes varies between 0.08 and 55 ohms depending on different gate signal voltage values. During the balancing process, the initial voltages of the batteries were selected as 3.52V. After about 16 minutes, the battery cells were charged to approximately 3.67V voltage. During this charging process, the power supply voltage was kept constant at 17.4V and the charging current was measured as 0.6A.

In the first BMS system with active balancing technique, two battery modules were charged from 3.40V voltage to 3.55V voltage. This charging process took approximately 10 minutes. During this charging process, the supply voltage is constant at 8.5-8.6V and the charging current is 0.6A. When the voltage of the four cells is approximately equal to each other, the two cells in the bypass mode leave the bypass mode and are included in the charging process. For this reason, the supply voltage was increased to 17.4V and charging process was continued. During this charging process, 3.55V cells were charged to 3.6V voltage and charging process was completed. This process was completed in approximately 4 minutes. The temperature of the batteries varied between 23-26 degrees in the charcing process.

In the second BMS system, only passive balancing method was used. During the passive charging process of the second BMS system, charging process was carried out when the voltage levels of the battery cells were around 3.4V. During this charging process, the voltage at the gate end of N-channel type MOSFET was reduced to 2.43V and operated in transmission mode. In this mode, the balancing current is limited to 0.69A levels using a 4.7 Ohm resistor. While balancing process, balancing current values of 0.69A were observed. It has been determined in the experimental studies and applications that the resistance value of MOSFET used for balancing purposes varies between 0.04 and 77.8 ohms depending on different gate signal voltage values. During the balancing process, the initial voltages of the batteries were chosen at approximately 3.40V. After approximately 21 minutes, the battery cells were charged to a voltage of 3.70V.

During this charging process the supply voltage was kept constant at 17V and the charging current was measured as 0.6A. When charging, the temperature of the batteries varied between 26-32 degrees.

In this thesis, firstly, the proposed battery charging circuit topology is aimed to be realized in practice. In this direction, studies have been made for the operation of the circuit gradually and it has been proved that the system works successfully. The communication infrastructure required for the charging system has been established. Software and hardware systems have been developed to record data.

The rapid charging of the batteries depends directly on the charging current and the nature of the battery. In this study, switching elements with small internal resistance value have been tried to be selected in order to minimize losses. However, the primary objective of the thesis is to prove the operation of the proposed circuit topology. Therefore, rapid charging could not be emphasized. Higher power studies can be made in this field by using the existing circuit structure. Silicon carbide based semiconductors can be used for fast and high power transmission.

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