DEVELOPMENT OF CELL-TO-CELL BALANCING CIRCUIT FOR LITHIUM-ION BATTERIES

WONG WEI JUN

UNIVERSITI TUNKU ABDUL RAHMAN

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Electrical and Electronic Engineering with Honours

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

May 2024

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature :

Name : Wong Wei Jun

ID No. : 1902895

Date : 17 May 2024

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DEVELOPMENT OF CELL-TO-CELL BALANCING CIRCUIT FOR LITHIUM-ION BATTERIES"** was prepared by **WONG WEI JUN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Electrical and Electronic Engineering with Honours at Universiti Tunku Abdul Rahman.

Approved by,

Signature : ______________________

Supervisor : Dr Hau Lee Cheun

Date : 17 May 2024

Signature : ______________________

Co-Supervisor : Ts Dr Chew Kuew Wai

Date : 17 May 2024

ABSTRACT

This study provides a thorough investigation into the design and evaluation of a single switch capacitor active balancer prototype designed for lithium-ion batteries. Additionally, it explores both hardware testing and software simulations, with the main goal of examining its effectiveness in different operational modes, such as stationary, charging, and discharging conditions. The hardware evaluation revealed promising results of approximately 80% and 30% improvement compared to situations without balancer during the stationary and charging phases to demonstrate significant balancing effects, indicating that the prototype can reduce voltage variations between cells to 0.1 V. On the other hand, the balancer's performance showed clear limitations when discharging, indicating a gap in its effectiveness under operating circumstances between charging and discharging conditions. Software simulations, on the other hand, generated more promising results, suggesting possible capability under all three circumstances and evaluating balancing efficiency using indicators like standard deviation and percentage difference. Interestingly, more comparison with prototypes created by other final year project students showed a repeated trend in which balancers primarily demonstrated their effectiveness only in the stationary and charging phases, similar to the difficulties in getting stable balancing performance over a battery's lifetime.

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LIST OF SYMBOLS / ABBREVIATIONS

AC-DC	Alternating Current to Direct Current
ACTC	Adjacent Cell to Cell
Arduino IDE	Arduino Integrated Development Environment
BMS	Battery Management System
CC	Coulomb Counting
COM	Common
CTP	back pressure, kPa
CTPTC	Cell To Pack to Cell
DCTC	Direct Cell to Cell
DC-DC	Direct Current to Direct Current
ICSP header	In-Circuit Serial Programming
LC Converter	Inductor-Capacitor Converter
LED	Light Emitting Diode
NO	Normally Opened
MCU	Microcontroller Unit
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
PCB	Printed Circuit Board
PTC	Pack to Cell
PWM	Pulse Width Modulation
SOC	State of Charge
USB	Universal Serial Bus
VRLA Battery	Valve-Regulated Lead-Acid Battery

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Batteries are energy storage device that able to convert chemical energy to electrical energy through chemical reaction. After connecting the battery through an external circuit, chemical reactions will happen inside the battery and trigger the chemical reaction to cause the electrons flow. The flow of electrons due to the chemical reaction produce electric current and therefore the conversion of chemical energy to electrical energy. Different combination of electrodes and electrolytes produce different chemical reaction and how much energy can be stored and also determine whether the battery is rechargeable. According to Talbot (2015), battery has already existed since late 18th century, which was first invented by an Italian physicist named Alessandro Volta in 1800. This first ever chemical battery was a consisted of alternating layers of copper and zinc discs separated by cloth soaked in saltwater or the electrolyte and was called Voltaic Pile. In late 19th century, the oldest example of rechargeable battery, the lead-acid battery was invented which is still be using in cars to provide power for starting the vehicle nowadays. Technology for battery continues to evolve rapidly and lithium-ion battery emerges as one of the dominance technologies for various applications including electric vehicles.

Batteries are widely used across different industries and application for several important reasons. Firstly, the battery is highly portable due to its compact and self-contained characteristic. Electrical energy can be stored in small and lightweight batteries which allow them to power consumer electronics such as smartphone, laptop, tablets and wearables. Besides, batteries have high reliability and versatility as they are able to provide stable and consistent power and are able to power a diverse array of applications from small electronic devices such as smartphone or smartwatch to large scale energy storage system such as renewable energy storage, uninterruptible power supplies and grid- scale energy storage. They can be adapted into different voltage level, energy requirement and operating conditions and therefore applicable to many different industry's needs. Batteries are more environmentally friendly and have low impact on the environment when compared with other source of power such as fossil fuels which they will be able to reduce greenhouse gas emission when using electric vehicles or electric transportations.

However, a good battery pack would require a good battery management system (BMS) that is able to monitors, controls and safeguard the operation of batteries to ensure that the batteries can be used in a more efficient and safe manner and its general structure is shown in Figure 1.1. A BMS can contributes to a good battery usage by monitoring the batteries charge status, batteries temperature, batteries voltage level and battery's fault. This information can help to determine which function in the BMS to be applied. In a multi cell battery pack or battery module, balancing of cells is required using a balancing circuit. This is because after a long-time usage of the battery pack, every individual cell in the pack may have charge or discharge at different rates and their charge status will be different and cause imbalance between the cells. If the problem of imbalance between cells persists, it may reduce the cell life span and cell capacity. Other than that, BMS checks for the temperature of battery to prevent overheating, controls the charge and discharge rate to prevent overloading of the battery and ensures the battery to operate only in safe voltage range to prevent overvoltage or undervoltage conditions. All the abnormal conditions may lead to potential safety hazard such as thermal runaway.

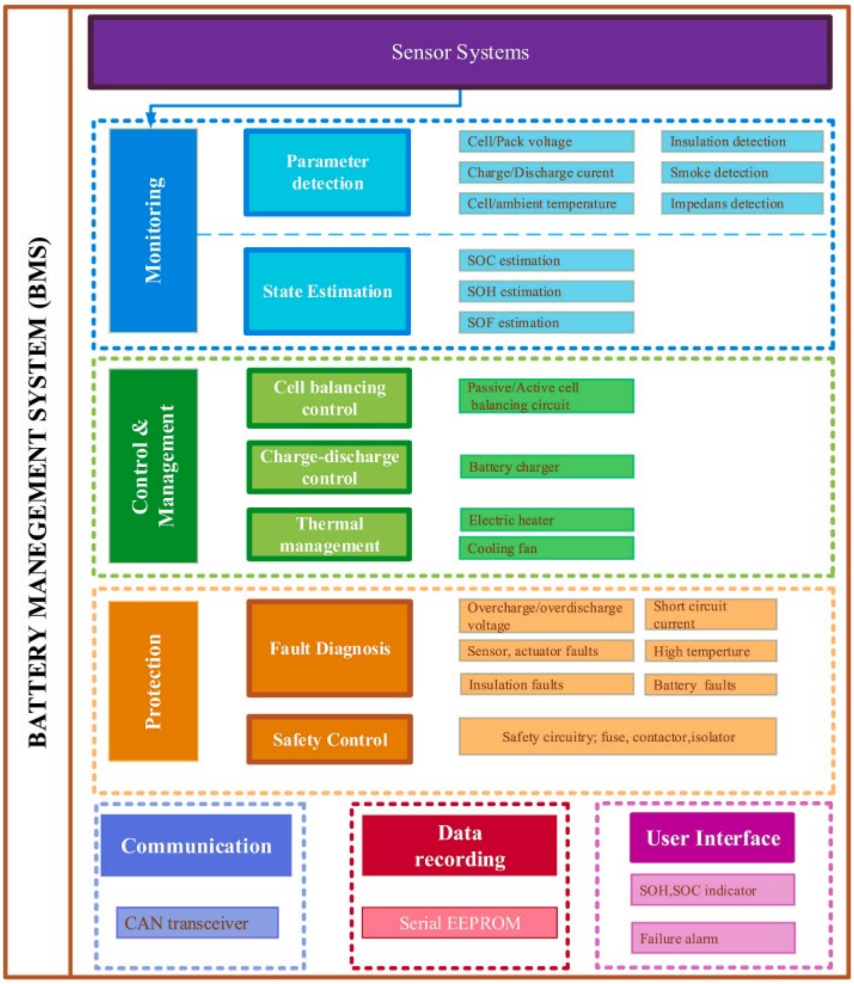


Figure 1.1: Structure of Battery Management System (Turksoy, Teke and Alkaya, 2020).

1.2 Importance of the Study

Balancing circuit is the fundamental component of a BMS, it is very crucial in optimizing the performance of every cell in the battery pack. The main role of the balancing circuit is to do cell voltage balancing in a battery pack. It is normal for individual cells to have different voltage level due to the usage pattern. The imbalance between the cells may cause conditions such as overcharging and over-discharging, overvoltage and undervoltage, overheating and overloading. All these conditions may ultimately cause issues such as reduced overall capacity, reduced lifespan and potential safety hazard. Therefore, balancing circuit can solve these issues by keeping the voltage of every cell at same level. By actively equalizing the voltage level across cells, every cell is able to operate at its specified voltage range and thus extend the cell life. Balanced cells can operate efficiently because all the cells provided equal energy to the application and none of the cell will be overloading. Optimized performance is achieved, and abnormal conditions reduced, potential safety hazard caused by overcharging may be avoided. Most importantly, downtime and maintenance cost can be effectively reduced after eliminating all the abnormal conditions and keeping the battery at good health.

1.3 Problem Statement

Existing balancers may face some common problems which leads to a series of consequences such as the imbalance of the battery and further leading to damaging the health and longevity of the battery pack. Energy loss as one of the commonly seen problems occurred due to low efficiency balancer wasting the energy during balancing process especially passive balancers. Passive balancers would also cause excessive heat generation which can negatively impact battery performance and lifespan. The slow response time of the balancer during different conditions such as charging and discharging is also a problem. When comes to the testing of battery balancing circuit, majority of the existing balancing circuit only be tested in the situation when the battery is stationary. The balancing circuit will neither be tested when the battery is in charging process nor discharging process. However, in the real-life application, the battery will not always be in stationary, instead most of the time the battery will be used frequently in charging or discharging process. Testing of the battery balancing circuit which involve only the stationary condition is inadequate to understand how majority balancing circuit performance under dynamic condition, and also their efficiency in application when experiencing frequent charging and discharging cycle.

1.4 Aim and Objectives

The objectives of this project are to design and develop an active balancer which is a prototype of single switched capacitor balancing circuit for 4S1P configuration lithium-ion batteries. This prototype will carefully consider about different design parameter such as the component selection, circuit topology and control algorithm. Besides, performance of the developed prototype will be tested under different dynamic conditions such as stationary, charging and discharging. Prototype should then be evaluated for its performance not only by observing the overall trend of the voltage but also the overall trend of the standard deviation and its percentage difference. By accomplishing these objectives, this project aims to contribute to the advancement of cell balancing technology and enhance the performance and lifespan of lithium-ion battery packs.

1.5 Scope and Limitation of the Study

In this project, the studies involve the development of a cell-to-cell active balancing circuit for lithium-ion batteries which the cell configuration will be in 4S1P (4 series and 1 parallel). The scope will also be covering the testing conditions for cell balancing circuit which the batteries are in stationary, charging and discharging states. The limitations of this project would be lacking study about the charging algorithms. Some aspects of charging algorithm such as the constant current phase, constant voltage phase and temperature compensation will not be included in this project. Some of the state of charge estimation method will be studied, however it is not the main focus of this project and acts only as a fundamental to understand the design of active cell to cell balancing circuit.

1.6 Contribution of the Study

This study analyses the testing of another kind of single switched capacitor balancer designed for a 4S1P lithium-ion battery configuration. This project investigates how well it performs in different operating conditions, such as stationary periods, charging cycles, and discharging cycles. It is to find out if it can maintain voltage balance between individual cells and improve battery performance in every condition. This study wants to provide valuable insights into the practical effectiveness of the balancer in real-world battery management scenarios through investigation. By examining the balancer's potential contributions to improving battery longevity and efficiency, this analysis should advance the field of energy storage systems.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, type of batteries and analysis about their capabilities will be reviewed in Chapter 2.2. Chapter 2.3 introduces the passive and active balancing circuit and their working principle. Chapter 2.4 discusses about the State of Charge (SOC) estimation methods. In Chapter 2.5, different balancing circuits from various journals and research papers are studied and compared based on their energy transfer topologies, triggering topologies, methodologies, and results and performance. Lastly, Chapter 2.6 provides a summary for the literature review.

2.2 Batteries

There are many rechargeable batteries applied in the industry, for example the lead-acid batteries, nickel-based batteries, lithium-based batteries and other type of batteries beyond lithium. Among these batteries, lithium-ion batteries are the one which has gained a widespread use in the electric vehicle due to its high energy density, specific energy and specific power characteristics (Turksoy, Teke and Alkaya, 2020). The body of lithium-ion batteries would typically have anode, cathode and electrolyte. The basic working principle of these batteries are by shuttling lithium ions between the two electrodes during the charging and discharging processes. Batteries other than lithium-ion batteries would also have similar working principle.

According to Liu, Placke and Chau (2022), Lead-acid batteries was one of the batteries that has been used for a long period started since last century due to its well-established technology and cost-effectiveness. Although, popularity of the lead-acid batteries has declined due to the rising of lithium-ion batteries technology, it still undergoes significant improvement particularly the valve-regulated lead-acid battery (VRLA). This VRLA battery emerged as a more powerful battery in term of its specific energy, specific power and recharging speed. VRLA battery also excel in performance across a wide range of temperature, offers the flexibility in term of battery size selection and high energy efficiency.

Nickel-acid batteries were also one of the popular batteries to use before lithium-ion battery. There are many types of combination of nickel-acid batteries using nickel oxyhydroxide as the cathode like the nickel-iron, nickel-cadmium, nickel-zinc, nickel metal hydride and nickel-hydrogen. Among all the nickel-acid batteries, nickel-iron and nickel-cadmium are the most popular battery. Nickel-iron battery is known for their durability and long life, often lasting for several decades while for nickel-cadmium battery, it is known for relatively high discharge rates and long cycle life (Liu, Placke and Chau, 2022).

Lithium-based batteries are considered as new emerging technology to take over the lead-acid and nickel-acid batteries due to its higher energy density, lighter weight, no memory effect and relatively fast charging. Lithium-based batteries are batteries that use lithium-ions as charge carrier and can be divided into two parts which are the lithium-ion batteries and lithium-metal batteries. lithium metal batteries use metallic lithium anode and non-aqueous electrolyte which can result in larger energy density and higher specific energy while maintaining low weight. However, lithium-metal batteries still facing challenges in safety concern and cannot be commercialised yet but remain as a potential candidate for electric vehicle propulsion. Lithium-ion batteries also have similar advantages as lithium-metal batteries in term of energy density and specific power but lower than what can be provided by lithium-metal. Therefore, lithium-ion battery is still the better choice for electric vehicles and renewable energy storage system (Liu, Placke and Chau, 2022).

There is also battery that uses technology that is beyond lithium. Firstly, the metal-air batteries, as its name suggested, this battery uses metallic anode and air cathode which also offer high specific energy and energy density (Liu, Placke and Chau, 2022). However, some of these metal-air batteries suffer from low specific power and carbonation of alkaline electrolyte such as zinc-air battery. Sodium-beta batteries also among the batteries beyond lithium and they are sodium-metal chloride and sodium-sulphur batteries (Liu, Placke and Chau, 2022). Besides, magnesium-ion battery, solid state battery and zinc-ion battery also use technology that is beyond lithium as one can tell from their name. These batteries are batteries to be researched in the future to find out their yet-to-be-discovered potential.

2.3 Balancing Circuits

Battery balancing circuit is an electronic circuit that help to balance the voltage different of every battery in the battery module. Balancing circuit will continuously detect the voltage of each cell in the battery module, if there is any cell that has higher or lower voltage level than other cell, it indicates an imbalance. After imbalance is detected, balancing between the cells will start and typically there are two ways for balancing which are passive balancing and active balancing.

2.3.1 Passive balancing circuits

A balancing circuit helps the battery to balance the voltage of individual cells. Passive balancing circuit achieve this function by relying on the resistance to dissipate excess energy from the higher voltage cells (Carter, Zhong and Jun, 2020). This needs the help of passive components such as the resistor. When one or more cells in a battery pack have higher voltage than the other or their voltage level hits certain threshold, the passive lancing circuit will create a path for the excessive energy to flow through the resistor and dissipate the energy as heat (Bouchhima et al., 2016).

There are basically two methods of building this passive balancing circuit which are either using fixed resistor or switched resistor. For the fixed resistor, there is a continuous bypass current that can limits the voltage level of the cells. However, this method is not recommended for battery which cannot withstand overcharging. While on the other hand, the switched resistor only helps the cell with highest voltage level and switch on the path for the excess energy to flow through the resistor. The switch for the resistor will be turned on until the rest of the batteries have the same voltage level (Manjunath and Kalpana, 2022).

The advantages of this passive balancing circuit are that this particular circuit is simple to build and relatively low cost when compared to active balancing circuit (Seonwoo Jeon, Jae-Jung Yun and Sungwoo Bae, 2015). This is because active balancing circuit would require additional control circuitry and energy transfer components such as the capacitor, inductor, transformer, MOSFET switch and IC chip that can help to control the energy flow. Besides, due to its simplicity in building the balancer, it also contributes to a lower power consumption because rather than active balancing circuit that has many active components such as transformer that use up a lot of power, passive balancing circuit only consists of resistors and switches that consume power, thus result in lower power consumption. High reliability provided by passive balancing circuit also considered one of the advantages since passive balancing circuit has no moving parts and are less prone to failure compared to active balancers, which may have switches or relays (Seonwoo Jeon, n.d.).

2.3.2 Active balancing circuit

Active balancing circuit is another type of balancing method. It differs from the passive balancing circuit because they help to transfer the excess energy from higher voltage level cell to a lower voltage level cell rather than dissipating the excess energy as heat. Generally, in the active balancing circuit, there will be active components which can temporarily store energy such as the capacitor, inductor, and transformer, active balancing circuit uses these components to store and later discharge the energy to the lower voltage level cell to achieve the balancing. Such balancing behaviour will normally work together with respective switches for each of the cell or battery module. In this active balancing method, there are various energy flow topologies which are the adjacent cell to cell (ACTC), direct cell to cell (DCTC), cell to pack (CTP), pack to cell (PTC) and cell to pack to cell (CTPTC) (Turksoy, Teke and Alkaya, 2020).

Firstly, the adjacent cell to cell method transfers energy from one cell to its adjacent cell. Therefore, if there are four cells in a string, the energy would need to transfer from the first cell then to the second and third cell, and finally transfer to the fourth cell if the first cell has the highest voltage level while the fourth cell has the lowest voltage cell. This method has the advantage of it does not require complex control or voltage sensing and is easy to implement. The disadvantage of this method is that its balancing speed is greatly depends on the number of cells in the string and the position of the cell within the string. Thus, balancing speed would be much slower and balancing time will increase significantly if there are large number of cells in one string and results in low efficiency.

Direct cell to cell method is another method of transferring the excess energy from one cell to another cell but the energy transfers no need to flow through the adjacent cell, and directly transfer to the target cell with lower voltage level. It has eliminated the disadvantage of adjacent cell to cell method and only perform the energy transfer between two cells and hence higher balancing speed when compared to adjacent cell to cell method. However, even it has higher balancing speed, the balancing speed could also be much slower if the battery string is huge due to too many switching elements in the balancing circuit and causes the efficiency of this method to be low.

In cell to pack method, the excess energy is distributed from most overcharged cell to a whole battery pack or battery module. This method will continue until the battery pack is balanced. Since the most overcharged cell is selected to transfer the excess energy, sensing and controller are needed to do so. Generally, the balancing efficiency of this method will be low, but its balancing speed is high due to the huge different in voltage level between the cell and battery pack.

In pack to cell method, the energy flow is opposite of the cell to pack method as it transfers the energy from the pack to the lowest voltage level cell. This method is similar to cell to pack but with opposite direction of energy flow, therefore it would also need sensing and controller to select which cell for the energy to be transferred. The strengths and weaknesses for this pack to cell method are also the same as cell to pack method.

In cell to pack to cell method, there two ways for this method to be implemented. The first approach is the excel energy is temporarily stored in an inductor or capacitor and then the energy will be transfer to a lower voltage cell in which this approach is similar to the direct cell to cell method. The second approach would be the balancing occurs for two conditions. The cell to pack method will be used when the voltage level or the state of charge (SOC) of a cell is higher than the reference value while pack to cell method will be used when voltage level and the SOC of a cell are smaller than the refraction. This method can achieve higher balancing speed when compared to cell to pack and pack to cell methods, but it has higher implementation cost, and the size of the balancing circuit would be bulky (Srinivasan and Parimi, 2022).

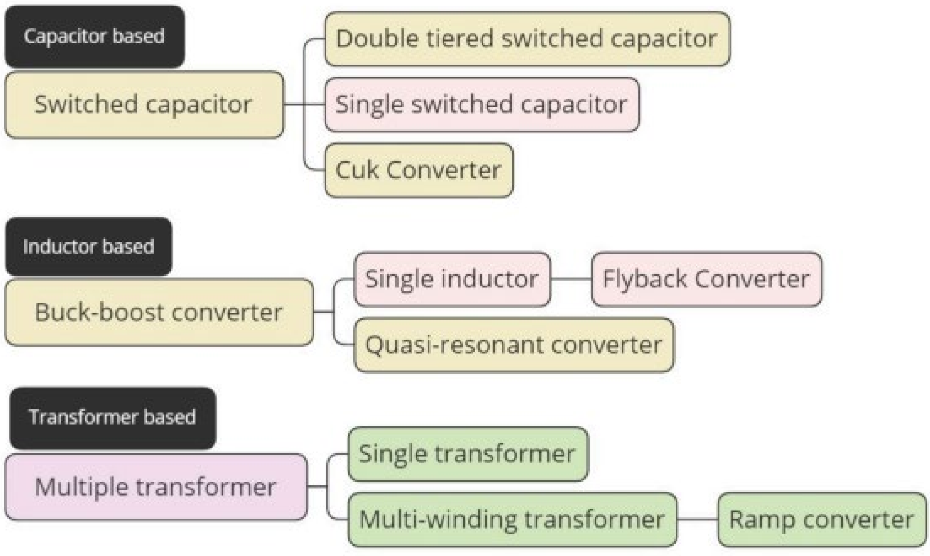


Figure 2.1: Capacitor, inductor and transformer-based balancer (Carter, Zhong and Jun, 2020).

Aside from the energy flow topology, cell balancing circuit could also be built based on capacitor, inductor and transformer which shown in Figure 2.1 (Carter, Zhong and Jun, 2020). Capacitor based balancing circuits use the capacitor as the main temporary energy storage element to achieve the transfer of excess energy. They can also be constructed into different configuration such as double tiered switched capacitor, single switch capacitor and Cuk converter. All capacitor in different configuration will be switched to achieved energy transfer but the energy flow topology may not be the same. Single capacitor configuration is shown in Figure 2.2, it has only one capacitor in the circuit and is said to be direct cell to cell when transferring energy. This configuration has advantage that any cell in string can be used to balance other cell in the string, but the disadvantages would be very slow overall balancing speed. Another configuration would be the double tiered switched capacitor. This configuration uses additional tier of capacitor and would incur more cost because the number of components increases. Cuk converter configuration in other hand, provides high efficiency for cell to cell balancing but it also suffers from low balancing speed, high cost and large volume of the circuit (Hasan et al., 2020).

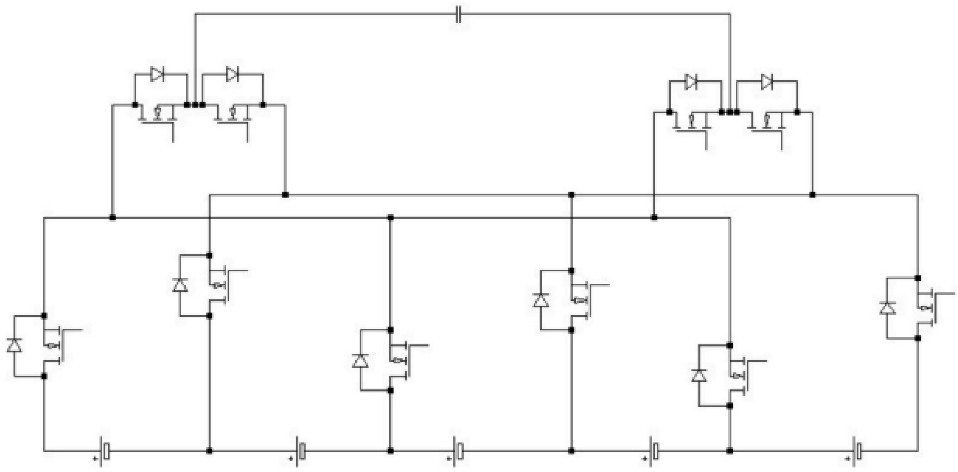


Figure 2.2: Single Switched capacitor configuration (Carter, Zhong and Jun, 2020).

For the inductor based balancing circuit, while having inductor as the main energy storage element, they can be configured into single inductor, Flyback converter and Quasi-resonant converter. An example of inductor based balancing circuit shown in Figure 2.3. Single switched inductor configuration is similar to the single capacitor configuration which it only has one inductor in the balancer and also suffers from low balancing speed. For the flyback converter configuration, it is similar to the single inductor configuration, but it has primary side to store energy and secondary side to provide isolation. Since it has primary and secondary side, it is also similar to a transformer. Flyback converter configuration able to provide cell to pack, pack to cell and cell to pack to cell energy flow topologies. It can provide benefit such as high efficiency but has drawback such as bulky high cost and high control complexity. Quasi-resonant converter configuration is cell to cell balancer with high efficiency and able to achieve zero current switching which reduce switching losses. However, this configuration needs to have 4n cells relays and causes it to be expensive and bulky.

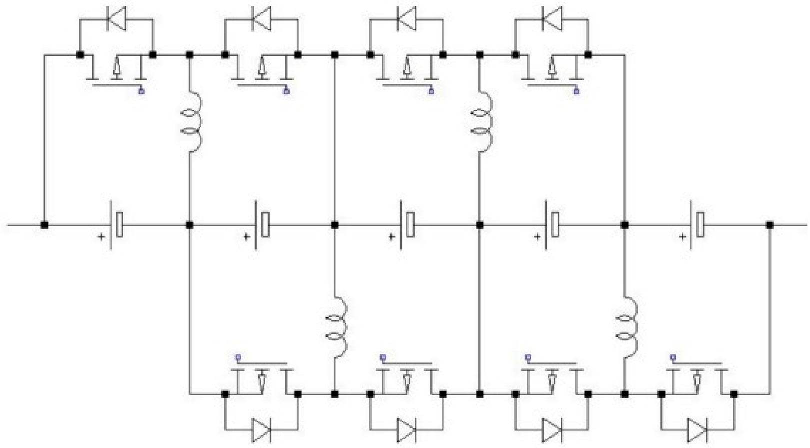


Figure 2.3: Switched Inductor based balancing circuit (Carter, Zhong and Jun, 2020).

Thirdly, the transformer-based balancing circuit. Transformers consist of multiple coils of wire, allowing for the magnetic coupling of circuits while maintaining electrical isolation. Transformer-based balancing circuit would generally be considered to have high efficiency and balancing speed but with trade-off of large size, expensive and high control complexity. The example that uses transformer-based configuration are the single transformer, multiple transformer and transformer with multi-secondary winding. Single transformer configuration is like the flyback converter, it only has one transformer in the circuit while the multiple transformer configuration provides each cell with one transformer which cause it to be bulky and expensive. For the multi-secondary winding transformer, it has single primary winding but has multiple secondary winding correspond to the number of cells as shown in the Figure 2.4.

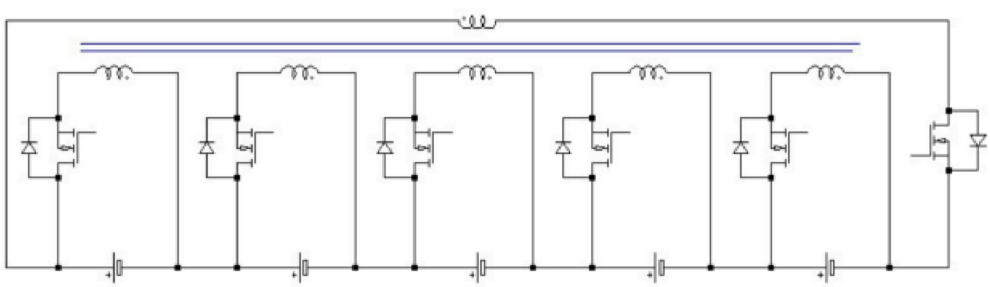


Figure 2.4: Multi winding transformer balancing circuit (Carter, Zhong and Jun, 2020).

All the above discussed balancing circuit topologies can be concluded and shown in Figure 2.5. Other than all the capacitor, inductor and transformer-based configurations that has been discussed. There are as well some different configuration-based converters such as Resonant LC converter, dual active bridge converter, half-bridge converter and push-pull converter which most of them would also be considered as inductor or transformer based. Their energy transfer topology, balancing control algorithm and performance parameter are shown in Figure 2.6 on the next page, where the balancing circuits-based on DC-DC converter topology are compared.

CEC type	Current path	Speed	Components							Cost	Circuit Volume	Control complexity
			Switches	R	C	L	Diodes	T	MWT			
Switched Capacitor	AC2C	Slow	192	0	95	0	0	0	0	Low	Medium	Easy
Double tiered switched capacitor	AC2C	Medium	192	0	189	0	0	0	0	Medium	Medium	Easy
Single switched capacitor	DC2C	Slow	384	0	1	0	0	0	0	Low	Small	Medium
Cuk Converter	AC2C	Medium	190	0	95	96	0	0	0	Medium	Medium	Complex
Buck-Boost converter	AC2C	Medium	190	0	0	95	0	0	0	Medium	Medium	Complex
Single inductor	DC2C	Slow	194	0	0	1	1	0	0	Medium	Small	Medium
Flyback converter	DC2C	Slow	192	0	0	2	193	0	0	Medium	Large	Complex
Quasi-Resonant	AC2C	Medium	190	0	95	190	0	0	0	High	Large	Complex
Single transformer	C2P or P2C	Slow	192	0	0	0	193	1	0	High	Large	Medium
Multi-windings transformer	C2P or P2C	Slow	96	0	0	0	1	0	1	High	Large	Complex

Figure 2.5: Comparison of balancing circuit for capacitor, inductor and transformer based (Carter, Zhong and Jun, 2020).

2.4 State of Charge Estimation (SOC)

SOC estimation is a crucial aspect of BMS in energy storage systems and electric vehicles. SOC represents the remaining usable capacity of a battery relative to its full charge. Accurate estimation of SOC would help to provide information to the balancer to solve the imbalance between cells (Hannan *et al.*, 2017).

2.4.1 Coulomb Counting Method (CC)

The Coulomb Counting method estimates SOC by continuously monitoring the current flowing into and out of the battery (Shete et al., 2022). It essentially measures the amount of charge that enters and exits the battery. The BMS measures the current and integrates it with respect to time to calculate the accumulated charge. While the CC method is relatively simple, it has limitations, such as errors caused by inaccuracies in current measurement and the accumulation of errors over time (Xiao et al., 2023).

DC-DC converter topology	Balancing Method	Balancing Control Algorithm			Performance parameter								
		Control variable	SOC estimation method	Control algorithm	# of cell	Max. initial difference	Max. Efficiency	Balancing time (s)	Cost	Size	Efficiency	Speed	Control complexity
Quasi-resonant LC converter &boost converter	DCTC	Cell voltage	–	PI&FLC	8	0.259 V	98%	3200	VH	VH	E	E	M
Resonant-LC and Buck Converter	PTC	Cell voltage	–	FLC	8	0.422 V	88%	3800	H	H	G	S	M
Buck-boost converter	ACTC	SOC	EKF	FLC	8	20.5%	97.37%	1150	VH	VH	E	E	H
Buck-boost converter	ACTC	SOC	OCV	Fixed duty cycle	8	22.4%	82.5%	4450	VH	VH	S	G	H
Quasi-resonant buck-boost converter	ACTC	Cell voltage	–	Fixed duty cycle	3	1 V	85.6%	3000	VH	VH	G	VG	M
Cuk converter	ACTC	Cell voltage	–	FLC	3	0.6 V	NA	~2300	VH	VH	–	VG	H
Cuk converter	ACTC	Cell voltage		ANFIS	2	0.25 V	NA	3000	VH	VH	–	VG	H
Cuk converter	ACTC	Cell voltage	–	FLC	3	0.75 V	61.8%	7000	H	H	S	P	H
Cuk converter	ACTC	Cell voltage	–	Modified FLC	4	0.323 V	NA	4437	VH	VH	–	G	H
Cuk converter	ACTC	SOC	SMO	QSMC	4	11%	87.8%	2286	VH	VH	G	E	VH
Unidirectional flyback converter	CTP	SOC	NA	Fixed duty cycle	4	26%	88%	5500	H	H	G	S	M
Bidirectional flyback converter	CTPTC	SOC	OCV	NA	8	14.4%	80.5%–82.7%	1800	H	M	S	E	H
Bidirectional flyback converter	CTPTC	SOC	NA	Fixed duty cycle	88	20%	81.6%	3600	H	H	S	VG	H
Bidirectional multiple flyback converter	CTPTC	SOC	NA	MPC	6	27%	%90	~1500	VH	VH	VG	E	H
Bidirectional flyback converter	CTPTC	SOC	NN-FLC	GA	48	43%	%93.1	1002	H	H	VG	E	VH
Two unidirectional Flyback	CTP-PTC	Cell voltage	–	Fixed-duty cycle	10	NA	NA	NA	H	H	NA	E	H
Two unidirectional Flyback	CTP-PTC	SOC	OCV	PI	90	20%	91.96%-92.68%	5040	H	H	VG	E	H
Dual active bridge converter	CTP-PTC	SOC		PSO/phase shift	12	20.5%	NA	3522	H	H	NA	E	VH
Dual active bridge converter	DCTC	SOC	EKF	Mean difference/PSC	8	10%	NA	~1500	VH	VH	NA	E	VH
Half-bridge converter	CTP	SOC	NA	PSC	6	23%	%95.3	10,800	VH	VH	E	P	VH
Push-pull converter	DCTC	Cell voltage	–	Heuristic	12	0.2 V	NA	2820	VH	VH	–	E	M

E: Excellent, VG: Very Good, G: Good, S: Satisfactory, P: Poor.
VH: Very high, H: High, M: Medium.
NA: Not available.

Figure 2.6: Comparison of balancing circuits-based on DC-DC converter topology (Turksoy, Teke and Alkaya, 2020).

2.4.2 Kalman Filter

The Kalman Filter is a recursive mathematical algorithm that estimates SOC by combining measurements from various sensors, such as current and voltage sensors, while accounting for measurement noise and system dynamics. It simulates the battery's behaviour as a dynamic system and updates its SOC estimate based on the most recent measurements(Kassim, Jamil and Sabri, 2021). The Kalman Filter is especially useful when measurements are uncertain and battery behaviour is complicated due to temperature variations, ageing, and other factors. When compared to simpler methods such as CC, it provides a more accurate and robust SOC estimation. However, the drawback of this method would be its strong dependency on the precision of battery model and requires highly complex mathematical calculations (Wang *et al.*, 2020).

2.4.3 Other methods

Aside from CC method and Kalman Filter, there are still many more ways to do the SOC estimation. According to Hannan et al. (2017), the SOC estimation methods can be separated into five different categories where CC method is under conventional method and Kalman filter is under adaptive filter algorithm. The other three categories are the learning algorithm, non-linear observer and other methods. Under these three categories, the examples are Fuzzy Logic, Sliding Mode Observer and Hybrid method, each with their respective pros and cons. These estimation methods under different categories are shown in Figure 2.7 and the abbreviations of the SOC method are in Figure 2.8.

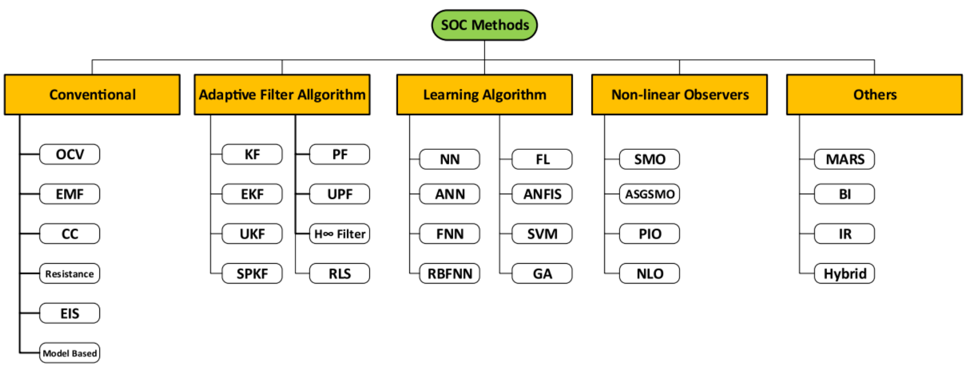


Figure 2.7: Pros and Cons of SOC methods (Hannan *et al.*, 2017).

ANFIS	Adaptive Neural Fuzzy Interface System	KF	Kalman Filter
ANN	Artificial Neural Network	MARS	Multivibrate Adaptive Regression Splines
ASGSMO	Adaptive Switching Gain Sliding Mode Observer	NLO	Nonlinear Observer
BI	Bi-linear Interpolation	NN	Neural Network
CC	Coulomb Counting	OCV	Open Circuit Voltage
EIS	Electrochemical Impedance Spectroscopy	PF	Particle Filter
EKF	Extended Kalman Filter	PIO	Proportional-integral Observer
EMF	Electro-Motive Force	RBFNN	Radial Basis Function Neural Network
FL	Fuzzy Logic	RLS	Recursive Least Square
FNN	Fuzzy Neural Network	SMO	Sliding Mode Observer
GA	Genetic Algorithm	SPKF	Sigma Point Kalman Filter
IR	Impulse Response	SVM	Support Vector Machine
		UKF	Unscented Kalman Filter
		UPF	Unscented Particle Filter

Figure 2.8: Abbreviations of the SOC Method (Hannan *et al.*, 2017).

2.5 Research and Studies of Different Balancing Circuits

The first study of balancing circuit is from Lee et al. (2023), it is a balancing circuit based on Master-Slave Battery Management System (MS-BMS) shown in Figure 2.9. Basically, this master-slave BMS has two distinct balancing units which are the master unit and the slave unit. For both the master unit slave unit, they have different balancing components to do the balancing. For the master unit, it has flyback converter with MOSFET switching array while for the slave unit, it has bidirectional flyback converter and photoMOS arrays. The master unit is used for balancing the voltage level between the battery modules while the slave unit is to balance the voltage level between the cells within the battery modules. This means that this slave unit is applying the DCTC method to the individual cell within battery modules and master unit also uses same idea as DCTC method, but it is from battery module to another battery modules.

All the while, there is also a microcontroller unit to manage the switching of the MOSFET based on the voltage signal achieved from master and slave unit and collected by the Master-Slave Modbus communication protocol. This balancing circuit is design for three 6S1P battery modules. This balancing circuit is tested in both practical and simulation with the battery in stationary condition. This balancing circuit is tested with five different condition which are activating slave unit, master unit, slave unit then master unit, master unit then slave unit and both slave unit and master unit simultaneously. The final results showed that the best operating condition is both BMS master and slave work simultaneously. If any one of BMS master and slave work first and follow by another, the first one to operates will have to do the balancing again and will be using a longer time to balance all the cells and modules and this balancing circuit achieved an average absolute error of 3.12% in balancing duration when comparing the practical and simulation results.

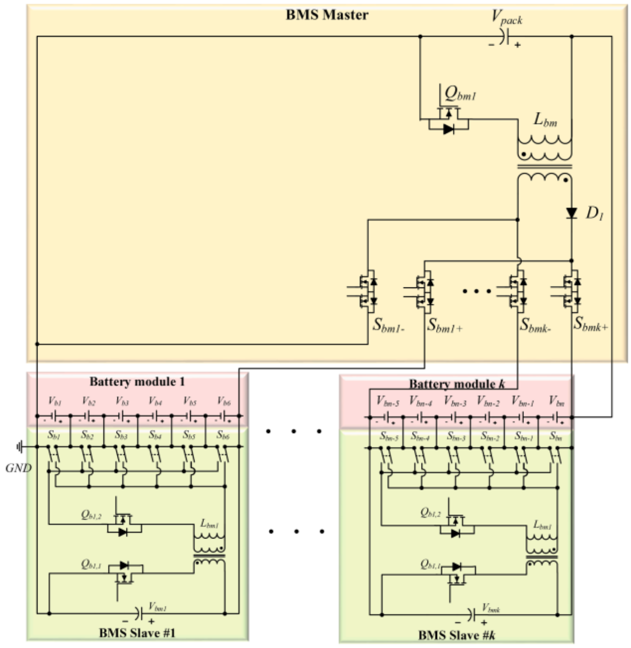


Figure 2.9: Basic circuit structure of the balancer based on MS-BMS (Lee *et al.*, 2023).

Besides, a similar balancing circuit from same author Lee et al. (2022) has also been studied which is battery management system with dual-concentration architectures using modified flyback converter with an active clamp shown in Figure 2.10. Similar to the previous balancing circuit, three 6S1P battery modules are used. The balancing circuit works by microcontroller collecting the voltage of the battery modules using differential voltage circuit and the system will determine whether to begin the balancing function depending on the calculated voltage different for each battery modules. Finally, the circuit will extract the energy from battery pack and transfer it to the battery module with lowest voltage level for a duration determine by user and deactivate the balancing. Tests for different balancing strategies are conducted, the strategies are cell balancing then battery module balancing, battery module balancing the cell balancing, both cell and module balancing at same time for both stages, and both cell and module balancing at same time for both stages, but first stage is individual balancing decision, and second stage is global balancing decision. The results showed that the balancing duration and maximum voltage error of the balancing circuit can be reduces by approximately 34% and 73% respectively when compared to worst-case scenario in four balancing strategies.

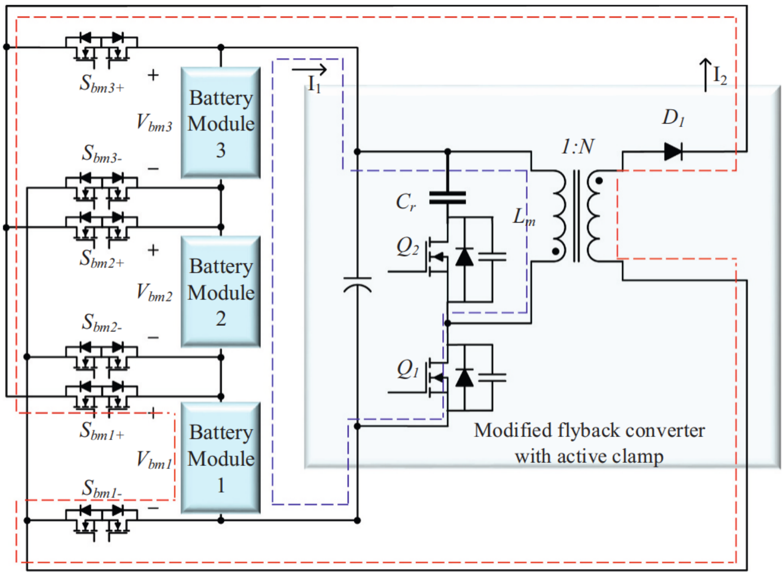


Figure 2.10: Schematic of the balancer dual-concentration architectures using modified flyback converter with an active clamp (Lee *et al.*, 2022).

Furthermore, a balancing circuit that uses a single resonant converter proposed by Habib and Hasan (2023) is shown in Figure 2.11. This balancing circuit uses the direct cell to cell topology and consists of n-4 bidirectional MOSFET switches and a single LC tank in one string of cells. The active balancing circuit offers several advantages, including high efficiency, rapid balancing, compact size, cost-effectiveness, and efficient energy recovery. This balancing circuit is able to achieve for all MOSFET switches to operate in a near-zero current system and are controlled using complementary wide modulation signals in synchronous trigger patterns. This system also achieves zero voltage different between cells and circuit's resonant frequency aligns with the switching frequency to reducing the resonant frequency. Experimental results show that two 4200 mAh Li-ion cells with state-of-charge levels of 95%

(3.958 V) and 66% (3.712 V) reach a voltage difference of zero (0 V) after 79 minutes. Additionally, the circuit's performance is assessed with lead-acid batteries and super-capacitors, demonstrating its stability and suitability for battery management systems in electric vehicles (Hasan et al., 2020).

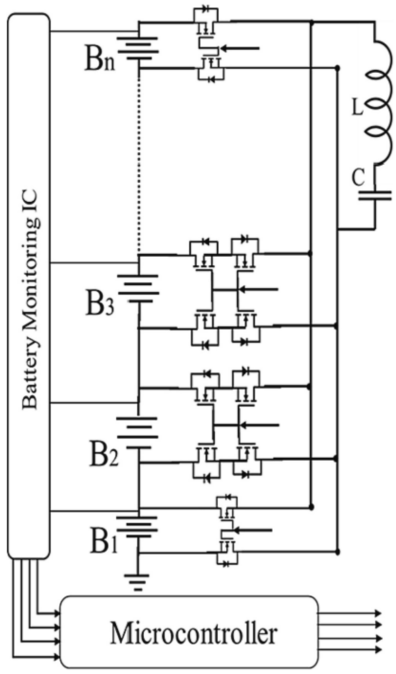


Figure 2.11: Schematic of balancer with single resonant converter (Habib and Hasan, 2023).

Next, a multi-winding transformer with self-driven switches balancing circuit is proposed by Ye, Wang and Wang (2023) as shown in Figure 2.12. This H-bridge inverter in the circuit determines the polarity of the voltage at the primary winding to switch between the operating modes based on the voltage different between cell voltage and balancing voltage. The secondary winding for each cells has a centre tap that divided the secondary windings into two sub winding which one is for controlling the transistor and anther one is for energy storage. There will be four operation modes which first two modes are when the cell voltage is lower than balancing voltage, the cell will be charged however which cell to be charged is based on the polarity of the primary voltage. While the next two modes are when the cell voltage is higher than the balancing voltage, the cell will be discharged and which cell to be charged is based on the polarity of the primary voltage. This balancing circuit can reduce the system cost because balancing can automatically without switch driving circuit and voltage sensors. Experiment using lithium-ion battery is conducted and it shows that cell balancing can be achieve after 120 minutes with maximum voltage different of 157 mV.

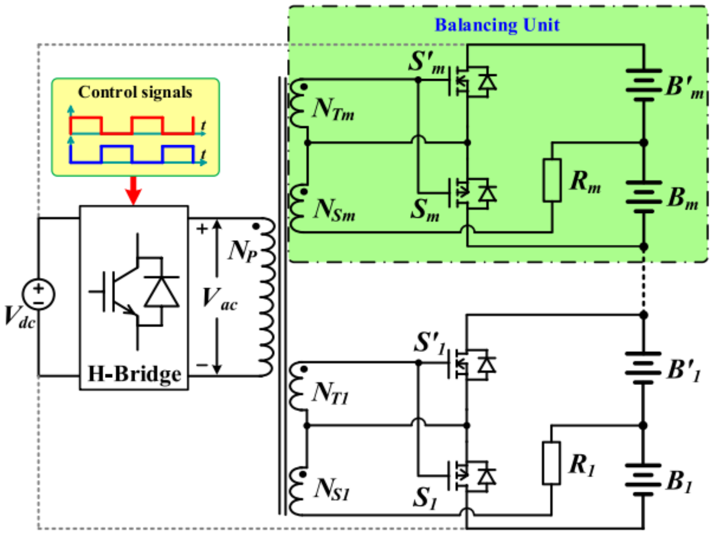


Figure 2.12: Schematic of balancer with multi-winding transformer (Ye, Wang and Wang, 2023).

2.6 Summary

Literature review for different batteries, type of balancing method, the energy flow topologies, SOC estimation method and different research paper about balancing circuit are studied.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter will be discussing about the overview of the battery arrangement and the implementation of balancing circuit including system block diagram and flowchart. All the hardware composts and software programs needed for the implementation will be listed. Testing method to validate the balancing circuit will be discussed and project planning for this project will be showed.

3.2 Overview of Balancing Circuit

The balancing circuit in this project will be developed using 4S1P configuration single switched capacitor balancing circuits for the lithium-ion batteries. The balancing circuit using two super capacitors will be developed because it has lower cost and lower control complexity as the design does not involve transformer, while the design also able to maintain good efficiency and fast balancing speed.

Figure 3.1 shows the block diagram of the balancing circuit in this project. The battery module will be connected to the switches and to the super capacitors, while the switches are controlled by the microcontroller and start the balancing action by turning on and off for the switches. The power supply and battery discharger are used to conduct the testing under different dynamic conditions such as stationary, charging and discharging. The voltage sensors will collect the voltage level of each battery and send to the microcontroller for data analysis. Balancing circuit will continuously be checking for the cell voltage different, and the balancing will be stopped after observing the voltage difference of the batteries. The flowchart shown in Figure 3.2 is to show the process of testing the prototype balancing circuit.

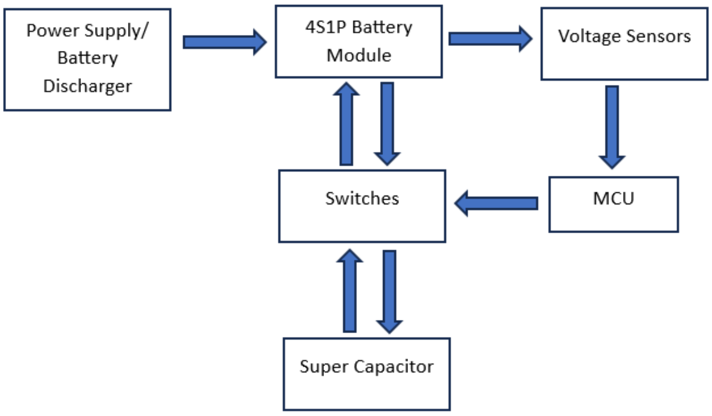


Figure 3.1: Block Diagram of the Balancing System.

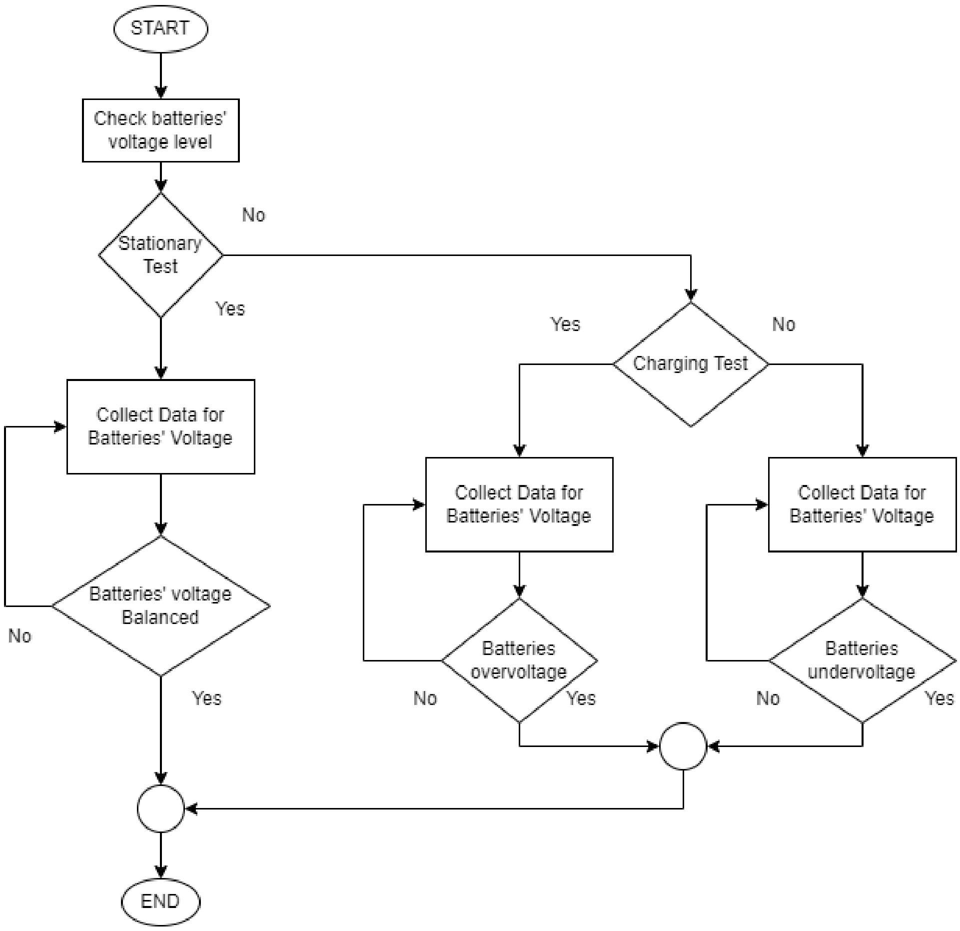


Figure 3.2: Flowchart for testing the prototype balancing circuit.

3.3 Hardware Components

This section describes the hardware components to be used in the balancing circuit.

3.3.1 Arduino Uno Atmega328P

Arduino Uno is a microcontroller board that uses the ATmega328P IC shown in Figure 3.3. It has 14 digital input/output pins of which 6 provide PWM output, 6 analogue inputs, a 16 MHz ceramic resonator (CSTCE16M0V53-R0), a USB connection, a power jack, an ICSP header, and a reset button. It can be powered by connecting it to a computer via USB or power it via an AC-to-DC adapter or battery. Its operating voltage is 5V and the recommended input voltage would be 7 to 12V. It is programmable with the help of Arduino IDE to upload the code to the Arduino board.

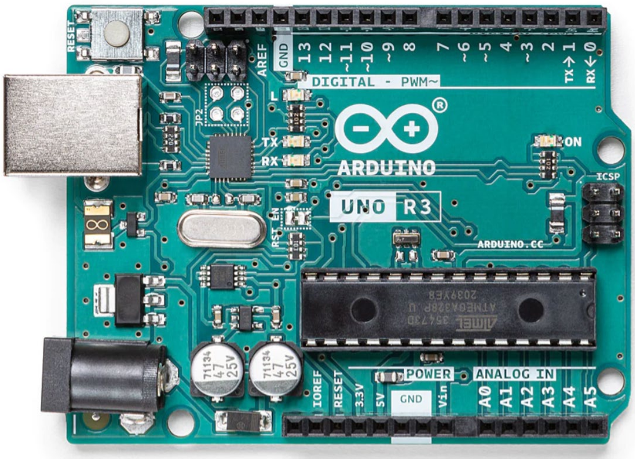


Figure 3.3: Arduino Uno ATmega328P.

3.3.2 IRFP450A and 2N7000 MOSFET Switches

IRFP450A shown in Figure 3.4 is a n-channel power MOSFET designed for high current and voltage application. Typically, this power MOSFET is used in applications such as power electronics and amplifications for high voltage and current. It can handle drain-source voltage for few hundred volts, high drain current for up to ten ampere and it has low on state resistance for minimizing power dissipation. 2N7000 shown in Figure 3.5 is smaller and lower power n-channel MOSFET used for low voltage and current switching application. IRFP450A will be used as the switch for the first cell and fourth cell while the 2N7000 will be used as the switch for the second and third cell.

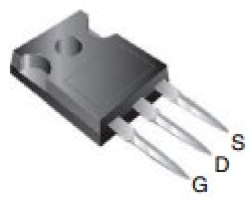


Figure 3.4: IRFP450A N-channel MOSFET.

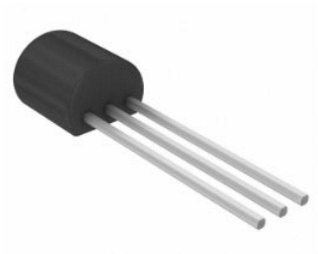


Figure 3.5: 2N7000 N-channel MOSFET.

3.3.3 817C Optocoupler

817C optocoupler shown in Figure 3.6 is used to build the gate driver in the balancing circuit to control the switches. 817C optocoupler has light emitting diode (LED) on one side and a phototransistor on another side. To work with 817C optocoupler, if there is current flow through and light up the LED, the light will be detected by the phototransistor and allow current flow on another side to provide isolation.

Figure 3.6: 817C optocoupler.

3.3.4 B25 Voltage Sensor Module

B25 voltage sensor module shown in Figure 3.7 is a small electronic gadget designed to monitor voltage levels in a range of applications. Its main function is to provide accurate readings for analysis and control operations by detecting and monitoring voltage changes within a specified range. The module's compact form enables easy integration into electronic systems. Therefore, it will be used monitor the voltage level the cells and interface it with the microcontroller. After detecting the voltage of the batteries, signal will be sent to the microcontroller and data will be collected.

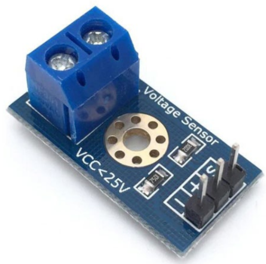


Figure 3.7: B25 voltage sensor module.

3.3.5 8 Channel 12 V Relay Module

The 8 channel 12 V relay module shown in Figure 3.8 is used as a switch to control the energy flow in the designed balancing circuit prototype. It is good for controlling components such as lights, motors, and more. Its opto-isolated inputs, which isolate control devices from voltage spikes, ensure stable and safe operation. It is small in size yet powerful in capability, it fits very well with a number of arrangements. Its 8-channel relay fits the number of the batteries used in the circuit as one battery need two relays.

Figure 3.8: 8 Channel 12 V Relay Module.

3.3.6 Super Capacitor

The Super Capacitor shown in Figure 3.9 is a versatile energy storage device, its compact size and robust design make it suitable for a wide array of applications, from providing backup power for batteries to standalone use in renewable energy systems. It offers quick charging and discharging cycles, it's ideal for portable electronics and automotive applications. With its high capacitance and voltage rating, it is suitable for projects. It can be used as the temporary energy storage in the balancing circuit to transfer energy from higher voltage cell to lower voltage cell and it has rating of 2.7 V and 100 F.

Figure 3.9: Super Capacitor.

3.3.7 Power Supply and 18650 Battery Discharger

An 18650-battery discharger shown in Figure 3.10 and bench power supply shown in Figure 3.11 are essential tools in electronics. With its precise voltage and current control, the bench power supply offers a reliable and adaptable source of electrical power, making it easier to test, troubleshoot, and design electronic circuits. Besides, 18650 lithium-ion battery dischargers are good at testing and securely draining these batteries to specified voltage levels. It helps evaluate the health, performance, and capacity of batteries, which is important for uses such as portable devices and renewable energy systems. Bench power supply and 18650 Battery discharger will be used to test the prototype under different conditions.

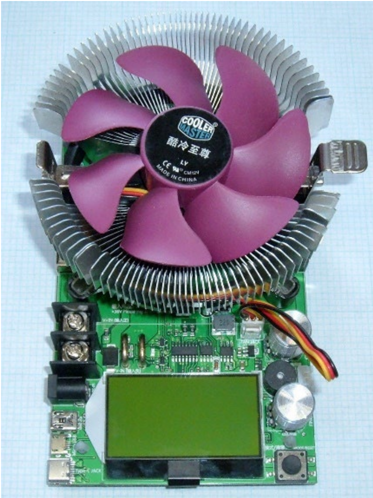


Figure 3.10: 18650 Battery Discharger.

Figure 3.11: Power Supply.

3.3.8 2000 mAH, 3.7 V 18650 Lithium-ion Battery

For the cells to be in 4S1P configuration, total of four lithium-ion batteries are needed. Lithium-ion batteries use will have 2000 mAH capacity, and able to provide 3.7 V. Lithium-ion batteries is use for experimenting the equalizing efficiency, equalizing speed and overall reliability of the balancing circuit when imbalance happen. Figure 3.12 shows a 2000 mAH, 3.7 V Lithium-ion battery.

Figure 3.12: 2000 mAH, 3.7 V Lithium-ion battery.

3.4 Software Selection

This section describes the software to be used in developing the balancing circuit.

3.4.1 Autodesk Fusion 360

Autodesk Fusion 360 shown in Figure 3.13 revolutionizes PCB design by integrating mechanical design, simulation, and collaboration tools. It helps to effectively layout traces and optimise designs for performance using its easy-to-use UI and powerful routing tools. Fusion 360 enables users to rapidly develop and refine their designs because to its wide range of materials and components. Fusion 360 is a unified platform that is great for engineers and designers looking to improve their PCB design workflows. It can be used to design the PCB layout for the balancing circuit.

Figure 3.13: Autodesk Fusion 360.

3.4.2 MATLAB Simulink

MATLAB Simulink shown in Figure 3.14 provides a solution for accurately and effectively operating battery balancing circuits. It may help to improve battery performance and longevity by precisely designing battery cells and balancing circuits. Testing of different configurations and operating situations can be done by Simulink's adaptable simulation environment. It is used for the software simulation of the balancing circuit to test the prototype under different conditions.

Figure 3.14: MATLAB Simulink.

3.4.3 Arduino IDE

Arduino Integrated Development Environment (IDE) shown in Figure 3.15 is a software program used to do programming code and upload it to any Arduino microcontroller board. It is open-source platform and the programming language used for coding is in C++. Arduino IDE is used to make the decision making for controlling the switch or relays. Signals will be received from the sensors and make decision to balance cell by controlling the MOSFET switches or relays.

Figure 3.15: Arduino Integrated Development Environment (IDE).

3.4.4 CoolTerm

CoolTerm shown in Figure 3.16 is a good tool available for collecting and analysing serial data from different kinds of devices. CoolTerm is a flexible solution for monitoring and troubleshooting serial communications, supporting several serial protocols as RS-232, RS-485, and USB. Its extensive logging features enable the recording of data to disc for later study, and its adjustable display options let users see incoming data in real-time. CoolTerm can be used for many different types of data gathering jobs, such as hardware debugging, sensor monitoring, and embedded system data collection. It is used to collect the data send by the sensors.

Figure 3.16: CoolTerm.

3.5 Testing Method

The performance of the developed balancing circuit should be tested when batteries are in stationary, charging and discharging state. The voltage level of the batteries when underdoing the testing will be measured and collected, then the data will be plotted into graph and be analysed. Analysis will mainly be done by observing the trend of the voltage level of each battery, calculating the standard deviation and observe its trend to determine whether there is balancing effect from the prototype balancing circuit.

3.5.1 Stationary, Charging and Discharging Condition

In this stationary condition, the 4S1P batteries will be connected to the prototype balancing circuit. Immediately after connecting to the balancer, CoolTerm will be used to collect the data send from the voltage sensor for their current voltage values. It will be left undisrupted for the balancing process to continue for one to five hours. After the duration of one to five hours, the balancer will be disconnected, and the data collected will be plotted into graphs. This includes the measurement of the battery's voltage and the stationary balancing of the battery.

In charging conditions, it almost same as what to do in stationary condition. The only different matter is the 4S1P batteries will be connected to not only the balancer but also the power supply. The positive and negative terminal of power supply are connected to the positive and negative terminal of batteries respectively. The voltage of the power supply is set to four times of the maximum voltage level of the lithium-ion batteries which is 16.8 V, and the current is set to 1 A. after connecting the batteries to power supply and balancer, the data should be collected immediately using CoolTerm. The whole process of charging would about one and a half to two hours for the batteries to fully charged. When the current on power supply showing that the voltage reaches 16.8 V and current reaches somewhere near 0.1 A to 0.2 A, the charging process will be stopped as the batteries already fully charged. This charging process will be repeated a few times with and without balancer to get more results to compare.

In discharging condition, the setting is still the same as stationary condition, but the batteries will also be connected to a battery discharger. The positive and negative terminal of battery discharger are connected to the positive and negative terminal of batteries respectively. The current of the discharger is set to 0.5 A. The whole process would likely take about one hour. The testing should be stopped immediately if the any battery voltage reaches value lower 2V. Data will be collected via CoolTerm and be plotted into graph using Excel. This discharging process would also need to be repeated a few times with and without balancer to get more results to compare.

3.6 Project Planning

The project planning for the FYP 1 is shown in Table 3.1. The project started by making a proper project planning for FYP 1 and FYP 2. Then the project is continued by doing research and reading journal as the literature review. After reviewing some related research papers, the methodology of the project is decided on the research done. Finally, all the literature review and methodology are written into the report and will continue with preparation of presentation for FYP 1.

Table 3.1: Gantt Chart for FYP 1.

No	**Project Activities**	**Week**													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Project Planning	■	■												
2	Literature Review		■	■	■	■	■	■	■	■	■	■			
3	Methodology									■	■	■	■	■	
4	Report Writing and Presentation												■	■	■

The project planning for the FYP 2 is shown in Table 3.2. The project will start by collecting all the electronic components needed for the balancing circuit. After receiving the electronic components and tested that the component can work perfectly, project will proceed to build the balancing circuit and program the microcontroller to control the balancing process. Challenges and problems will be face during the testing of the balancing circuit. After obtaining the result from the balancer performance, the analysis of the data will be discussed and written into the report. At the same time, designing the poster for presentation. Once, the report and poster are done, project will go on with the submission of report and poster and preparation for presentation.

Table 3.2: Gantt Chart for FYP 2.

No	Project Activities	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Purchase of electronic components	■	■												
2	Construction of balancer		■	■	■										
3	Programming of the balancer				■	■	■	■	■						
4	Testing of balancer							■	■	■	■				
5	Results discussion, conclusion and recommendation								■	■	■	■	■		
6	FYP poster design								■	■	■	■	■	■	
7	Submission of final report and poster														■
8	Presentation														■

3.7 Summary

In this chapter, the system overview of the balancing circuit is show and discussed using the block diagram and flowchart. The hardware and software needed for the project are explained and listed. By understanding the specification and limitation of the components, the development can be done in a proper way. The reasons for the hardware component selection and software implementation are explained. The testing method and project planning are also included.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the hardware and software implementation of the prototype is showed. The results of the hardware prototype and software simulation under different dynamic conditions will be collected and plotted into graphs and evaluated using the standard deviation, its trending and the voltage difference between the batteries. Additionally, there is also a comparison between the prototypes done in this project and other final year project students' prototypes. A discussion will be made based on their performances under different dynamic conditions.

4.2 Hardware and Software Implementation

The hardware components selected are the Arduino UNO, 8 channel 12 V relay module, voltage sensors and super capacitor. Instead of choosing MOSFET switches and optocoupler as gate driver to build balancer is mainly due to lacking experience that led to fail attempts on controlling MOSFET switches that lead to fail attempt. As the original design was to use MOSFET switches to control the balancer process, however every attempt to do balancing using MOSFET switches yielded with failure for weeks. Balancer build using MOSFET switches is shown in Figure 4.1. Therefore, due to time constraint, using relay module is the easier solution to replace MOSFET switches. At the same time, the PCB of the balancer using MOSFET switches had finish fabrication which is designed using Autodesk Fusion 360. Unfortunately, with the replacement of MOSFET switches to relay module, the PCB board shown in Figure 4.2 can no longer be used. Luckily with the replacement, the balancer would work perfectly.

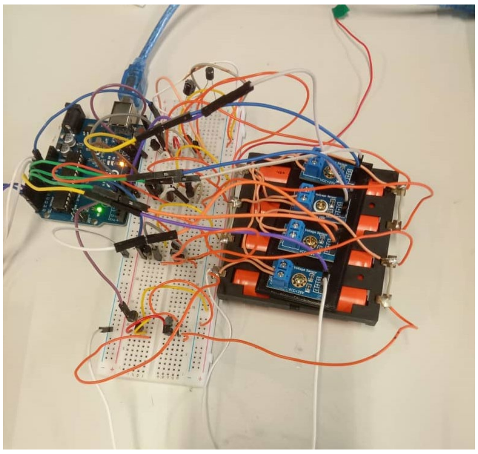


Figure 4.1: Prototype build using MOSFET switches.

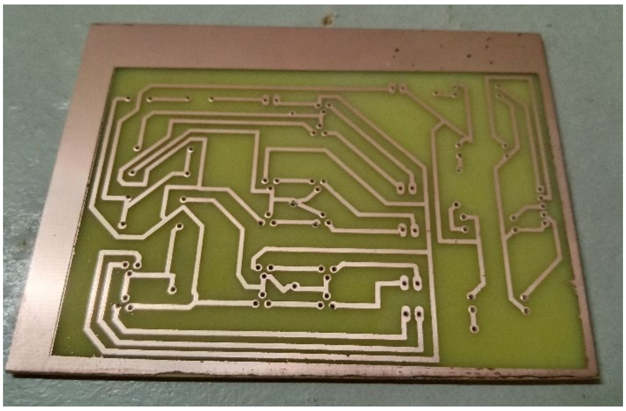


Figure 4.2: PCB Board Version 2.

The connection of the balancer is every battery's positive and negative terminals are connected the Normally Open (NO) of the relay module. The positive terminals of the batteries are connected to 1st, 3rd, 5th, 7th relay's NO port respectively while the negative terminals are connected to 2nd, 4th, 6th, 8th relay's NO respectively. Then the COM port of 2nd, 4th, 6th, 8th relay are connected to the negative terminal of the super capacitor respectively while the 1st, 3rd, 5th, 7th relay are connected to the positive terminal of the super capacitor respectively. The connection of the voltage sensor is shown in Figure 4.3. This connection enables the microcontroller to calculate each of the voltage level for every battery. This is because throughout the project, it is found that the connection of voltage sensors cannot be each sensor parallel to each battery, this would cause short circuit. The calculation to obtain the voltage of each battery is by subtracting the first voltage level of first battery from total voltage of two batteries to get the second battery's voltage, then do the same for the third and fourth battery.

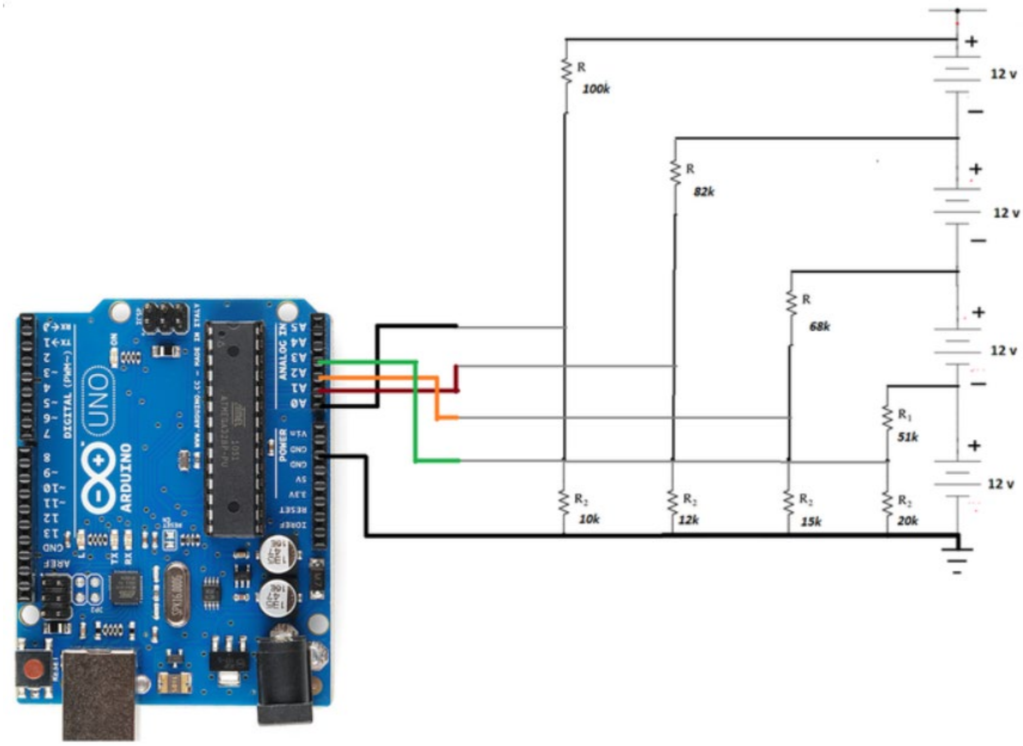


Figure 4.3: Connection of the Voltage Sensors (Eg Projects, 2019).

The microcontroller is programmed using the Arduino IDE. In the code, the sensor pins are set to pin A0 to A3 while the relay pin are set to pin 2 to 9. There is a monitoring system that collect the voltage from sensors calculate the respective voltage and send it to the serial port. By default, the relays are set to off. In the loop, the monitoring system will be run first then followed by the turning on of 1st and 2nd relays for three seconds, and the rest of the relays are off. 3rd and 4th relays will be turned on after 1st and 2nd relays turned off which followed by 5th and 6th relays then 7th and 8th relays. The whole cycle for the loop is twelve second, thus the voltage of the batteries will be recorded for every twelve second. The loop will keep on run until manually disconnecting the power supply to the relay module.

The CoolTerm is set to the same serial COM port as the microcontroller and same baud rate in the Arduino code. The testing for the prototype under stationary, charging and discharging are conducted. CoolTerm is immediately connecting to the serial port and collecting the data from the sensors shown in Figure 4.4.

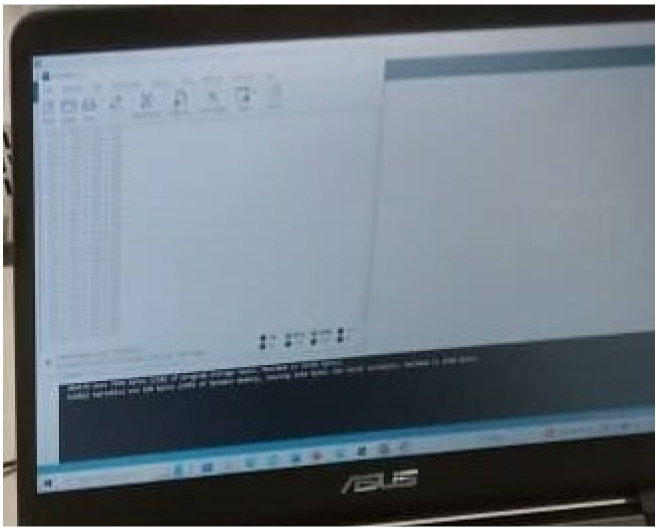


Figure 4.4: CoolTerm collecting Data from Balancer.

After finished setting up for the hardware components and software code shown in Figure 4.5. Figure 4.6 to Figure 4.10 show the stationary balancing test, charging without balancing, charging balancing test and discharging without balancing, discharging balancing test respectively using the prototype.

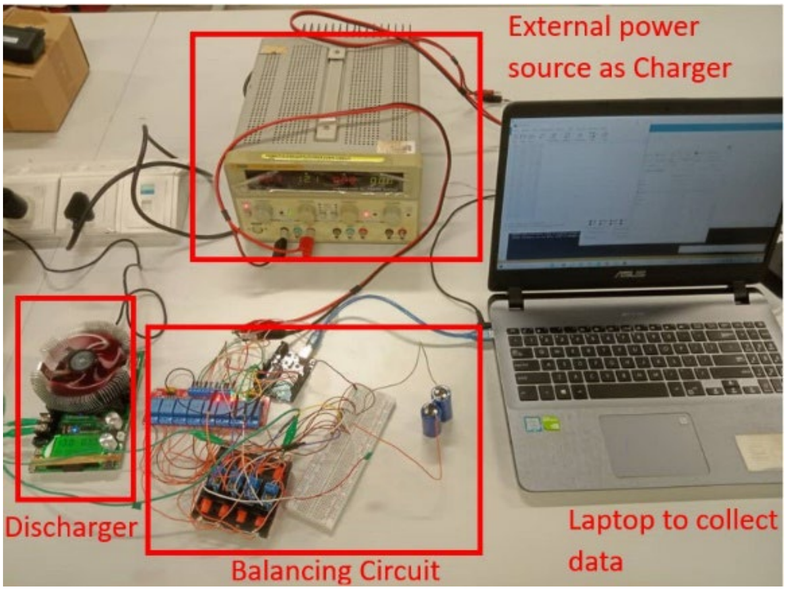
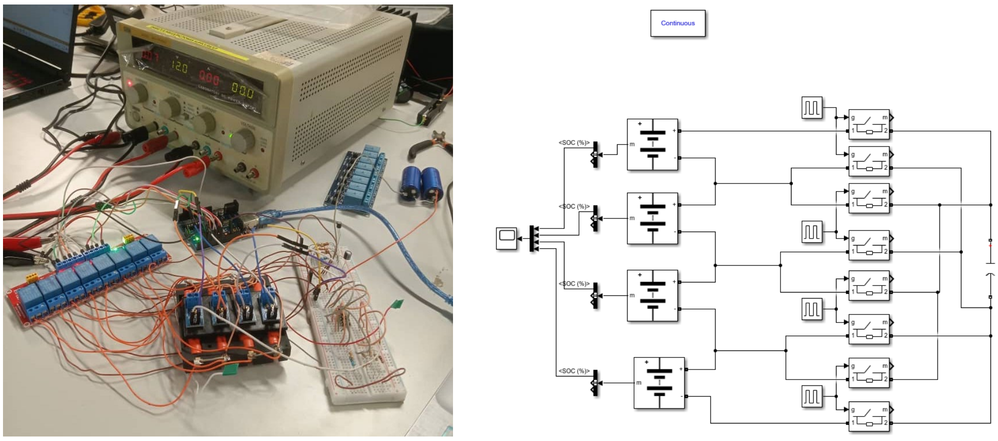
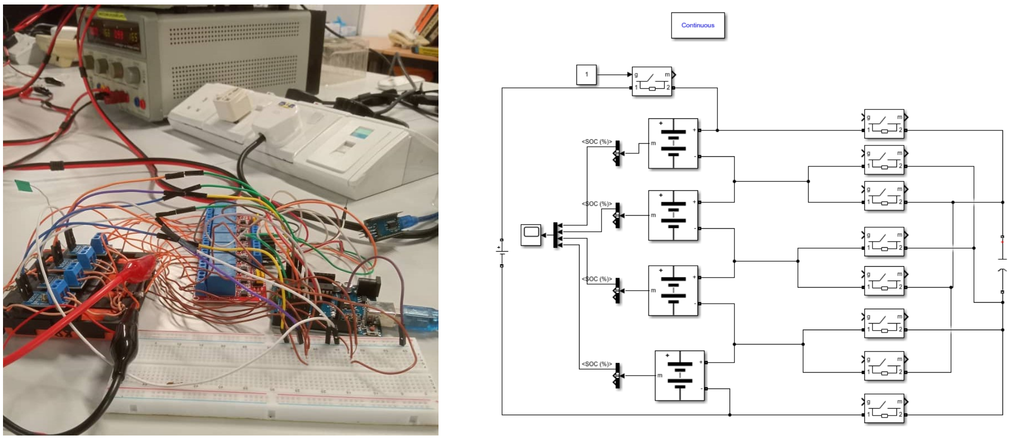


Figure 4.5: Setting for the Hardware components and Software coding.



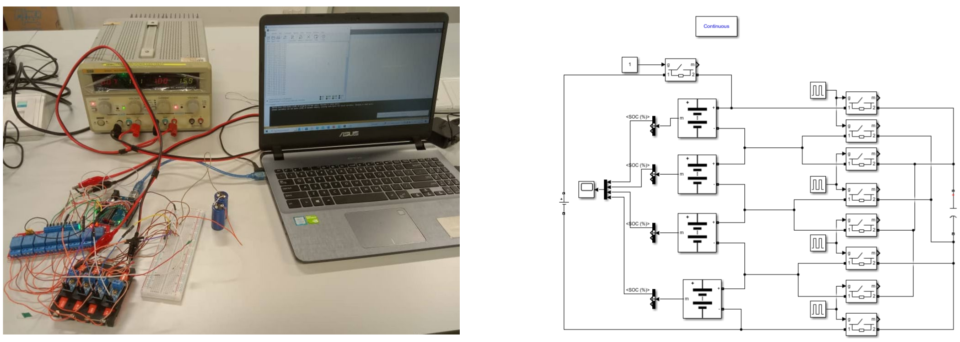
(a) (b)

Figure 4.6: Stationary Balancing Test Setting for (a) Hardware Prototype and (b) Software illustration.



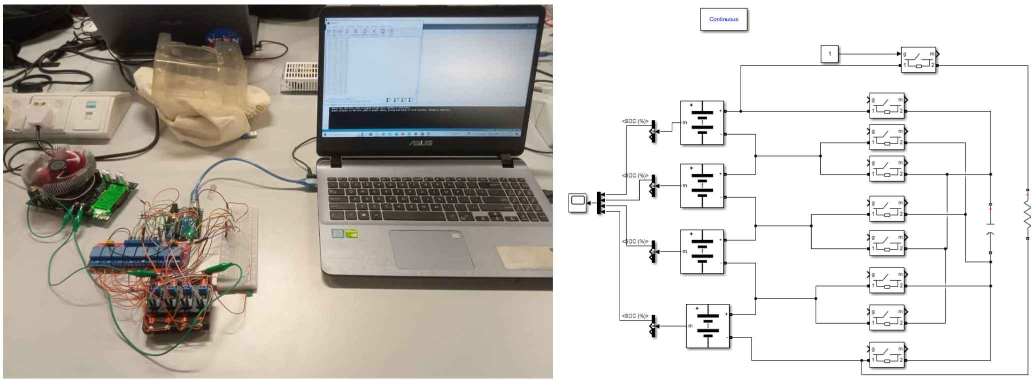
(a) (b)

Figure 4.7: Charging without Balancing Setting for (a) Hardware Prototype and (b) Software illustration.



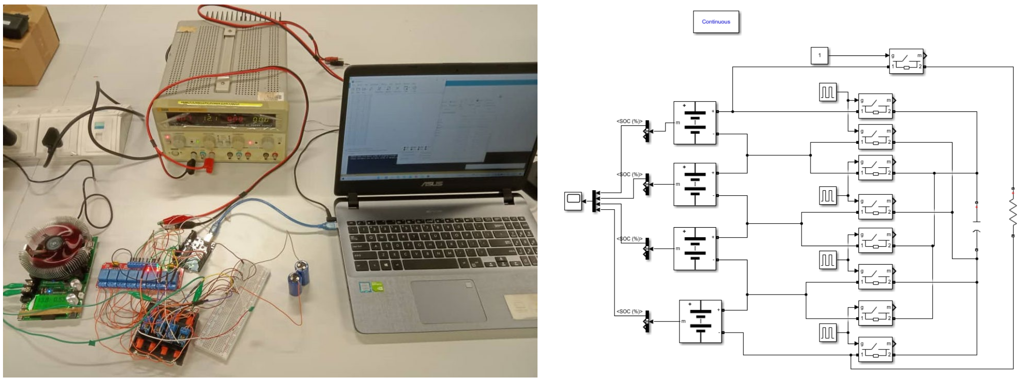
(a) (b)

Figure 4.8: Charging Balancing Test Setting for (a) Hardware Prototype and (b) Software illustration.



(a) (b)

Figure 4.9: Discharging without Balancing Setting for (a) Hardware Prototype and (b) Software illustration.



(a) (b)

Figure 4.10: Discharging Balancing Test Setting for (a) Hardware Prototype and (b) Software illustration.

For the software simulation, the circuit shown in Figure 4.11 is constructed using MATLAB Simulink. For batteries, their SOC are set to 80%, 70%, 60% and 50% respectively. The pulse generators are used to turn on and off the relay while the first ideal switch is used to decide whether to do the charging and the second ideal switch is used to decide whether to do the discharging. After running the program, the result will be displayed in the scope and can be exported to excel to plot standard deviation.

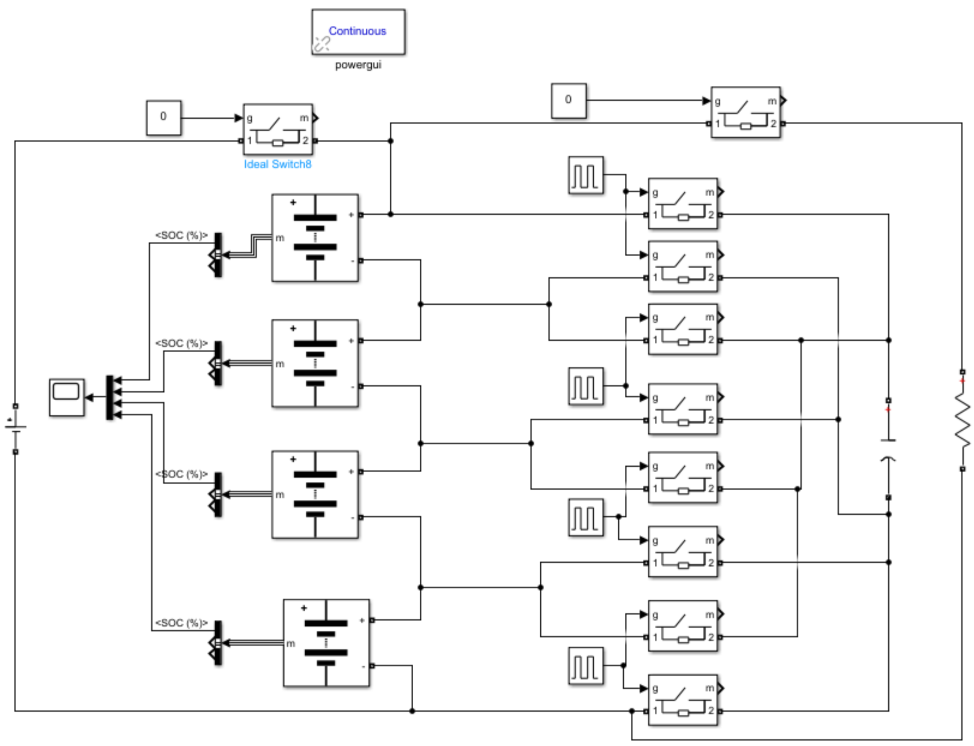


Figure 4.11: Balancer constructed in MATLAB Simulink.

4.3 Hardware Prototype’s Results and Discussion

Standard deviation is used as an indicator to observe its overall trend and its percentage different from the starting and ending of the process from the graph, whether there is any balancing effect. Standard deviation is a statistical tool used to quantify the level of variation or dispersion in a collection of data points is the standard deviation. It shows the degree to which individual data points differ from the dataset's mean or the average. Stated differently, it calculates the average difference between the data points and the mean. A higher standard deviation indicates a greater degree of dispersion among the data points, whereas a lesser standard deviation suggests that the data points are generally near the mean. The standard deviation would be good to use when evaluating how battery voltages converge over time. It shows how closely the voltages are approaching each other as the batteries balance in a straightforward and understandable manner.

4.3.1 Voltage measurement, Charging and Discharging without Balancing

Figure 4.12 shows the one-hour measurement of the four batteries in series. From the graph, there is no significant changes, and it has a relatively stable voltage profile over the duration of the measurement, other than some fluctuation which is majorly caused by the noise from the voltage sensor module. These fluctuations are noticeable, but it did not have correlation with significant changes in battery voltages. The standard deviation from the starting point of the measurement is 0.330 while the ending point of the measurement is 0.322. By using the percentage difference formula which is the ending point of the measurement minus the starting point of the measurement then divided by the starting point and multiplied by one hundred. From the calculation, the standard deviation has decreased approximately by 2.42%.

However, with the present of the noise, the difference between the standard deviation from starting and ending point will be affected by the fluctuation. With the noise present in the data, the standard deviation will be affected by some random variation that does not represent any meaningful shifts in battery voltages. Which in this case, the slight change in the standard deviation can be ignored. Fortunately, the standard deviation can still interpret the data well with minor effect from the noises. Absence of balancing mechanism is the cause of the stable battery voltages over duration of one hour. Thus, it shows that only with measurement of the batteries and without balancing action, the standard deviation will not change.

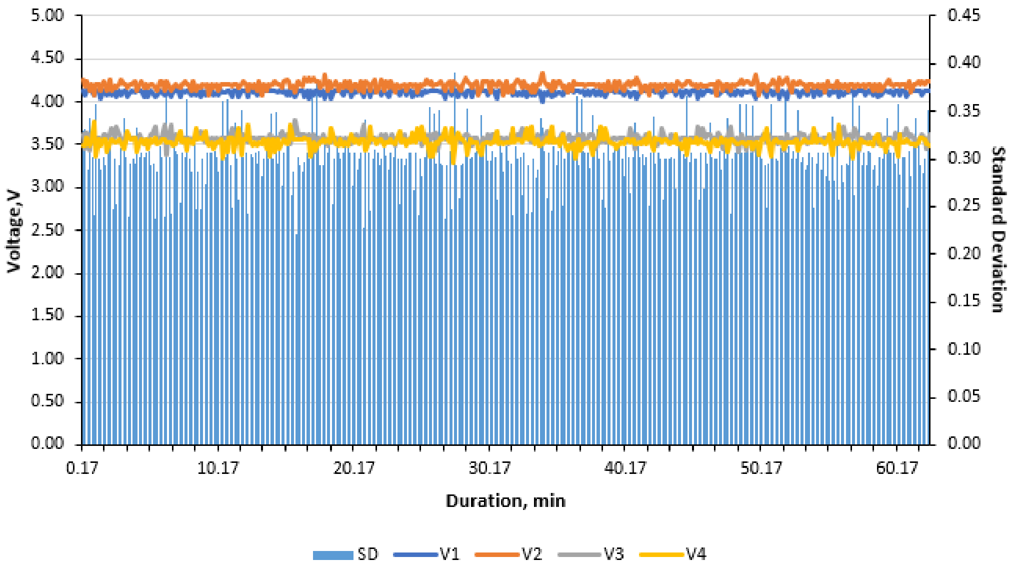


Figure 4.12: Stationary test of the batteries without prototype.

Figure 4.13 shows the charging without balancing action for the batteries. From the graph, it shows that all four of the battery voltages increase rapidly at first five minutes and then turned to increase gradually over time and steadily approaching to each other in value throughout seventy minutes of charging. After seventy minutes of charging period, a noticeable reduction in voltage differences among the batteries was observed. The standard deviation from the graph shows a trend of decreasing and its value at the starting point is 0.0940, while the standard deviation at the ending point is 0.0371 which a significant drop of 60.53% was observed.

This result shows that the battery voltages have smaller differences at the end of the charging cycle. This is because of the batteries that have lower voltage (V1 and V2) are charged up faster than the batteries that have higher voltage (V3 and V4) due to their reduced capacity and internal resistance. Besides, the charging current is affecting the charging rate of the batteries as lower voltage batteries can handle higher charging current with their lower stored energy and without facing negative effects such as overheating. Hence, lower stored energy and internal resistance adding to higher charging current caused the battery voltage to increase much faster than higher voltage batteries and speed up the charging process for lower voltage batteries. However, after the battery voltage reach a value near to higher voltage batteries, the charging process will slow down and charging rate will become more or less the same as the higher voltage batteries. Same as what the graph showed, the battery voltages increase drastically and then after the battery voltages are near to each other in value, the increment of voltage slows down and increase gradually throughout the charging process. Ultimately, it revealed the notable trends in the convergence of battery voltages over time.

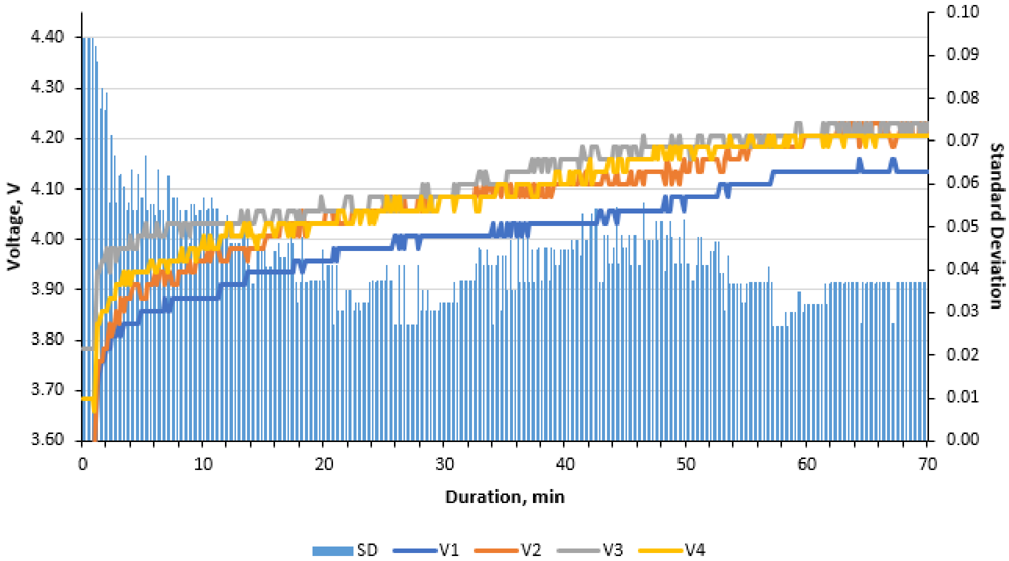


Figure 4.13: Charging test of the batteries without prototype.

Figure 4.14 shows the discharging without balancing of the four series batteries. By observing the graph, it can be seen that the battery voltages are decreasing steadily throughout the seventy minutes of discharging process. Similar to the charging without balancing, the battery voltages also gradually closing to each other in value and show trend of the voltages getting nearer to each other.

At the first three minutes, the voltages dropped rapidly and continue to drop steadily after that. Similar to the explanation in the charging process of battery, the lower voltage batteries (V1 and V4) will discharge faster also due to the reduced stored energy capacity. Reduced stored energy indicates less energy stored and it will deplete the energy faster. Lower voltage batteries also often have lower capacity and lead to less energy stored compared to higher voltage batteries (V2 and V3). Thus, the combination of lower stored energy capacity and lower overall capacity in lower voltage batteries results in faster discharge rates compared to higher voltage battery. The trend of the standard deviation also showing a decreasing sign. The standard deviation at the beginning is 0.0746, while the value becomes 0.0280 at the ending of the process, marking a 62.47% drop in standard deviation. This shows that the voltage difference between the batteries has indeed been reduced.

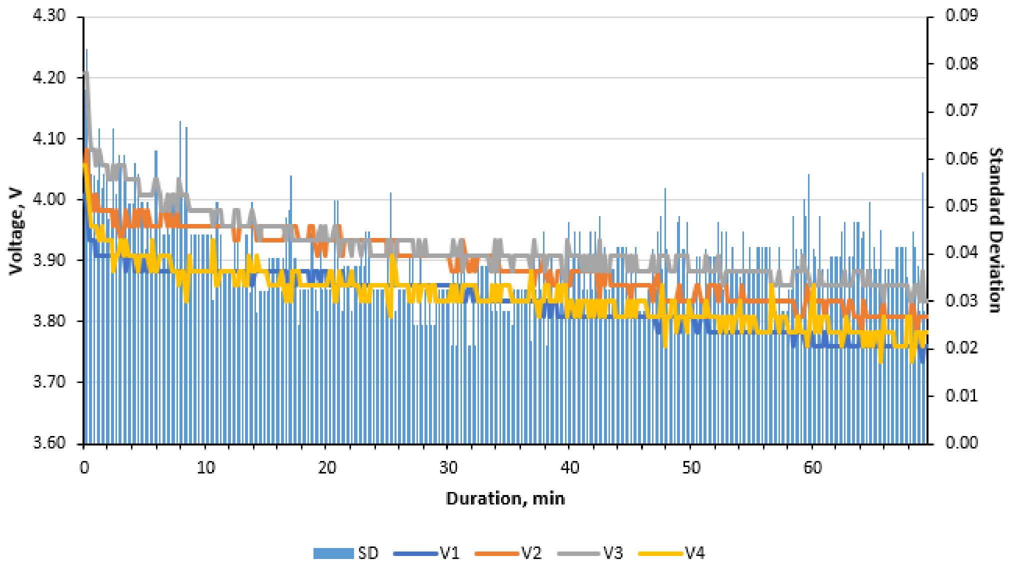
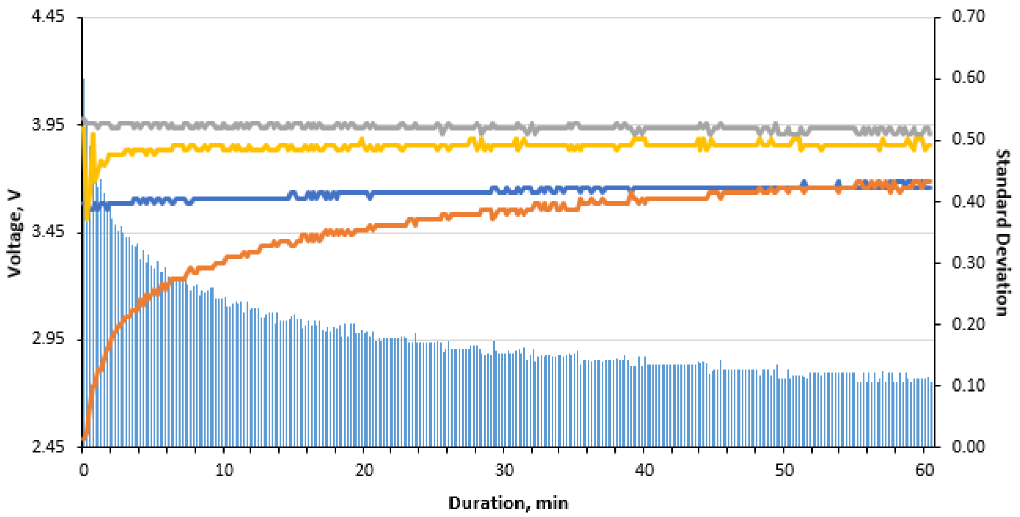


Figure 4.14: Discharging test of the batteries without prototype.

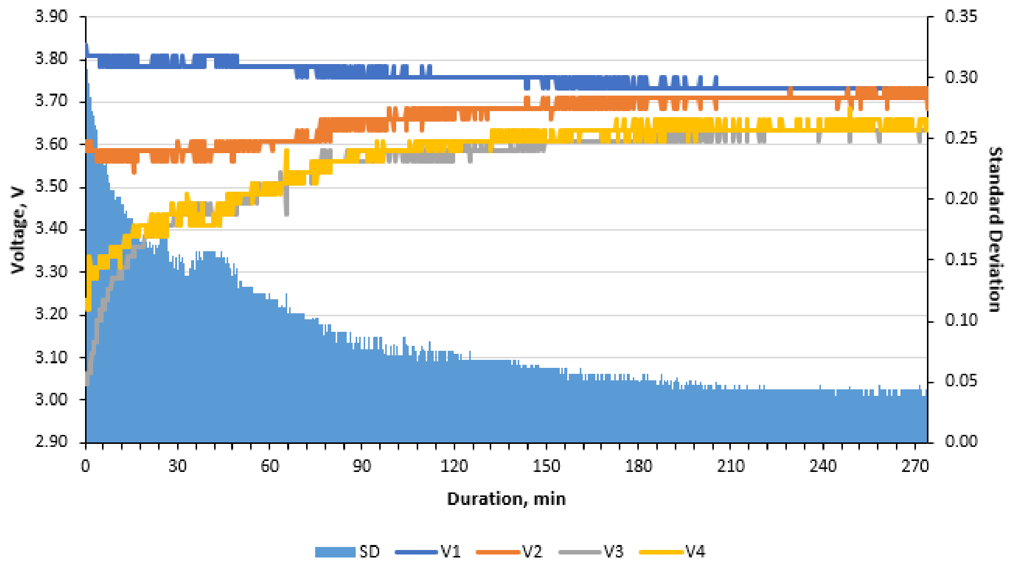
4.3.2 Stationary Test

Figures 4.15 shows the performance of prototype balancing circuit under stationary balancing conditions for different durations which is one hour and four and a half hours. Given the results, they show that the voltage will increase for the lower voltage batteries and the voltage will drop for higher voltage batteries, and there is the evident balancing effect achieved by the prototype circuit in the process. Throughout the balancing process, the lower voltage batteries (V2 in first graph, V3 and V4 in second graph) gets significant increase in voltage level, while the higher voltage battery (V1, V3 and V4 in first graph, V1 in second graph) decreases slightly in voltage level.

This behaviour indicates a successful redistribution of charge among the batteries, resulting in a more uniform voltage distribution across the battery pack. The important aspect of the analysis is the balancing effect shown through standard deviation reduction. The standard deviation is comparatively high at the start of the balancing process, indicating large differences in voltage between the batteries. Yet as the balancing goes on, the standard deviation significantly drops, showing a declining trend, and by the time the stationary balancing phase ends, the numbers are noticeably lower. For example, the standard deviation in the first graph decreases by 82.06%, from 0.602 to 0.108. Comparably, the standard deviation in the second graph drops from 0.303 to 0.0392, reflecting a significant 87.06% reduction. The standard deviation difference at the beginning of both is due to the initiate batteries' voltage level are different, therefore higher initial standard deviation for first graph due to larger difference in batteries' voltage levels.



(a)



(b)

Figure 4.15: Stationary tests of the batteries with prototype under (a) wider and (b) narrower starting point standard deviation.

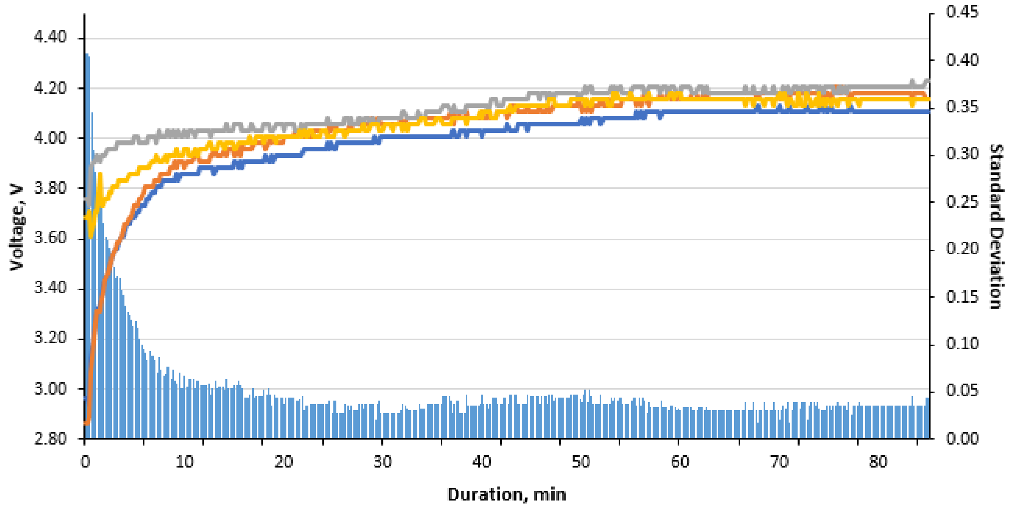
These results demonstrate the way the prototype circuit works to reduce voltage variations and maintain battery voltage stability when operating stationary balancing. Comparing the results between the one hour and four and a half hour balancing durations provides valuable insights into the long-term effectiveness of the balancing circuit. While both durations demonstrate significant standard deviation reduction and voltage stability, the stationary balancing with longer duration shows slightly better performance by a 5% difference in standard deviation.

4.3.3 Charging Test

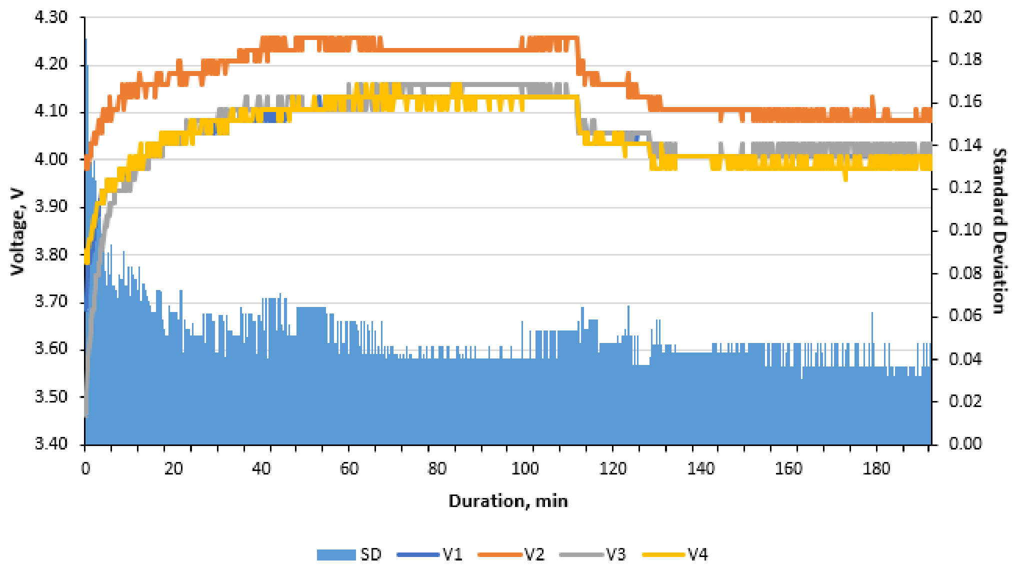
The charging process using the prototype balancing circuit is demonstrated by the results is shown in Figure 4.16. In the first charging process, charging continues unaffected for 85 minutes. In the second charging process, charging lasts for 112 minutes before going into a 75-minute phase of balancing, for a total of 187 minutes.

The batteries' voltage values show an obvious balancing effect in both plots as they converge over time. All batteries charge quickly for the first ten to twenty minutes, following that their voltage values slowly approach. From both graphs, the trending of decreasing standard deviation is observed. In the first graph, there is a 90.54% difference in standard deviation from the beginning at 0.467 to the end of the charging period at 0.0442 shows a drop in the trend of the standard deviation. similarly in the second graph, at the ending of the charging period, the initial standard deviation of 0.190 drops to 0.0446 which has decrease in percentage by 76.53%, and then it drops even lower to 0.0370 by percentage difference of 17.04% during the following 75-minute balancing phase.

The batteries' voltages slightly decrease after the charging stops, but they then stabilise during the balancing procedure that follows. As the explanation for this phenomenon, it is called voltage relaxation, which occurs when chemical reactions within batteries achieve equilibrium and cause a little voltage to decrease. After charging, the voltage stabilises and stays mostly constant as long as there is no demand on the batteries or any external or internal factors causing significant shifts. Overall, the results indicate that the prototype is capable of providing effective balancing even during the charging phase.



(a)

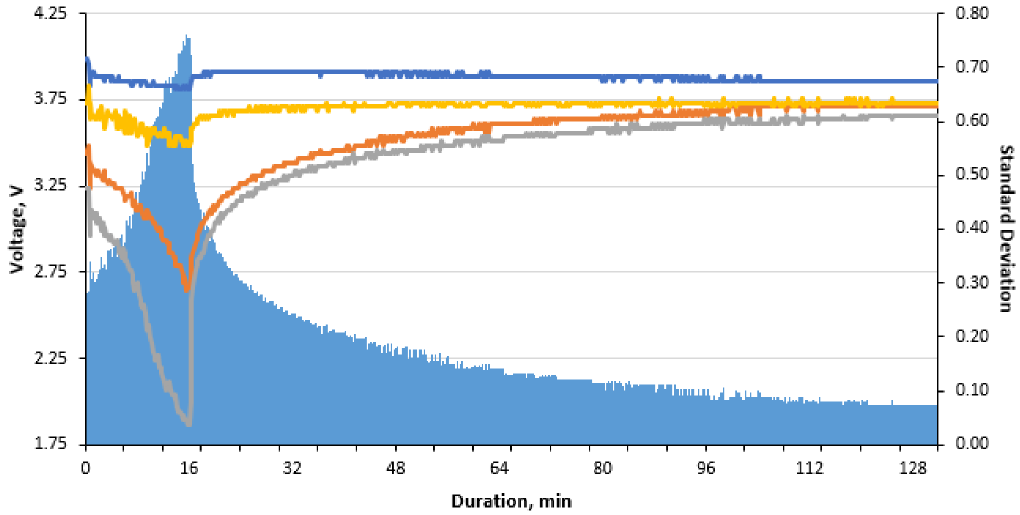


(b)

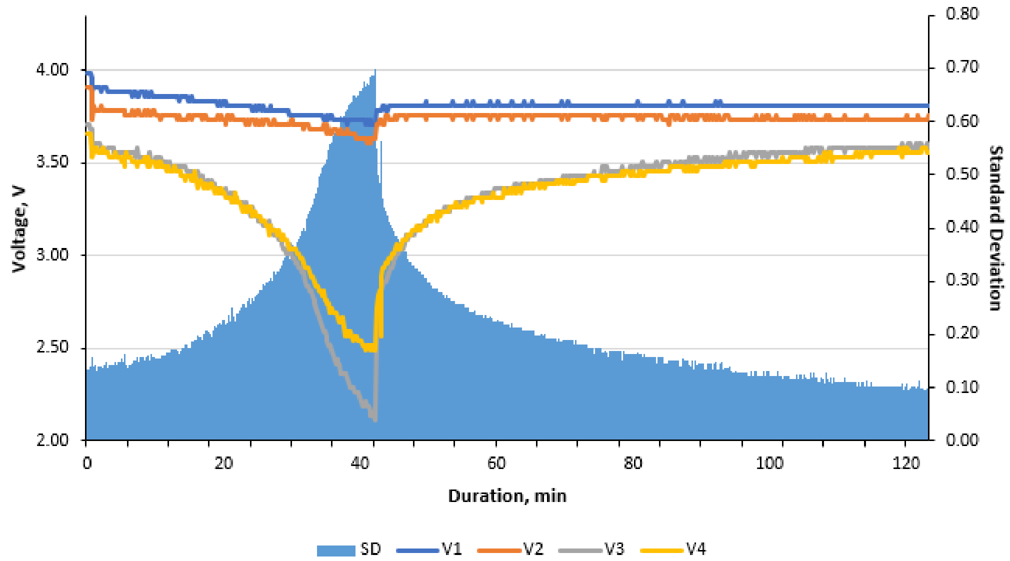
Figure 4.16: Charging tests of the batteries with prototype under (a) wider and (b) narrower starting point standard deviation.

4.3.4 Discharging Test

Figure 4.17 shows the discharging with balancing using the prototype. In the first discharging process, the discharging process continues until one of the batteries which is V3 reaching voltage level of 2 V which lasts for 16 minutes and stop discharging and continue with balancing only for another 115 minutes where the whole process takes 131 minutes. For the second discharging process, same as first discharging process the discharging process continues until one of the batteries which is also V3 reaching voltage level of 2 V then which lasts for 42 minutes and stop discharging and continue with balancing only for another 81 minutes where the whole process takes 123 minutes.



(a)



(b)

Figure 4.17: Discharging tests of the batteries with prototype under (a) wider and (b) narrower starting point standard deviation.

The differences between the first and second discharging process are first process has higher initial standard deviation which means that their batteries voltage difference is larger, and second process takes slightly shorter time. The initial standard deviation for first process is 0.285, and it goes up to 0.724 at the end of discharging, and finally drop to 0.0733 after the balancing process. The standard deviation increases by a surprising percentage of 154% after discharging follow by a drop in percentage of 89.88%. While for the second process, the initial standard deviation is 0.134, then it goes up to 0.698 after discharging, then drop to 0.0985 after balancing. The standard deviation increases by 421% after discharging follow by a drop in percentage of 85.89%.

From both discharging processes, they reveal that the prototype does not have balancing effect during the discharging process as the trend of standard deviation shown is increasing. This is because the discharging process is too much for the prototype to handle as the discharging rate is much faster than the balancing rate.

4.4 Software Simulation Results and Discussion

The relationship between voltage and state of charge (SOC) in many battery systems is nonlinear, which means that a battery's voltage does not fluctuate in a linear fashion with its SOC. Instead, depending on factors such as battery chemistry, temperature, load conditions, and ageing, the voltage may show complex behaviour, such as voltage hysteresis or nonlinear voltage profiles.

It can be difficult to simulate this nonlinear relationship between SOC and voltage accurately. Sophisticated modelling approaches or large computational resources may be required to obtain precise voltage values for each battery in different states of charge, depending on the complexity of the simulation model and the unique characteristics of the batteries being simulated.

Since it is difficult to obtain precise voltage values directly from the simulation, comparing the voltages using standard deviation can be used as a replacement to determine whether the battery voltages are convergent. Without needing exact voltage readings for each battery at different levels of charge, the standard deviation able to give an estimate of the spread or dispersion of the voltage values, allowing to determine how closely the voltages of the batteries are approaching each other as they balance.

4.4.1 Voltage measurement and Charging without Balancing

Figure 4.18 shows the software simulation conducted to measure the voltage levels of four lithium-ion batteries arranged in series for a duration of 1 hour. The graph's analysis shows that there were no obvious fluctuations or noise during the test time, and each battery's voltage levels stayed constant as well as the standard deviation. At the end of the measurement, the initial standard deviation, which was measured at 11.18, did not change, indicating a 0% change in standard deviation. This consistency indicates that the batteries' voltage levels remained constant throughout the simulation, indicating a perfect situation free from noise and losses. The prototype can be compared to the simulation as a clear reference point to determine how well it performs in practical settings.

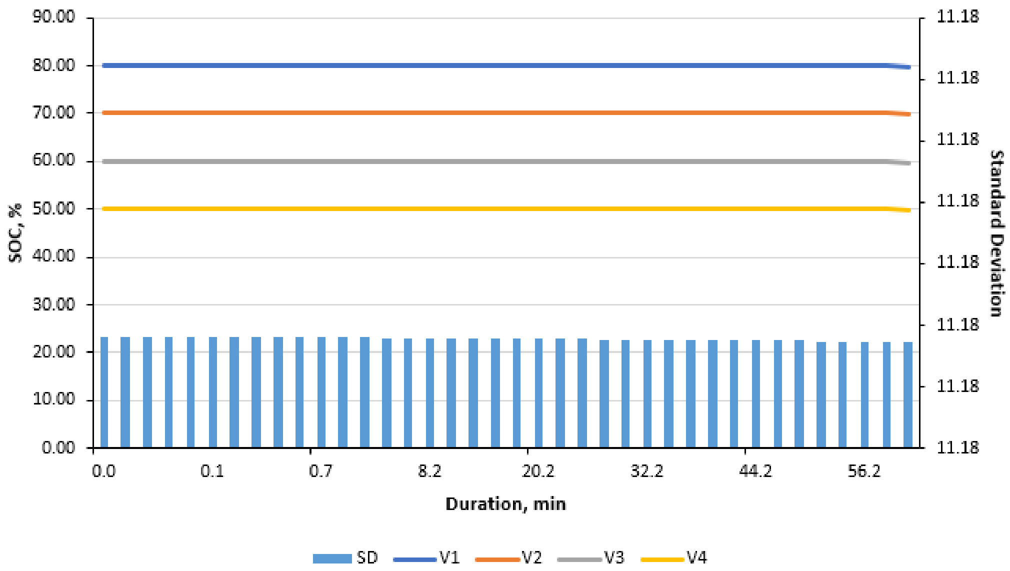


Figure 4.18: Stationary test of the batteries without prototype.

Figure 4.19 shows the software simulation of charging without balancing. As what can be observed in the graph, the charging process that is carried out without the use of prototype balancing circuit is showing that it takes a longer time taken for each battery to reach full charge. All batteries eventually reach full charge, but it takes a lot longer than expected. By analysing the standard deviation, it shows a trending of decreasing and can be seen that the starting value of 11.18 has significantly decreased to 0.870, indicating a reduction of 92.22%. Therefore, showing a successful balancing action.

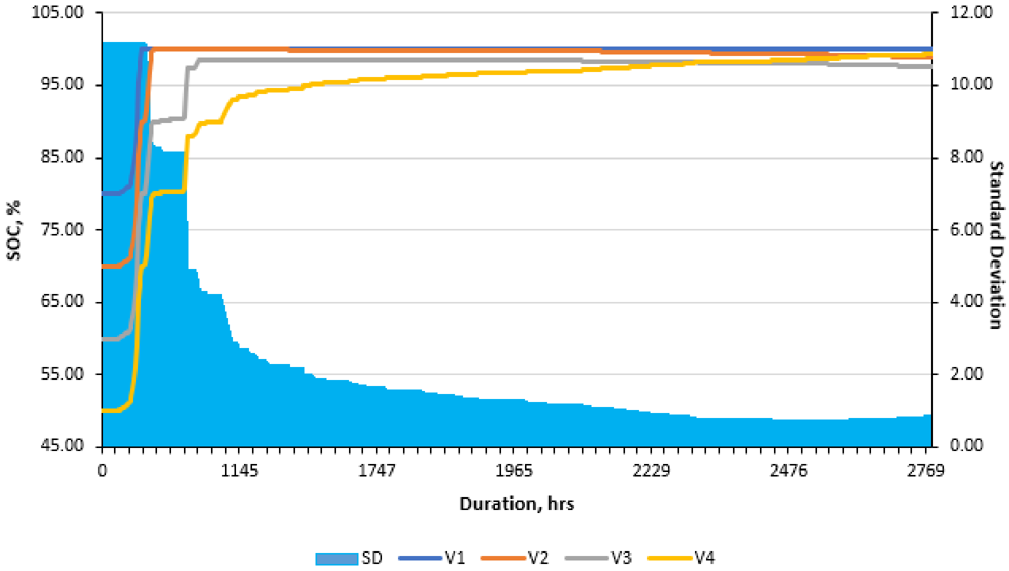


Figure 4.19: Charging test of the batteries without prototype.

4.4.2 Stationary Test

Figure 4.20 shows the stationary test with prototype balancing circuit using software simulation. The software simulation is conducted to show the stationary balancing process using the prototype circuit, it reveals that the voltage levels of the batteries gradually equalize over a period of 27 hours. Over this time, the standard deviation gradually drops from 11.18, the starting value, to 0.221, signifying that the voltages of the batteries have been fully balanced. This 98.02% reduction in standard deviation indicates that there are no longer any noticeable variations between the batteries' voltage levels, which are perfectly balanced. This has shown how well the prototype circuit achieved voltage uniformity and maximised battery performance in an ideal case.

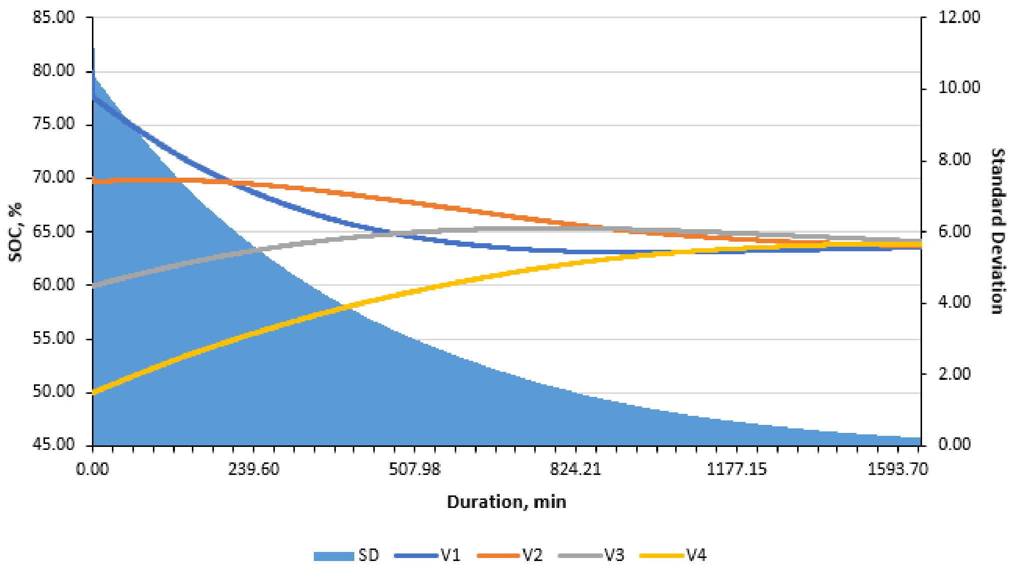


Figure 4.20 Stationary test of the batteries with prototype.

4.4.3 Charging Test

Figure 4.21 shows the charging test with prototype balancing circuit using software simulation. The charging process is conducted with the prototype balancing circuit, it demonstrates the capability of achieving complete voltage equalization among the batteries within approximately 105 minutes, as evidenced by the graph. The variation starts out at 11.18 and goes down to 0.000124 during the process, thus signifying an approximately 100% reduction in standard deviation and perfectly balanced battery voltages. This demonstrates the ideal situation on the ability of the prototype to perfectly balanced the battery voltages under charging condition.

4.4.4 Discharging Test

Figure 4.22 shows the discharging test with prototype balancing circuit using software simulation. The discharging process is conducted using the prototype and it spans approximately 500 minutes. The graph shows that, in ideal scenarios, the prototype may achieve perfect balancing. All batteries show balanced voltages at the end of the operation, with a 100% decrease in standard deviation. This result highlights the prototype's ability to balance battery voltages properly and shows that, under ideal conditions, it can achieve optimal voltage uniformity.

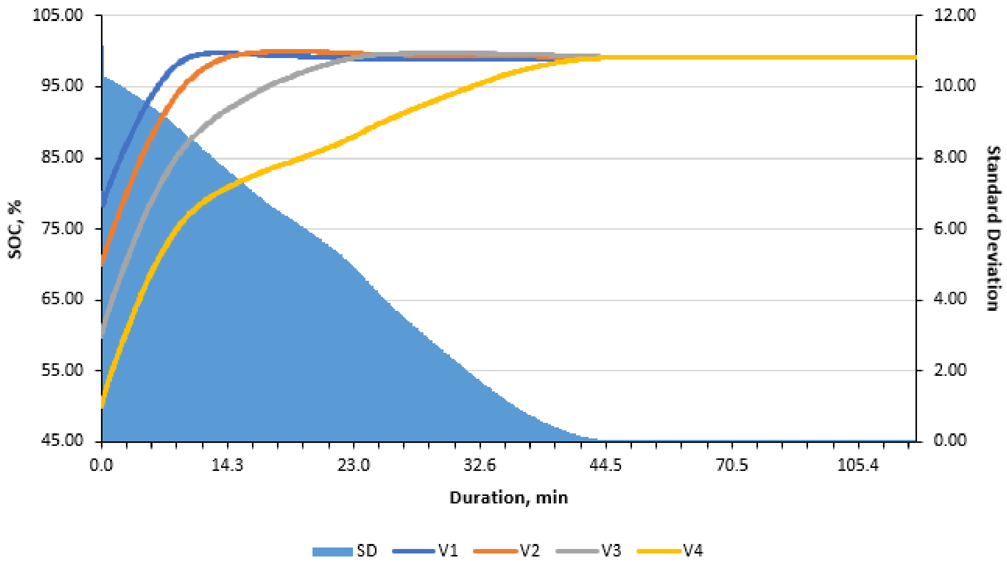


Figure 4.21: Charging tests of the batteries with prototype.

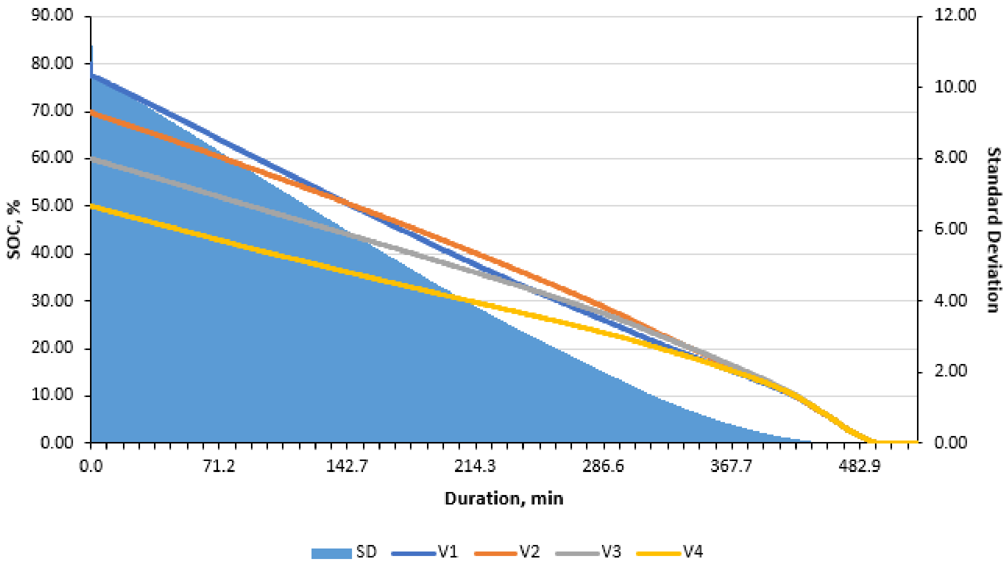


Figure 4.22: Discharging tests of the batteries with prototype.

4.5 Comparison of Hardware and Software Prototype's Results

To compare the software simulation and hardware prototype, the trend of the standard deviation observed in the graph and the percentage difference of the standard deviation at the start and end of the graph are used as the indicator. The results of both hardware prototype and software simulation are tabulated in Table 4.1. For the voltage measurement for hardware prototype, is it clearly that there is no balancing effect as there is no balancing circuit to be used. There is 2.42% change in the standard deviation, but it can be ignored as it has only insignificant change in value. This can also be proven in the software simulation that there is 0% change in standard deviation. While for the charging without balancing and discharging without balancing using hardware prototype, even though the percentage difference of the standard deviation for the charging and discharging without balancing have a reduction in standard deviation and battery voltages are approaching each other in value as if there were balancing effect. It is actually the nature of the battery as they are fully charged or discharged, the voltage level of the batteries will eventually become the same and the difference in voltage level will disappear, each meeting at maximum value of 4.2 V or minimum value of 0 V. The software simulation shows the same thing as there is 92.22% reduction in standard deviation for charging without balancing.

For the stationary balancing, the hardware prototype has proven to be balancing the batteries charges indicated by the reduction of standard deviation by 82.06% and 87.06%, and the overall trend of standard deviation are dropping for 2 sets of results. During the stationary condition, the respective relay module for each battery will be turned on and off to transfer the energy from higher voltage battery to lower voltage battery. As there is no load to use the energy nor source to supply the energy to the batteries, it takes longer time to equalize the energy between the batteries. In the software simulation, the ideal case shows that the prototype is able to perform with no waste or losses and achieve 98.02% balancing which can be approximate to 100% as well as the trend of the standard deviation shows that it dropped to value approximate to zero at the end of balancing. However, in the simulation, it would need to take up to 27 hours to achieve the complete balancing which is much longer duration than the hardware prototype which used 5 hours. The software simulation has a better performance when compared to the hardware prototype as it has greater percentage change of 13% to 18% than the hardware prototype.

For the charging with balancing, the hardware prototype has also proven that it is able to achieve balancing effect indicated by the reduction of standard deviation by 90.54% and 76.53% for 2 sets of results. When compared to the charging without balancing, the reduction of standard deviation of charging with balancing is 10% to 30% more than charging without balancing. This shows that there is a rise in reduction of standard deviation indicating there is indeed balancing effect when using the hardware prototype. When compared it to stationary balancing, it has faster balancing speed as the charging process also helps in storing energy to lower voltage batteries. In the software simulation, it also showed that the prototype is able to achieve complete balancing with shorter duration when compared to others. The result obtained in software simulation is much better than the hardware prototype, as it only need to take shorter duration to complete the balancing by 100% using only 45 minutes which almost twice as fast. Overall, it can be said that under charging condition, it has the faster balancing speed and balancing efficiency when compared to stationary balancing and discharging with balancing.

For the discharging with balancing, the hardware prototype results showed that it does not have the ability to balance the batteries voltage. Observing the standard deviation trending, it shows only increase in the value when under discharging process which are 154% and 421% increase in percentage for 2 sets of results. This is because the discharging rate is much faster than the balancing rate and cause it to have no impact on the voltage level and thus no balancing effect. Even with the slowest discharge rate at I = 0.5 A, the balancing speed is still not enough to make an impact to the volage level. However, in the software simulation, the prototype is able to achieve complete balancing in ideal case scenario as the standard deviation shows a trending of declining. As in ideal case, the losses can be ignored, the prototype will then be able to achieve balancing. By observing the trending of standard deviation, the sign of it decreasing reveals that it actually has balancing effect contradict to the results showed in hardware prototype.

Table 4.1: Comparison of Hardware and Software Results.

Conditions	Software Simulation				Hardware Prototype			
	Starting Point Standard Deviation, σ	**Ending Point Standard Deviation, σ**	**Percentage Difference, %**	**Balancing**	**Starting Point Standard Deviation, σ**	**Ending Point Standard Deviation, σ**	**Percentage Difference, %**	**Balancing**
Voltage Measurement	11.18	11.180	0.00	No	0.3300	0.3220	2.42	No
Charging Without Balancing	11.18	0.870	-92.22	No	0.0940	0.0371	-60.53	No
Discharging Without Balancing	-	-	-	NA	0.0746	0.0280	-62.47	No
Stationary Balancing	11.18	0.000	-98.02	Yes	0.6020 0.3030	0.1080 0.0392	-82.06 -87.06	Yes Yes
Charging With Balancing	11.18	0.000	-100.00	Yes	0.4670 0.1900	0.0442 0.0446	-90.54 -76.53	Yes Yes
Discharging With Balancing	11.18	0.000	-100.00	Yes	0.2850 0.1340	0.0724 0.6980	154.00 421.00	No No

4.6 Comparison of Hardware Prototypes from other Final Year Project Student

In this section, the comparison of active balancing circuit prototypes done in this project and prototype done by three other final year project student will be discussed. The first prototype is the prototype in this project which the results has already been taken.

The second prototype is done by a mechatronic engineer student, Lee Wei Ren shown in Figure 4.23. The prototype is a closed-loop switched-capacitor structure (CLSCS) is a proposed cell balancing technique that manages the charge among battery cells in a series-connected configuration shown in Figure. In the circuit structure, it consists of four series-connected cells, each linked to capacitors via switches, allowing for modular and efficient balancing. The result of this prototype is presented in Figure 4.26.

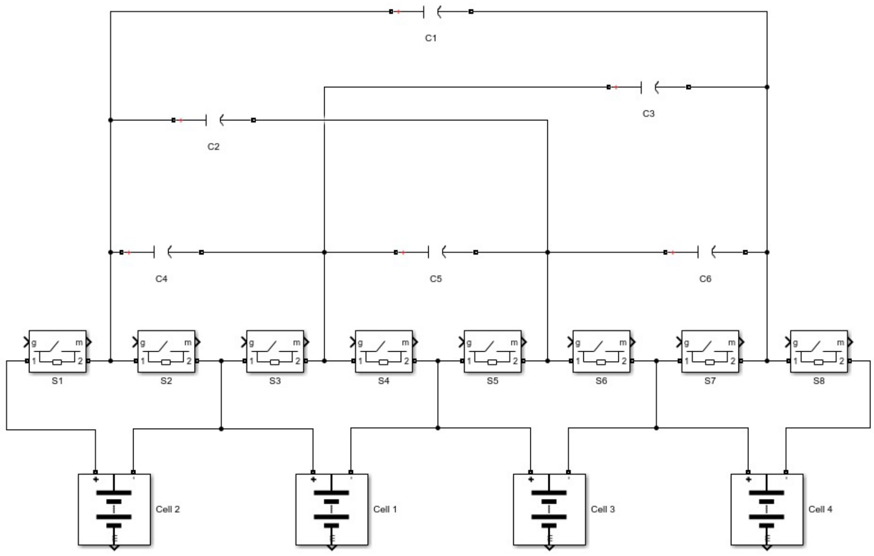


Figure 4.23: Closed loop Switched Capacitor Balancer by Lee Wei Ren.

The third prototype is done by electrical and electronic engineer student Jacky Wong Chew Soon shown in Figure 4.24. The prototype is a Single-tiered switched capacitor balancing circuit shown in Figure. In this circuit, there are three capacitors and 4 batteries in series, where the capacitors are placed parallel to the batteries. This allows the balancing to take place when the switch toggles, forming two states to link the capacitors in parallel with upper or lower batteries. The result of this prototype is presented in Figure 4.27.

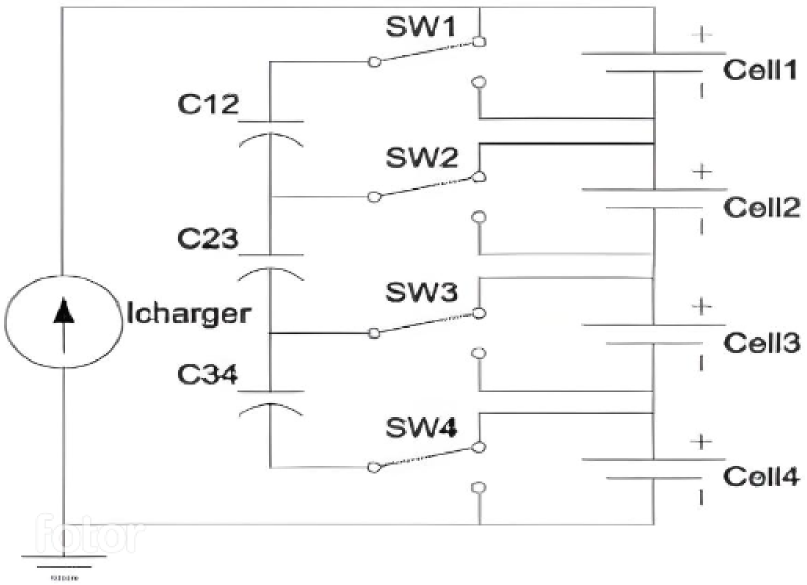
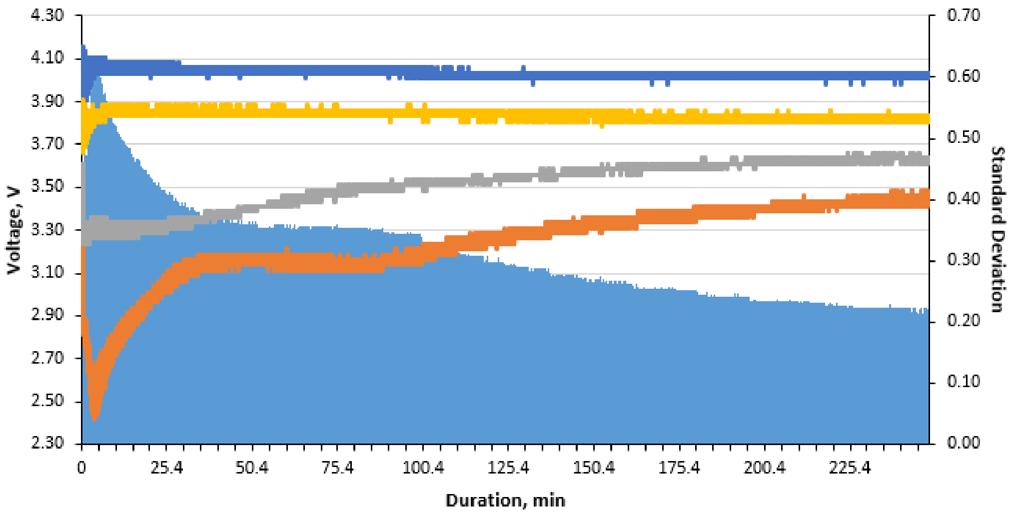


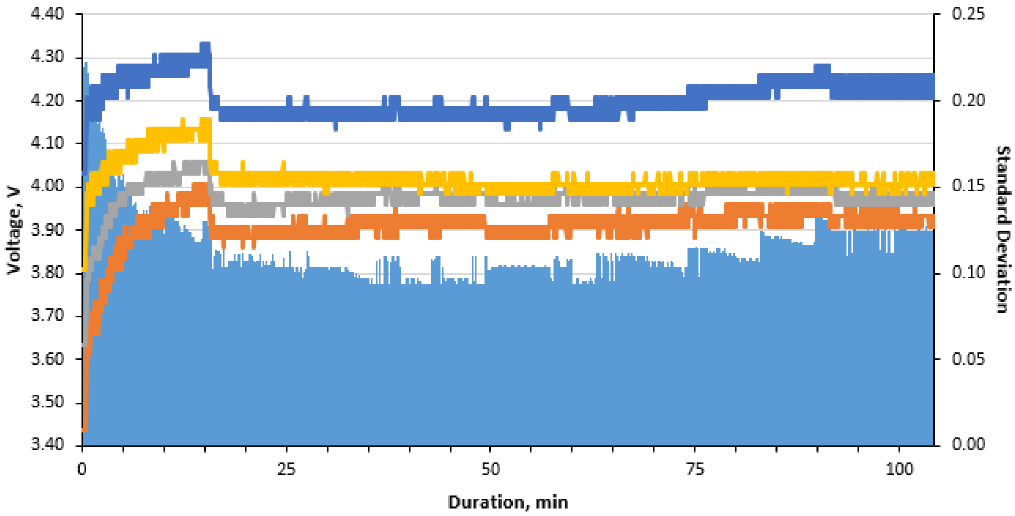
Figure 4.24: Single-tiered Switched Capacitor Balancer by Jacky Wong Chew Soon.

The last balancing circuit is brought from the market and done testing by Lee Yong Jun shown in Figure 4.25. This is an active balancing circuit from brand DALY, it supports 8S1P batteries configuration and balancing current of 1 A shown in Figure. This active balancing circuit comes with a smart BMS which enable consumer to monitor the voltage of each battery through phone using Bluetooth. The result of this prototype is presented in Figure 4.28.

Figure 4.25: Active Balancer from DALY by Lee Yong Jun.



(a)



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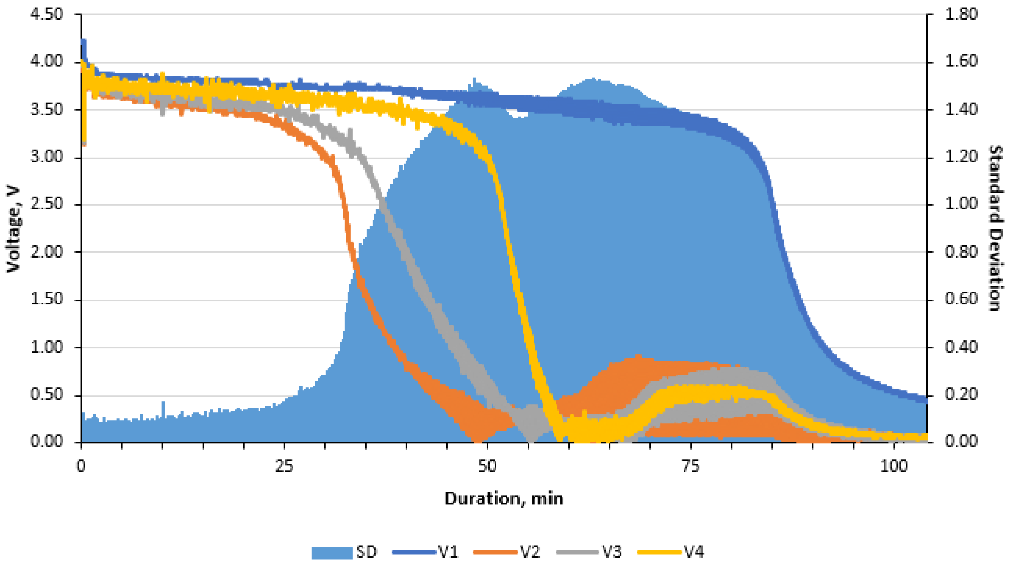


(c)

Figure 4.26: (a) Stationary, (b) charging, and (c) discharge tests of batteries with the prototype developed by Lee Wei Ren.

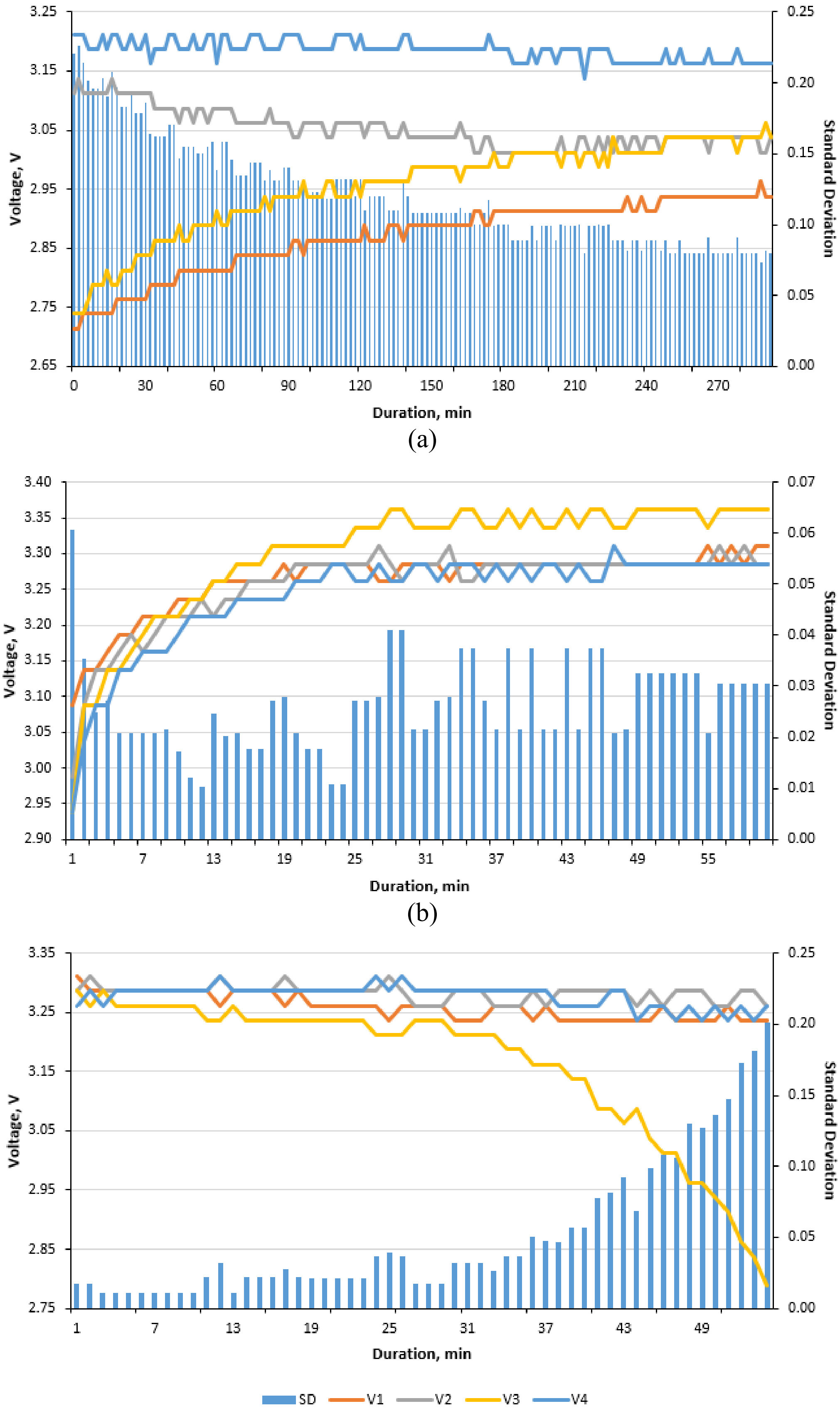
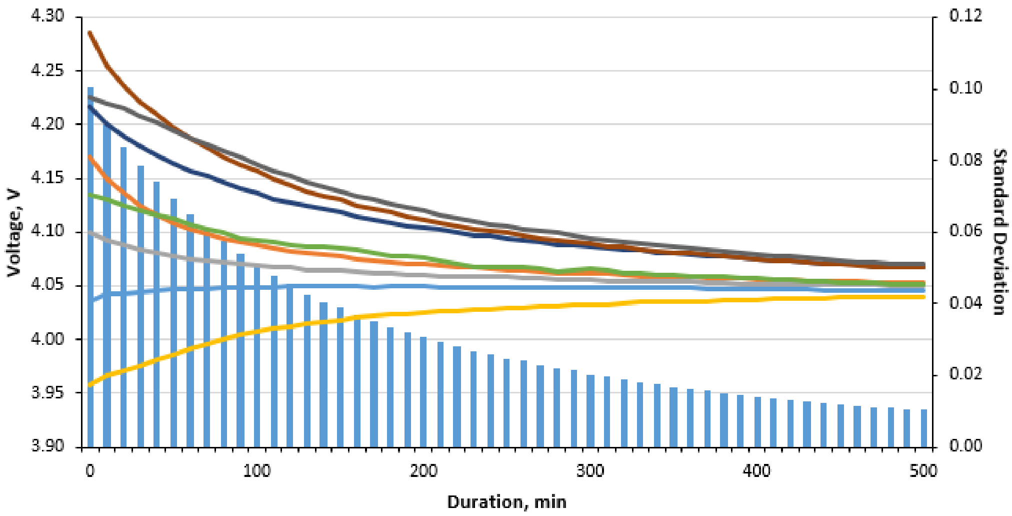
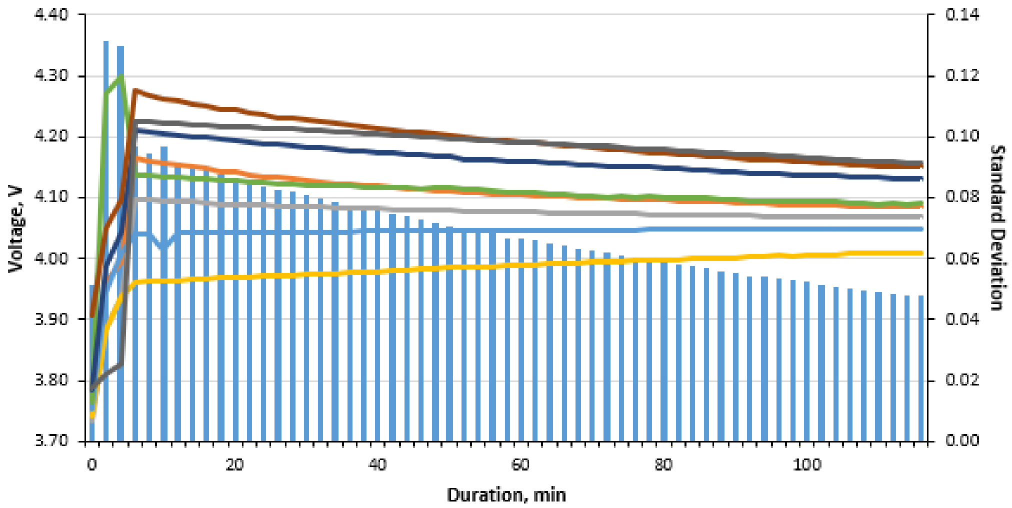


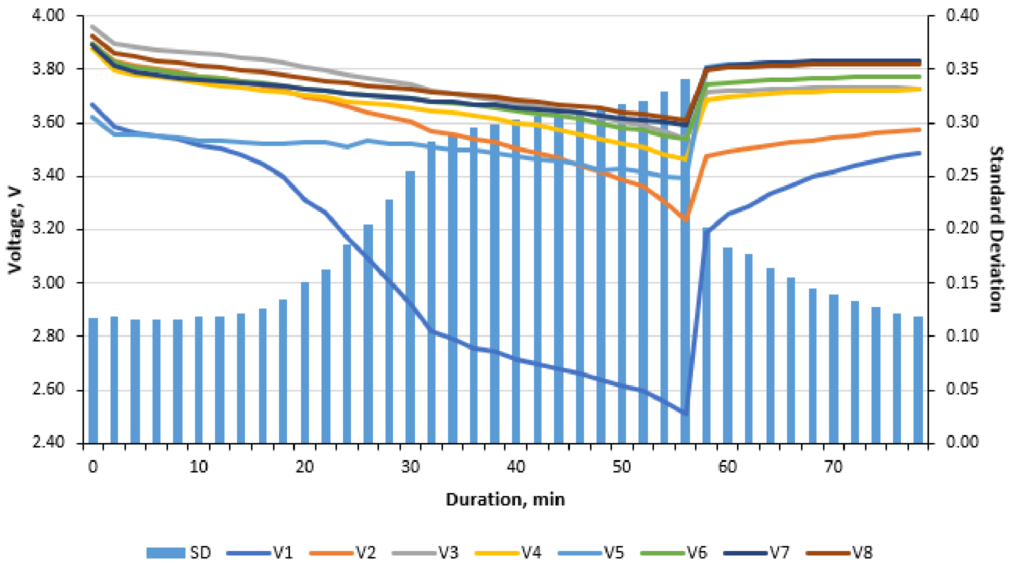
Figure 4.27: (a) Stationary, (b) charging, and (c) discharge tests of batteries with the prototype developed by Jacky Wong Chew Soon.



(a)



(b)



(c)

Figure 4.28: (a) Stationary, (b) charging, and (c) discharge tests of batteries with the prototype brought by Lee Yong Jun.

To compare the results from all four prototypes, the trend of the standard deviation during the testing under different conditions will be used. From Table 4.2, it has collected the data from each prototype to be analysed. Comparing to other prototypes, the balancing circuit in this project seems to have larger percentage different for the standard deviation, this is because the voltage level of each battery in this project when undergo testing has larger gap. Thus, other prototypes' testing started with smaller battery voltage different will have smaller percentage differences in standard deviation and with smaller percentage differences in standard deviation does not mean that the prototypes show no sign of balancing effect. The percentage difference is used to show the trend of the standard deviation whether there is balancing effect doe by the prototype. While the ending point standard deviation can be used to determine how well the prototype performed, it means that with smaller ending point standard deviation, the better the balancing effect of the prototype.

From the table, it can be said that the testing under stationary and charging conditions of all three prototypes have proven their balancing capability while the testing under discharging condition does not show any balancing sign. This is due to the trend of standard deviation shown in the graphs under stationary and charging test have decreasing trend while discharging test has increasing trend in standard deviation. This shows that the voltage difference between cells under discharging test only getting bigger and not approaching each other in value which means no balancing.

From their ending point standard deviation, the prototypes' performance can be evaluated. Under the stationary and charging tests, the ending points standard deviation are 0.0392 and 0.0442, 0.211 and 0.107, 0.0795 and 0.0306 and 0.0106 and 0.0477 for the prototype in this project, Lee Wei Ren's prototype, Jacky's prototype, and Lee Yong Jun's prototype respectively. Under stationary and charging tests, everyone's prototype except Wei Ren's prototype can achieve value standard deviation under 0.1. Jacky's prototype has the best performance in charging test as it has 0.0306 which is lowest standard deviation among the prototypes. While Lee Yong Jun's prototype has the best performance in stationary test which has 0.0106 as its ending point standard deviation.

Table 4.2: Comparison of Prototype Balancers among Final Year Project Students.

Prototype	Metrices	Conditions		
		Stationary Balancing	**Charging with Balancing**	**Discharging with Balancing**
Closed-loop Switched-Capacitor balancer (Lee Wei Ren)	Starting point standard deviation, σ	0.603	0.220	0.107
	Ending point standard deviation, σ	0.211	0.107	1.350
	Percentage difference, %	-65.01	-51.36	1162.00
	Balancing	Yes	Yes	No
Single-tiered switched capacitor balancer (Jacky Wong Chew Soon)	Starting point standard deviation, σ	0.2260	0.0608	0.0177
	Ending point standard deviation, σ	0.0795	0.0306	0.2010
	Percentage difference, %	-64.82	-49.67	1036.00
	Balancing	Yes	Yes	No
Active Balancer from DALY (Lee Yong Jun)	Starting point standard deviation, σ	0.100	0.131	0.177
	Ending point standard deviation, σ	0.0106	0.0477	0.3420
	Percentage difference, %	-89.40	-63.59	192.00
	Balancing	Yes	Yes	No

4.7 Summary

This section analyses data under stationary, charging, and discharging conditions in order to evaluate the hardware and software performance of a prototype balancing circuit. It observes the convergence of battery voltages, an indicator of effective balancing, using standard deviation as a metric. In both stationary and charging conditions, the hardware prototype showed encouraging results, obtaining significant decreases in standard deviation, indicating successful balance. However, due to the fast discharge rate exceeded the balancing mechanism's speed, it had trouble maintaining balance while discharging. On the other hand, the hardware prototype performed well in charging and stationary conditions but failed in discharging. Comparisons with different prototypes indicated different levels of success in balancing. The hardware prototype was promising overall, but it still needs to be improved, especially for high rate discharging conditions.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

To conclusion, this study provided significant knowledge on the design and evaluation of a single switch capacitor active balancer prototype for lithium-ion batteries. Through conducting a thorough evaluation that included software simulations, hardware testing, and a comparison with other prototypes, it is said to have clarified the advantages and disadvantages of the balancer in several operational scenarios.

In the hardware testing, the balancer showed excellent balancing effects during the stationary and charging phases as it revealed promising results of approximately 80% and 30% improvement compared to situations without balancer during the stationary and charging phases, indicating that the prototype can reduce voltage variations between cells to 0.1 V. However, it showed limitations during the discharging phase and unable to balance the cells' voltage difference. The different results from the software and hardware evaluations demonstrate how difficult it is to maintain reliable balancing performance throughout all of the battery operating stages.

These results highlight the importance of looking to develop better balancer designs that are capable of ensuring good cell-to-cell balancing throughout all stages in the battery's operational cycle, especially during discharge, with the objective to optimise battery longevity, safety, and efficiency in a variety of applications. In the future, overcoming these obstacles will be essential for improving battery management systems and encouraging the broad use of lithium-ion battery technology in modern sectors like portable devices, renewable energy storage, and electric cars.

5.2 Recommendations for future work

In order to advise future research on single switch capacitor active balancers for lithium-ion batteries, this study provides several of important recommendations. First and foremost, in order to solve noticed limits while discharging, it is necessary that switch circuit topologies, component arrangements, and control approaches be investigated. Including sophisticated control algorithms, like model predictive control, could improve responsiveness and flexibility in dealing with of changing operational conditions.

To understand realistic performance and scalability, real-world validation experiments using different lithium-ion battery packs are important. Working together with universities or industry partners could make it easier to get access to relevant testbeds and datasets for full verification under a range of operational situations. Additionally, investigating hybrid balancing strategies that combine passive and active strategies shows potential for positive benefits. Hybrid techniques have the potential to fulfil more types of balancing requirements across different battery systems by combining targeted high-power balancing with continuous low-power balancing.

Last but not least, continuous improvement study aimed at enhancing control parameters is important for enhancing efficiency and effectiveness across many different battery chemistries and configurations. This process might be simplified by using complex optimisation algorithms, which would result in more effective balancing techniques. Researchers can improve lithium-ion battery management systems and contribute to the development of more effective, dependable, and sustainable energy storage technologies by following these suggestions.

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APPENDICES

Appendix A: Arduino Coding.

```
#include <Wire.h>

const int voltageSensorPins [] = {A0,A1,A2,A3};          // sensor pin
const int numSensors = 4;
float vIn[numSensors];                                // measured voltage
float vOut;
float voltageSensorVal;                        // value on pin A3 (0 - 1023)
const float factor = 5.09375;                   // reduction factor of the Voltage Sensor shield
const float vCC = 5.00;                        // Arduino input voltage
const int relayPins[] = {9,8,7,6,5,4,3,2};      // Define the digital pins connected to the relay modules
const int numRelays = 8;                      // Define the number of relays


void setup() {

  // Initialize each relay pin as an output
  for (int i = 0; i < numRelays; i++) {
    pinMode(relayPins[i], OUTPUT);
  }

  digitalWrite(2,LOW);
  digitalWrite(3,LOW);
  digitalWrite(4,LOW);
  digitalWrite(5,LOW);
  digitalWrite(6,LOW);
  digitalWrite(7,LOW);
  digitalWrite(8,LOW);
  digitalWrite(9,LOW);

  Serial.begin(115200);

}


void monitoring_system(){



  //Measuring Voltage
  voltageSensorVal = analogRead(voltageSensorPins[0]);    // read the current sensor value (0 - 1023)
  vOut = (voltageSensorVal / 1023) * vCC;             // convert the value to the real voltage on the analog pin
  vIn[0] =  vOut * factor;                            // convert the voltage on the source by multiplying with the factor
  Serial.print(vIn[0], 3); // print with 3 decimals
  Serial.print(",");

  voltageSensorVal = analogRead(voltageSensorPins[1]);    // read the current sensor value (0 - 1023)
  vOut = (voltageSensorVal / 1023) * vCC;             // convert the value to the real voltage on the analog pin
  vIn[1] =  vOut * factor;                            // convert the voltage on the source by multiplying with the factor
  Serial.print(vIn[1] - vIn[0], 3); // print with 3 decimals
  Serial.print(",");

  voltageSensorVal = analogRead(voltageSensorPins[2]);    // read the current sensor value (0 - 1023)
  vOut = (voltageSensorVal / 1023) * vCC;             // convert the value to the real voltage on the analog pin
  vIn[2] =  vOut * factor;                            // convert the voltage on the source by multiplying with the factor
  Serial.print(vIn[2] - vIn[1], 3); // print with 3 decimals
  Serial.print(",");

  voltageSensorVal = analogRead(voltageSensorPins[3]);    // read the current sensor value (0 - 1023)
  vOut = (voltageSensorVal / 1023) * vCC;             // convert the value to the real voltage on the analog pin
  vIn[3] =  vOut * factor;                            // convert the voltage on the source by multiplying with the factor
  Serial.print(vIn[3] - vIn[2], 3); // print with 3 decimals
  Serial.println("");

}
```

```
void loop() {

  monitoring_system();

  // Turn on relays 1 and 2
  digitalWrite(relayPins[0], HIGH);
  digitalWrite(relayPins[1], HIGH);
  delay(3000); // Wait for 3 seconds

  // Turn off relays 1 and 2
  digitalWrite(relayPins[0], LOW);
  digitalWrite(relayPins[1], LOW);

  // Turn on relays 3 and 4
  digitalWrite(relayPins[2], HIGH);
  digitalWrite(relayPins[3], HIGH);
  delay(3000); // Wait for 3 seconds

  // Turn off relays 3 and 4
  digitalWrite(relayPins[2], LOW);
  digitalWrite(relayPins[3], LOW);

  // Turn on relays 5 and 6
  digitalWrite(relayPins[4], HIGH);
  digitalWrite(relayPins[5], HIGH);
  delay(3000); // Wait for 3 seconds

  // Turn off relays 5 and 6
  digitalWrite(relayPins[4], LOW);
  digitalWrite(relayPins[5], LOW);

  // Turn on relays 7 and 8
  digitalWrite(relayPins[6], HIGH);
  digitalWrite(relayPins[7], HIGH);
  delay(3000); // Wait for 3 seconds

  // Turn off relays 7 and 8
  digitalWrite(relayPins[6], LOW);
  digitalWrite(relayPins[7], LOW);

}
```