DESIGN OF A BATTERY MANAGEMENT SYSTEM WITH ACTIVE BALANCING TOPOLOGY

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ABSTRACT

Graduation Thesis

DESIGN OF A BATTERY MANAGEMENT SYSTEM WITH ACTIVE BALANCING TOPOLOGY

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2023, 61 pages

Batteries are packages that contain and use multiple cells. However, not all cells that make up the battery can charge and discharge equally, and this imbalance leads to a loss of efficiency in the battery. Even if they were produced on the same date, in the same factory, with the same method, for example, one of them is consumed by 40% while the other is consumed by 50%. At this point, battery management systems (BMS) are gaining importance. BMS, which is divided into two main headings as active and passive methods, is the focus of this paper. Both active and passive cell balancing are effective ways to improve system health by monitoring and matching the state of charge (SoC) of each cell. Active cell balancing redistributes the charge during the charge and discharge cycle, unlike passive cell balancing, which simply distributes the charge during the charge cycle. Thus, active cell balancing increases system uptime and can improve charging efficiency. At the same time, it is a method that is more reliable, avoids energy wastage as it sends excess energy to the low-energy cell, and has a faster balancing speed. Active balancing creates a more complex, larger carbon footprint and passive balancing is more cost-effective. Therefore, passive balancing is more preferred in the sector. However, active balancing is more suitable for high-voltage applications and electric vehicle technologies. Considering the disadvantages of active balancing, the main objectives are to develop this method, to provide know-how for the sector, and to increase energy efficiency in many popular areas of technology.

Keywords: Active battery management system, battery efficiency, state of charge, Arduino

ÖZET

Lisans Tezi

AKTİF DENGELEME YÖNTEMİ KULLANILARAK BATARYA YÖNETİM SİSTEMİ GELİŞTİRİLMESİ

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Bataryalar, birden fazla hücre içeren ve kullanan paketlerdir. Ancak, bataryanın oluşturan tüm hücrelerin eşit şekilde şarj olup boşalması mümkün olmayabilir ve bu dengesizlik bataryanın verimliliğinin azalmasına neden olur. Örneğin, aynı tarihte, aynı fabrikada, aynı yöntemle üretildiği halde biri %40, diğeri ise %50 oranında tükenmiş olabilir. Bu noktada, batarya yönetim sistemleri (BYS) önem kazanmaktadır. Bu makalenin odak noktası, aktif ve pasif yöntemler olmak üzere iki ana başlık altında incelenen BYS'dir. Aktif ve pasif hücre dengeleme, her hücrenin şarj durumunu izleyerek eşleştirmeyi sağlayarak sistem sağlığını iyileştirmenin etkili yollarıdır. Aktif hücre dengeleme, sadece şarj döngüsü sırasında değil, şarj ve deşarj döngüsü boyunca da şarjı yeniden dağıtırken, pasif hücre dengeleme sadece şarj döngüsü sırasında şarjı eşit şekilde dağıtır. Bu şekilde, aktif hücre dengeleme sistem süresini artırır, şarj verimliliğini iyileştirebilir ve aynı zamanda fazla enerjiyi düşük enerjili hücreye ileterek enerji israfını önler ve daha hızlı dengeleme hızı sağlar. Aktif dengeleme daha karmaşık bir yapıya ve daha büyük bir karbon ayak izine sahiptir, pasif dengeleme ise maliyet açısından daha etkilidir. Bu nedenle, sektörde pasif dengeleme daha tercih edilen bir yöntemdir. Ancak, aktif dengeleme yüksek gerilim uygulamaları ve elektrikli araç teknolojileri için daha uygundur. Aktif dengelemenin dezavantajları göz önüne alındığında, bu yöntemi geliştirmek, sektöre bilgi sağlamak ve birçok popüler teknoloji alanında enerji verimliliğini artırmak ana hedeflerdir.

Anahtar Kelimeler: Aktif batarya yönetim sistemi, batarya verimliliği, şarj durumu, Arduino

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LIST OF ABBREVIATIONS

AC: Alternative Current

ACFCSR: Active Cell Front-End Shunt Regulator

ALU: Arithmetic and Logic Unit

BMS: Battery Management System

C: Capacitor

CPU: Computer's Central Processing Unit

DC: Direct Current

F: Frequency

HDMI: High Definition Multimedia Interface

I/O: Input/Output

Li-ion: Lithium-ion

NTD: Negative Temperature Coefficient

PCB: Printed Circuit Board

RTD: Resistance Temperature Detectors

SoC: State of Charge

SoH: State of Health

SPDT: Single Pull Double Throw

SPST: Single Pull Single Throw

SQL: Structured Query Language

UPS: Uninterruptible Power Supply

USB: Universal Serial Bus

V: Volt

1. Introduction

With the developing technology, electric vehicles, electric scooters and renewable energy systems have started to take up more space in our lives. Because of this, the batteries which are in charge of providing energy to them also gain importance. The service life and efficiency of these batteries are of great importance. Batteries are packages that contain and use multiple cells. These packages store and distribute the energy required for the system. However, not all cells that make up the battery can charge and discharge equally, and this imbalance leads to loss of efficiency in the battery. Even if they were produced at the same date, in the same factory, with the same method, for example, one of them is consumed by 40% while the other is consumed by 50%. At this point, battery management systems (BMS) are gaining importance. BMS, which is divided into two main headings as active and passive methods, is the focus of this project. Both active and passive cell balancing are effective ways to improve system health by monitoring and matching the state of charge (SoC) of each cell[1].

1.1. Passive Balancing

The primary distinction between the two approaches lies in how they address the balancing of series-connected cells. Passive cell balancing achieves balance by dissipating excess energy from the highly charged cells, while active cell balancing redistributes energy from strong cells to weak cells. Passive cell balancing is extensively employed in industrial applications due to its simplicity, reliability, and cost-effectiveness [2],[3]. Typically, the passive method involves discharging surplus energy from overcharged cells through a resistor element until it aligns with the state of charge (SoC) reference or voltage reference [4].

Passive balancing encompasses two methods: fixed shunt resistor and switched shunt resistor. The fixed shunt resistor method involves placing a resistor in parallel with each cell, which facilitates charge drainage from individual cells. The dissipated energy from the cell is converted into heat. This method boasts straightforward electronic designs and is commonly found in passive balancing systems.

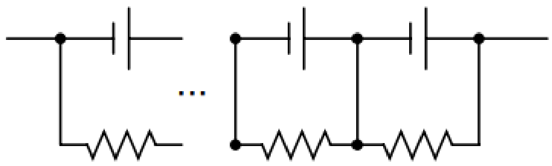

Figure 1. The simplest design of all is the “fixed shunt resistor design.” [5]

The concept behind passive balancing is that high-voltage cells exhibit a higher balancing current, resulting in faster self-discharge compared to low-voltage cells. It is important to note, however, that the circuit continuously dissipates charge, even when the battery pack is perfectly balanced.

In the case of the Switched shunt resistor method, the inclusion of electronics to control the transistor adds complexity to the design. Nevertheless, this approach offers greater flexibility in balancing strategies. The Battery Management System (BMS) closes switches on cells that have an excessive charge, allowing them to discharge.

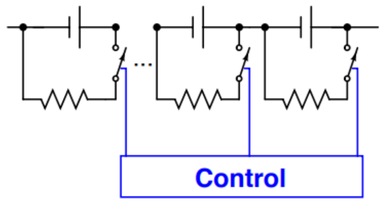

Figure 2. Switched shunt method design [5]

It is worth mentioning that the increased complexity is less of a concern nowadays. Modern battery-stack monitoring chips come equipped with built-in circuitry to control either an internal transistor switch (for slower balancing) or an external transistor switch (for faster balancing).

Passive balancing offers a prominent advantage in terms of the simplicity and cost-effectiveness of the circuitry, irrespective of the specific method employed, when compared to active balancing designs. However, it is crucial to consider several drawbacks associated with passive balancing. Firstly, there is an inherent energy wastage in the form of heat, which could otherwise be utilized for productive purposes. Secondly, in a balance-at-top configuration, energy remains trapped in cells even when a weak cell is fully discharged, whereas an active balancing system has the capability to harness this energy.

Additionally, the generation of heat necessitates high-wattage requirements for balancing resistors and high-current ratings for balancing transistors. Lastly, the lifespan of a battery pack may be shorter when utilizing passive balancing, as the overall life of the pack is determined by its weakest cell. In contrast, active balancing systems leverage the strength of robust cells to support weaker cells, resulting in a uniform end-of-life configuration for the pack.

1.2 Active Balancing

Cell balancing methods can be broadly categorized into passive and active approaches. Passive balancing methods are typically implemented during the battery pack charging process to ensure the attainment of full charge for each cell [6]. On the other hand, active balancing methods involve the redistribution of cell energy, which proves to be more energy-efficient compared to passive balancing methods that dissipate excess cell energy through resistors. Active balancing methods are also well-suited for both charging and discharging operations [7].

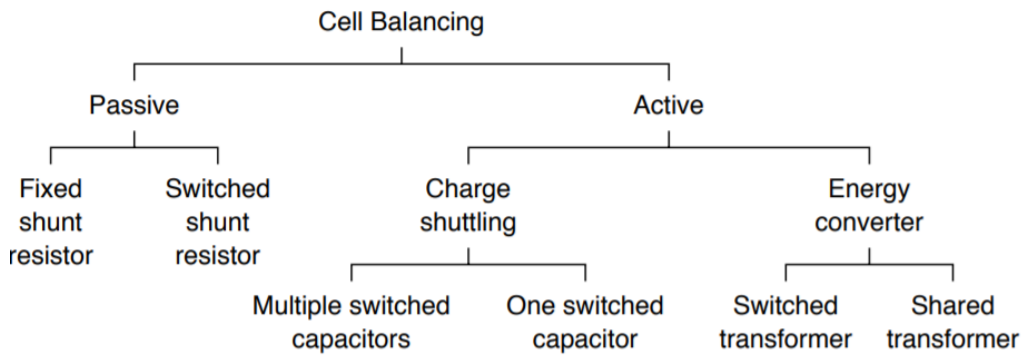

Figure 3. Methods of BMS [5]

Figure 4 showcases a circuit of an active balancing system utilizing a bidirectional ACFC-SR (Active Cell Front-End Shunt Regulator). This particular circuit has been employed by Texas Instruments in their active balancing product, such as the TI EM1402 active balancing board. The energy redistribution among cells is facilitated by the exchange of energy between the battery cells and an auxiliary power source. The magnitude and direction of the balancing current can be effectively controlled by managing the inductor current of the bidirectional ACFCSR [8].

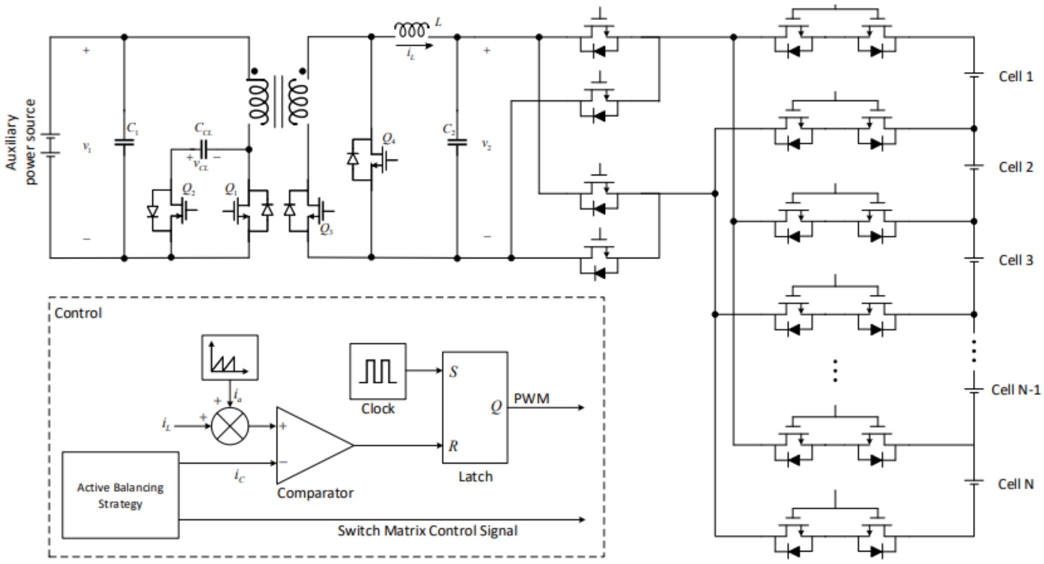

Figure 4. Circuit of an active balancing system utilizing a bidirectional ACFC-SR

While active balancing circuits offer the advantage of reduced energy loss compared to passive methods, they introduce additional power consumption due to the presence of switching devices, passive components, power electronics driver circuits, and control circuits. Active balancing methods can be categorized based on the charge transferring element utilized, such as inductor-based, capacitor-based, and transformer-based approaches [9] [10] [11]. The introduction of active methods aimed to address the heating issues associated with passive methods and enhance the balancing speed. However, capacitor-based topologies in active methods tend to have longer balancing times. As a result, inductor-based topologies were introduced to improve the balancing speed. Transformer-based methods leverage transformers to reduce the number of switches and further enhance the balancing speed [12].

1.3 Topologies of BMS

Battery management systems (BMS) possess a complex structure comprising multiple electronic components. The primary objectives of a BMS include voltage and current measurement at the cell level, determination of charge level (SoC), determination of health level (SoH), cell-level balancing, and continuous monitoring of voltage and current limits for targeted cells. The design of a BMS can incorporate various topologies.

In a centralized topology, cells are directly connected within a single BMS circuit.

This configuration entails all measurements, decision mechanisms, and balancing operations being performed within a single circuit. However, a drawback of this approach is the use of excessive cables, which can lead to overheating issues. Alternatively, the modular topology involves multiple BMS circuits, with one of them serving as the master circuit. While this configuration provides flexibility, there can be challenges in achieving effective communication at the cell level. In the Master-Slave topology, the circuit board acting as the manager does not have a direct connection with the cells. It oversees the operations and communication of individual cell-level circuits.

Lastly, the distributed topology employs analog circuits for each cell. However, these circuits lack control functions and primarily consist of circuit elements dedicated to balancing operations. Each of these topologies presents its own advantages and limitations in terms of system complexity, communication efficiency, and control capabilities [11].

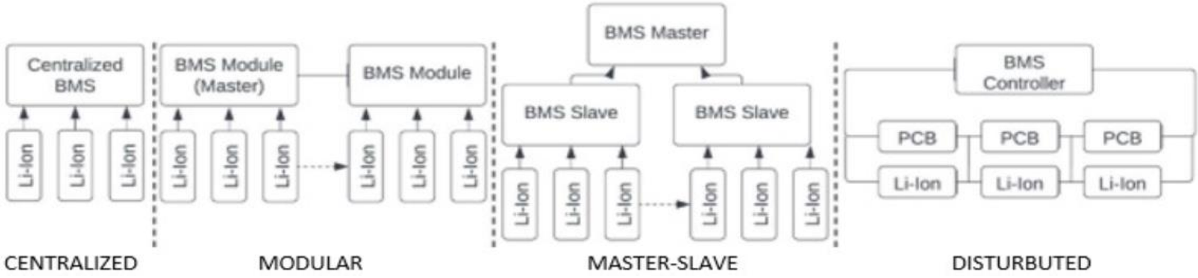

Figure 5. Schematic overview of BMS topologies

1.3. Purpose of the Project

Considering the disadvantages of active balancing, the main objectives are to develop this method, to provide know-how for the sector, and to increase energy efficiency. With this study, it is aimed that the study team will gain know-how on the management of batteries to be used in renewable energy and electric vehicle systems, which are popular topics of the last period. It is thought that this study will also make significant contributions to the electric vehicle industry in the near future when the number of domestic and national electric vehicles will increase.

2. BATTERIES

A battery is a source of electric power consisting of one or more electrochemical cells with external connections [13] for powering electrical devices. When a battery is supplying power, its positive terminal is the cathode and its negative terminal is the anode [14]. The terminal marked negative is the source of electrons that will flow through an external electric circuit to the positive terminal. When a battery is connected to an external electric load, a redox reaction converts high-energy reactants to lower-energy products, and the free-energy difference is delivered to the external circuit as electrical energy. Historically the term "battery" specifically referred to a device composed of multiple cells; however, the usage has evolved to include devices composed of a single cell [15].

Primary (single-use or "disposable") batteries are used once and discarded, as the electrode materials are irreversibly changed during discharge; a common example is the alkaline battery used for flashlights and a multitude of portable electronic devices. Secondary (rechargeable) batteries can be discharged and recharged multiple times using an applied electric current; the original composition of the electrodes can be restored by reverse current. Examples include the lead–acid batteries used in vehicles and lithium-ion batteries used for portable electronics such as laptops and mobile phones.

Batteries come in many shapes and sizes, from miniature cells used to power hearing aids and wristwatches to, at the largest extreme, huge battery banks the size of rooms that provide standby or emergency power for telephone exchanges and computer data centers. Batteries have much lower specific energy (energy per unit mass) than common fuels such as gasoline. In automobiles, this is somewhat offset by the higher efficiency of electric motors in converting electrical energy to mechanical work, compared to combustion engines.

2.1 History of Batteries

2.1.1 Invention

Benjamin Franklin first used the term "battery" in 1749 when he was doing experiments with electricity using a set of linked Leyden jar capacitors [16]. Franklin grouped a number of the jars into what he described as a "battery", using the military term for weapons functioning together [17].

Italian physicist Alessandro Volta built and described the first electrochemical battery, the voltaic pile, in 1800 [18]. This was a stack of copper and zinc plates, separated by brine-soaked paper disks, that could produce a steady current for a considerable length of time. Volta did not understand that the voltage was due to chemical reactions. He thought that his cells were an inexhaustible source of energy [19], and that the associated corrosion effects at the electrodes were a mere nuisance, rather than an unavoidable consequence of their operation, as Michael Faraday showed in 1834 [20].

Although early batteries were of great value for experimental purposes [21], in practice their voltages fluctuated and they could not provide a large current for a sustained period. The Daniell cell, invented in 1836 by British chemist John Frederic Daniell, was the first practical source of electricity, becoming an industry standard and seeing widespread adoption as a power source for electrical telegraph networks [22].

These wet cells used liquid electrolytes, which were prone to leakage and spillage if not handled correctly. Many used glass jars to hold their components, which made them fragile and potentially dangerous. These characteristics made wet cells unsuitable for portable appliances. Near the end of the nineteenth century, the invention of dry cell batteries, which replaced the liquid electrolyte with a paste, made portable electrical devices practical [23].

2.1.2 Future

Between 2010 and 2018, annual battery demand grew by 30%, reaching a total of 180 GWh in 2018. Conservatively, the growth rate is expected to be maintained at an estimated 25%, culminating in demand reaching 2600 GWh in 2030. In addition, cost reductions are expected to further increase the demand to as much as 3562 GWh [24].

Important reasons for this high rate of growth of the electric battery industry include the electrification of transport [24], and large-scale deployment in electricity grids [24], supported by anthropogenic climate change-driven moves away from fossil-fuel combusted energy sources to cleaner, renewable sources, and more stringent emission regimes.

Distributed electric batteries, such as those used in battery electric vehicles (vehicle-to-grid), and in-home energy storage, with smart metering and that are connected to smart grids for demand response, are active participants in smart power supply grids [25], new methods of reuse, such as echelon use of partly-used batteries, add to the overall utility of electric batteries, reduce energy storage costs, and also reduce pollution/emission impacts due to longer lives.

In echelon use of batteries, vehicle electric batteries that have their battery capacity reduced to less than 80%, usually after service of 5–8 years, are repurposed for use as backup supply or for renewable energy storage systems [26]. Grid scale energy storage envisages the large-scale use of batteries to collect and store energy from the grid or a power plant and then discharge that energy at a later time to provide electricity or other grid services when needed. Grid scale energy storage (either turnkey or distributed) is an important component of smart power supply grids [27].

2.2 TYPES OF BATTERY

2.2.1 Primary Battery (or) Primary Cells

In these cells, the electrode and the electrode reactions cannot be reserved by passing external electrical energy. The reactions occur only once and after use they become dead. Therefore, they are not chargeable. Primary batteries have 3 types. These are Alkaline, Aluminum-air and dry cell batteries**.** Alkaline Batteries drive the energy by a reaction of zinc metal and manganese oxide and we named it an alkaline battery because instead of using an acidic electrolyte, we use an alkaline electrolyte like potassium hydroxide (KOH).

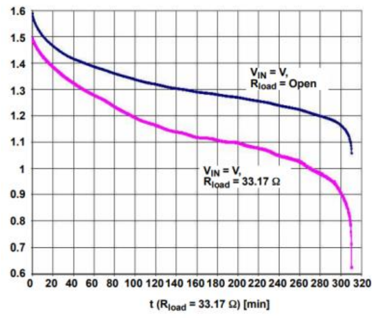

Figure 6. A Typical AA-Size Alkaline Battery Voltage at

No Load Versus at 330-mW Discharge[28]

The advantages of alkaline batteries are that they have more life, shelf life is more, small in size, highly efficient, low internal resistance so that discharge state in idle state is less and leakage is low.

Aluminum-Air Batteries have the highest energy density and produce energy from the reaction of oxygen with aluminum. Once the aluminum is consumed and all aluminum gets reacted with air oxygen, we can’t use this battery further and we need to dispose of it after a single use.

Dry Cell is another type of primary battery and most of us used it in our toys and Tv remote control but these batteries are now getting replaced by alkaline batteries because of their high lifetime and energy density over the dry cells. The dry cell is named after its electrolyte type as we use the dry electrolyte in it instead of liquid or wet electrolyte.

There are many other kinds of primary batteries as well but we mostly use mentioned above batteries.

Table 1. Comparison of the battery types

Battery Type	**Energy Density (Wh/kg)**	**Life Cycle**	**Toxicity**
Li-Ion	**126-190**	**500-1,000**	**Low**
Ni-Cd	**45-80**	**1000**	**High**
Ni-MH	**100**	**300-500**	**Low**
Li-ion polymer	**185**	**300 – 500**	**Low**
Lead Acid	**30-50**	**200-300**	**High**
Lithium–Sulfur	**55**	**50-100**	**Non- Toxic**

2.2.2 Secondary Battery (or) Secondary Cells

In these cells, the electrode reactions can be reversed by passing external electrical energy. Therefore, they can be recharged by passing an electric current and used again and again. These are also called Storage cells (or) Accumulators.

There are lots of different types of secondary batteries. Lead acid storage cell, Nickel-cadmium cells, Li-ion batteries, Li-Po Batteries, Ni-MH Batteries, and Lead-acid Batteries are the most used ones of them.

Li-Ion Batteries are kind of battery that uses Lithium metal so named Li-Ion battery. These batteries are composed of cells and lithium ions from the negative electrode move to the positive electrode and when we charge, the ions move back to their place; this cycle occurs in each charging and discharging process. The power density of Li-ion batteries is 126 Wh/Kg. Also, Li-ion Batteries can survive low temperature.

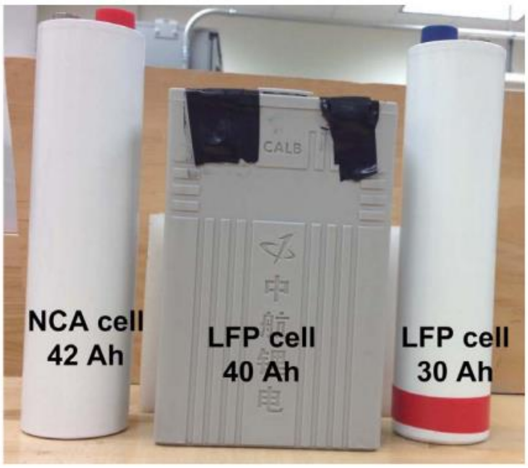

Figure 7. Li-ion batteries in different form factors: a prismatic cell LFP type (40 Ah), a cylindrical cell LFP type (30Ah), and a cylindrical cell NCA type (42 Ah) [29].

The Li-Po battery lithium polymer battery and we named polymer battery because they use polymer electrolyte instead of liquid electrolyte. The high conductivity gel polymer form of electrolyte is used. These batteries carry high energy density compared to their weight. These are mostly used in drones due to their lightweight and high density of energy. It has a Power density of 185 Wh/Kg.

Ni-MH (nickel metal hydride) battery uses nickel oxide hydroxide and they are quite similar to Nickel cadmium NiCd battery but here they use a hydrogen-absorbing alloy instead of cadmium and have a lower impact on the environment compared to others. The power density of these batteries is 100 Wh/Kg.

Lead-acid Batteries have electrodes submerged in sulfuric acid electrolytes. These batteries are quite bulky and are mostly used in automobiles, UPS, Grid power stations, etc.

There are lots of other kinds of secondary batteries. Aluminum-ion battery, Calciubatry, Flow battery, Vanadium redox battery, Zinc–bromine battery, Zinc–cerium batteries are examples of secondary batteries.

2.3 Selection and Application of Batteries

The many and varied requirements for battery power and the different environmental and electrical conditions under which they must operate necessitate the use of a number of different types of batteries and designs, each having the most advantageous performance under specific operational conditions.

Although many advances have been made in battery technology in recent years, both through the continued improvement of a specific electrochemical system and the development and introduction of new battery chemistries, there is still no one ‘‘ideal’’ battery that performs optimally under all operating conditions. As a result, over time, many different electrochemical systems and battery types have been and are still being investigated and promoted. However, a relatively small number have achieved wide popularity and significant production and sales volumes. The less conventional systems are typically used in military and industrial applications requiring the specific capabilities offered by these special batteries.

The ‘‘ideal’’ electrochemical cell or battery is obviously one that is inexpensive, has infinite energy, can handle all power levels can operate over the full range of temperature and environmental conditions, an has unlimited shelf life, and is completely safe and consumer proof. In practice, energy limitations do exist as materials are consumed during the discharge of the battery, temperature, discharge rate affect performance, and shelf life is limited due to chemical reactions and physical changes that occur, albeit slowly in some cases, during storage. The use of energetic component materials and special designs to achieve high energy and power densities may require precautions during use to avoid electrical and physical abuse and problems related to safety. Further, the influence of the conditions of discharge, charge and the use of the battery must the considered.

It should be recognized that while the demands of battery-using equipments continually seek smaller and more energetic and powerful batteries, these requirements may not necessarily be met because of the theoretical and practical limits of battery technology. The selection of the most effective battery and the proper use of this battery is critical in order to achieve optimum performance in an application [30].

A number of factors must be considered in selecting the best battery for a particular application. The characteristics of each available battery must be weighed against the equipment requirements and one selected that best fulfills these needs.

It is important that the selection of the battery be considered at the beginning of equipment development rather than at the end when the hardware is fixed. In this way, the most effective compromises can be made between battery capabilities and equipment requirements.

The considerations that are important and influence the selection of the battery include:

1. Type of Battery: Primary, secondary, or reserve system

2. Electrochemical System: Matching the advantages and disadvantages of the battery characteristics with major equipment requirements

3. Voltage: Nominal or operating voltage, maximum and minimum permissible voltages, voltage regulation, the profile of discharge curve, start-up time, voltage delay

4. Load Current and Profile: Constant current, constant resistance, or constant power; or others; the value of load current or profile, single-valued or variable load, pulsed load

5. Duty Cycle: Continuous or intermittent, cycling schedule if intermittent

6. Temperature Requirements: Temperature range over which operation is required

7. Service Life: Length of time operation is required

8. Physical Requirements: Size, shape, weight; terminals

9. Shelf Life: Active/ reserve battery system; state of charge during storage; storage time a function of temperature, humidity, and other conditions

10. Charge-Discharge Cycle (if Rechargeable): Float or cycling service; life or cycle requirement; availability and characteristics of charging source; charging efficiency

11. Environmental Conditions: Vibration, shock, spin, acceleration, atmospheric conditions (pressure, humidity, etc.)

12. Safety and Reliability: Permissible variability, failure rates; freedom from outgassing or leakage; use of potentially hazardous or toxic components; type of effluent or signature gases or liquids, high temperature, etc.: operation under severe or potentially hazardous conditions; environmentally friendly

13. Unusual or Stringent Operating Conditions: Very long-term or extreme-temperature storage, standby, or operation; high reliability for special applications; rapid activation for reserve batteries, no voltage delay; special packaging for batteries (pressure vessels, etc.); unusual mechanical requirements, e.g, high shock or acceleration, nonmagnetic

14. Maintenance and Resupply: Ease of battery acquisition, accessible distribution; ease of battery replacement; available charging facilities; special transportation, recovery, or disposal procedures required

15. Cost: Initial cost; operating or life-cycle cost; use of critical or exotic (costly) materials

In order to realize a highly efficient wireless energy transfer from the grid to the battery, it is necessary to construct a complex circuit. In this circuit, both AC to DC and DC to AC conversions are done where needed.

3. SENSORS

3.1 Voltage

Voltage sensors play a crucial role in monitoring, measuring, calculating, and determining voltage supply. These sensors enable us to assess the level of AC or DC voltage.

They operate by taking voltage as input and providing outputs such as output switches, analog voltage signals, current signals, audible signals, and more.

Certain sensors available in the market generate output waveforms like sine waveforms or pulse waveforms using modulation techniques such as pulse width modulation (PWM) or frequency modulation (FM). The size of these sensors is influenced by the mains voltage divider.

A voltage sensor is a device designed to detect or sense specific electrical or optical signals and respond accordingly. The adoption of voltage and current sensor technology has emerged as a preferred choice over traditional methods of current and voltage measurement. These sensors can be classified into two types: resistive type sensors and capacitive type sensors.

3.1.1 Resistive Sensors

This particular sensor type comprises two main circuits: a voltage circuit breaker and a bridge circuit. The sensing element in this circuit is a resistor. The voltage is divided across two resistors, typically a variable resistor and a reference voltage, forming a voltage divider circuit. The voltage supplied to this circuit can be determined by the resistance used in the output voltage circuit. As a result, changes in voltage can be amplified [31].

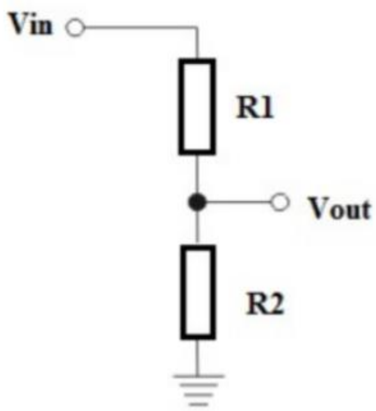

Figure 8. Circuit design of a resistive voltage sensor [31]

The bridge circuit can be configured using four resistors, where one of these resistors can serve as a voltage-sensing element. The variation in voltage can be directly detected and displayed. While the voltage difference can be amplified individually, it is important to note that the voltage divider circuit does not solely amplify the voltage difference.

3.1.2 Capacitive Sensors

Capacitors consist of two conductor plates separated by a non-conductive material called a dielectric. The dielectric material keeps the conductors isolated from each other. When an AC voltage is applied across these plates, the current starts to flow as electrons are attracted to or repelled by the voltage on the opposite plate. The space between the plates effectively forms a complete AC circuit without the need for any physical connection. This is the fundamental principle behind how capacitors operate [32].

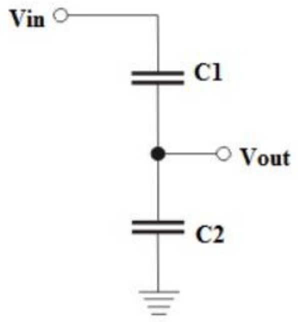

Figure 9. Circuit design of a capacitive voltage sensor [31]

When capacitors are connected in series, the voltage is divided between them. In a series circuit, the component with a higher impedance tends to develop a higher voltage [32]. In the case of capacitors, the relationship between capacitance and impedance is inversely proportional. Capacitive reactance, which represents the impedance of a capacitor, increases as the capacitance decreases. As a result, in a series circuit with capacitors, the capacitor with smaller capacitance will have a higher impedance and thus develop a larger voltage compared to the capacitor with larger capacitance. This follows Ohm's Law, where the largest voltage develops across the component with the largest impedance.

3.2. Current Sensors

A current sensor is a device designed to detect and convert current into an accessible output voltage. The output voltage of the sensor is directly proportional to the current flowing through the measured path.

This output voltage signal can be utilized for various purposes, such as displaying the measured current on an ammeter, for control applications, or for storage and analysis within a data acquisition system. Essentially, the function of a current sensor is to enable the measurement and monitoring of electric current.

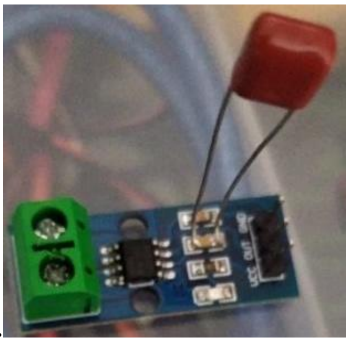

Figure 10. A current sensor with a capacitor

In the market, there are various types of current sensors available, each designed for specific current ranges and environmental conditions. Among these sensors, the current sensor is widely used as it acts as a current-to-voltage converter by incorporating a resistor in the current path. This allows the conversion of the current into a proportional voltage in a linear manner. The technology employed in current sensors is crucial, as different sensor types possess different characteristics suited for various applications.

The working principle of a current sensor involves the occurrence of a voltage drop when current flows through a circuit or wire, accompanied by the generation of a magnetic field around the current-carrying conductor. Consequently, there are two main types of current sensing: direct current sensing and indirect current sensing.

Direct sensing relies on Ohm's law and is employed to measure the voltage drop across passive electrical components caused by the current flow. On the other hand, indirect sensing utilizes Ampere's and Faraday's laws to measure the magnetic field surrounding a current-carrying conductor. The generated magnetic field is then used to induce a proportional current or voltage, which is subsequently converted for measurement or control purposes. The specifications of a current sensor primarily describes its operation and performance in specific environmental conditions. These specifications play a vital role in assessing the suitability of the sensor for a given application.

3.2.1 Shunt Resistor

Shunt resistor type current sensors are primarily utilized for measuring DC current. The principle behind these sensors is that when a DC current flows through a resistor, a voltage is generated across the resistor. The shunt resistor is designed based on this principle to enable current measurement.

These sensors offer several advantages, including low cost, fast response speed, and high accuracy. However, it's important to note that the measurement circuit is not electrically isolated from the current being measured, which can be a drawback. This type of current sensor is suitable for small amplitude and low-frequency current measurements [33].

Figure 11. Shunt resistor

3.2.2 Hall Effect Current Sensors

Hall current sensors are designed based on the principles of the Hall effect and Ampere's law. These sensors are capable of measuring both AC and DC currents, typically up to a frequency of 100 KHz. The construction of these sensors involves a Hall effect device, a core, and signal conditioning circuitry [34]. The operation of Hall current sensors relies on the Hall Effect, which states that when current flows through a conductor, it generates a magnetic field.

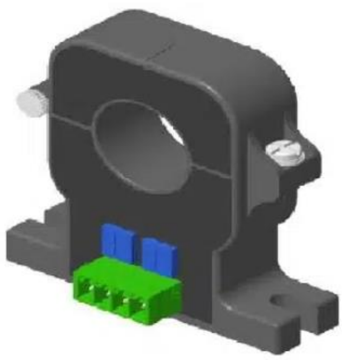

Figure 12. A Hall Effect Current Sensor

When the conductor of a Hall current sensor is exposed to an external magnetic field, the magnetic field generated by the current-carrying conductor interacts with the external field. As a result, electrons within the conductor are displaced to one side, leading to the generation of a voltage proportional to the current flowing through it. This voltage can be measured as an indication of the current being sensed. Hall current sensors offer several advantages, such as good electrical isolation and high precision in current measurements. However, they also have certain drawbacks.

One limitation is their relatively slow response speed, which means they may not be suitable for applications requiring rapid measurements or fast-changing currents. Additionally, when it comes to measuring small currents, the accuracy of Hall current sensors may be compromised.

In summary, Hall current sensors provide good isolation and high precision in current measurements, but they have a slow response speed and may exhibit reduced accuracy when measuring small currents [34].

3.3 Temperature Sensors

Temperature sensors play a crucial role in various everyday applications, ranging from temperature control in buildings to regulating water temperatures and monitoring refrigerators. They are also essential in consumer, medical, and industrial electronics, among other fields. The specific temperature sensing requirements can vary depending on the application, including the type of measurement (air, mass, or liquid), the location of measurement (interior or exterior), and the temperature range being monitored. In modern electronics, four main types of temperature sensors are commonly used: thermocouples, RTDs (resistance temperature detectors), thermistors, and semiconductor based integrated circuits (IC) [35] [36].

3.3.1 Thermocouples

Thermocouples are indeed one of the most widely used types of temperature sensors in various industries, automotive systems, and consumer applications. They offer several advantages that make them suitable for a range of temperature measurement needs. Some key characteristics of thermocouples include: being self-powered, requiring no excitation, can operate over a wide temperature range, and having quick response times. Thermocouples are made by joining two dissimilar metal wires together.

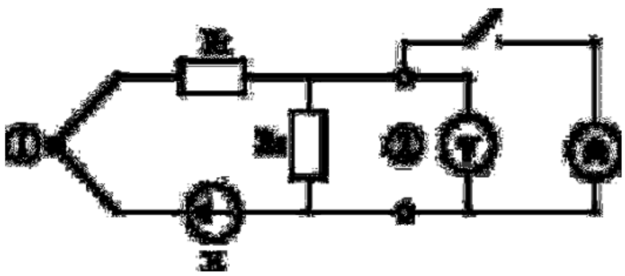

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Figure 13. The measurement circuit of thermocouple resistance [37]

This causes a Seebeck Effect. The Seebeck Effect is a phenomenon that occurs when a temperature difference exists between two dissimilar conductors and generates a corresponding voltage difference. This voltage difference is utilized to measure and calculate the temperature. Several types of thermocouples are made from a variety of different materials, which allows for different temperature ranges and different sensitivities.

Different types of thermocouples are available, distinguished by designated letters. Among the various types, the K type thermocouple is widely used [38].

3.3.2 RTD (Resistance Temperature Detector)

RTDs (Resistance Temperature Detectors) are temperature sensors that utilize the variation in electrical resistivity of metals with temperature. These sensors are essentially resistors with well-defined resistance-temperature characteristics. Platinum is the most commonly used material for RTDs due to its chemical stability and relatively linear response to temperature changes. Platinum RTDs are available with resistance values of 100Ω and 1kΩ at 0°C, commonly referred to as PT100 and PT1000. Additionally, other metals such as nickel and copper can also be employed in the construction of RTDs. Platinum RTDs offer several advantages, including a wide temperature range, often up to 750°C or higher, excellent accuracy and repeatability, and reasonable linearity. These features make them suitable for precision applications, including instruments and process control, where accuracy and stability are crucial factors to consider. RTDs are preferred in situations that demand high precision due to their reliable performance over a wide temperature range [36].

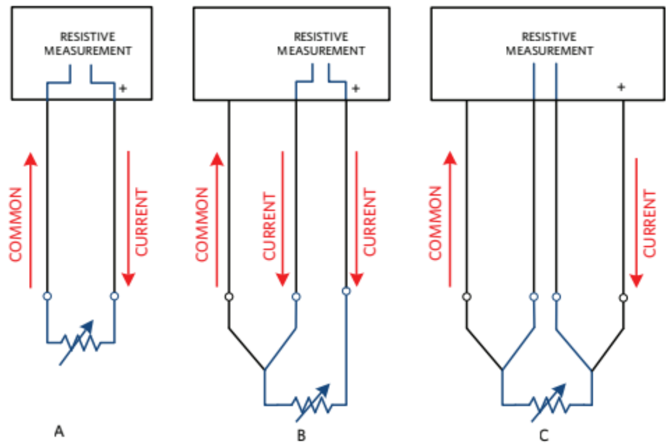

Figure 14. Two-Wire, Three-Wire, and Four-Wire RTD [8]

Bare RTD elements typically have higher thermal mass compared to bare thermocouples, which results in slower response times to temperature changes. To protect both RTDs and thermocouples, they are often enclosed in stainless-steel sheaths. When encased, the overall mass of the sensor probe becomes similar for both types, leading to similar response times. In RTD temperature measurement, signal conditioning plays a crucial role.

An excitation current is applied to the RTD, and the voltage across the RTD is measured. By knowing or deriving the excitation current, the resistance of the RTD can be calculated. Different configurations, such as two-/three-/four-wire, can be employed for RTD measurements, as depicted in Figure 14.

3.3.3 Thermistors

Thermistors, similar to RTDs, exhibit changes in resistance with variations in temperature. However, unlike RTDs which are primarily made of pure metals, thermistors are typically constructed using polymer or ceramic materials. Thermistors are generally less expensive and less accurate than RTDs, although there can be exceptions to this generalization. Most thermistors are available in a two-wire configuration, similar to the RTD illustrated in Figure 14. Negative Temperature Coefficient (NTC) thermistors are commonly utilized for temperature measurement applications. As implied by their name, the resistance of an NTC thermistor decreases as the temperature increases. The temperature range for a thermistor is typically narrower, ranging from -90°C to +130°C, which is considerably lower compared to thermocouples and RTDs. However,wider-range thermistors are also available. Thermistors exhibit highly non-linear relationships between temperature and resistance, necessitating significant linearity correction. The resistance of a thermistor as a function of temperature is approximated using the Steinhart-Hart equation, which allows for the estimation of individual thermistor curves [36].

4. MICROPROCESSORS, MICROCONTROLLERS AND ARDUINO

4.1 Microprocessors

Computer's Central Processing Unit (CPU) built on a single Integrated Circuit (IC) is called a microprocessor. A digital computer with one microprocessor which acts as a CPU is called a microcomputer. It is a programmable, multipurpose, clock-drivenen, register-based electronic device that reads binary instructions from a storage device called memory, accepts binary data as input and processes data according to those instructions, and provides results as output. The microprocessor contains millions of tiny components like transistors, registers, and diodes that work together.

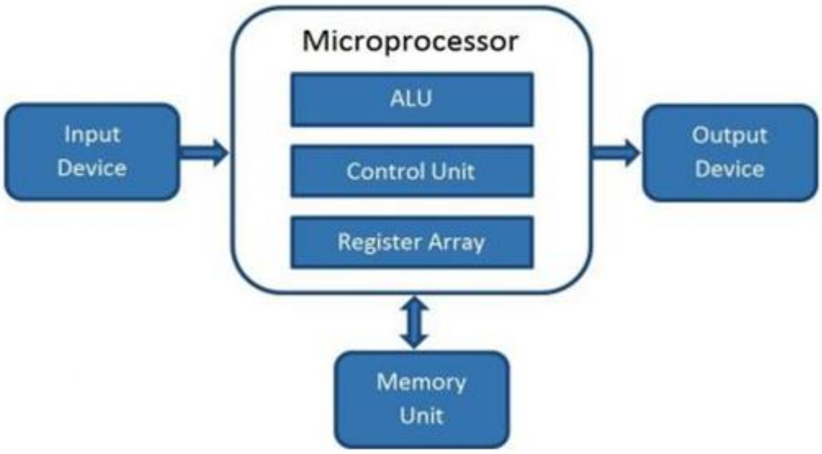

Figure 15. Block Diagram of a Microcomputer

A microprocessor consists of an ALU, control unit, and register array. Where ALU performs arithmetic and logical operations on the data received from an input device or memory. The control unit controls the instructions and flow of data within the computer. And, register array consists of registers identified by letters like B, C, D, E, H, L, and accumulator.

4.1.1 Working Principle of Microprocessor

The microprocessor follows a sequence to execute the instruction: Fetch, Decode, and then Execute. Initially, the instructions are stored in the storage memory of the computer in sequential order. The microprocessor fetches those instructions from the stored area (memory), then decodes them and executes those instructions till the stop instruction is met.

Then, it sends the result in binary form to the output port. Between these processes, the register stores the temporary data and ALU (Arithmetic and Logic Unit) performs the computing functions.

4.1.2 Features of Microprocessor

- Low Cost - Due to integrated circuit technology microprocessors are available at very low cost. It will reduce the cost of a computer system.
- High Speed - Due to the technology involved in it, the microprocessor can work at very high speed. It can execute millions of instructions per second.

- Small Size - A microprocessor is fabricated in a very less footprint due to very large scale and ultra large scale integration technology. Because of this, the size of the computer system is reduced.
- Versatile - The same chip can be used for several applications, therefore, microprocessors are versatile.
- Low Power Consumption - Microprocessors are using metal oxide semiconductor technology, which consumes less power.
- Less Heat Generation - Microprocessors use semiconductor technology which will not emit much heat as compared to vacuum tube devices.
- Reliable - Since microprocessors use semiconductor technology, therefore, the failure rate is very less. Hence it is very reliable.
- Portable - Due to their small size and low power consumption microprocessors are portable.

4.2 Microcontroller and Its Types

A microcontroller (MCU) is a small computer on a single integrated circuit that is designed to control specific tasks within electronic systems. It combines the functions of a central processing unit (CPU), memory, and input/output interfaces, all on a single chip.

Microcontrollers are widely used in embedded systems, such as home appliances, automotive systems, medical devices, and industrial control systems. They are also used in consumer electronics products, such as gaming systems, digital cameras, and audio players.

A typical microcontroller consists of a processor core, volatile and non-volatile memory, input/output peripherals, and various communication interfaces.

The processor core is responsible for executing instructions and controlling the other components of the microcontroller. The memory is used to store data and program code, while the input/output peripherals are used to interact with the external environment.

Microcontrollers are programmable, which means that they can be customized to perform specific tasks. The programming languages used to write code for microcontrollers vary depending on the manufacturer and the type of microcontroller. Some of the commonly used programming languages include C, C++, and assembly language.

A microcontroller is a self-contained desktop that can be utilized in an embedded system. A few microcontrollers may run at clock rate rates and use four-bit expressions. Because many of the devices they control are battery-operated, microcontrollers must often be low-power. Microcontrollers are found in a wide range of products, including consumer electronics, automobile engines, computer peripherals, and test and measurement equipment. These are also well-suited to long-term battery usage. The vast majority of microcontrollers in use today are embedded in other devices.

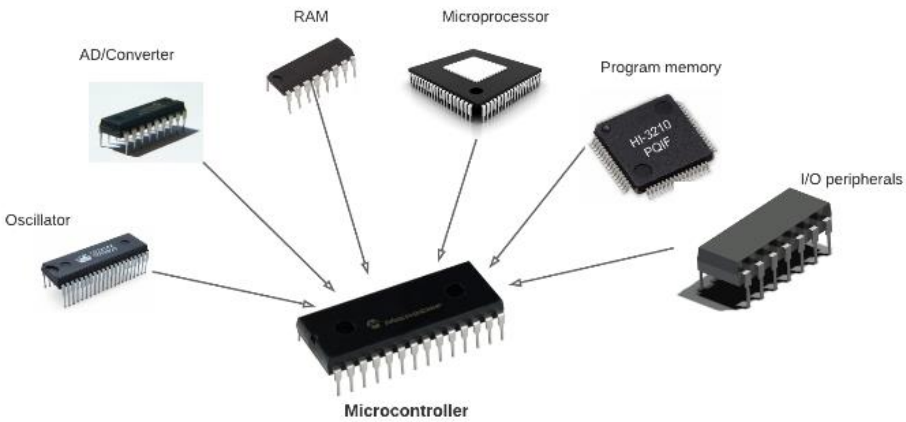

Figure 16. Types of microcontrollers

The microcontroller used in Embedded System. Security Systems, laser Printers, automation Systems and robotics are some examples of this usege.

4.2.1 Working Principle of Microcontroller

The microcontroller chip is a high-speed device, yet it is slow when compared to a computer. As a result, each command will be executed quickly within the microcontroller. The quartz oscillator is enabled and through control logic register once the supply is powered on. Parasite capacitors will be recharged for a few seconds while the early preparation is taking place. Once the voltage level reaches its maximum value and the oscillator's frequency stabilizes, the operation of writing bits through special function registers becomes stable.

Everything is controlled by the oscillator's clock, and the whole electronics will begin to function. All of this happens in a matter of nanoseconds. A microcontroller's major role is that it can be thought of as a self-contained system with a processor memory. Its peripherals can be used in the same way that an 8051 microcontroller can.

The bulk of microcontrollers in use today are embedded in other types of machinery such as telephones, appliances, vehicles, and computer system peripherals.

4.2.2 Types of Microcontroller

There are lots of different types of microcontrollers. Some of the most common types of microcontrollers are:

8-bit Microcontrollers: These are the most basic type of microcontrollers, typically used in simple applications such as toys, small appliances, and remote controls. They have a limited processing power and memory capacity, but they are easy to use and cost-effective.

16-bit Microcontrollers: These are more advanced than 8-bit microcontrollers and are capable of performing more complex tasks. They are commonly used in applications such as medical devices, automotive systems, and industrial control systems.

32-bit Microcontrollers: These are the most powerful and feature-rich microcontrollers, capable of handling large amounts of data and performing high-speed processing. They are used in applications such as gaming systems, multimedia devices, and high-end industrial automation.

CPU: The microcontroller is referred to as a CPU device since it is utilized to carry and decode data before effectively completing the assigned duty. All microcontroller components are connected to a specific system utilizing a central processing unit. The CPU can decode instructions retrieved from the programmable memory.

Memory: The memory chip of a microcontroller functions similarly to a microprocessor in that it stores all of the data as well as programming. Microcontrollers have a limited quantity of RAM/ROM/flash memory for storing program source code.

Input and Output ports: In general, these ports are used to interface or otherwise drive various appliances like LEDs, LCDs, printers, and so on.

Serial Ports: Serial ports are used to offer serial interfaces between the microcontroller and a range of additional peripherals, such as the parallel port.

Timers: Timers and counters are included in a microcontroller. In a microcontroller, they are used to manage all timing and counting activities. The fundamental function of a counter is to count external pulses, whereas timers conduct clock tasks, pulse production, modulations, frequency measurement, and oscillations, among other things.

4.2.3 Microcontroller Applications

In contrast to microprocessors, which are used in personal computers and other devices, microcontrollers are mostly employed in embedded devices.

These are mostly utilized in a variety of products such as implantable medical devices, machine tools, automotive engine control systems, office equipment, remote-controlled appliances, and so on. The following are some of the most common uses for microcontrollers.

4.2.4 Microcontroller Properties

Microcontroller devices are capable of having words longer than 64 bits. Microcontroller consist of RAM, ROM, Timer, I/O Ports. Microcontroller ROM is used for program storage and RAM is used for data storage. It is designed by using CISC architecture. The power consumption of modern microcontrollers is significantly lower and have operating voltage range from 1.8V to 5.5V The latest feature of microcontroller is flash memory like EPROM and EEPROM. The most recent feature of a microcontroller is flash memory, such as EPROM and EEPROM.

4.3 Difference Between Microprocessor and Microcontroller

Both microprocessors and microcontrollers are types electronic devices that come in the form of integrated circuits (ICs) and are used in different modern electronic equipment such as computers, laptops, washing machines, air conditioners, and many other automated electronic gadgets. The primary function of both microprocessors and microcontrollers is to automate the processes.

Table 2. Difference Between Microprocessor and Microcontroller

Parameter	Microprocessor	Microcontroller
Definition	Microprocessors can be understood as the heart of a computer system.	Microcontrollers can be understood as the heart of an embedded system.
What is it?	A microprocessor is a processor where the memory and I/O component are connected externally.	A microcontroller is a controlling device wherein the memory and I/O output component are present internally.
Circuit complexity	The circuit is complex due to external connection.	Microcontrollers are present on chip memory. The circuit is less complex.
Memory and I/O components	The memory and I/O components are to be connected externally.	The memory and I/O components are available.
Compact system compatibility	Microprocessors can’t be used in compact system.	Microcontrollers can be used with a compact system.
Efficiency	Microprocessors are not efficient.	Microcontrollers are efficient.
Zero status flag	Microprocessors have a zero status flag.	Microcontroller doesn’t have a zero status flag.
Number of registers	Microprocessors have less number of registers.	Microcontrollers have more number of registers.
Applications	Microprocessors are generally used in personal computers.	Microcontrollers are generally used in washing machines, and air conditioners.

4.4 Arduino

Arduino is an open-source electronics platform based on easy-to-use hardware and software. Arduino boards are able to read inputs - light on a sensor, a finger on a button, or a Twitter message - and turn it into an output - activating a motor, turning on an LED, publishing something online.

You can tell your board what to do by sending a set of instructions to the microcontroller on the board. To do so you use the Arduino programming language (based on Wiring), and the Arduino Software (IDE), based on Processing. Over the years Arduino has been the brain of thousands of projects, from everyday objects to complex scientific instruments.

A worldwide community of makers - students, hobbyists, artists, programmers, and professionals - has gathered around this open-source platform, their contributions have added up to an incredible amount of accessible knowledge that can be of great help to novices and experts alike.

Arduino was born at the Ivrea Interaction Design Institute as an easy tool for fast prototyping, aimed at students without a background in electronics and programming. As soon as it reached a wider community, the Arduino board started changing to adapt to new needs and challenges, differentiating its offer from simple 8-bit boards to products for IoT applications, wearable, 3D printing, and embedded environments [39].

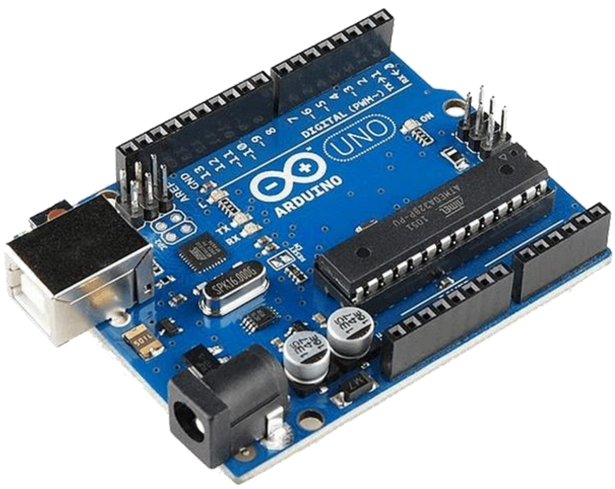

Figure 17. An Arduino board

4.4.1 Different Types of Arduino Boards

Arduino board was designed in the Ivrea Interaction Design Institute intended for students without a background in electronics and programming concepts. This board started altering to adapt to new requirements and challenges, separating its presence from simple 8-bit boards to products for IoT (Internet of Things) applications, 3D printing, wearable, and embedded surroundings. All boards are entirely open-source, allowing users to build them separately and finally adapt them to their exact needs. Over the years the different types of Arduino boards have been used to build thousands of projects, from daily objects to compound scientific instruments. An international community of designers, artists, students, programmers, hobbyists, and experts has gotten together around this open-source stage, their donations have added up to an unbelievable amount of available knowledge that can be of immense help to beginners and specialists alike. This paper discusses an overview of different types of Arduino boards and their comparison.

Table3. Features of Different Types of Arduino Boards

Arduino Board	**Processor**	**Memory**	**Digital I/O**	**Analogue I/O**
Arduino Uno	**16Mhz ATmega328**	**2KB SRAM, 32KB flash**	**14**	**6 input, 0 output**
Arduino Due	**84MHz AT91SAM3X8E**	**96KB SRAM, 512KB flash**	**54**	**12 input, 2 output**
Arduino Mega	**16MHz ATmega2560**	**8KB SRAM, 256KB flash**	**54**	**16 input, 0 output**
Arduino Leonardo	**16MHz ATmega32u4**	**2.5KB SRAM, 32KB flash**	**20**	**12 input, 0 output**

Arduino Uno (R3) is a huge option for your initial Arduino. This Arduino board depends on an ATmega328P based microcontroller. As compared with other types of arduino boards, it is very simple to use like the Arduino Mega type board.

It consists of 14-digital I/O pins, where 6-pins can be used as PWM(pulse width modulation outputs), 6-analog inputs, a reset button, a power jack, a USB connection, an In-Circuit Serial Programming header (ICSP), etc. It includes everything required to hold up the microcontroller; simply attach it to a PC with the help of a USB cable and give the supply to get started with an AC-to-DC adapter or battery.

Figure 18. Arduino Uno

Arduino Uno is the most frequently used board and it is the standard form apart from all the existing Arduino Boards. This board is very useful for beginners.

Arduino Nano is a small board based on the microcontrollers like ATmega328P otherwise ATmega628 but the connection of this board is the same as to the Arduino UNO board. This kind of microcontroller board is very small in size, sustainable, flexible, and reliable.

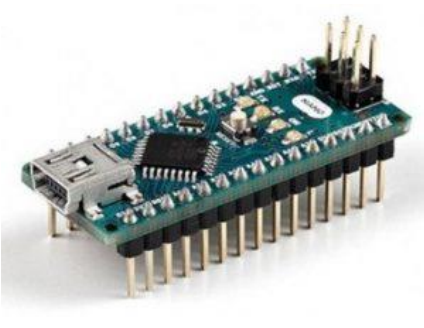

Figure 19. Arduino Nano

As compared with the Arduino Uno board, it is small in size. The devices like mini USB and Arduino IDE are necessary to build the projects. This board mainly includes analog pins-8, digital pins-14 with the set of an I/O pin, power pins-6 & RST (reset) pins-2.

The Arduino Micro board mainly depends on the ATmega32U4 based Microcontroller that includes 20-sets of pins where the 7-pins are PWM pins, 12-analog input pins.

This board includes different components like an ICSP header, RST button, small USB connection, crystal oscillator-16MHz. The USB connection is inbuilt and this board is the shrunk version of the Leonardo board**.**

Figure 20. Arduino Micro

Arduino Due depends on the ARM Cortex-M3 and it is the first Arduino microcontroller board. This board includes digital I/O pins-54 where 12-pins are PWM o/p pins, analog pins -12, UARTs-4, a CLK with 84 MHz, an USB OTG, DAC-2, a power jack, TWI-2, a JTAG header, an SPI header, two buttons for reset & erase.

Figure 21. Arduino Due

This board works with 3.3V where the highest voltage that the pins of input/output can stand is 3.3V because providing a high voltage to any I/O pin can lead to damage the board. This board is simply connected to a computer through a small USB cable otherwise it can be powered through an AC to DC adapter.

The Arduino Mega is similar to the UNO's big brother. It includes lots of digital I/O pins (from that, 14-pins can be used as PWM o/ps), 6-analog inputs, a reset button, a power jack, a USB connection, and a reset button. It includes everything required to hold up the microcontroller; simply attach it to a PC with the help of a USB cable and give the supply to get started with an AC-to-DC adapter or battery. The huge number of pins make this Arduino board very helpful for designing projects that need a bunch of digital i/ps or o/ps like lots of buttons

Figure 22. Arduino Mega (R3) Board

4.4.2 How to Select the Right Arduino Board

There are different types of Arduino boards existing in the market today such as the FreeDuino & NetDuino. The best way to select the Arduino board is by checking and differentiating the trade names on the original boards. So getting low-cost Arduino boards is easy through online sites as well as electronic stores.

These boards are available with different versions as well as specifications. The programming of all the boards can be done with the Arduino IDE software that permits anyone to write as well as upload the code, but each board varies based on the inputs, outputs, speed, form factor, voltage, etc. The voltage required to operate these boards range from 3.7V to 5V.

4.4.3 Why Arduino?

Thanks to its simple and accessible user experience, Arduino has been used in thousands of different projects and applications. The Arduino software is easy-to-use for beginners, yet flexible enough for advanced users. It runs on Mac, Windows, and Linux. Teachers and students use it to build low cost scientific instruments, to prove chemistry and physics principles, or to get started with programming and robotics. Designers and architects build interactive prototypes, musicians and artists use it for installations and to experiment with new musical instruments. Makers, of course, use it to build many of the projects exhibited at the Maker Faire, for example. Arduino is a key tool to learn new things.

Anyone - children, hobbyists, artists, programmers - can start tinkering just following the step by step instructions of a kit, or sharing ideas online with other members of the Arduino community [40].

There are many other microcontrollers and microcontroller platforms available for physical computing. Parallax Basic Stamp, Netmedia's BX-24, Phidgets, MIT's Handyboard, and many others offer similar functionality. All of these tools take the messy details of microcontroller programming and wrap it up in an easy-to-use package. Arduino also simplifies the process of working with microcontrollers, but it offers some advantage for teachers, students, and interested amateurs over other systems:

Inexpensive - Arduino boards are relatively inexpensive compared to other microcontroller platforms. The least expensive version of the Arduino module can be assembled by hand, and even the pre-assembled Arduino modules cost less than \$50

Cross-platform - The Arduino Software (IDE) runs on Windows, Macintosh OSX, and Linux operating systems. Most microcontroller systems are limited to Windows [41].

Simple, clear programming environment - The Arduino Software (IDE) is easy-to-use for beginners, yet flexible enough for advanced users to take advantage of as well. For teachers, it's conveniently based on the Processing programming environment, so students learning to program in that environment will be familiar with how the Arduino IDE works.

Open source and extensible software - The Arduino software is published as open source tools, available for extension by experienced programmers. The language can be expanded through C++ libraries, and people wanting to understand the technical details can make the leap from Arduino to the AVR-C programming language on which it's based. Similarly, you can add AVR-C code directly into your Arduino programs if you want to.

Open source and extensible hardware - The plans of the Arduino boards are published under a Creative Commons license, so experienced circuit designers can make their own version of the module, extending it and improving it. Even relatively inexperienced users can build the breadboard version of the module in order to understand how it works and save Money [42].

4.4.4 Is Arduino a Microprocessor or a Microcontroller?

Arduino isn't a microcontroller nor a microprocessor: It's a simple and easty-to-use development board that is relying on a microcontroller in it.

Microprocessor is the brain of all computing systems (such as your PC, smartphone, home assistant, blood sugar measuring device etc). It's the unit responsible for all necessary calculations which allow a system to work and produce the expected output. A Microprocessor can't work alone because it needs to receive data from other units, and this is why you'll need other parts such as registers, memory units and Input/Output ports (at least).

Microcontroller is an embedded sytem, and this means it embeds several unit in one single chip: Microprocessor + Memory units (RAM, ROM, FLASH) + Input/Ouput Ports + other peripherals (such as Analog-to-Digital Converter or Analog-Comparator or Timer etc.). Microcontrollers are special because they allow developers to build a functioning system in short time, since you don't need to chose several parts and make sure that they are compatible with each other. Again, a Microcontroller is a single chip that cannot work alone: You'll need to give it power and to have proper interface to load and flash your program into it, as well as having ways to display the processed data out of it.

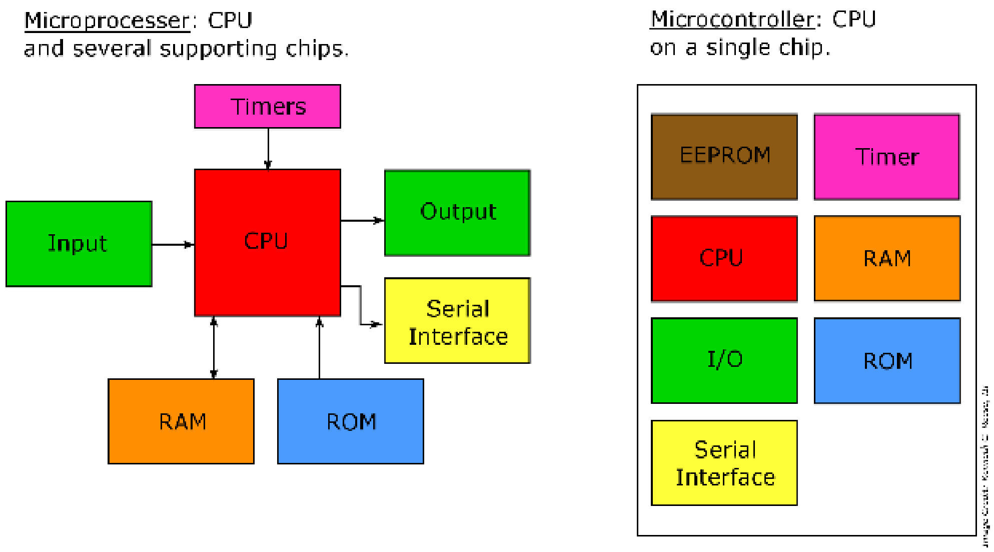

Figure 23. Comparison of controllers and processers

Development Board: Take a microcontoller (or a microprocessor) and provide it with usb-port, HDMI-port, power-input port, display unit such as Alphanumeric-LCD or other meaningful ways to display information (such as LEDs or Seven-Segment) and you'll have a development board.

Arduino is one of the most famous (and very simple) development boards and there are many versions and types of Arduinos, each of which has different capabilities in terms of computing characteristics (type of microcontroller, size of memories, max. clock speed…) as well as interface functionalities (usb, hdmi, ethernet, number of Input/Output ports, LCD, LEDs).

In short, using development boards will allow you to start testing your projects and ideas in a very fast way, but it also have a downside which the limitation with the already available hardware inside it.

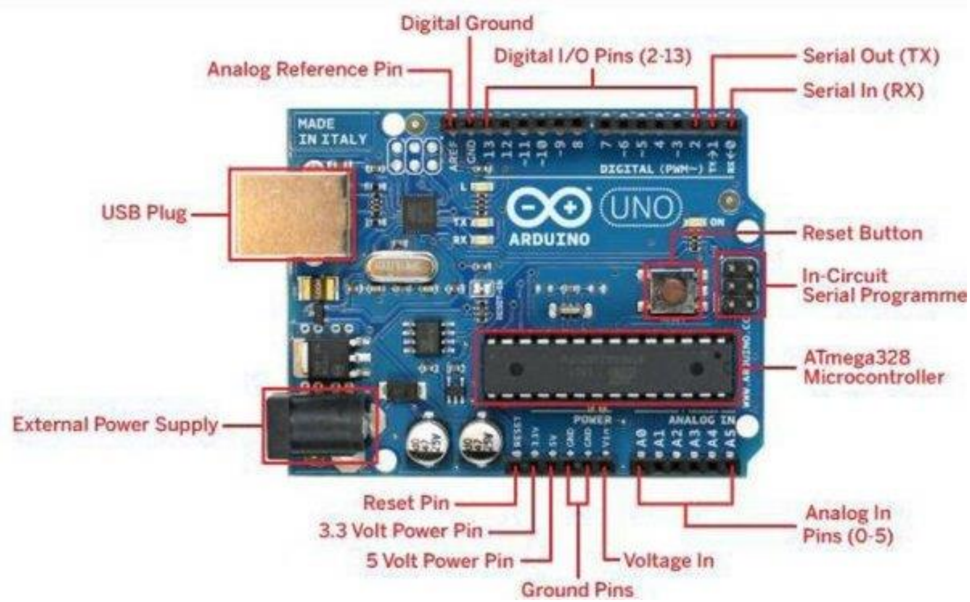

Figure 24. Structure of an Arduino board

5. DESIGN OF THE BATTERY MANAGEMENT SYSTEM

5.1 One Switched Capacitor

Table 4. Comparison of different BMS methods

	Switched transformer	**Shared transformer**	**Multiple switched capacitors**	**One switched capacitor**
Balancing speed	High	High	Low	Middle
Control	-	-	-	High
Cost	High	High	Middle	Low
Ease of supply	Low	Low	High	High
Reliability	High	High	Middle	High

One switched capacitor is an active balancing method. As seen in the figure 25 one switched capacitor method consists of set of switches and one capacitor. The working principle is based on high voltage cell charging the capacitor and then capacitor discharging to low voltage cell. This method ensures that energy is transferred with minimum amount of loss.

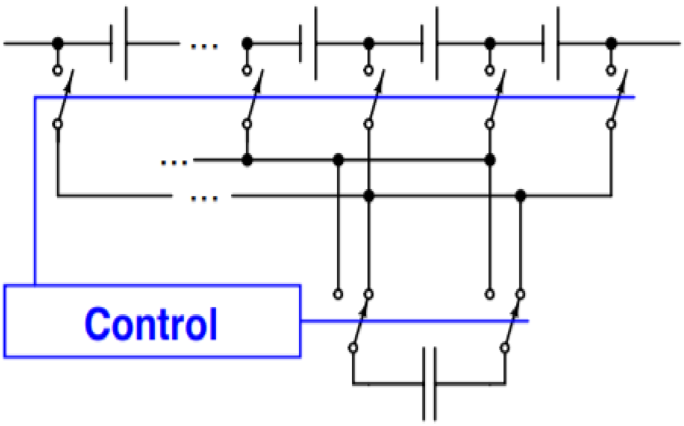

Figure 25. One switched capacitor method.

5.2. Synthesis Topology

There are central and distributed BMS topologies. The design has features of both of such topologies. All sensor values are directly sent to Arduino Uno which is related with the central topology. However, Arduino Uno controls balancing PCBs separately which is in distributed topology. Resulting topology is named as the synthesis topology and given in the figure.

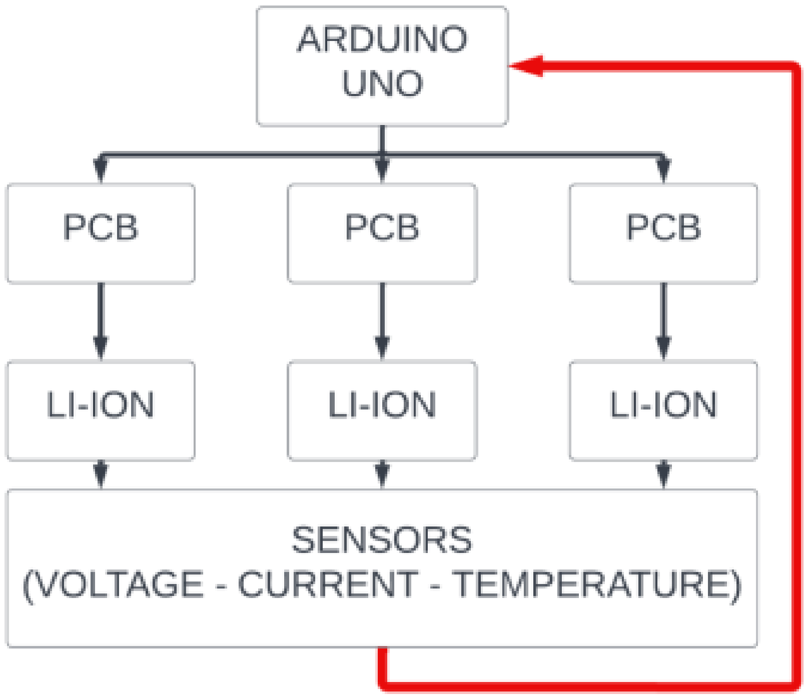

Figure 26. Sythesis topology

5.3.State of Charge

State of charge represents how much energy does a cell or a battery has left in percentage. There are various methods to calculate or estimate state of charge. Depending on the battery type, methods differ.

Since Li-ion cells are used in the design, Coulomb Counting method is used to estimate state of charge. Because of the fact that, charge and discharge curve of Li-ion cells are not linear, as given in the figure, it is not possible to estimate state of charge with only using voltage value. Even if it is calculated, there are huge amounts of error.

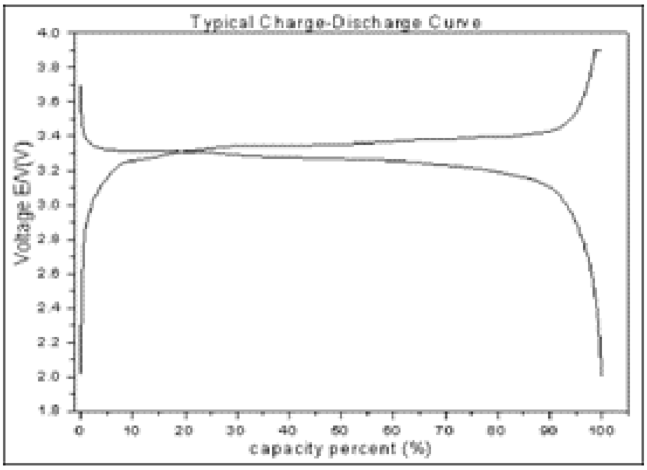

Figure 27. Li-Ion charge discharge curve

In Coulomb counting method, current value is multiplied with time interval to obtain Ah value. Later, addition of spent Ah values are subtracted from the total Ah capacity of the battery. Lastly, left Ah value is turned into a percentage as SoC.

$$SoC(t) = SoC(t-1) + \frac{I(t)}{Q_n}\Delta t \qquad (1)$$

SoC(t-1) = SoC at previous time step

η = efficiency

t = current time step

t-1 = previous time step

Q = Charge capacity of the battery

5.4 PCB Design

BMS is designed for 3 18650 Li-ion batteries in series. As given in the figure about synthesis topology sensors read voltage, current and temperature values. Sensor values are sent to microcontroller which is chosen to be Arduino Uno. Microcontroller calculates and estimates further values from voltage, current and temperature. Other than that, Arduino also runs such code capable of both deciding whether balancing is activated or not and performing required switching operations for balancing.

5.4.1. Sensors

As mentioned before, sensors provide voltage, current and temperature values. For temperature, the design has DS18B20 sensors included. DS18B20 is connected to digital input of the Arduino Uno with a pull-up resistor of 4.7k Ω as given in the figure and uses one wire communication protocol.

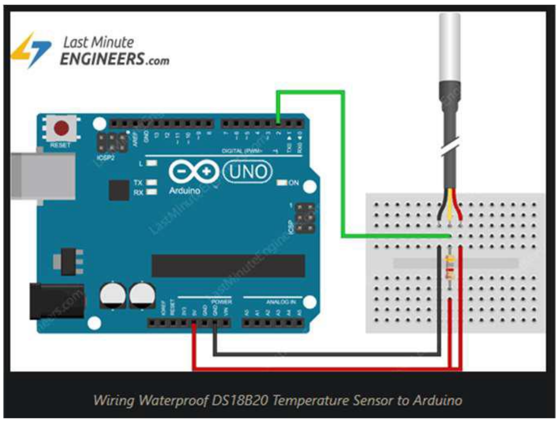

Figure 28. DS18B20 temperature sensor

MAX471 is used for the current sensor. MAX471 is bidirectional and it has 35m Ω current-sense resistor which is capable of measuring ±3A. MAX471 is chosen over ACS712 since it provides better accuracy.

Figure 29. MAX471 current sensor

There are no voltage sensors in the design. Voltage values of three 18650 Li-ion cells are measured using analog inputs of the Arduino Uno. Arduino is capable of measuring direct voltages up to 5V. Voltage values of cells are divided using specific resistor values as voltage dividers to make analog input of the Arduino less then 5V as seen in the figure. Later, voltage values are calculated using resistor values in the code.

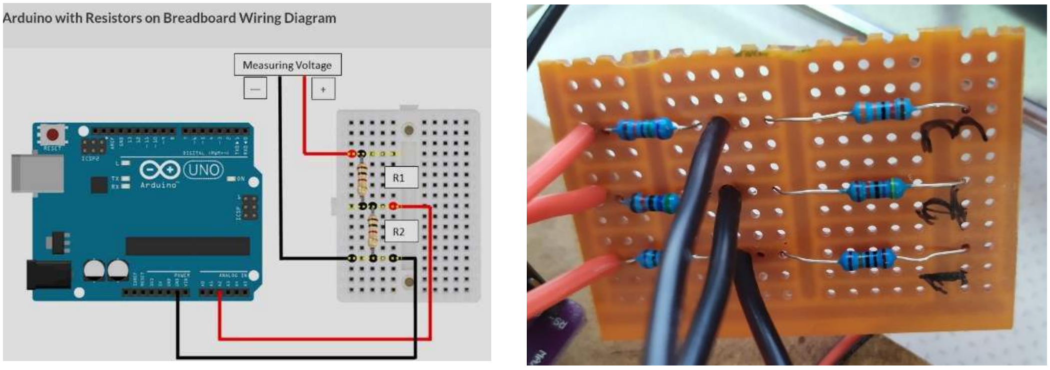

Figure 30. Voltage dividers for voltage measurement

Since common ground is needed while measuring voltages of 3 cells and Arduino Uno is able to measure voltages up to 5V. Such circuitry given in the figure is done to make each voltage less than 5V. Calculation of voltage values from analog inputs are given in the code.

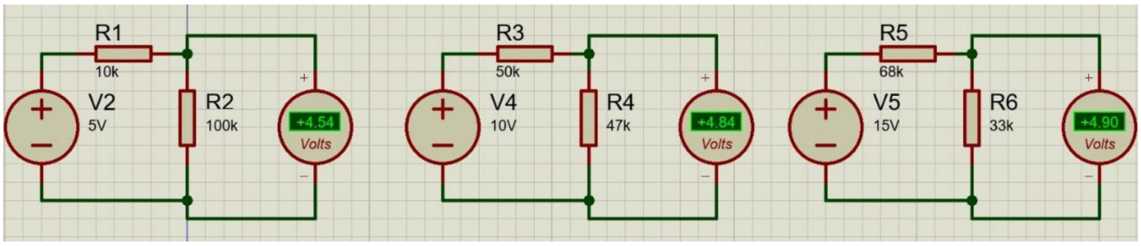

Figure 31. Voltage divider circuit desing in proteus

5.4.2. Relays

Three types of relays are used in the BMS. A 5V, mechanical and normally closed relay is used to open and close the contact of battery with the system during balancing and in case of an emergency.

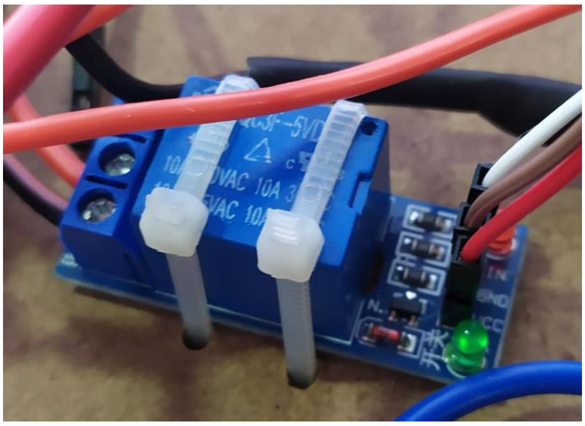

Figure 32. 5 V mechanical emergency relay

Other than that, six 5V SPDT relays are used in the balancing part where it is indicated which cells are going to be balanced among three 18650s.

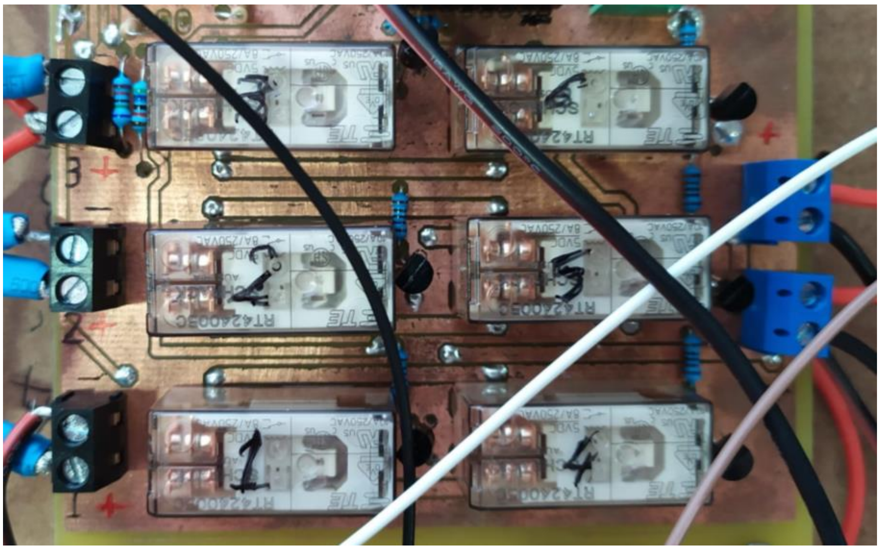

Figure 33. 5V mechanical SPDT Relays

For the last, there are four AQZ205 solid state relays. They form 2 SPDT relays for switching the one switched capacitor between two cells that are chosen to be balanced. Solid state relays are used since they provide significantly high switching speed.

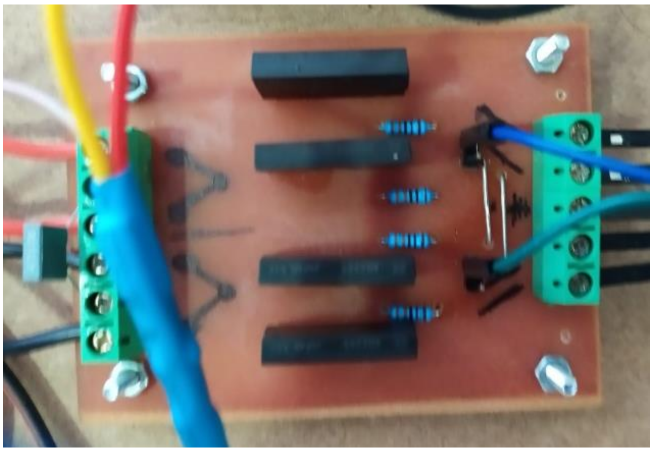

Figure 34. 4 solid state SPST relays that are forming two SPDT relays

5.4.3. Transistors

Since there are many relays used in both balancing and other parts of the circuit. Relay driver circuits consist of 2N2222 bipolar junction transistors that are equipped with 1N4002 flyback diodes. 5V is obtained from the voltage regulator that is connected to plug so that Arduino only provides signal output for all relays.

5.5 Circuit

A circuit is designed to charge, discharge and balance three Li-ion cells so that it is possible to demonstrate voltage, current and temperature measurements and calculations and estimations on SoC. Also, balancing is performed with designed PCBs.

Control of charging and discharging is done manually since it will be suitable to demonstrate functions of the BMS in short time.

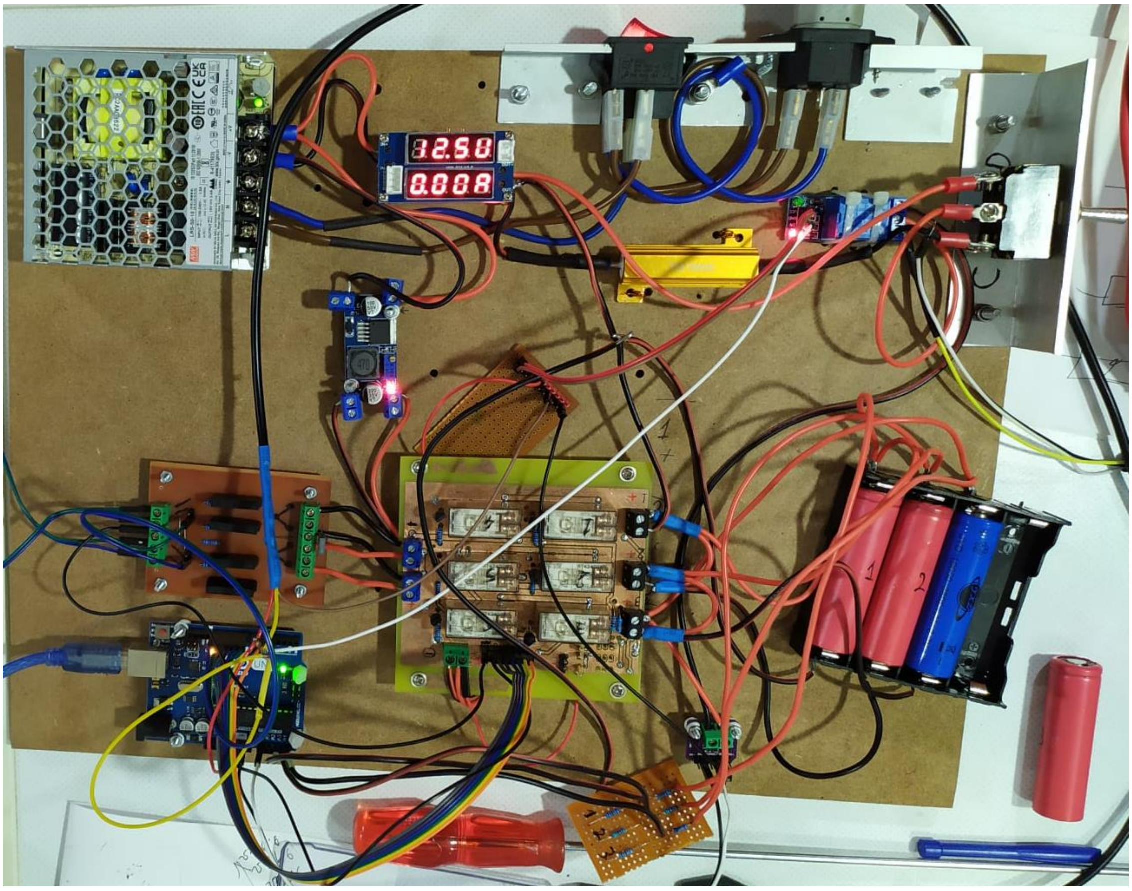

Figure 35. Overall circuitry

5.5.1 Charging

Charging is done using voltage regulators given in the figure, that are enabled to make voltage and current limiting. When it is manually switched, the circuit starts charging Li-ion cells. 12.5V and 5V outputs are provided for charging and mechanical relays respectively.

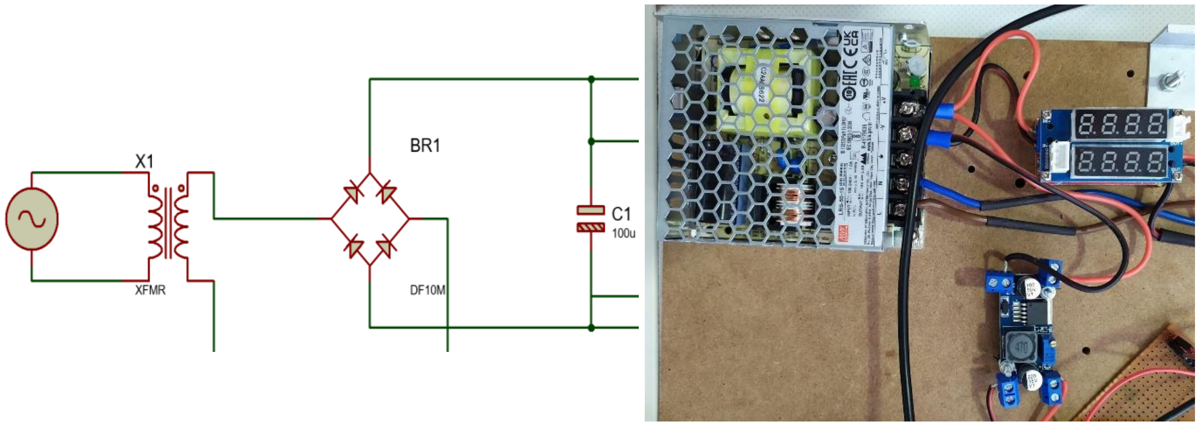

Figure 36. Charging circuit desing and voltage regulators in charging circuit

5.5.2 Discharging

Discharging of 12.6V Li-ion battery that consists of 3 Li-ion cells in series, is done using 8.2 Ω and 50W resistor given in the figure. Even though it is possible to increase current in the designed circuit, 1.43A of current is enough to simulate SoC estimation method using Coulomb counting. Also increasing current causes temperature of the load resistor to increase. Therefore, discharging current is decided to be 1.43A just in case of any accidents which may occur related with the high temperature.

Figure 37. High watt resistor in discharge circuit

5.5.3 Balancing

As it is already mentioned in the paper, one switched capacitor method is applied in the BMS. Two cells with the maximum amount of voltage difference are chosen and transferred into the part where solid states switch the capacitor frequently between two cells.

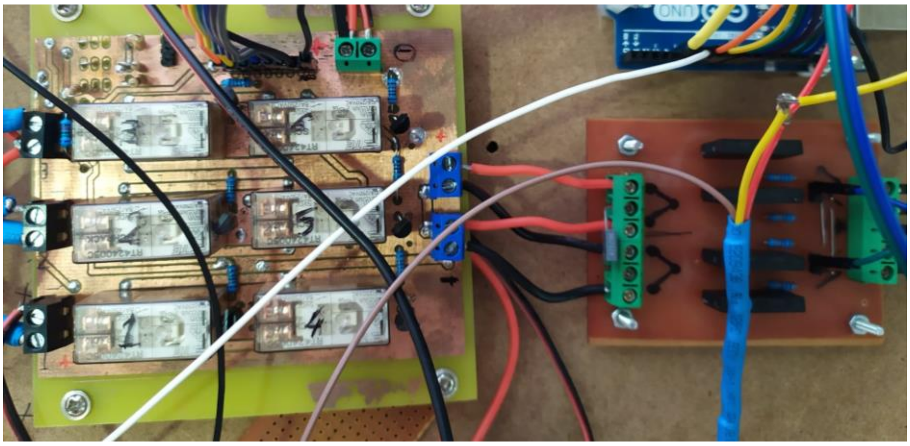

Figure 38. Balancing Circuit

In Figure 39, charge and discharge graph of the balancing capacitor is given. By evaluating the voltage and current formulas of a capacitor, required values are determined.

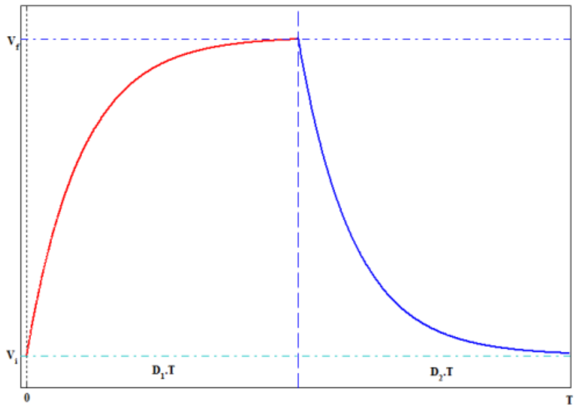

Figure 39. charge and discharge graph of the balancing capacitor [43].

$$V_{c_{charging}} = (V_f - V_i)\left(1 - e^{\frac{-t}{\tau}}\right) + V_i \qquad (2)\ [43]$$

$$= V_{diff}\left(1 - e^{\frac{-t}{\tau}}\right) + V_i$$

$$i_c = C\frac{dVc}{dt} = C\frac{1}{\tau}.Vd_{iff}.e^{\frac{-t}{\tau}} = \frac{V\,diff}{Rs}.e^{\frac{-t}{\tau}} \qquad (3)\ [43]$$

$$\text{Energy Charging}= C.V_{diff}\left\{\frac{V_{diff}}{2}.e^{\frac{2D}{\tau.F}} - V_f.e^{\frac{-D}{\tau.F}} - \frac{V_{diff}}{2} + V_f\right\} * F \text{ (Wh/h) (4) [43]}$$

$$\text{Energy Discharging}= C.V_{diff}\left\{\frac{V_{diff}}{2}.e^{\frac{-2D}{\tau.F}} - V_i.e^{\frac{-D}{\tau.F}} - \frac{V_{diff}}{2} - V_i\right\} * F \text{ (Wh/h) (5) [43].}$$

Figure 39 shows the amount of energy capacitor can be charged and discharged on various values of duty cycle. The duty cycle refers to the amount of time a signal is on during a given period. Therefore, decision of providing 0.9 of the periods for the charging process will result leaving only 0.1 for the discharging process which will cause capacitor to not fully discharge its energy into the low voltage cell during balancing. Because of that, even though energy transferred seem to increase with the duty cycle, due to the fundamentals of the term of duty cycle, 0.5 gives the best results for energy transfer during balancing.

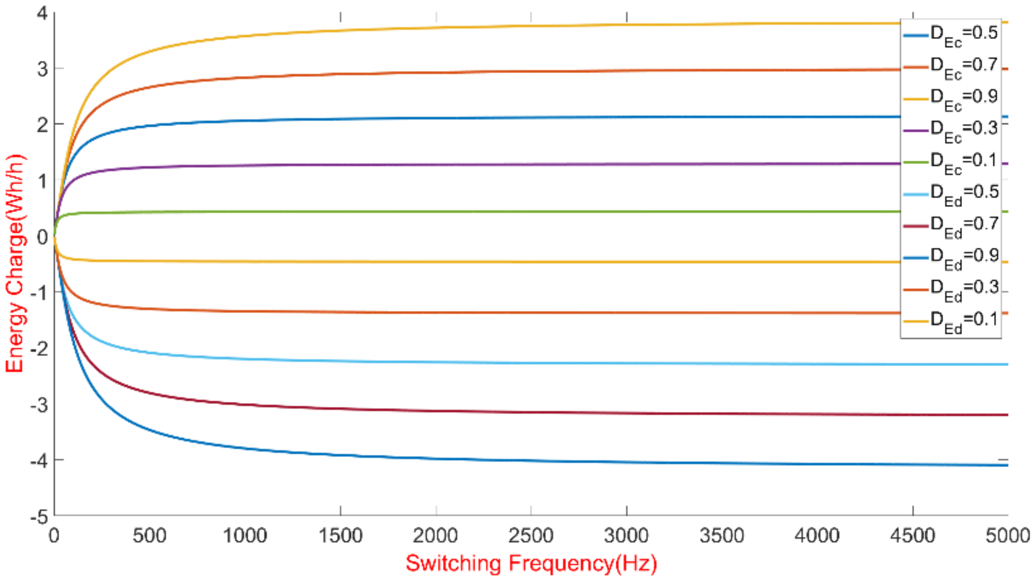

Figure 40. Energy Charge & Discharge Graph Depends on Duty Cycle

Figure 40 also states that increasing switching frequency over 500 Hz does not provide a significant difference in terms of the amount of energy transferred between cells and the capacitor. Therefore, switching frequency is chosen to be 500 Hz.

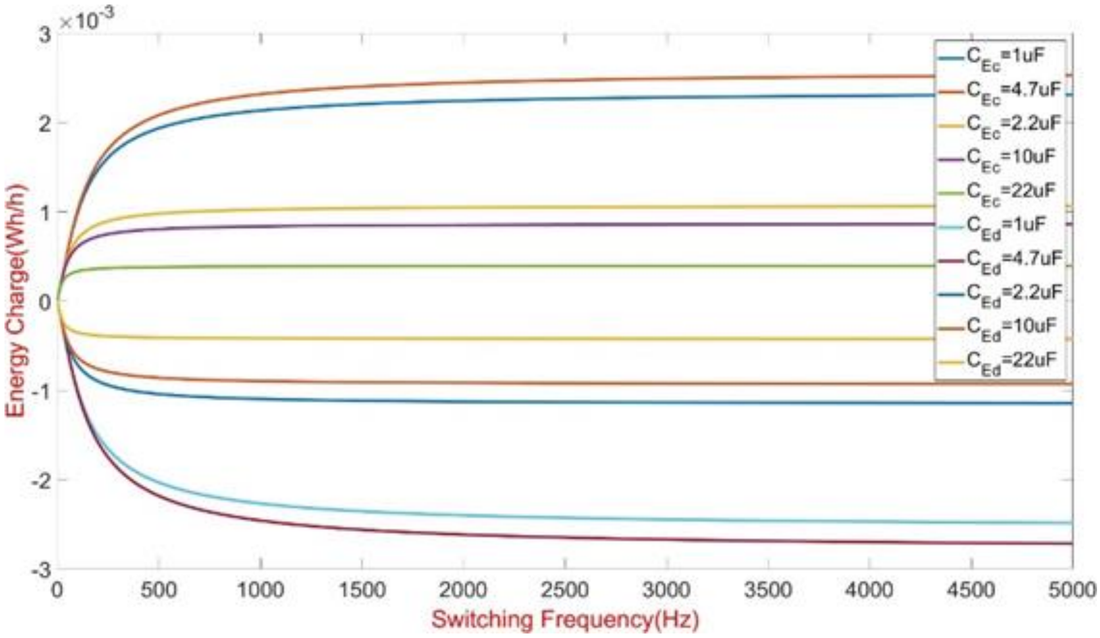

Figure 41. Capacitor Comparison

Based on the capacitor values already existing on the market, such graphs are drawn by only changing the capacitor value as shown in the Figure 41. Since the duty cycle is determined as 0.5 and switching frequency is 500 Hz, those graphs are obtained to determine the best capacitor value capacitor value as 4.7 µF for the most amount of energy transfer.

5.6 Software

5.6.1 Arduino Code

```
//Libraries required for temperature sensor are added.
#include <OneWire.h>
#include <DallasTemperature.h>
//Temperature sensor pin and variable defined.
#define ONE_WIRE_BUS 4
float T = 0;
OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature sensors(&oneWire);

//Digital pins controlling relays are named.
int R1 = 6;
int R2 = 7;
int R3 = 8;
int R4 = 9;
int R5 = 10;
```

```
int R6 = 11;
int HB_to_Cap = 12;
int Cap_to_LB = 13;
int Role_pin = 5;

//Global variables of SoC calculation are defined.
int lastTime1 = 0;
int nowTime1 = 0;
long T_diff = 0;
double total_Ah = 0;
double Cap_Ah = 3.3;
double I_amp1 = 0;
double SoC;

//Resistor values for voltage calculation are defined.
float r3 = 9.98;
float r4 = 98.6;
float r22 = 56.0;
float r21 = 46.5;
float r24 = 76.4;
float r23 = 32.6;

//Voltage values are defined.
float V_volt_1 = 0;
float V_volt_2 = 0;
float V_volt_3 = 0;

//Global values for balancing are defined.
int max_cell = 0;
int min_cell = 0;
float max_volt = 0;
float min_volt = 0;
int denge_cycle_no = 10000;
bool balance_ok = 1;

//Void setup is run once at the beginning.
void setup() {
  //Baudrate is given.
  Serial.begin(112500);

  //All digital pins are set whether they are inputs or outputs.
  pinMode(2, OUTPUT);
  pinMode(3, OUTPUT);
  pinMode(4, INPUT);
  pinMode(5, OUTPUT);
  pinMode(6, OUTPUT);
  pinMode(7, OUTPUT);
```

```
  pinMode(8, OUTPUT);
  pinMode(9, OUTPUT);
  pinMode(10, OUTPUT);
  pinMode(11, OUTPUT);
  pinMode(12, OUTPUT);
  pinMode(13, OUTPUT);

  //Initial values if the relays are set to LOW except emergency relay to prevent any short circuits between cells.
  digitalWrite(R1, LOW);
  digitalWrite(R2, LOW);
  digitalWrite(R3, LOW);
  digitalWrite(R4, LOW);
  digitalWrite(R5, LOW);
  digitalWrite(R6, LOW);
  digitalWrite(HB_to_Cap, LOW);
  digitalWrite(Cap_to_LB, LOW);
  digitalWrite(Role_pin, HIGH);
}

//A function to disconnect batteries.
void All_BATT_Disconnect (){
  digitalWrite(R1, LOW);
  digitalWrite(R2, LOW);
  digitalWrite(R3, LOW);
  delay(200);
  digitalWrite(R4, LOW);
  digitalWrite(R5, LOW);
  digitalWrite(R6, LOW);
  delay(200);
}

//A function to choose B1 and B2.
void BATT1_to_BATT2_contact (){
  All_BATT_Disconnect();
  digitalWrite(R4, HIGH);
  digitalWrite(R5, LOW);
  digitalWrite(R6, LOW);
  delay(200);
  digitalWrite(R1, HIGH);
  digitalWrite(R2, HIGH);
  digitalWrite(R3, LOW);
  delay(200);
}

//A function to choose B1 and B3.
void BATT1_to_BATT3_contact (){
```

```
  All_BATT_Disconnect();
  digitalWrite(R4, HIGH);
  digitalWrite(R5, LOW);
  digitalWrite(R6, LOW);
  delay(200);
  digitalWrite(R1, HIGH);
  digitalWrite(R2, LOW);
  digitalWrite(R3, HIGH);
  delay(200);
}

//A function to choose B2 and B3.
void BATT2_to_BATT3_contact (){
  All_BATT_Disconnect();
  digitalWrite(R4, LOW);
  digitalWrite(R5, HIGH);
  digitalWrite(R6, LOW);
  delay(200);
  digitalWrite(R1, LOW);
  digitalWrite(R2, HIGH);
  digitalWrite(R3, HIGH);
  delay(200);
}

//A function to balance two chosen cells.
void Dengele (int Count){
  Serial.print(" BALANCING= ");
  Serial.print(max_cell);
  Serial.print(" - ");
  Serial.print(min_cell);
  Serial.print("| ");
  int i = 0;
  while (i < Count)
  {
    digitalWrite(HB_to_Cap, HIGH);
    //AQZ205 Turn on time 5.8 ms
    delay(6);
    //Full Battery => Capacitor
    delay(2);
    digitalWrite(HB_to_Cap, LOW);
    //AQZ205 Turn off time 0.2 ms
    delay(1);
    digitalWrite(Cap_to_LB, HIGH);
    //AQZ205 Turn on time 5.8 ms
    delay(6);
    //Capacitor => Low Battery
    delay(2);
```

```
    digitalWrite(Cap_to_LB, LOW);
    //AQZ205 Turn off time 0.2 ms
    delay(1);

    i++;
  }
    //Solid state relays are left LOW to prevent short circuit.
    digitalWrite(Cap_to_LB, LOW);
    digitalWrite(HB_to_Cap, LOW);
}

//A function to read and print voltage values of 3 Li-ions cells.
void BATT_V_oku() {
  //Local raw analog sensor values are defined.
  int V_raw_sensor_value_1 = 0;
  int V_raw_sensor_value_2 = 0;
  int V_raw_sensor_value_3 = 0;

  float V_temp_1 = 0;
  float V_temp_2 = 0;
  float V_temp_3 = 0;

  //Analog values are read.
  V_raw_sensor_value_1 = analogRead(A3);
  V_raw_sensor_value_2 = analogRead(A4);
  V_raw_sensor_value_3 = analogRead(A5);

  //Voltage values are calculated considering each resistance value.
  V_temp_1 = (V_raw_sensor_value_1 * 5.0) / 1023.0;
  V_volt_1 = V_temp_1 / (r4/(r3+r4));

  V_temp_2 = (V_raw_sensor_value_2 * 5.0) / 1023.0;
  V_volt_2 = V_temp_2 / (r21/(r22+r21));

  V_temp_3 = (V_raw_sensor_value_3 * 5.0) / 1023.0;
  V_volt_3 = V_temp_3 / (r23/(r24+r23));

  V_volt_2 = V_volt_2 - V_volt_1;
  V_volt_3 = V_volt_3 - V_volt_2 - V_volt_1;

  //Voltage values are printed.
  Serial.print(" V1= ");
  Serial.print(V_volt_1);
  Serial.print("| ");

  Serial.print(" V2= ");
  Serial.print(V_volt_2);
```

```
  Serial.print("| ");

  Serial.print(" V3= ");
  Serial.print(V_volt_3);
  Serial.print("| ");
}

//A function to read and print current value.
void BATT_I_oku() {
  //Local raw analog sensor value is defined.
  int I_raw_sensor_value_1 = 0;
  //Analog value is read.
  I_raw_sensor_value_1 = analogRead(A0);
  //Current value in A is calculated
  //considering the output of MAX471.
  I_amp1 = I_raw_sensor_value_1 * (5.0 / 1023.0);

  //Current values are digitally filtered.
  if(I_amp1 < 0.03){
    I_amp1 = 0;
  }

  //Millisecond value is taken to be used in SoC calculation.
  nowTime1 = millis();
  //Considering the differentiation of the main loop,
  //time difference is taken into account.
  T_diff = nowTime1 - lastTime1;
  lastTime1 = nowTime1;

  //Millisecond is converted into hours.
  double T_diff_sec = (float)T_diff / 1000;
  double T_diff_min = T_diff_sec / 60;
  double T_diff_h = T_diff_min / 60;

  //Ah spent in each measurement is calculated.
  double Ah = T_diff_h * I_amp1;
  //Ah spent is added in each loop.
  total_Ah += Ah;
  //State of Charge is calculated using
  //total and spent Ah values.
  SoC = (Cap_Ah - total_Ah) / Cap_Ah * 100;

  //Printing current value in Amperes.
  Serial.print(" I= ");
  Serial.print(I_amp1);
  Serial.print("| ");
```

```
  //Printing SoC value in percentage.
  Serial.print(" SoC = ");
  Serial.print(" %");
  Serial.print(SoC, 6);
  Serial.print("| ");
}

//A function to read and print temperature value.
void BATT_T_oku() {
  //Sensor value is read.
  sensors.requestTemperatures();
  T = sensors.getTempCByIndex(0);

  //Sensor value is printed.
  Serial.print(" T= ");
  Serial.print(T);
  Serial.println("| ");
}

//A funtion to find max and min voltage cells.
void min_max_cell_bul(){
  max_cell = 0;
  min_cell = 0;

  max_cell = 1;
  min_cell = 1;

  max_volt = V_volt_1;
  min_volt = V_volt_1;

  if(V_volt_2 < min_volt){
    min_volt = V_volt_2;
    min_cell = 2;
  }

  if(V_volt_3 < min_volt){
    min_volt = V_volt_3;
    min_cell = 3;
  }

  if(V_volt_2 > max_volt){
    max_volt = V_volt_2;
    max_cell = 2;
  }

  if(V_volt_3 > max_volt){
    max_volt = V_volt_3;
```

```
    max_cell = 3;
  }
}

//A function to change balance_ok flag.
//balance_ok flag exists to prevent
//balancing in not ordinary conditions.
void balance_check(){
  if(V_volt_1 < 3 || V_volt_1 > 4.5 || V_volt_2 < 3 || V_volt_2 > 4.5 ||
V_volt_3 < 3 || V_volt_3 > 4.5){
    balance_ok = 0;
  }
}

//-MAIN-LOOP-
void loop() {
  //Flag is refreshed.
  balance_ok = 1;

  //Voltage values are read.
  BATT_V_oku();

  //Flag is updated.
  balance_check();

  //Current value is read.
  BATT_I_oku();

  //Temperature value is read.
  BATT_T_oku();

  //Max and min cells are found.
  min_max_cell_bul();

  //If balance_ok flag is one and voltage difference is larger than 0.3,
  //balancing is done between chosen max and min cells.
  if(max_volt - min_volt > 0.3 && balance_ok == 1){
    switch (max_cell) {
      case 1:
          switch (min_cell)
          {
          case 2:
          BATT1_to_BATT2_contact();
          Dengele(denge_cycle_no);
          break;

          case 3:
```

```
        BATT1_to_BATT3_contact();
        Dengele(denge_cycle_no);
        break;

        default:
        break;
        }
    break;

    case 2:
        switch (min_cell)
        {
        case 1:
        BATT1_to_BATT2_contact();
        Dengele(denge_cycle_no);
        break;

        case 3:
        BATT2_to_BATT3_contact();
        Dengele(denge_cycle_no);
        break;

        default:
        break;
        }
    break;

    case 3:
        switch (min_cell)
        {
        case 1:
        BATT1_to_BATT3_contact();
        Dengele(denge_cycle_no);
        break;

        case 2:
        BATT2_to_BATT3_contact();
        Dengele(denge_cycle_no);
        break;

        default:
        break;
        }
    break;

    default:
    break;
```

```
    }
  }

  //A string named Interface which consists of measured and processed
variables,
  //is formed to send values to the personal computer for interface.
  Interface = "|V1=" + String(V_volt_1,6) + "|V2=" + String(V_volt_2,6) +
"|V3=" + String(V_volt_3,6) + "|I=" + String(I_amp1,6) + "|SoC"
String(I_amp1,6) +  "|T=" + String(T,6) );
  Serial.println(Interface);
}
```

5.6.2 Output

Arduino Uno is connected to a personal computer with a USB cable. It sends data using serial monitor. Sent data is a line where V1, V2, V3, I, SoC, T values along with the information whether balancing is happening or not are placed. If microcontroller decides to do balancing it also indicates balancing is done between which cells. The output examples are given below.

```
20:10:20.827 -> V1= 3.92| V2= 3.88| V3= 3.92| I= 1.40| SoC = %99.368370| T= 28.25|
20:10:21.473 -> V1= 3.92| V2= 3.88| V3= 3.92| I= 1.40| SoC = %99.360969| T= 28.19|
20:10:22.106 -> V1= 3.92| V2= 3.88| V3= 3.92| I= 1.40| SoC = %99.353584| T= 28.19|
20:10:22.712 -> V1= 3.92| V2= 3.88| V3= 3.92| I= 1.40| SoC = %99.346199| T= 28.19|
20:10:23.357 -> V1= 3.92| V2= 3.88| V3= 3.92| I= 1.40| SoC = %99.338806| T= 28.12|
20:10:23.989 -> V1= 3.92| V2= 3.88| V3= 3.90| I= 1.40| SoC = %99.331436| T= 28.12|
20:10:24.620 -> V1= 3.92| V2= 3.87| V3= 3.93| I= 1.40| SoC = %99.324035| T= 28.12|
20:10:25.253 -> V1= 3.92| V2= 3.88| V3= 3.92| I= 1.40| SoC = %99.316658| T= 28.12|
20:10:25.840 -> V1= 3.92| V2= 3.88| V3= 3.92| I= 1.38| SoC = %99.309364| T= 28.06|
20:10:26.487 -> V1= 3.92| V2= 3.88| V3= 3.92| I= 1.39| SoC = %99.302055| T= 28.06|
20:10:27.120 -> V1= 3.92| V2= 3.88| V3= 3.92| I= 1.39| SoC = %99.294700| T= 28.06|
20:10:27.754 -> V1= 3.92| V2= 3.88| V3= 3.92| I= 1.39| SoC = %99.287376| T= 28.06|
20:10:28.342 -> V1= 3.92| V2= 3.88| V3= 3.92| I= 1.39| SoC = %99.280067| T= 28.06|
20:10:28.991 -> V1= 4.03| V2= 4.04| V3= 4.04| I= 0.00| SoC = %99.280067| T= 28.00|
20:10:29.637 -> V1= 4.03| V2= 4.05| V3= 4.03| I= 0.00| SoC = %99.280067| T= 28.00|
```

Figure 42. Serial monitor of arduino

5.6.3 Interface

A line of information which is sent to the personal computer using serial port connection, is transformed into a string by Arduino Uno. Another program written in Visual Basic divides given string into subgroups and assign values into variables to later display them in a designed interface. Those variables are stored in a database in SQL.

Designed interface is given in the figure. There are bars for temperature values between 0 and 50. Gauge panels show the SoC value of Li-ion cells. For the last, there are graphs for voltage and current values under the panels.

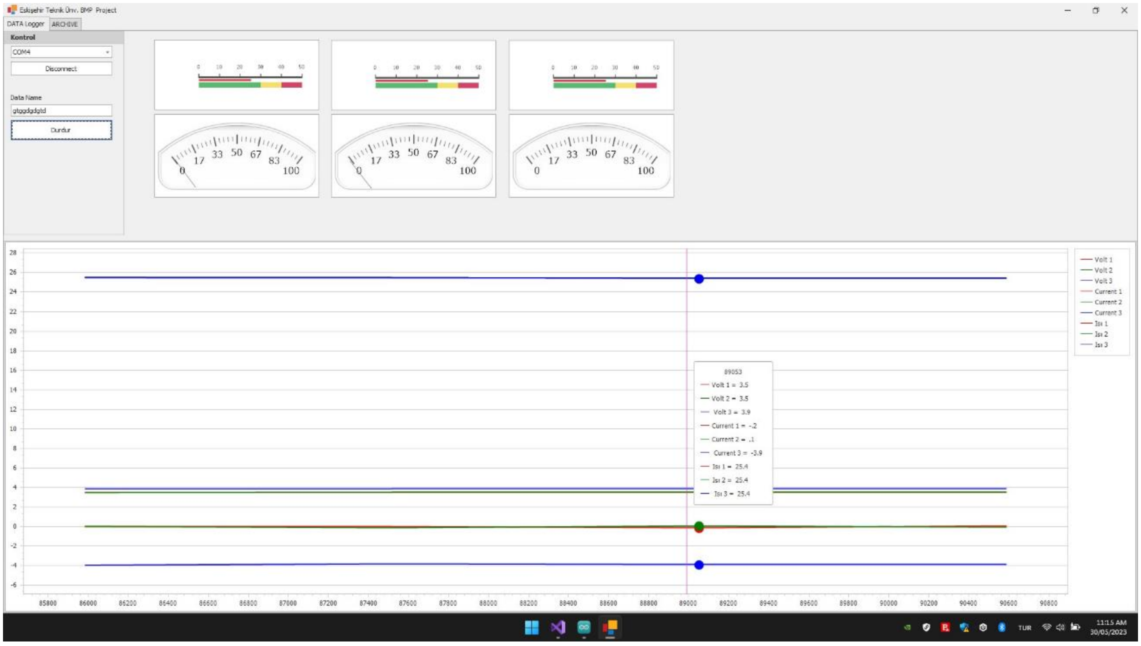

Figure 43. Interface

6. CONCLUSION

The major subject of this study is BMS, which is subdivided into active and passive techniques. In the sector, passive balancing is more prevalent. However, active balancing is more suitable for high-voltage applications and electric vehicle technologies. The main objectives of this paper are to develop this method, to provide know-how for the sector, and to boost energy efficiency in many common technological fields. Active balancing techniques are classified into two groups. Capacitive methods, the ones utilized in this study, use capacitors as the primary equipment while inductive methods focus on using transformers for balance. Additionally, there are various branches for capacitive methods. One switched capacitor technique involves connecting a capacitor to each neighbouring cell, and balancing is done by providing energy transfer between neighbouring cells. It benefits from being more dependable, less expensive, easy to control, and easy to execute. Numerous topologies may be used in the design of the battery management system. This work aims to balance at the cell level as well as use Arduino to cell measurement. Therefore, a synthesis of distributed topology and centralized topology is preferred. In this new synthesis topology, Arduino is planned to be used as the master board as it is suitable for sensor fusion, interface creation and application of different algorithms. Unlike the distributed topology, the current, voltage and temperature data from the cells will be transferred to the Arduino via the sensors and will be processed and interpreted there. Since the discharge voltage curve of Li-Ion batteries is relatively more linear than other battery types, it was decided to use coulomb counting instead of voltage measurement as a method of determining the state of charge to obtain more reliable SoC data.

For the types of sensors to be used; determined as voltage, current and temperature sensors. Decision of temperature sensor is made in favor of DS18B20. Arduino Uno is able to measure voltage values up to 5 Volts. For this reason, it is possible to use Arduino Uno itself along with a passive circuitry for voltage measurement. For current sensors, after a long consideration, it is decided to use MAX471. It is currently the most reachable current sensor in the market and its specifications are suitable for such BMS.

Also, a 5V relay is planned to be used to separate load from the battery in emergencies such as batteries overheating, current values increasing more than expected due to a short circuit and measuring unexpected high voltage values in Li-Ion cells during charging or discharging processes.

The most suitable switching frequency, capacitor and duty cycle values are determined by implementing capacitor charge and discharge equations on MATLAB to obtain better performance in the active balancing part of the BMS circuit. It is aimed to maximize the amount of energy transferred between high and low voltage cells using the capacitor. Later, such values are placed on electrical and electronic components in Proteus with the aim of designing a BMS with active balancing topology.

Finally, an active balancing BMS with one switched capacitor method within a synthesis topology is implemented using Arduino Uno, MAX471 current sensors, DS18B20 temperature sensors, and a 5V relay. Balancing PCBs with one switched capacitor method are designed and implemented to work with digital outputs of Arduino. Then, display is derived to show SoC, voltage, temperature, and current values of all cells.

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