DEVELOPMENT OF POWER CONDITIONING CIRCUIT FOR RELIABLE USE OF BATTERY ON AUTOMATED GUIDED VEHICLE

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DEVELOPMENT OF POWER CONDITIONING CIRCUIT FOR RELIABLE USE OF BATTERY ON AUTOMATED GUIDED VEHICLE

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

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May 2023

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.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DEVELOPMENT OF POWER CONDITIONING CIRCUIT FOR RELIABLE USE OF BATTERY ON AUTOMATED GUIDED VEHICLE"** was prepared by **Tan Wei Lun** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Mechatronics Engineering with Honours at Universiti Tunku Abdul Rahman.

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ABSTRACT

This study focuses on the development of a hybrid energy storage system (HESS) for an automated guided vehicle (AGV) used in indoor navigation. The AGV relies on a 3000mAh LiPo battery as its primary power source, which experiences rapid swelling, leading to increased operational costs due to the replacement of the battery occurs every 8 months on average. The inrush current required by the battery during the start-up of inductive loads such as the AGV motor and robotic arm on board. To achieve this, a HESS which combined a super-capacitor and the LiPo battery is proposed. During starting of the inductive load, the supercapacitor works in parallel with the LiPo battery to power the load, reducing the current required by the battery. During normal running conditions when the current required is much lower, only the LiPo battery will provides the power. When the supercapacitor's voltage level is low which is around 12.5V, it is connected parallel to the LiPo battery through a boost converter for charging. This HESS approach effectively reduces the inrush current experienced by the LiPo battery during AGV start-up, thus minimizing swelling of the battery. The performance of the proposed HESS is evaluated experimentally, and the results demonstrate its effectiveness in reducing the current stress experienced by the LiPo battery.

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LIST OF SYMBOLS / ABBREVIATIONS

C	capacitance, F
ε	permittivity of dielectric, F/m
A	surface area of electrodes, m^2
d	distance between electrodes, m
E	energy, J
P	power, W
V	voltage, volt
I	current, A
k_T	motor torque coefficient, Nm/A
T	torque, Nm

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Automated Guided Vehicle (AGV) is a type of robot that is used in industrial sectors for loading and unloading materials. With the introduction of AGV to the industrial sector, the production efficiency could be increased massively. As compared to manual labour force, AGVs can move around quickly and efficiently. Eventually, more processes will be done during each shift by AGVs than manual labour alone (Pang,2022). The introduction and integration of AGVs allow the company workforce to focus on value-added manufacturing processes, as the movement of supporting materials is taken care by the AGVs (Michel, 2022).

The introduction and integration of AGVs into industrial sector started to bloom during the Covid 19 pandemic. With the pandemic hit at the early 2020, people around the world are forced to stuck in the house. Eventually it reduced the workers in every sectors. Resulting in labour shortage all around the world. With people staying at home, purchasing of goods are done through online, resulting in a surge in demand for eCommerce warehouse and distribution services. In order to keep up with the pace of the current market demand, companies forced to implement automation to their logistics, and AGVs is one of the popular automation solutions. AGVs with cart is used in the warehouse to transport objectives from places to places, while dealing with lifting stacks of objects, forklift AGVs is used.

The basic components that drive AGV to function consist of wheels, electric motor, controller, motor driver, and power supply. Wheels are the part that drive the movement of the AGV through rotation. This rotation is coming from rotating electrical motor through shafts, while electrical motor is powered up by connecting to power supply and motor driver connected in between them. As for the role of controller in AGV, it dictates what the AGV should perform by sending and receiving signals. With all these components, a basic AGV is said to be ready to go.

Among these basic components of the AGV, power source is the one required more consideration as it determines the operation time of the AGV before a recharge is needed. One of the costs that AGVs may become a burden to the user or company is the cost of replacing battery of the AGV. AGV is powered electrically, with the features of moving around, a portable electric power source is used in the AGV. The most common power source of AGV is using battery. In this project, the power source of the AGV is a Lithium-ion Polymer battery (LiPo). One of the drawbacks of LiPo being used on AGV is the price, which is RM88 as purchased in this project. Thus, if the battery life of LiPo can be prolonged further, it will reduce the cost of user or company to replace a new LiPo for the AGV.

1.2 Importance of the Study

With the demand of AGV in the market increasing, the demand of LiPo battery as well as the number of disposed LiPo are increasing. With the increment of disposal battery, the environment will be contaminated if the disposal of LiPo battery do not perform correctly.

As for the costing side, replacing LiPo battery will increase the cost of the project. Thus, if the lifecycle of LiPo battery can be prolonged, the increment of LiPo battery disposal will not be that fast and the cost of project will reduce as the number of replacements of LiPo battery drop.

1.3 Problem Statement

The focus of this project is the battery on the AGV, which is powered by a 3000mAh, 11.1V, 25C LiPo battery. The AGV is equipped with four wheels, and the LiPo battery powers two 12V DC motors that are connected to two of the AGV's wheels. Each DC motor is controlled by a motor driver. The AGV has been utilized in a robot competition.

During the AGV's testing stage, a significant phenomenon was observed: the thickness of the LiPo battery increased massively in comparison to a new one. This phenomenon is referred to as battery swelling, which is a common occurrence in LiPo batteries. However, the LiPo battery of this AGV swelled too quickly, which resulted in increased costs due to the need for frequent battery replacements. The occurrence of LiPo battery swelling also reduces battery life and energy storage density (Education, N/A).

1.4 Aim and Objectives

The aim of this project is to build a Hybrid Energy Storage System (HESS) to integrate on the current AGV to reduce the inrush current reuiqred from the LiPo battery. The study aims to achieve the following objectives:

i. To study on the possible causes of swelling of LiPo battery
ii. To design a circuit to reduce the current stress on LiPo battery.
iii. To evaluate the effectiveness of the designed circuit on reducing the current stress on LiPo battery.

1.5 Scope and Limitation of the Study

The scope of this study involved the investigation of causes of LiPo battery swelling and the development of conditioning circuit to reduce the effect of swelling. Research work related are explored in literature review. Different method for reducing the swelling effect on LiPo battery will be compared.

In this project, method of using Hybrid Energy Store System (HESS) will be studied and focused on how to reduce the swelling effect of LiPo battery with the implementation of HESS. The ambient temperature of the operating environment of LiPo battery is considered suitable for normal operating temperature.

1.6 Contribution

The contribution of this project could be significant, as it sheds light on the effects of battery swelling on the performance and longevity of LiPo batteries. The results of this study could be valuable to researchers and engineers who are developing AGVs and other battery-powered devices. By understanding the causes and effects of battery swelling, future designs of AGVs and other devices could be improved to minimize the impact of this phenomenon, thereby improving their reliability and reducing their overall costs.

1.7 Outline of the report

The report is structured into five chapters to provide a comprehensive analysis of this phenomenon. The first chapter serves as an introduction to the project and outlines the problem statement, aim, and objectives. In chapter two, we review the existing literature on battery swelling in LiPo batteries and explore potential root causes and solutions.

Chapter three details the methodology and work plan, including the proposed design and solution for the AGV and the testing methodology. Chapter four presents the results of the testing of the proposed solution and evaluates its effectiveness in mitigating the issue of battery swelling.

The final chapter of the report is the conclusion, where we summarize the project's findings and discuss the limitations and challenges encountered during prototyping. Additionally, we provide recommendations for future improvement of the proposed solution.

Overall, the contribution of this project lies in its analysis of the impact of battery swelling on the performance and longevity of AGVs and other battery-powered devices. The results of this project could inform future research and engineering efforts to improve the reliability and reduce the cost of battery-powered devices.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the introduction of lithium battery and supercapacitor will be covered. With the understanding through the introduction, possible root causes of LiPo battery swelling will be discussed. By listing out the possible root causes, possible solution will be carried out in this chapter too such as utilizing dumping resistor, regenerative braking and integration of secondary energy storage device to form a hybrid system.

2.2 Lithium Battery

Lithium battery is a type of battery that utilize the movement of lithium ions between electrodes for the charging and discharging process. According to Chapman (2019), during the discharging process, lithium ions move from the negative electrode, anode through electrolyte to the positive electrode, cathode, it is the reverse chemical process for the charging process. The characteristics of lithium battery depend on the active material of the cathode. In the market, there are six common types of lithium battery, which are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LHP), lithium nickel cobalt aluminium oxide (NCA), and lithium titanate (LTO).

2.2.1 Charging Characteristics

Generally, there are two steps for the charging of lithium-ion batteries. First, the lithium-ion battery will be charged at a constant current (CC). The function of this constant current charging is to rise the voltage of lithium-ion battery to a target voltage level, for most of the lithium-ion battery the target voltage level is around 4.2V and the current will be the maximum allowed charging current of the battery. When the voltage level of battery reaches the target voltage level, the next step of charging will be conducted in constant voltage (CV), the target voltage level is maintained by slowly decreasing the current.

Figure 2.1 shows the ideal charging characteristics graph of lithium-ion battery, but according to Staff (2021), in reality the idea charge characteristics of lithium-ion battery is often not applicable and might be unsafe for some scenario. If following the ideal charging characteristics of lithium-ion battery, a maximum allowed charging current will be charged to the battery. In the case of battery voltage is very low at the beginning, this large current will charge the battery too quickly which might lead to a potential failure, such as thermal runaway. Thus, to ensure a safer charging and avoid any type of failure, charging starts with a small current to revive a possibly dead cell is suggested to be perform Staff (2021). Once the battery reaches a safety voltage threshold, the charging process will continue according to the ideal charging characteristics by constantly applying maximum current until the voltage reaches target voltage level, then followed by constant voltage and slowly decrease the current to maintain the voltage. Figure 2.2 shows the graph of realistic charging of a lithium-ion battery.

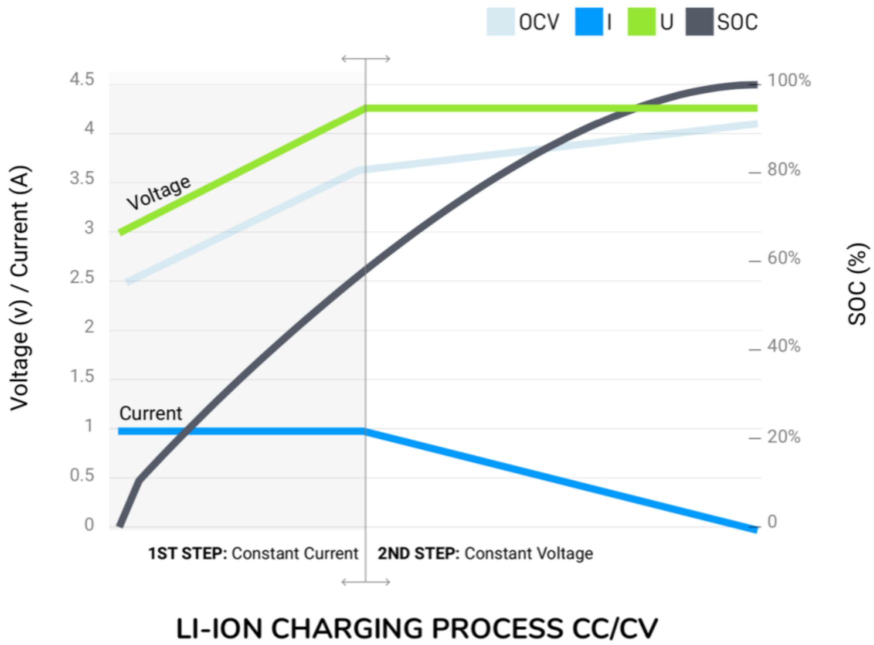

Figure 2.1: Ideal charging characteristics of Li-ion (Sourmey, 2022)

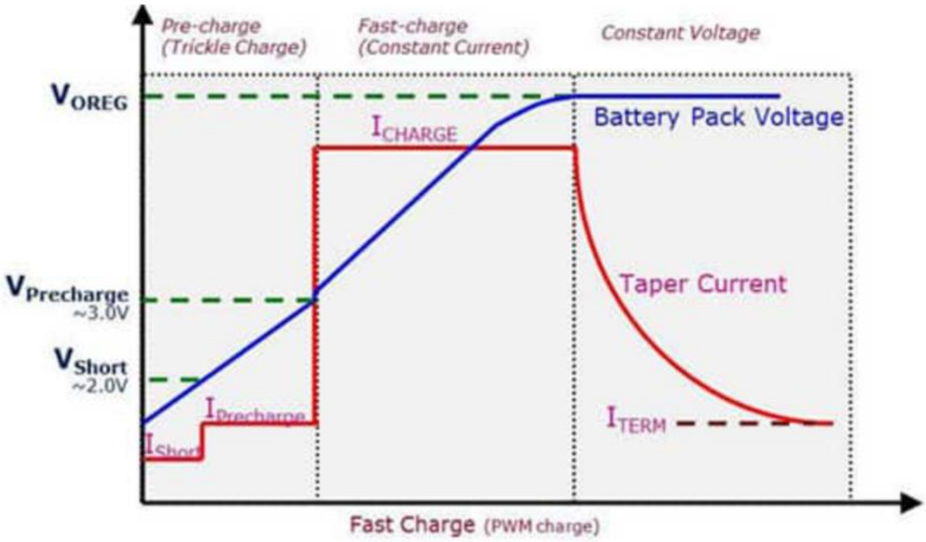

Figure 2.2: Realistic charging scenario of lithium-ion battery (Staff, 2021)

2.2.2 Discharge Characteristics

For the discharge of lithium-ion battery, the C-rating is playing an important role which will affect the discharge performance of the battery. C-rate is the measure of normalization of the discharge current of a battery against its maximum capacity (Xiong, 2019). For example, the definition of 1 C rate is that the total discharge time of the battery will be one hour.

When Lithium-ion battery discharge at high C-rate, it shows low endurance and less capacity (Xiong, 2019). Figure 2.3 shows the discharge process of a lithium-ion battery at various C-rate, 1C, 3C, and 6C. At the end of discharge process, battery that discharged at 6C produced below 6000mAh which is the lowest among the other C-rate. Thus, lithium-ion battery discharged at lower C-rate, more capacity is produced at the end of discharge. The discharge curve also shows that the discharge pattern of lithium-ion battery has a flat discharge curve which represent the voltage is constant throughout out the discharge period of battery. With this flat discharge curve, it indicates that the battery might not fully discharge to deliver a 100% depth of discharge (DOD) (Bollini, 2022).

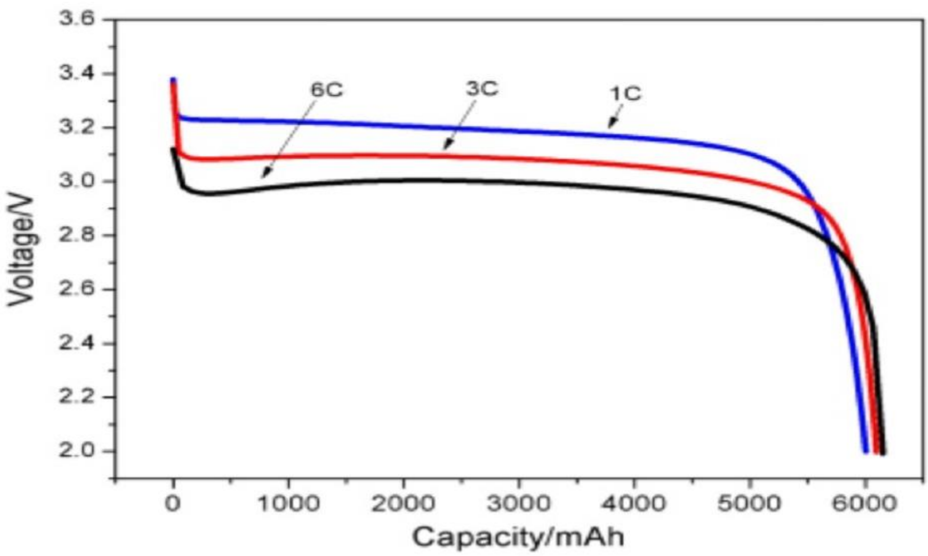

Figure 2.3: Discharge curve of lithium-ion battery at various C-rate (Bollini, 2022)

2.3 Background of Lithium-ion Polymer Battery

Lithium-ion polymer (LiPo) battery is a rechargeable Li-ion battery with a polymer electrolyte while in the convectional Li-ion batteries, liquid electrolyte is used in convectional (Shepard, 2021). According to BatteryUniveristy, 2021, LiPo battery is basically the same as the Li-ion battery, both batteries use identical cathode and anode material and contain a similar amount of electrolyte. One of the differences between LiPo and Li-ion battery is that the separator between electrodes of LiPo is made of a micro-porous polymer while Li-ion battery is using the traditional porous film as separator (Contributor, n.d.). Separator is used to prevents the electrodes from touching another and enables electrons flow through.

Lithium-ion polymer (LiPo) battery consist of three main components, cathode, anode, separator, and electrolytes. As mentioned, the separator of LiPo battery is micro-porous polymer. As for the material of the positive electrode, cathode, there are few commonly used materials such as lithium cobalt oxide, lithium-ion ternary, lithium-ion manganese oxide, and lithium iron phosphate. While the material for anode is mostly graphite, which provide good conductivity. Different from Li-ion battery, the electrolyte of LiPo battery is polymer electrolyte. There are two common types of polymer electrolyte which is solid polymer electrolytes and gel polymer electrolytes. It facilitates the transport of positive lithium ions between cathode and anode.

2.4 Advantages

2.4.1 Charging rate

AGV are mostly used in the production industry, charging time is one of the crucial requirements to the battery used on the AGV. If the charging time of the AGV is long, it will reduce the availability of AGV. To reduce the charging time, faster charge rate of battery is needed. This is where LiPo battery stands out from the other batteries as only require 1- 5 hours to charge from 60%-100% while the charging duration of AGM Pure lead and GEL range between 4-5 hours which is taking a lot of time compared to LiPo batteries.

2.4.2 Cycle

With the cost of LiPo batteries are higher compared to the other batteries, having a longer life span will be beneficial to the user. Deepest Depth of Discharge (DOD) is the critical factor that determine the cycle life of batteries. The higher the DOD, the more energy can be used before the batteries go for recharge. For the case of LiPo batteries, it can handle DOD of 80% while maintaining an excellent battery life, where the life cycle around 2500 cycles. In another words, the AGV can consume 80% of the energy of the LiPo before it goes for recharge. When compared to GEL batteries at 50% DOD, lithium batteries are having a more cycles around 5000 cycles while cycles of GEL battery are below 2000. The more recharging cycles the longer the lifespan. Thus, lithium battery has a longer life span.

2.5 Disadvantages

2.5.1 Performance Restricted by Temperature

Other than charging rate and life cycle of the battery will affect the performance of the battery, temperature is one of a factor that will affect the performance as well. According to Ji et al. (2022) the state of charge of battery will be higher and the discharge capacity of the battery will be lesser when the ambient temperature is lower. This phenomenon is due to the increase of resistance and viscosity of electrolyte of the battery when the ambient temperature drop, which leads to the electrochemical reaction activity inside the battery decreases, and the migration rate of lithium ions in electrolyte decreases, thus the electrochemical reaction rate inside the battery is decreased drastically. Hence, the battery performance in a low temperature is considered bad and the decay rate is faster as the charging time is shortened, and the discharge capacity is reduced significantly. This phenomenon for ambient temperature around 30 Celsius to 40 Celsius is the opposite, the discharge capacity of battery increased, while the state of charge of the battery decreased. However, the ambient temperature should not be too high, as the electrochemical reaction inside the battery will further increase its reaction rate as the temperature keep increasing, and there will be side reaction occur too, which will release a lot of heat. In a worse circumstance, the heat generated inside the battery is higher than the external heat dissipation rate, thermal runaway will occur which is dangerous to the user.

Thus, lithium-ion battery does not perform well when the temperature is too low around 20 Celsius or below, the decay rate of the battery is faster. In a more critical temperature, the battery might be stop performing. However, the temperature cannot be too high as well, as there might be accident such as thermal runaway may occur. Thus, the ambient temperature should be taken into consideration when using lithium battery for any purposes.

2.5.2 Risk of Serious Accident

As mentioned above, ambient temperature will not only affect the performance of lithium-ion battery, but it may also be one of the factors that caused lithium-ion battery to fail. Explosion is one of the worse failures of lithium-ion battery which will injure human. Before the event of explosion, the temperature of battery will first increase, and further speed up the chemical reaction inside the battery, and through the chemical reaction the temperature will be further rise. Thus, resulting in thermal runaway which will lead to smoking, igniting, and worse exploding.

One of the most infamous explosion accidents of lithium-ion battery is happened in 2016, where a smartphone, Samsung Galaxy Note 7 got exploded on an airplane when the user tried to shut it down before the plane take off. According to Vice, during the year of 2016 by mid-September, there were 92 claims of batteries overheating, 26 instances of burns, and 55 reports of property damage caused by the explosion of Galaxy Note 7. The company carried out an investigation and confirmed the failure lithium-ion battery is the reason of explosion. According to (Moynihan, 2017), one of the reasons caused failure of lithium-ion battery in the Galaxy Note 7 is the internal room of the lithium-ion battery was not large enough between the heat-sealed protective pouch around the battery and its internals, which caused electrodes inside each battery to crimp, weaken the separator between electrodes and cause short circuiting inside the battery. Short circuit can lead to a massive amount of current discharge which heats up the battery (Mitchell, 2016). With the temperature of the battery keep increasing, the rate of chemical reaction inside the battery increased as well, and the temperature will keep increase which caused the event of explosion of the smartphone.

Thus, whenever dealing with lithium-ion battery, the ambient temperature needed to be taken extra care. The other factor which will cause the internal short circuit between electrodes is the abusive use of lithium-ion battery such as overcharge or over discharge. For the overcharge scenario, metal on the cathode oxidized to metallic ion, and some of the metallic ions diffused to anode driven by concentration difference between cathode and anode, where the metallic lithium started to deposit onto the anode surface, resulting in thickening the SEI layer (Ouyang, et al., 2018). Thickened SEI layer brings the electrodes closer to each other, as the overcharge process continue, lithium plating appears to further shorten the distance between electrodes causing internal short circuit inside the battery to be occur any time. As for the case of over discharge, there is a massive amount of lithium-ion loss in the anode and form metallic lithium deposit onto the surface of cathode, resulting in SEI layer decomposed, while the metallic dendrites grow which led to separator between electrodes become penetrate and short circuit occur (Ouyang, et al., 2018).

2.6 Possible Root Causes

As battery is electrochemical power source, chemical reaction inside the battery cell is playing a major role of the performance of the battery cell as well as the health of battery. The process of charging and discharging of the battery are done by the chemical reaction inside the battery cell. During chemical reaction, there might be an event of releasing gas or even absorbing gas depend on the chemical reaction. In the case of this report, gas generated during the chemical reaction in the battery cell is one of the main factors that cause LiPo battery pack bloated in size. Abusive use of battery by overcharging it or over discharging it will speed up the chemical reaction inside the battery cell.

2.6.1 Overcharged

Love & Gaskins (2012) conducted an experiment analysis on the effects of overcharge and over discharge on the performance of LiPo battery. In the experiment, a 30mAh LiPo battery is used to undergo overcharge testing. The abuse overcharge experiment was done by voltage driven where voltage will be increased out of the normal range 4.2V, the charge voltage varied at 4.4V,4.6V,4.8V, and 5.0V, while the lower voltage boundary was held at 2.8V.

In the experiment the change in cell z-direction thickness of LiPo bells after 200 overcharge cycles was obtained and concluded that overcharge will increase the thickness of LiPo cell which is the phenomenon of swelling of LiPo cell. Overcharge not only will cause the LiPo cell to swell, and it caused the discharge capacity of the cell drop significantly as well. It only takes a single cycle of discharge for the cell that has been overcharged at 5V to drop 57% of its initial discharge capacity, and after 18 cycles the cell had no discharge capacity.

Ciorba, et al. (2020) conducted a similar experiment of overcharging on a 30Ah LiPo cell. They found out that when the voltage increased out of the nominal voltage 4.2V at about 4.5V the cell temperature increased rapidly corresponding to cell swelling and formation of gases inside the cell. The total amount of produced gas is mainly affected by capacity, energy density and state of charge, at the same time charge rate affects the magnitude of gas formation, the cell swells under small current. This proved that overcharge the LiPo cell will increase the gas formation inside the cell which led to cell swelling even worse there will be thermal runaway if the cell is under high current.

2.6.2 Overdischarge

Over discharge is another abuse on the LiPo cell that frequently happen in the real world. Especially when the LiPo cell is used to power up capacitor, motor, and other devices, there will be a high starting current known as inrush current at the beginning, which will lead to voltage drop at the LiPo cell. If the voltage drop is below the recommended cut-off voltage, the cell is considered over discharged.

In the over discharge testing on a 300mAh LiPo cell conducted by Love & Gaskins (2012), the thickness of the cell slightly increased, 0.01mm when it discharged at 2.0V which is 800mV below the lower limit voltage of the cell, 2.8V after 200 cycles. This increment on thickness is considered mild compared to over discharge at 1.2V, which is 1600mV lower than the lower limit voltage of the cell. The thickness increased drastically to 3.54mm when the cell discharged at 1.2V. This significant increase in thickness solidified that more gases generated when the cell over discharge way below its lower voltage limit.

Critical over discharge the cell way below the lower voltage limit, result in the thickness of cell increased dramatically, this can be solidified with the result from Li, et al. (2008). The cell swelled a lot when discharge at 0V compared with 3.0V. Li, et al. (2008) concluded that when the lithium ion batteries over discharged to 0V the carbon dioxide and carbon monoxide generated more than the cell discharge at 3.0V, which cause the cell swell significantly at 0V, and the content of copper in cathode was higher at cell discharged at 0V which will greatly reduce the cell efficiency of Li-ion intercalation and de-intercalation. The result of the testing carried out by Love and Gaskins (2012) also shows that after 200 cycles of mild discharge on LiPo cell at -800mv, the capacity of the cell is around 80% which is still consider usable as a cell. However, a more critical over discharge at -1600mV and -1800mV reduced the cell capacity significantly, the useable lifespan only left to 57 and 8 cycles respectively.

2.7 Supercapacitor

Supercapacitor also known as ultracapacitor, electric double layered capacitor (EDLC). From the name itself, supercapacitor, it is known that it has capacitance way greater than the normal capacitor. According to Energy Education (2022), the difference between normal capacitor and supercapacitor is that supercapacitor is a modified capacitor. With the modification is on the electrode of supercapacitor, where it is coated or made of porous material. The basic structural of a supercapacitor is shown in Figure 2.4.

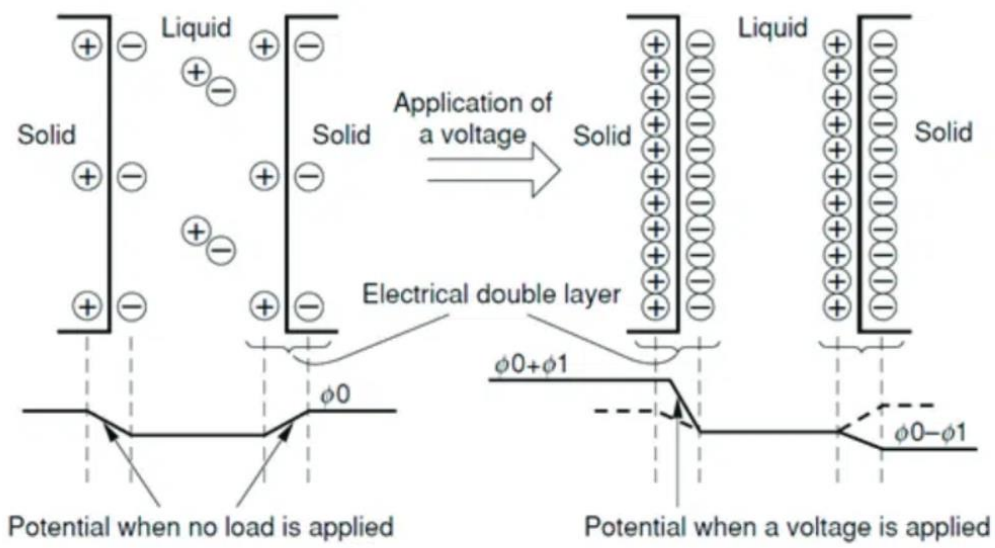

Figure 2.4: Basic structure of supercapacitor

Supercapacitors consist of two electrodes and these electrodes are separated by an electrolyte. As mentioned above, the material of electrodes is porous material, most commonly are activated porous carbon, and most of them are coated with a thin layer of conducting polymer or metal oxide to improve their performance. In Figure 2.4, solid represent electrode while liquid represent electrolyte. Initially when there is no voltage applied across the electrodes, uncharged, the positive and negative charged particles of electrolyte are moving freely across the electrodes. Once the electrodes are charged, with voltage applied, ions of electrolyte will be attracted to their opposite charged electrodes respectively, such that positive ions will be attracted to the surface of negative electrodes, while negative ions will be attracted to the surface of positive electrode. With the layer of these ions formed on the surface of the electrodes, the electric double layer is formed. According to Musashi Engineering, the larger the surface area of the same volume of electrodes, the more electricity being stored in. As the material of electrodes are activated porous carbon, the porous increases the surface area of the same volume of electrodes (energyeducation.ca n.d.), Thus, compared to normal capacitor, supercapacitor able to store larger number of charges in it.

The basic equation for the capacitance of supercapacitor is exactly the same applied for a normal capacitor. The equation is described below:

$$C = \frac{\varepsilon A}{d} \tag{2.1}$$

C is the capacitance, with unit in farads, F, ε is the permittivity of the dielectric material, with unit farads/meter, F/m; while A is the surface area of electrodes and d is the distance between the electrodes with unit of meter square and meter respectively. Even though the equation for supercapacitor and normal capacitor is the same, but with the surface area of electrodes increased due to the porous material of electrode of supercapacitor, with the same permittivity and distance between electrode, the capacitance of a supercapacitor mathematically will be higher than normal capacitor by using the equation.

As for the equation of energy and power, both capacitor and supercapacitor are sharing the same equation too. The equations are described below:

$$E = \frac{1}{2}CV^2 \tag{2.2}$$

$$P = VI \tag{2.3}$$

Where E represent the energy in unit of joules, J, V is the voltage of capacitor, with unit in volts. By applying equation, with the same surface area of electrodes and spacing between electrodes, supercapacitor will be able to store more energy as its capacitance higher than normal capacitor.

2.7.1 Charging of supercapacitor

The most notable feature of a supercapacitor is its ability to charge and discharge at a rapid pace. These two distinct characteristics make it highly advantageous for applications that require high levels of instantaneous power for short periods. Figure 2.5 shows the charging profile of a supercapacitor charged with a constant current supply and a voltage limit that is appropriate for the capacitor's rated voltage, while Figure 2.6 displays its discharge profile.

Figure 2.5 illustrates that the voltage of a supercapacitor increases linearly during charging, and the current decreases naturally as the capacitor becomes fully charged, without needing a full-charge detection circuit. Supercapacitors have a charging characteristic similar to that of electrochemical batteries, with the charge current largely limited by the charger's current handling capacity. While the initial charge can be performed rapidly, the topping charge may require more time. When charging an empty supercapacitor, precautions should be taken to limit the inrush current since it can draw as much current as possible. Unlike traditional batteries, supercapacitors cannot be overcharged, and full-charge detection is not required since the current will stop flowing when the capacitor is fully charged.

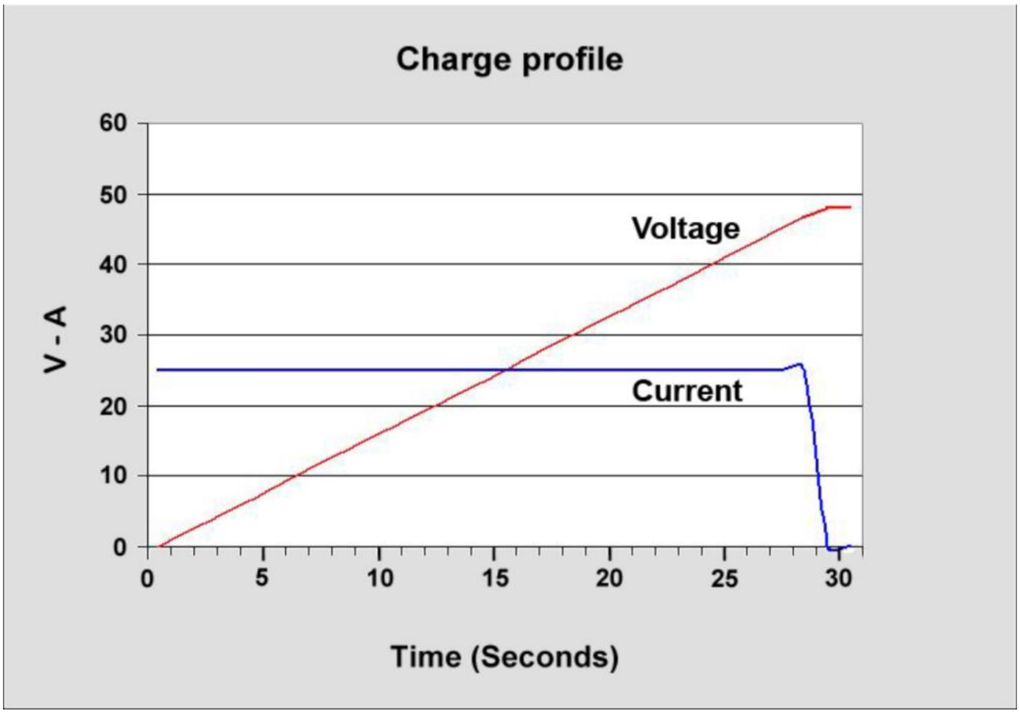

Figure 2.5: Charging profile of supercapacitor (Battery University,2021)

2.7.2 Advantages of supercapacitor

Due to the unique design and porous material of supercapacitor, these factors make supercapacitor stand out among normal capacitors. The most significant advantage of supercapacitor is its high-power density. The power density of supercapacitor is said to be greater than battery, where supercapacitor able to deliver and absorb power in a very short interval. Thus, in application where fast charging and discharging of high power, supercapacitor is the idea passive component to be used.

Another stand out advantage of supercapacitor is the life cycle. Supercapacitor has a very long-life cycle compared to battery. According to Battery University, supercapacitor can undergo millions cycles of charging and discharging without significant degradation on the supercapacitor. Other than high power density and long cycle life, supercapacitor has the advantages such as wide operating temperature range, environmentally friendly, as it does not contain toxic chemicals in it, and it does not require periodic maintenance.

2.7.3 Disadvantages of supercapacitor

While there are advantages of supercapacitor, there are another side of it too. Even though supercapacitor has the advantage such as high-power density, but its energy density is the opposite of it. Supercapacitor unable to store more energy per unit volume compared to battery, but still its energy storage is better than normal capacitor.

Another significant disadvantage of supercapacitor is voltage discharge linearly. As discussed above, the characteristics of discharging of supercapacitor prevents fully utilize the energy stored. In term of discharging, self-discharge of supercapacitor is one of the disadvantages too. Due to the large surface area of electrodes, which increases the possibility of ion migration and self-discharge.

Voltage range of supercapacitor is one of the disadvantages too. As the normal range of rated voltage is around 2 – 3.7V, which is very low compared to battery. Thus, in order to use supercapacitor as energy source, series connecting them is the common way to increase the rated voltage. But series connecting supercapacitors will bring up another disadvantage too. Series connecting supercapacitor require a voltage balancing module to ensure the charging and discharging of each of the supercapacitor is balanced.

2.8 Possible Solution for Overcharge

2.8.1 Dumping resistor

The alternative and simpler way to protect the lithium battery away from voltage spike from the motor is to dump the regenerated energy from the motor to a resistor and despite it as heat to the surrounding.

Rehorst (2022), experienced power supply blew up when the servomotor in his circuit sudden stopped and the kinetic energy converted to electrical energy which ended up on the 200W 24V power supply. From this incident, it solidified that there is energy regenerated when the motor sudden stop and without any protection circuit the energy will flow back to the supply line can may damage components that are connected to it. As for the case of lithium battery, if the energy flow back to the battery at a voltage level higher than its upper voltage limit, the battery is considered overcharged even though the return of energy may be brief moment but frequently occurred it may lead to certain degradation of the battery.

Rehorst (2022) constructed a returned energy dump circuit which is connected in between the power supply and the motor driver. Figure 2.6 shows the returned energy dump circuit by Rehorst (2022). During normal driving condition, current flow from the power supply through the diode to the motor driver. While for the sudden stop condition, the reverse current spike will cause the voltage on the capacitor to rise above the power supply voltage, the diode is in reverse biasing resulting in switching on the transistor, and the reverse current will go to the ground through the 33 Ohm resistor.

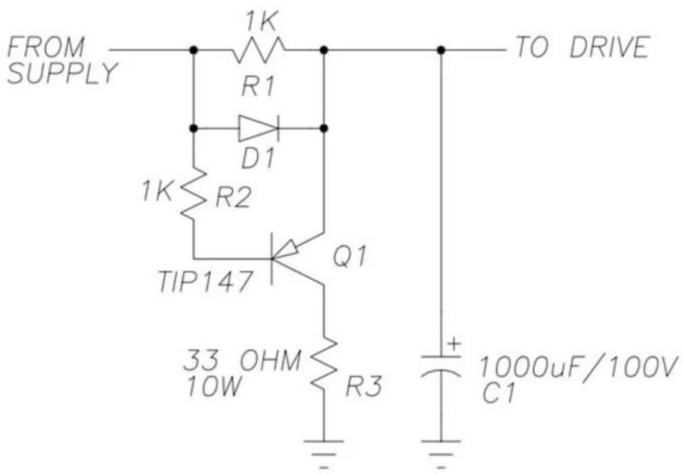

Figure 2.6: Dumping circuit

2.8.2 Regenerative Braking

Regenerative braking is an energy harvesting method that is commonly used in modern electric vehicles (EVs). In traditional vehicles, braking and deceleration are achieved through the use of mechanical brakes, which create resistance to slow down or bring the vehicle to a complete stop. However, during this process, the kinetic energy stored in the vehicle is dissipated as heat waste, which is lost to the surrounding environment. Instead of wasting this energy during deceleration and braking, it can be put to good use.

According to Bobba and Rajagopal (2010), the kinetic energy of the vehicle can be converted back into electrical energy and stored in the battery, provided that it is properly managed and controlled without causing any damage to the motor and electronic components. Regenerative braking has become a well-known method for harvesting the kinetic energy from the vehicle and converting it into electrical energy that can be used later. The electrical energy can be stored in either the battery or a supercapacitor for future use.

Since the back-EMF (electromotive force) from the motor may not be sufficient to charge the battery or supercapacitor, Bobba and Rajagopal (2010) suggested using a dc-dc converter to boost up the back-EMF to the appropriate voltage level. This would enable the harvested energy to be stored effectively and efficiently for later use.

2.8.2.1 Regenerative Braking with H-bridge Converter

Figure 2.7 shows the regenerative braking circuit proposed by Boba and Rajagopal (2010). In this circuit, H-bridge is used to create paths for energy to flow back to battery for charging without directly strikes back to the battery and caused damage to the battery such as overcharge, by switching the MOSFETs in the H-bridge. MOSFETs of the H-bridge are operated in a particular sequence using control algorithm based on the position feedback from hall-effect sensors.

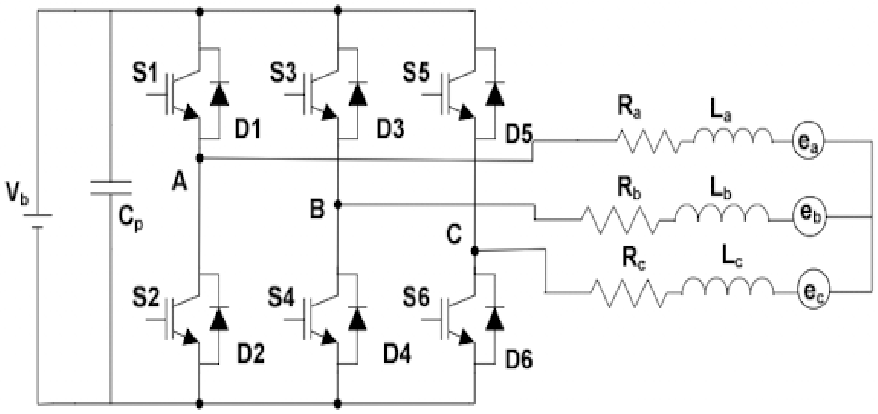

Figure 2.7: Proposed regenerative braking circuit (Bobba & Rajagopal, 2010)

Figure 2.8 shows the flow of energy inside the circuit when EV is moving around. During this period, EV is in motoring mode, where energy is consumed from the battery for the rotation of wheel to drive the EV. During motoring mode, S1 and S4 in the H-bridge is closed, current flow from battery to the BLDC motor for the EV to drive.

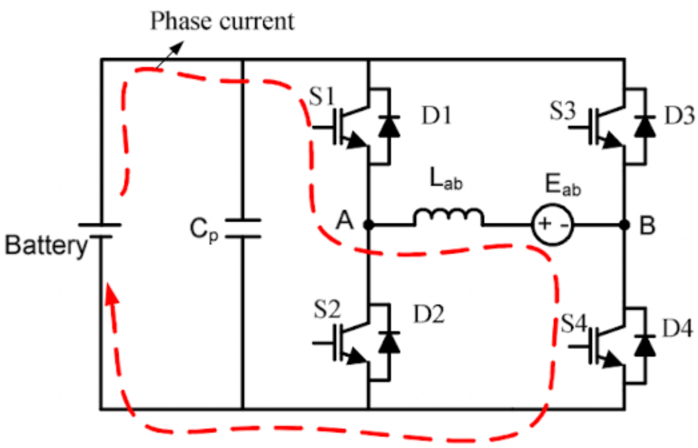

Figure 2.8: S1 and S4 are closed with PWM-ON for motoring. (Bobba & Rajagopal, 2010)

Figure 2.9 indicates the energy path during the free-wheeling of the EV, When the EV brakes, only S4 will be closed, in this period the EV is in free-wheeling mode where the energy will be free-wheeling through S4 and D2, the inductor of BLDC motor will be charging as well.

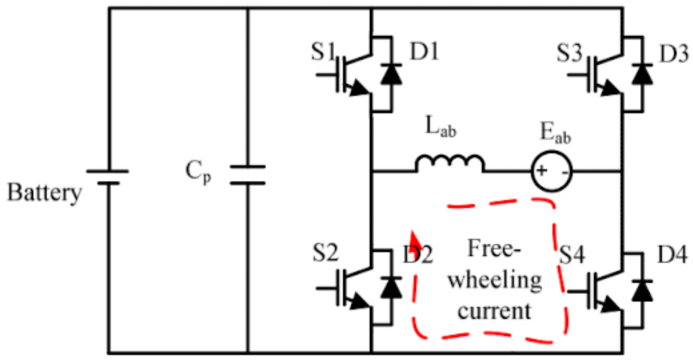

Figure 2.9: S4 closed only for free-wheeling mode (Bobba & Rajagopal, 2010)

When S2 and S3 are switched on while the PWM is on, the power from battery is transferred to phases A and B of the BLDC motor in opposite direction so that braking of the vehicle will be faster. Once the switches S2 and S3 is opened, the energy stored inside the inductor of the motor will be feed back to the battery through diodes D1 and D4 as both of them are forward biased to the energy. Figure 2.10 and Figure 2.11 show the energy path during regenerative for PWM-ON and PWM-OFF respectively.

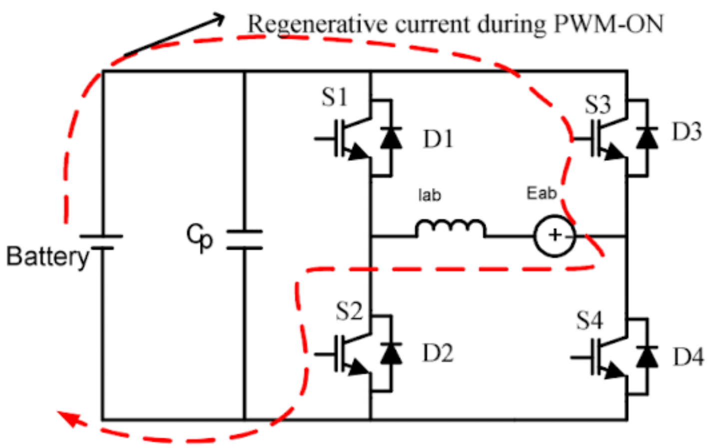

Figure 2.10: S2 and S3 closed with PWM-ON for regenerative. (Bobba & Rajagopal, 2010)

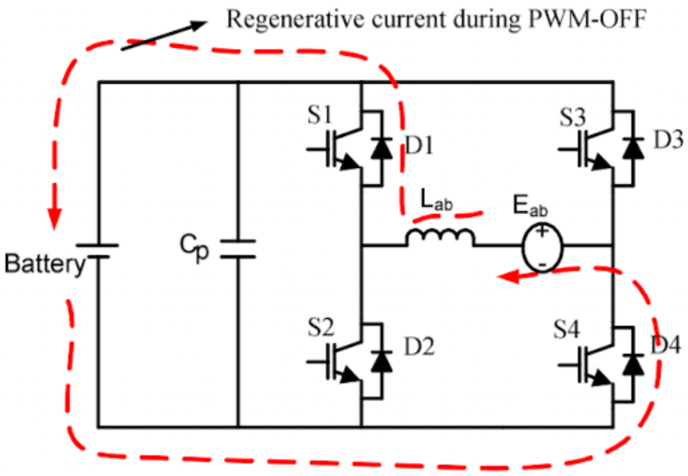

Figure 2.11: S2 and S3 open with PWM-OFF for regenerative. (Bobba & Rajagopal, 2010)

2.8.2.2 Hybrid Energy Storage System with Supercapacitor

Just as Boba and Rajagopal, Adib & Dhaouadi (2017) proposed a regenerative braking system with H-bridge control the motor rotation and harvest the energy, back EMF, produced as the motor is used as a generator when the motor is experiencing braking. However instead of using this regenerated energy to charge back the vehicle's battery like Boba & Rajagpal proposed, Adib & Dhaouadi (2017) use the regenerated energy to charge a supercapacitor instead. The topology of the design of Adib & Dhaouadi is shown in Figure 2.12. By integrating supercapacitor alongside with battery as power source, the lifespan of battery will be slightly prolonged, as supercapacitor can be used to provide heavy initial starting current, which relieve battery from stress of huge currents (Hatwar et al.,2013). Cao et al. (2019) also recommended that supercapacitor can be used alongside the main power source of vehicle as it helps reduces high energy demand from the main power source, when vehicle requires high power at situation such as starting of vehicle and climbing up hills.

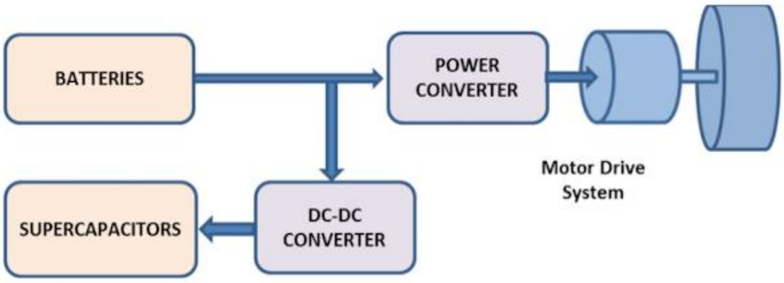

Figure 2.12: Topology of the battery-supercapacitor energy storage system (Adib & Dhaouadi, 2017)

The method of Adib & Dhaouadi (2017) used to harvest the back-EMF to charge the supercapacitor is similar to the method of Boba & Rajagopal (2010) used to charge the battery with H-bridge and PWM for the switching of switches of the H-bridge. However, in the method proposed by Boba & Rajagopal (2010), the current direction to the motor is still in the same direction during the freewheeling period. While in the method proposed by Adib & Dhaouadi (2017), the current direction to the motor is reversed during the freewheeling period as Q4 closed. Based on Figure 2.14, the current flow in opposite direction through Q4 and D3 to the motor. During this period, the inductor of motor is being charged. Once Q4 is opened, the current forced to flow through D3 and D1 and back to the supercapacitor, thus the supercapacitor is charged by the back-EMF generated from the rotation of motor, the flow of current is shown in Figure 2.15.

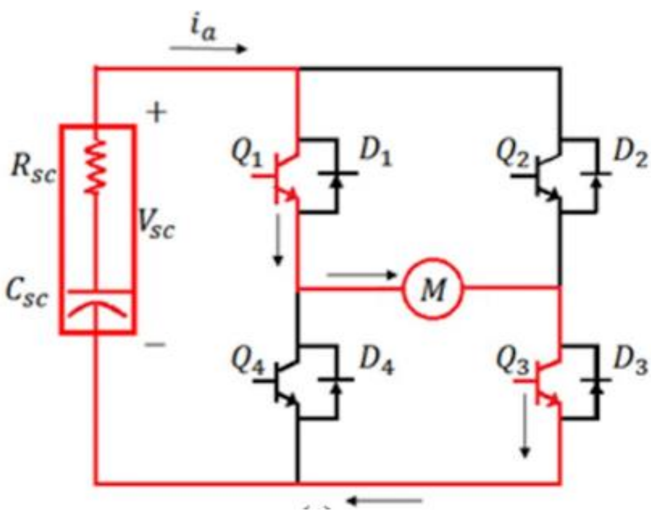

Figure 2.13:Q1 and Q3 closed for the motoring (Adib & Dhaouadi, 2017)

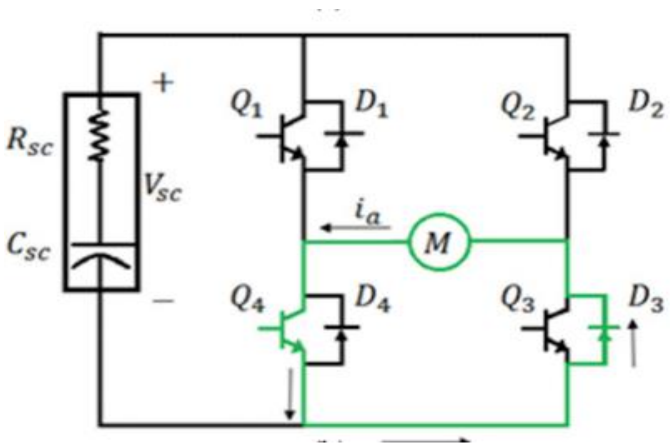

Figure 2.14: Q4 closed during freewheeling of motor. (Adib & Dhaouadi, 2017)

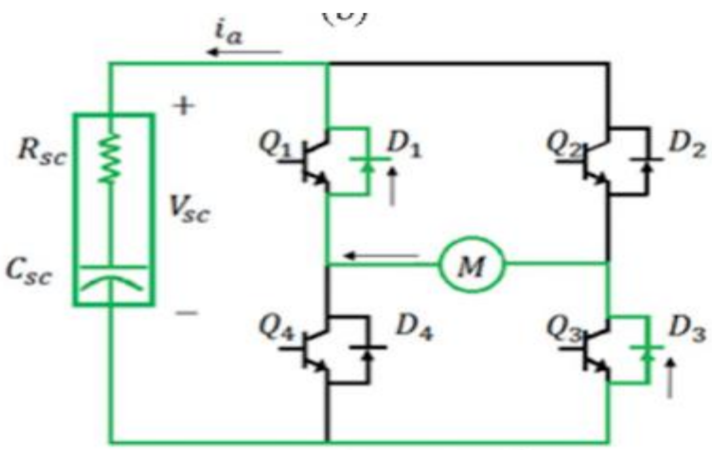

Figure 2.15: All switches closed during the charging of supercapacitor. (Adib & Dhaouadi, 2017)

Other than using H-bridge in the regenerative braking system, bidirectional DC/DC converter such as buck-boost converter is being used in the regenerative braking system as well. Cao et al. (2019) integrated a bidirectional DC/DC converter and supercapacitor bank as the regenerative braking system with the main power supply of electric vehicle, mostly battery to use the energy generated during the braking state to charge the supercapacitor bank. Figure 2.16 shows the topology of regenerative braking system using bidirectional DC/DC converter proposed by Cao et al. (2019).

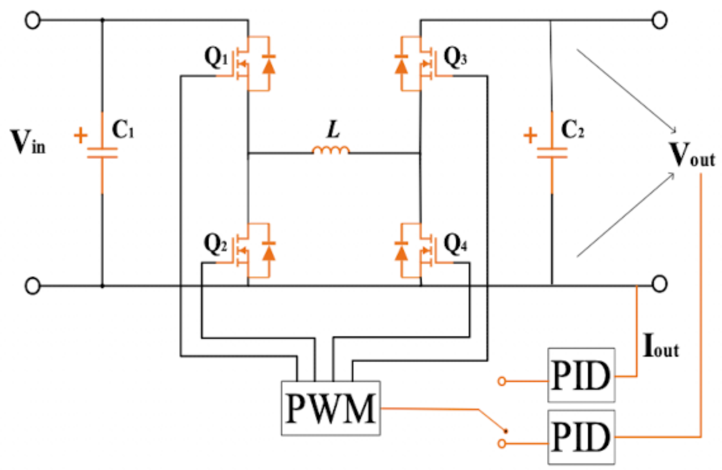

Figure 2.16: Topology of bidirectional synchronous rectification Buck-Boost circuit (Cao, et al., 2019)

Supercapacitor bank supplies energy to power up the motor during starting or accelerating, in this operation, the Buck-Boost converter operates in the boost mode. During this state, Q3 is switched on and Q4 is switched off, while Q1 and Q2 complementarily switched on. Resulting in the voltage of supercapacitor bank continuously reduced to provide energy to the motor driver, while bus voltage is maintained at a certain value by control circuit. With the bus voltage managed to maintain at a certain value as shown in Figure 2.17, this regenerative braking circuit is said to be able to alleviate the damage caused by high power discharge from the main power source and effectively extend the life of endurance.

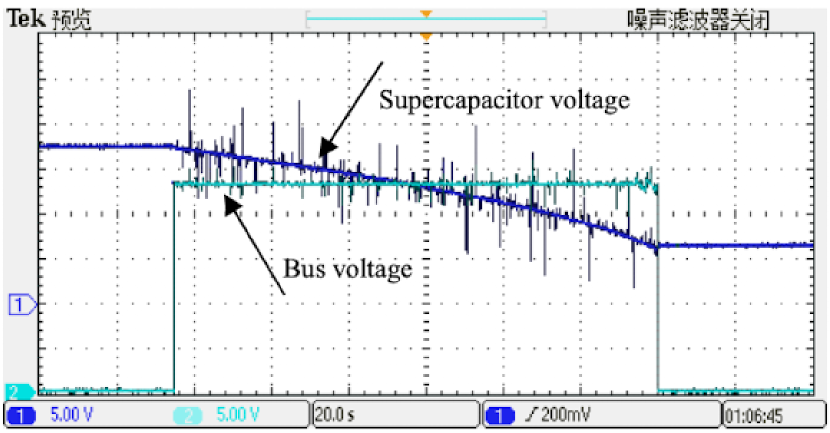

Figure 2.17: Waveform of bus voltage and supercapacitor voltage during motor starting state (Cao, et al., 2019)

During the braking period, the supercapacitor bank is in charging mode, as the bidirectional DC/DC converter works in buck mode to charge the supercapacitor. To works in the buck mode, Q1 is switched on and Q2 is switched off, while Q4 is controlling the charging of supercapacitor bank by switching on and off. Figure 2.18 shows the braking energy recovered in supercapacitor.

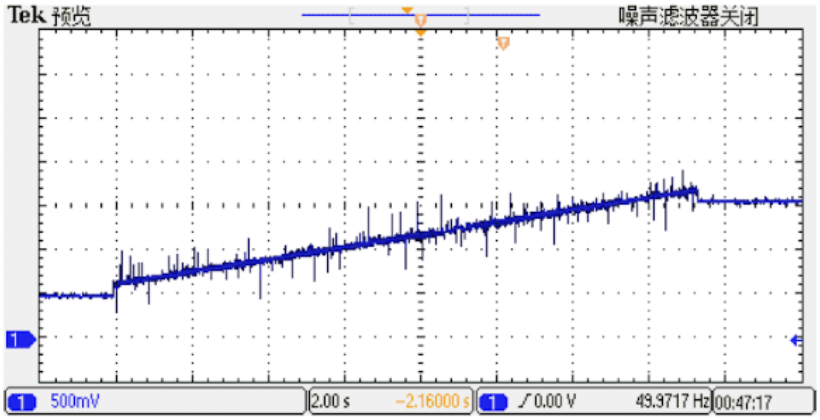

Figure 2.18: Waveform of electric brake energy recovery in supercapacitor bank (Cao, et al., 2019)

Based on Figure 2.18, it can be observed that the voltage of supercapacitor bank rises. Thus, it verified that the kinetic energy of the vehicle during braking mode is converted into electric energy and stored back in the supercapacitor bank.

2.9 Type of Hybrid Energy Storage System (HESS)

The integration of supercapacitor and battery into a single energy system is called Hybrid Energy Storage System (HESS). In HESS there can be multiple energy storage devices. In this report, supercapacitor and LiPo battery are used. Thus, the HESS in this report is considered as a Dual Energy Storage System (DESS). Battery supercapacitor HESS can be classified into three categories, Passive HESS, Active HESS, and Semi-active HESS.

2.9.1 Passive HESS

Passive HESS is the simplest way to have a hybrid energy storage device. Figure 2.19 shows the topology of a simple passive HESS. Passive HESS involves direct coupling of the battery and supercapacitor without any use of any external interfacing converter and keeps the two storage devices at the same voltage level (Banerjee, et al., 2021).

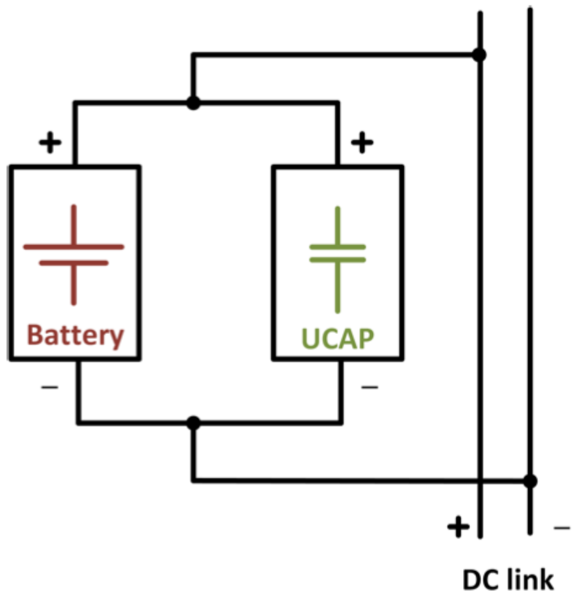

Figure 2.19:Passive HESS topology

As the energy storage devices are connected directly to the DC link in the form of parallel connected device, there is no control over the active power flow through these storage devices in the passive HESS. Without any control of the power flow in passive HESS, the current drawn will solely depends on the internal resistance of the storage devices in the HESS. Thus, the high-power density, high charging and discharge characteristic of the supercapacitor do not fully utilize in this passive HESS. However, due to its simple configuration, the energy lost between the storage devices and the DC link will be less, as there is no converter in the system.

2.9.2 Active HESS

With the disadvantage of passive HESS is the lack of control of the energy storage devices. The power distribution cannot be manipulated for efficient utilization of stored energy. To manipulate stored energy efficiently, active HESS is then introduced. Active HESS is based on the passive HESS but with DC/DC converter integrated into the circuit either connected parallelly to one of the energy storage devices or all the energy storage devices are connected to the DC link through a DC/DC converter. Active HESS can be classified as Fully Active HESS and Semi Active HESS.

2.9.2.1 Fully Active HESS

As mentioned in section 2.8.2, there can be a DC/DC converter between each of the energy storage devices and the DC link to gain fully control of the energy stored inside the storage devices. Bidirectional DC/DC converters actively controlled the power flow of the HESS (Sai , et al., 2021). Fully active HESS can be in two patterns, parallel and series connected. Figure 2.20 and Figure 2.21 shows the topology of parallel active HESS and cascaded active HESS respectively.

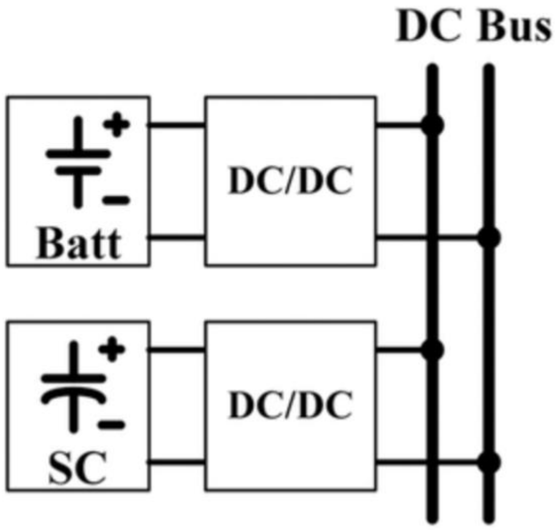

Figure 2.20:Parallel active HESS topology

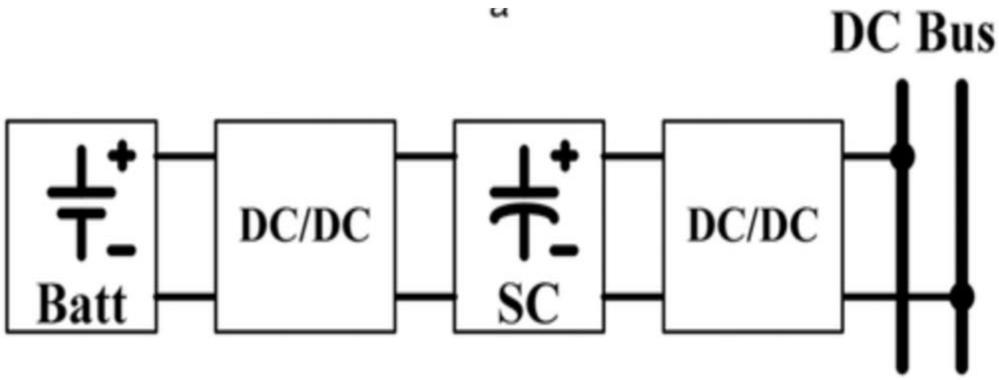

Figure 2.21: Cascaded active HESS topology

In parallel active HESS, energy storage devices are isolated to the DC link by a DC/DC converter. With this topology, a well-designed control strategy can improve the life cycle of battery and the stability of DC bus (Jing, et al., 2016).

In the cascaded active HESS, the bidirectional DC/DC converters are connected in series with the energy storage devices. The converters are connected in between the energy storage devices and isolates them from the DC link. Converter that isolates battery is commonly current controlled for a smooth power exchange with battery, which at the same time relief the stress of battery from critical charge or discharge. As for the converter isolate the supercapacitor bank from DC link, it is normally voltage controlled. As the converter function to regulate the DC link voltage and absorb the high frequency power exchange between supercapacitor and DC link. With the wide operating voltage range of supercapacitor, large voltage swing between the supercapacitor and DC link is expected, resulting in the power losses in the converter will high and the efficiency is hard to be maintained (Jing, et al., 2016)

2.9.2.2 Semi Active HESS

Different from the full active HESS, semi active HESS only consist of one bidirectional DC/DC converter regardless the number of energy storage devices in the HESS. In semi active HESS, only one of the energy storage devices can be actively controlled through the bidirectional DC/DC converter. Energy storage device that needed to be actively controlled will be connected to the DC link via a bidirectional DC/DC converter, it can either be the supercapacitor bank being actively controlled or the battery. Figure 2.22 and Figure 2.23 shows the topology of semi-active HESS with supercapacitor connecting to a DC/DC converter and semi-active HESS with battery connecting to a DC/DC converter respectively.

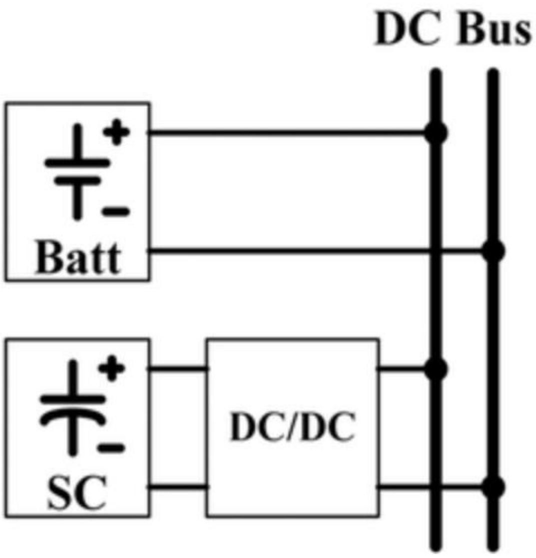

Figure 2.22: Supercapacitor semi-active HESS topology

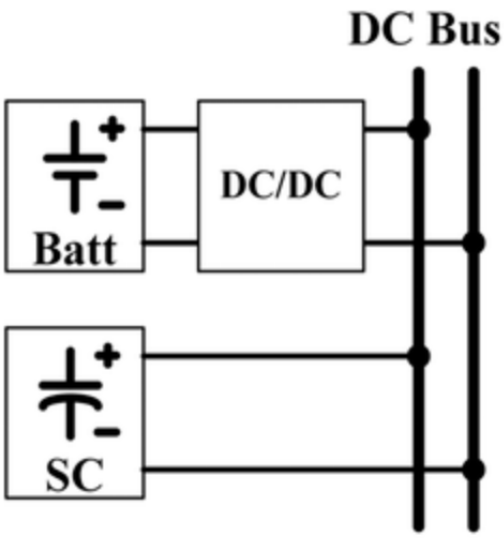

Figure 2.23: Battery semi-active HESS topology

2.10 Summary

With all those journals been reviewed, lithium battery is said to be very sensitive to the C rate, which the lithium battery's performance will degrade faster at a higher C rated. And lithium battery is vulnerable to abusive use such as overcharge and over discharge. Overcharge and over discharge will not only degrade the performance of the battery, but they are also one of the reasons of the lithium battery bloated in thickness as well. Even though swelling of lithium battery is unavoidable, but there are ways to reduce the effect of it to the battery. Regenerative braking system is one of a solution to overcharge the lithium battery from the back-EMF spike generated when the motor is breaking or stalling. Regenerative braking not only able to protect back-EMF spike to the battery, it also able to store it back to the battery or supercapacitor for later use, which is beneficial to electric vehicle for the travel range. Integration of supercapacitor with battery as power source to the system is called Hybrid Energy Storage System (HESS). Each type of the HESS has their own pros and cons.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

In this chapter, the methodology and work plan of the project will be discussed. Specifications of tools that will be used in this project, such as supercapacitor, controller, and more will be covered in this chapter as well. The work plan of this project is included in this chapter too.

3.2 Work Plan

In this section, the overall work plan of this project will be shown in the Gantt Chart format. The work plan for FYP 1 is shown in Figure 3.1 while FYP 2 is shown in Figure 3.2.

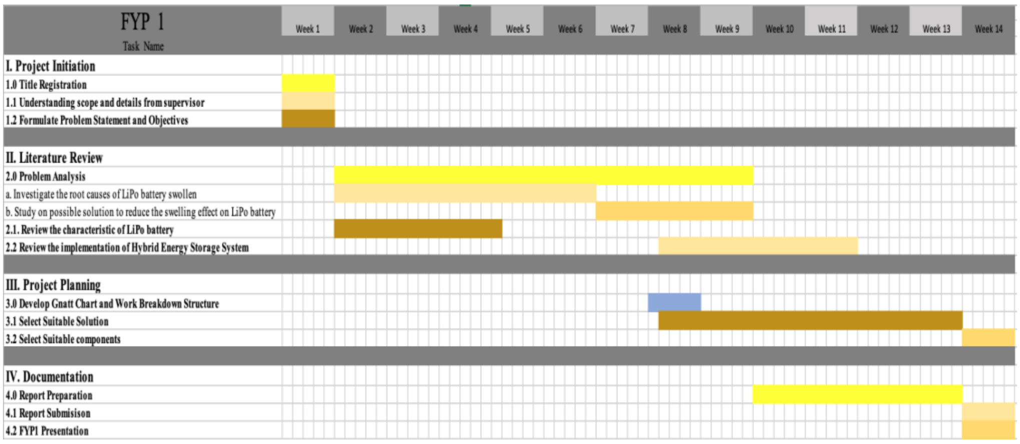

Figure 3.1: Work Plan for FYP 1

Figure 3.2: Work Plan for FYP 2

3.2.1 Significant works during FYP 1

During the time frame of the first half of the project, a circuit system was proposed to be implemented into the energy storage system of the AGV. The proposed solution to reduce the current stress experienced by the LiPo was to integrate a supercapacitor module to the LiPo as a hybrid energy storage system (HESS) to power up the AGV.

3.2.2 Proposed design during FYP 1

As the reviewed in Chapter 2, there are various type of Hybrid Energy Storage System (HESS) been used for integration of dual energy storage into one system. In this report, the energy source of HESS being used is LiPo battery and supercapacitor. These two energy sources are connected in series with a DC/DC converter in between. Figure 3.3 shows the draft of the proposed power conditioning circuit for the AGV. The reason of connecting the LiPo battery and supercapacitor bank in series is due to the simplicity of components connection and simpler cell balancing. Another reason of choosing this method of connection for HESS is due to one of the team of Massachusetts Institute of Technology lead by Shane Colton in 2009 using this method in their light vehicle project. Thus, with the success of integrating this HESS circuit into their light vehicle, the success rate of integrating supercapacitor into the current circuit of AGV to build a HESS is much higher. In this report further study and application of this circuit will be carried out. With a proper control strategy, the supercapacitor bank in the circuit will relief the LiPo battery from stress during the starting of motor, which require instantaneous power. Supercapacitor bank will provide this high frequency power to the motor alongside with LiPo battery, and LiPo battery will provide the low frequency power.

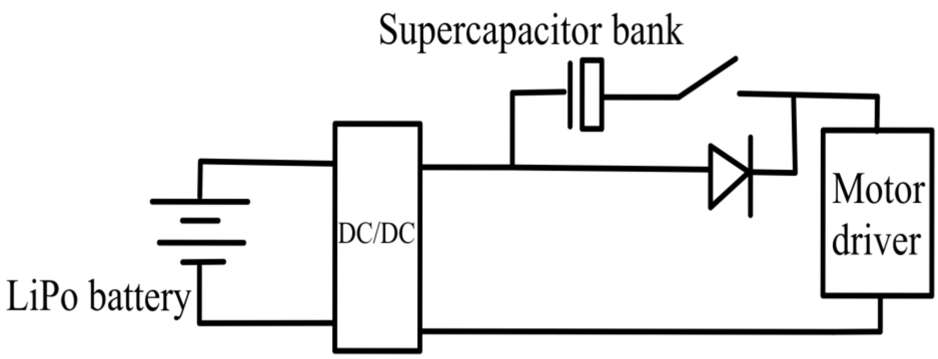

Figure 3.3: Draft of Proposed Power Conditioning Circuit for AGV

3.2.3 Working Principle of the design

Figure 3.4 shows the draft schematic diagram of proposed power conditioning circuit. Based on Figure 3.4, DC/DC converter used in this circuit is a half bridge buck converter, there are two MOSFET switches connecting in series and a capacitor connecting parallel to them. Switches of the DC/DC buck converter is controlled by a PWM controller for switching on and off depending on the voltage across the supercapacitor bank.

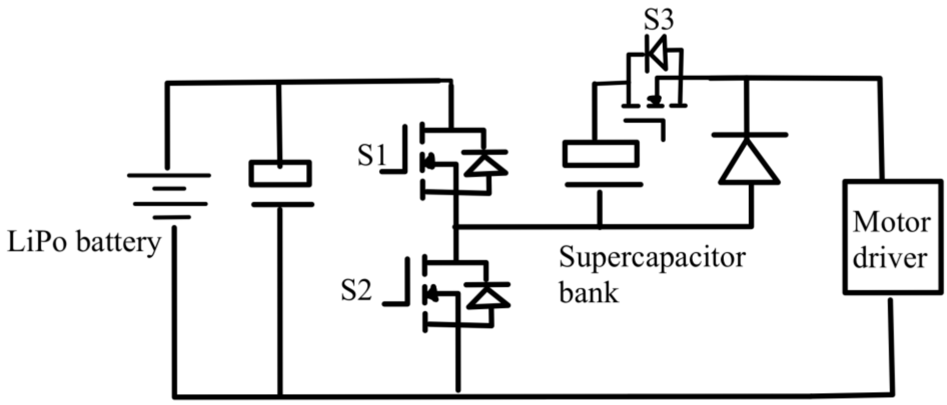

Figure 3.4: Schematic Diagram of Proposed Power Conditioning Circuit for AGV

S1 and S2 are the MOSFETs in the DC/DC half bridge buck converter, while the input capacitor of the converter is used to maintain the voltage across the converter against inductive spike from the motor. There is a voltage sensor measuring the voltage across the supercapacitor bank and it will send signal to the PWM as feedback.

During the operation of the circuit, the voltage sensor will measure and send feedback to the PWM in real time. When the voltage across the supercapacitor is below a pre-set value, S1 will be controlled by PWM for ON/OFF while the rest of the MOSFETs remain opened. Resulting in only the LiPo battery providing power to the motor driver. The charging of supercapacitor is only done by regenerative breaking, where the kinetic energy of braking convert into electrical energy and store in the supercapacitor bank.

During braking or deceleration of the AGV, S2 and S3 is closed, the rest of the MOSFETs are opened. This created a path for the regenerated energy to flow to the supercapacitor bank, avoiding the energy back to the LiPo battery as unexpected high voltage spike. With the energy return to the supercapacitor bank, not only LiPo battery is protected against regenerated voltage spike back from the motor, but the supercapacitor bank is also being charged as well. This energy stored in the supercapacitor bank can be used for the next cycle of motor starting.

When the supercapacitor bank is fully charged, the voltage sensor will send a signal to PWM for the control of S3. For the occasion of S1 and S3 both closed, the voltage provide to the motor driver will be the sum of V_{cap} and V_{bat}, as shown in equation 3.1. With the assist of supercapacitor bank providing additional voltage, the current drawn from the LiPo battery will be reduced, the equation of the total power is shown in equation 3.2. This help in reducing the stress of LiPo battery when the current demand is high which will reduce its life cycle as well as its energy storage.

Assuming the total power required by the motor driver is a constant, P_{total}.

With LiPo battery providing power to motor driver,

$$P_{total} = V_{bat} I_{bat} \tag{3.1}$$

With the assist from supercapacitor bank

$$P_{total} = \left(V_{bat} + V_{cap}\right) I \tag{3.2}$$

3.2.4 Implementation of proposed solution

With the proposed solution been presented, review of the proposed circuit and the current circuit on the AGV was carried out before purchasing the components and the implementation of the circuit into the AGV. After the review on the proposed circuit, there was one major factor that caused this proposed solution to be aborted. In this section the factor will be discussed.

After reviewed the current circuit on the AGV, the factor that caused the proposed solution not suitable to the AGV was there were not voltage spike back from the motors to the LiPo. The connection of LiPo and the DC motor driver of the AGV was shown in figure 3.4.

According to the datasheet from the manufacture, Cytron, the motor driver used in the AGV has regenerative braking function. Which during the braking of the AGV, the regenerated voltage instead of flowing back to the LiPo directly, it will flow through the motor driver and with the regenerative braking function of the motor driver, the regenerated voltage is prevented to flow back to the LiPo. As the proposed circuit, the supercapacitor module will be charged by the regenerated voltage during the braking of the AGV, with there is not reverse voltage back, the supercapacitor module will not be charged, and it only can be discharge once. Thus, the proposed circuit is not suitable for the AGV, as the assist from supercapacitor module only last for one time.

Even though this proposed solution theoretically may stand a chance in reducing the current stress on the LiPo for powering the AGV, but when there is no power transfer between the LiPo and supercapacitor module, and the charging of supercapacitor module is solely depends on the regenerated voltage during the braking of motors, the supercapacitor module will only able to discharge once, and will not able to discharge for the next cycle when the LiPo require assist from it. Thus, this proposed solution during the first half of the project has been aborted. A new solution will be proposed in the section 3.4.

3.3 Component

Components that are used in the prototype circuit are listed in Table 3.1. Components such as DC motor and motor drivers are the loads in the circuit, while LiPo battery and supercapacitor module are the energy storage devices in the circuit.

Table 3.1: Table of Components

Components	Model/Rating	Quantity
DC motor	CHP-36GP-555-ABHL (12-24V)	2
Motor driver	MD10CR3	2
LiPo battery		1
Supercapacitor module	13.5V 3F	1
DC/DC Boost Converter	XL6009	1
DC/DC Buck converter	XL4015	1
Fast recovery diode	FR207	3
Current sensor	ACS712 20A	1

Voltage sensor	Arduino voltage sensor	1

3.3.1 DC Brushed Motor

For the AGV being discussed in the project, there are four wheels to provide the movement to the AGV. This AGV is front wheel drive, the main movement is coming from the two wheels at the front. Each of the front wheels is connected directly to a DC motor to convert the energy from electrical to mechanical energy, rotation for the wheels and thus the AGV can move. The DC motor used in this project is CHP-36GP-555-ABHL manufactured by Chihai motor. It is a permanent magnet planetary coding deceleration motor with back cover. The rated voltage of the motor ranging from 12 – 24V. The maximum output power of the motor when 24V applied on it is 120W, while the maximum power of motor when 12V applied is 30W. In the case of the AGV in the project, it is powered up by a 12.6V fully charged LiPo battery.

3.3.2 Motor Driver

The motor driver used in this project is MD10CR3, which is manufactured by Cytron. MDD10A is fully utilized to control the speed, direction, and activation of two DC geared motor of the AGV. The operating voltage for this motor driver is ranging between 5V to 30V, and the maximum continuous current draw is up to 10A, peak current is valued at 30A. The 30A peak current is timed for 10 second. This motor driver support 3.3V and 5V logic input for the direction and PWM. The frequency for the speed control is up to 20kHz. One of the drawbacks of this motor driver is that it does not have reverse polarity protection at the output terminal to DC motor, thus extra care of the polarity connection of the DC brushed motor to the driver need to be taken before powering up. The specification of the motor driver is listed in Table 3.1.

Table 3.2: Specification of Motor Driver

Number of output terminals	2
Operating voltage (V)	5 to 30
Maximum Rated Current (A)	10
Maximum Peak Current (A)	30
Dimension (mm)	84.5 x 62

3.3.3 LiPo Battery

The power source for the movement of AGV is achieved by using a three cell in series Lithium-ion Polymer Battery (LiPo). The LiPo battery used in the AGV is rated at 11.1V, 6000mAh, 25C manufactured by POWER. LiPo is one of the most common types of battery being used on remote control vehicle, drone, and AGV, due to its high energy density characteristic and it is lightweight which will reduce the overall device's weight. But there is one major concerning drawback of LiPo which is the swelling of LiPo, the battery size will eventually bloat due to the gas generation produced by the chemical reaction inside the LiPo cell. The specification of LiPo battery is listed in Table 3.2.

Table 3.3: Specification of LiPo battery

Rated voltage (V)	11.1
Full-charge voltage (V)	12.6
Capacity (mAh)	3000
Maximum discharge current (A)	150
Maximum discharge rate (C)	25
Recommended charging rate (A)	0.5-1.5

3.3.4 Supercapacitor

In order to make a HESS by integrating supercapacitor module with LiPo battery, the rated voltage of both energy storage devices should be as close as possible. With the fully charged voltage of LiPo battery is 12.6V, thus the rated voltage of the supercapacitor should be the around the same. With the rated voltage of a supercapacitor is around 2.7V, thus in order to have a higher rated voltage, series connecting supercapacitor is one of the ways. By series connecting supercapacitor as a module, the rated voltage will increase but the total capacitance of the supercapacitor module decreases. The equation is shown below:

$$C_{TOTAL} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots \frac{1}{C_n}} \tag{3.3}$$

As the rated voltage of supercapacitor on the market is 2.7V, it is impossible to have a supercapacitor module with rated voltage exactly the same as 12.6V. Through calculation, it is either a module with four supercapacitors in series with rated voltage of 10.8V or five supercapacitor in series with rated voltage of 13.5V. Comparing these two voltages to the fully charge LiPo, 13.5V is closer to the fully charge LiPo battery. Thus, a module with 5 supercapacitors in series was selected to be used in this project. As for the capacitance of the supercapacitor module, due to the module was ready made, the sizing of the capacitance was not carried out in this report.

One of a concern require to be took care when connecting supercapacitor in series, is the balance charging and discharging of each of the supercapacitor to prevent imbalance charge and discharge of the supercapacitor. With the supercapacitor module being bought, it came with a balancing circuit, which able to solve this issue.

3.3.5 DC/DC boost converter

As the rated voltage of the supercapacitor module is higher than the voltage of fully charged LiPo battery, a DC/DC boost converter is required to step up the voltage from LiPo battery during the charging of supercapacitor. The DC/DC boost converter used in this project is XL6009. XL6009 is one of the most common DC/DC step up converter used in electronics project. This is due to the wide range of input voltage, 3V to 32V, and its output voltage ranging from 5V to 35V. The efficiency of this converter is up to 94% as it has a 4A efficient MOSFET built in.

The working principle of XL6009 is based on inductor energy storage. There is inductor coil built in the XL6009. When input voltage is applied to the converter, energy from the input will be stored in the magnetic field of the inductor as there is current pass by the inductor. For the case of energy to the output, this is controlled by the MOSFET built in the converter. Inductor will be connected and disconnect to the input and output, the switching of ON/OFF is done at a high frequency, in the case of XL6009 400kHz. This high frequency switching of connecting and disconnecting the inductor to output, allows the input voltage to be boosted into higher voltage.

XL6009 has a feedback control circuit to regulate the output voltage by adjusting the duty cycle of the switching based on the output voltage level. Thus, the output voltage will maintain stable even when there is adjustment at the input voltage. The output voltage can be adjusted by user with the potentiometer on the XL6009. The potentiometer is connected to the feedback control circuit of the converter. By rotating the knob of the potentiometer, the duty cycle of the switch will be adjusted, and reference voltage is varying according to the duty cycle. Thus, user able to change the output voltage level of the XL6009.

By connecting the XL6009 between the LiPo battery and supercapacitor module during the charging process, the voltage of the LiPo battery is boosted to charge the supercapacitor module, while also controlling the discharge current from the battery. Furthermore, with a peak current rating of 4A, the converter is able to effectively manage the energy flow between the LiPo battery and supercapacitor module.

3.3.6 DC/DC bulk converter

As the rated voltage of supercapacitor is higher than the voltage of fully charged LiPo battery, when both of these energy storage devices are providing power to load together, they are connected in parallel. Thus, DC/DC bulk converter is placed after the supercapacitor module then to the output. This converter step down the voltage of the supercapacitor module to a lower voltage level around the voltage level of the LiPo battery. The bulk converter used in this project is XL4015.

The working principle of XL4015 is very similar to the DC/DC boost converter, XL6009 as introduced above. Both of the converters based on the inductor energy storage principle, but with the different in topologies, one of them is used to step up input voltage while another is used to step down the input voltage, which is the case for XL4015.

3.3.7 Current Sensor – ACS712

ACS712 is a current sensor based on the Hall effect principle. It was used to sense the current drawn from LiPo and send the current value to microcontroller, Arduino as feedback. According to Allegro Microsystems, ACS712 utilize the magnetic field generated on the conductor when there is current follow through the conductor to produce an output voltage that is proportional to the strength of the magnetic field. This output voltage will then send to the microcontroller, in our case Arduino UNO to process and perform calculation to get the value of current that is pass through the conductor. According to Sanchez (2019), the ACS712 output a value of 2.5V for a current of 0A and the voltage value keep increases proportionally according to the sensitivity. Sensitivity is the slop in the graph of Voltage vs Current, and the equation is shown in equation 3.4, where m is the slope of graph which is sensitivity with a unit of V/A.

$$V = mI + 2.5 \tag{3.4}$$

According to the data sheet, ACS712 with 20A rating has a sensitivity of 100mV/A. But this value is said to be an idea value, to ensure the accuracy of the sensor, calibration is required to be carried out. The calibration being done to the sensor is by getting the actual sensitivity value by using equation 3.2.

$$m = \frac{V_2 - V_1}{I_2 - I_1} \tag{3.5}$$

Equation 3.5 is derived from equation 3.4, where V_1 is the voltage generated by the sensor when current applied to it is 0A; while in our case V_2 is the voltage generated when constant 1A applied to the sensor. Both value of V_1, V_2 were acquired by using Arduino and DC power supply as a constant current reference. The current sensor is connected in series and in between the power source and a load, 12V DC motor. The current was set at 0A to get the voltage value from the sensor when it does not have current flow through; and the steps is repeated with the current set to 1A. Sensitivity of the sensor was calculated with these voltage value with the equation. Calibration of ACS712 was done.

3.3.8 Voltage sensor

Voltage sensor being used in this proposed circuit is a general Arduino Voltage Sensor Module. With the maximum input voltage of the Arduino analog pin is 5V, this voltage sensor module is based on a basic voltage divider circuit, with a ratio of 5:1 with the resistance on the module are 30kΩ and 7.5kΩ.

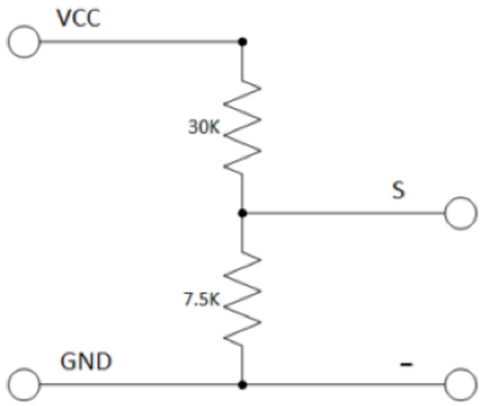

Figure 3.5: Schematic diagram of voltage divider in voltage sensor

The role of voltage sensor in the circuit is to measure the voltage of supercapacitor. As the voltage of supercapacitor is way more than 5V, it was necessary to use the voltage sensor to acquire voltage value to the Arduino for the control system of the circuit.

3.4 Proposed solution

With the possible causes of LiPo battery bloated may over discharge during the starting of motor. The proposed solution is to integrate supercapacitor module in the current energy storage system, which is just a LiPo battery. Utilizing the high-power density characteristic of supercapacitor to provide the high frequency power required by the DC geared motor during the starting state, preventing LiPo battery from the stress of instantaneous discharge.

3.4.1 Circuit design

As reviewed in Chapter 2, various types of Hybrid Energy Storage Systems (HESS) are being used to integrate dual energy storage into one system. In this report the purposed type of HESS is active HESS with the integration of supercapacitor module and LiPo battery as the energy source of the system. The main reason for selecting active HESS as the fundamental principle is its ability to efficiently control the energy of the LiPo and supercapacitor. By fully controlling the energy flow between the energy storage devices, it ensures that overcharging of the supercapacitor does not occur. With a proper control strategy, the proposed HESS circuit relieves the stress on the LiPo during the starting phase of the motor, which requires instantaneous power. The supercapacitor module provides this high-frequency power to the motor alongside the LiPo battery, which provides the low-frequency power required for continuous operation. The schematic diagram of the proposed circuit is shown in Figure 3.6. The working principle of the proposed circuit will be discussed in the next section.

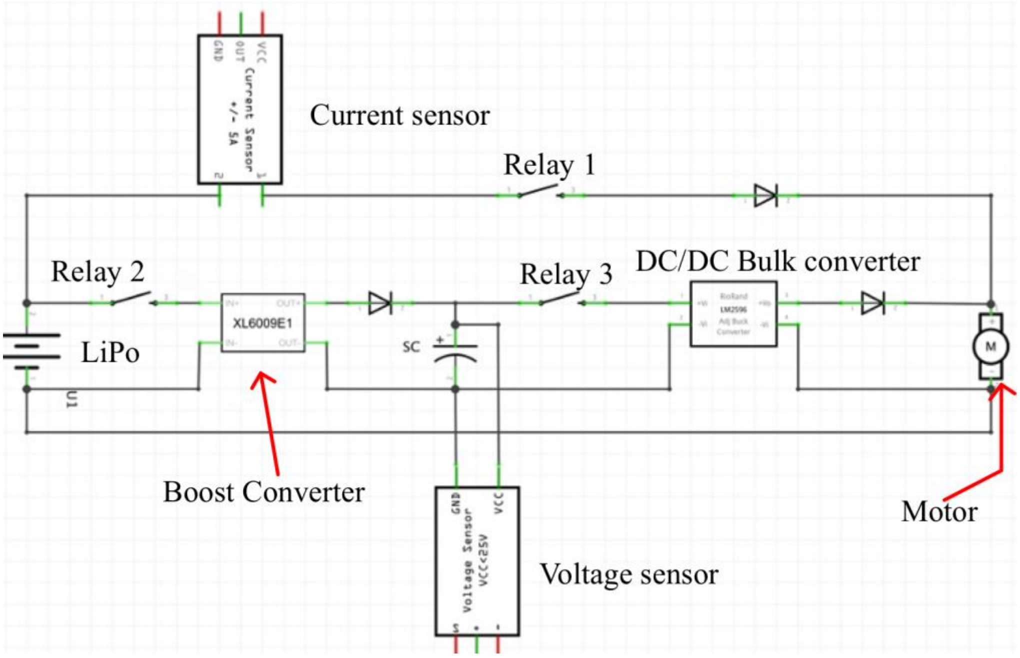

Figure 3.6: Schematic diagram of proposed circuit

3.4.2 Working principle

The overall working principle of the proposed HESS circuit is to utilize the high-power density characteristics of supercapacitor module to provide power to the load along with the LiPo when the current drawing to the load is high; when the supercapacitor is low of charge, LiPo will be connected parallel to it to charge it. Thus, the connection of LiPo and supercapacitor module is connected conditionally not permanently. The prototype of the proposed HESS circuit is shown in Figure 3.7, Table 3.4 shows the naming of each of the labels in Figure 3.4.

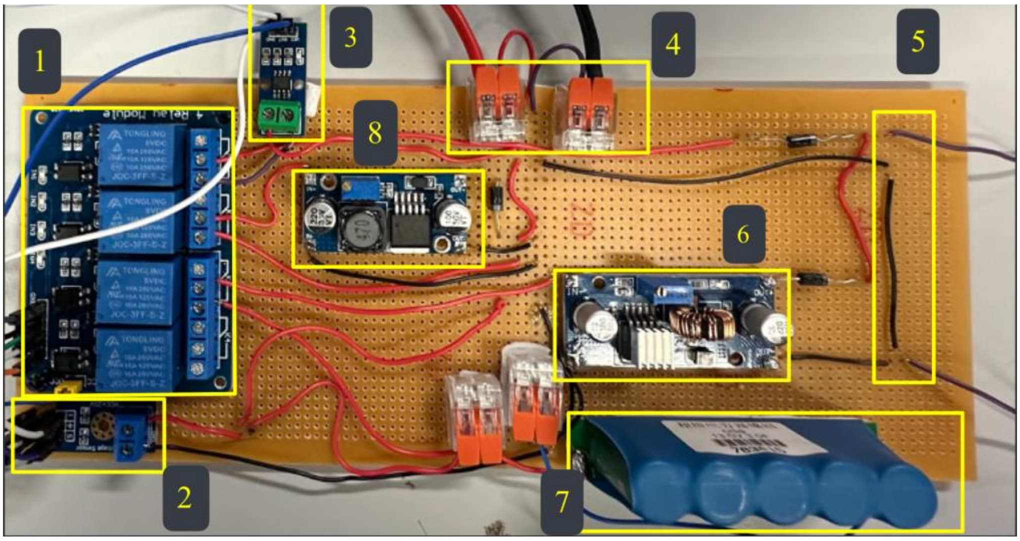

Figure 3.7: Prototype of circuit

Table 3.4: Component labelling

1.	Relay module
2.	Voltage sensor
3.	Current sensor
4.	Input terminal
5.	Output terminal
6.	DC/DC Bulk converter
7.	Supercapacitor module
8.	DC/DC Boost converter

From Figure 3.8, the connection between the LiPo and supercapacitor is connected through relay 2 and a DC/DC boost converter. This designed connection is to charge the supercapacitor module with the LiPo when the supercapacitor module is low charged. Figure 3.8 shows the current flow during the charging of supercapacitor, relay 2 is closed.

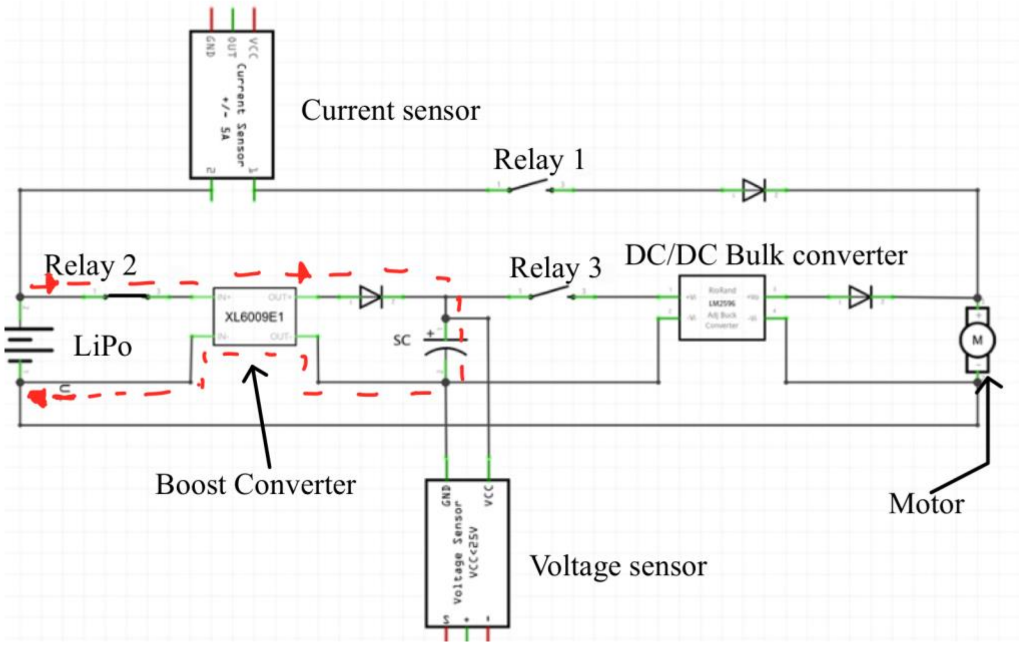

Figure 3.8: Current flow during charging of supercapacitor

As the rated voltage of the supercapacitor module used in the circuit is 13.5V while the fully charged voltage of LiPo is 12.6V, thus a DC/DC boost converter is connected between them. If both connected parallel directly the energy transfer between them is depends on the voltage level of the energy storage device. When the voltage of either energy storage devices is higher than the other, the higher voltage level devices will charge the lower voltage level device until the voltage between them are equalized. Thus, by directly connecting them in parallel will not fully charge the supercapacitor if the supercapacitor's voltage level is lower than the LiPo. In the other way, if the voltage level of supercapacitor is higher than LiPo, LiPo will be charged by supercapacitor, but due to the high-density power discharge of the supercapacitor it may not be a good practice to charge LiPo by connecting them directly in parallel. Thus, the role of DC/DC boost converter between the LiPo and supercapacitor is to ensure the supercapacitor can be fully charged to around 13.5V by boost the voltage of LiPo as input to the converter. While the fast recovery diode placed after the converter is to ensure the energy flow is unidirectional, where the energy will only flow from LiPo to the supercapacitor module through the DC/DC converter. This prevents the charging of LiPo from supercapacitor module too. Figure 3.9 shows the energy flow during the charging of supercapacitor module and providing power to motors.

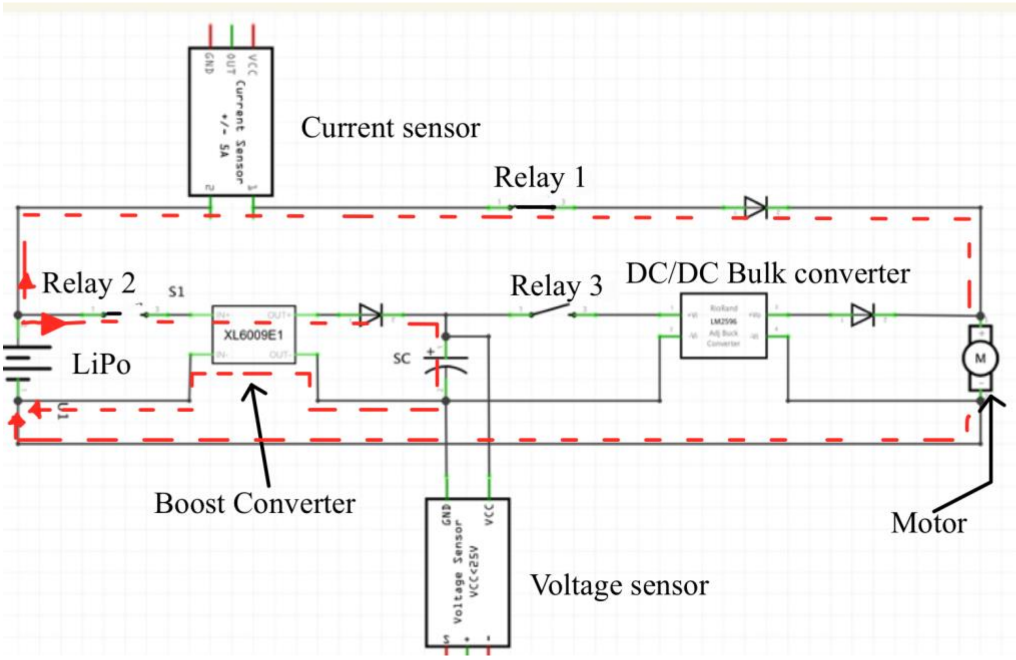

Figure 3.9: Current flow during charging supercapacitor and AGV moving.

For the discharging part from the hybrid energy storage system to the motor drivers to drive the motors, Figure 3.10 shows the connection in the circuit and the current flow through the circuit. During the kick in of supercapacitor module, relay 3 is closed to connect supercapacitor module to the output terminal through a fast recovery diode, this is to ensure no current flow between the LiPo and supercapacitor as both of them are connected to output terminal. Both LiPo battery and supercapacitor module are sharing the common ground as well as the negative output terminal as shown in Figure 3.10.

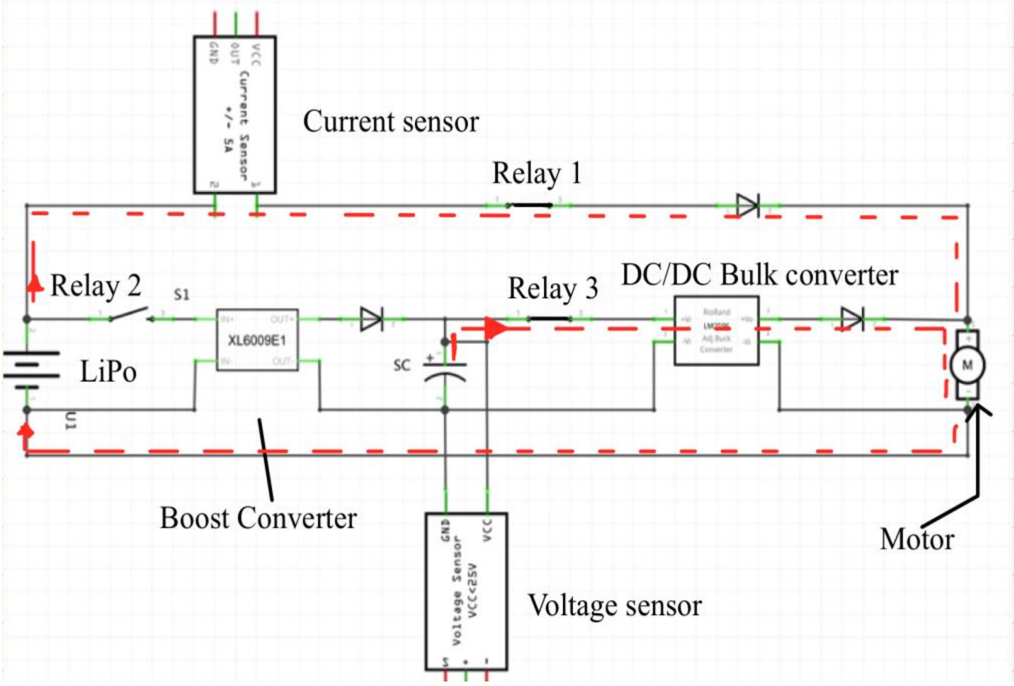

Figure 3.10: Current flow during supercapacitor kick in

The connection for the discharging is varying according to the condition of the current drawn from LiPo and the voltage level of the supercapacitor module. In this proposed circuit, relay 1 is always closed so that LiPo battery is always connected to the output to provide power to the motor drivers, while supercapacitor module only connected to the output terminal when the conditions are fulfilled. Conditions such as current drawn from LiPo is above a pre-defined value, and the voltage level of the supercapacitor module is above 12.5V. Thus, when the current drawn from LiPo is above the pre-defined value, scenario such as starting the motors of AGV, relay 3 will be closed to connect the supercapacitor module the output terminal of the circuit to power up the motors alongside LiPo battery.

During normal running of the AGV, where current drawn from LiPo is below the pre-defined value, only LiPo is connected to the output terminal, to power up the motors of AGV. From Figure 3.10, the supercapacitor is not connected directly to the output terminal, there is a DC/DC bulk converter placed parallel in between the supercapacitor and the output terminal. This DC/DC bulk converter is used to step down the voltage of the supercapacitor to a lower voltage around 12.6V, which is the fully charged voltage level of the LiPo. This is to ensure the voltage different between the LiPo and supercapacitor is not in a big gap. Through the DC/DC bulk converter, the current discharge from the supercapacitor module is controlled in a range, to prevent high current discharge to the motor drivers, causing unpredicted failure of the motor drivers. The output current of the supercapacitor module through the DC/DC bulk converter is limited to maximum 5A, as the converter capable to providing output current of 5A.

3.4.3 Control strategy

In this proposed Hybrid Energy Storage System (HESS), the controlling part of this system is done by a micro controller, Arduino UNO. Sensors such as current sensors, ACS712 20A, and voltage sensor are used in the system as feedback to the microcontroller to complete the control strategy of the system.

Microcontroller, Arduino is used as the core of the control strategy of the system. There are three outputs controlled by the Arduino. These three output pins are connected to three relay switches, which are responsible for the charging and discharging of the supercapacitor as well as the discharging of the LiPo to the output terminal of the proposed circuit. As for the inputs of the Arduino, there are current sensor, ACS712 and a voltage sensor. The current sensor is used to acquire the current drawing from the LiPo while the voltage sensor is sensing the voltage level of the supercapacitor module. Figure 3.11 shows the flowchart of the control strategy of the system.

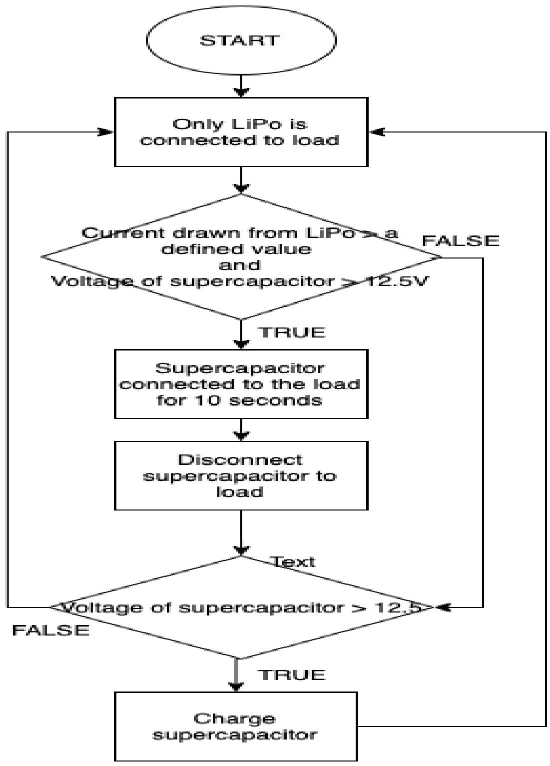

Figure 3.11: Control strategy flow chart

From Figure 3.11, at the initial state of the relay, only relay 1 is turned on, while the rest of the relays are remained off. Relay 1 is on for the whole time unless there is no power supply from the Arduino. The first execution done by Arduino it receives value from the current and the voltage sensor. With these two values, Arduino proceed to check the condition of whether the current value is more than 2.5 and the voltage value more than 12.5, if the condition is fulfilled Arduino will send a signal to turn on relay 3, which connect the supercapacitor to the output terminal of the system through the DC/DC bulk converter. Relay 3 will be turned on for 8 seconds. If the either one of the conditions is not fulfilled, Arduino will proceed to turn off relay 3. Once the if loop has executed, Arduino will proceed to the next if loop to compare the voltage value acquired from the voltage sensor is less than 12.5. If the condition is true, Arduino will turn on relay 2, to connect the LiPo and supercapacitor module to perform charging of supercapacitor through the DC/DC boost converter in the circuit. Relay 2 will be on for 8 seconds. If the conditions are false, Arduino will send a signal to keep the relay 2 off. With both if loops executed, Arduino loop back to the top of the codes and repeat the execution again.

3.5 Summary

In a nutshell, the proposed method for reducing the swelling effect on LiPo battery for the use of operating AGV is using supercapacitor bank as a secondary power source to the motors of the AGV. Using supercapacitor bank to provide additional power to the motor driver along with LiPo battery during high current demand from the motors, which reduced the current demand from two DC motors of the AGV at a given motors current demand.

For the charging of supercapacitor bank, the back-EMF regenerated during the braking or deceleration of AGV is utilized to charge the supercapacitor bank with the assist from MOSFETs controlled by PWM. The voltage across supercapacitor bank is measured in real time by a voltage sensor, depending on the voltage level of the supercapacitor bank MOSFETs of the circuit will be controlled by PWM and create path for current flow through. With this, the LiPo battery is protected against voltage spikes from motor.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, results from preliminary data collection and the integration of the proposed circuit into the current energy storage system of the AGV will be shown and further discussion will be carried out. Preliminary results and discussion will be carried out in section 4.2 while section 4.3 will be the result and discussion of the HESS on the AGV with the integration of the proposed circuit.

4.2 Preliminary Result

Before the implementation of the proposed circuit into the current power energy system, which is just a LiPo battery, data such as the current being drawn on the LiPo with current power energy system needed to be collect. With these data, the sizing of the supercapacitor can be done without oversized or undersized the voltage and capacitance of the supercapacitor.

The setup to record the current drawn from LiPo involved a microcontroller, Arduino UNO and a current sensor, ACS712 20A, which is connected in series in between the LiPo and the motor driver. There were two sets of data collected for the preliminary results. The first data collection for the preliminary result, where the loads were two 12V DC brushed motors with torque ranged from 0.49 Nm to 0.98 Nm. While the other set of data was collected with the loads were two 12V DC motor with rated torque of 1.7 Nm. Both set of data were collected for the motors powering up the AGV to move in a straight line then stop. Before the data collection with the ACS712, calibration was carried out on the current sensor to ensure the value collected was accurate and reduce the sizing error of the supercapacitor.

Figure 4.1 shows the graph of current drawn out from LiPo to two 12V DC brushed motors with torque ranged from 0.49 Nm to 0.98 Nm. In Figure 4.1, it managed to capture the current spike during the moment the motors start to rotate to move the AGV. The value of this spike of current was captured slightly above 4A, and it was the peak current drawn during this movement of AGV, and it last for a very short interval. This current spike is considered as the inrush current for the 2 DC brushed motors. Once the motors got sufficient current to kick start the rotation, the current drawn from LiPo dropped to around 3A, at this moment the AGV was moving in the straight line, and this was considered as the current drawn during the movement of AGV in straight line. There were some fluctuations shown in graph, where it could be noises captured by the current sensor. As the noises could not be totally eliminated in practical sensing.

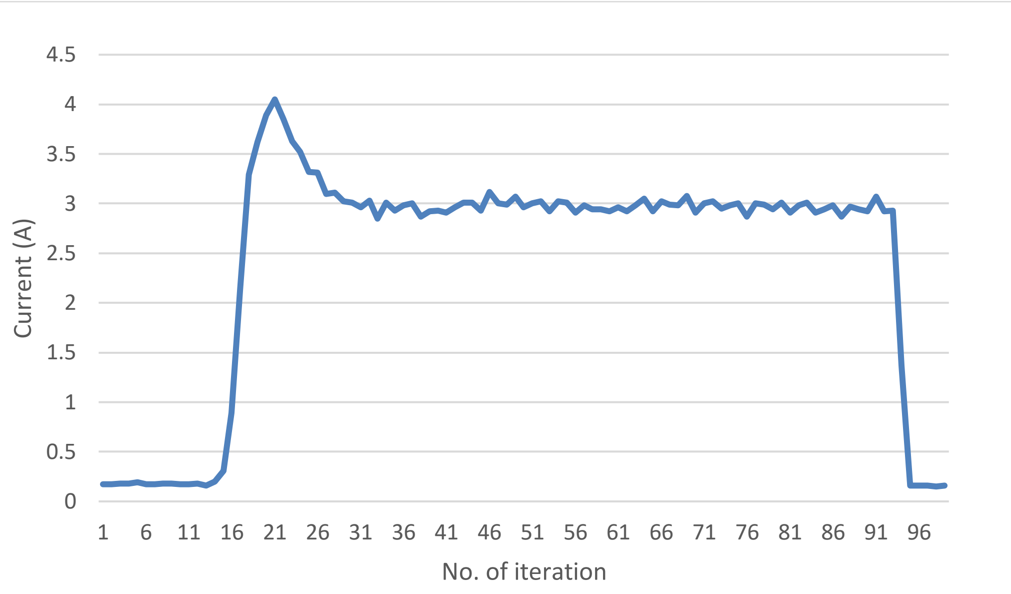

Figure 4.1: Current drawn out from LiPo set 1.

Figure 4.2 shows the graph of current drawn out from LiPo to two 12V DC motor with a higher rated torque. As observed from Figure 4.1 and 4.2, the waveform of the current drawn out from LiPo are similar, but the value of current of Figure 4.2 is lower compared to Figure 4.2. Where the peak current spike recorded in Figure 4.2 is slightly above 3.5A which is lower than the peak current spike recorded in Figure 4.1. And the current drawn during constant speed moving of the AGV recorded in Figure 4.2 was lower than Figure 4.1, around 1.5A. According to Collins, the output torque of a DC motor is directly proportional to the current through the windings with the relation shows by equation,

$$T = k_T I \tag{4.1}$$

Thus, the current drawn out from LiPo for set 2 should be higher than set 1 as the torque of DC motors used in set 2 is higher than DC motors used in set 1, but the recorded current drawn out from LiPo to power up them were lower for set 2 than set 1. This was due to the moving speed of the AGV was not the same for both set of data. The moving speed of the AGV for the set 1 was higher than set 2, thus it explained why with the DC motors in set 2 were higher than set 1, but the current drawn by the DC motors was lower than set 1.

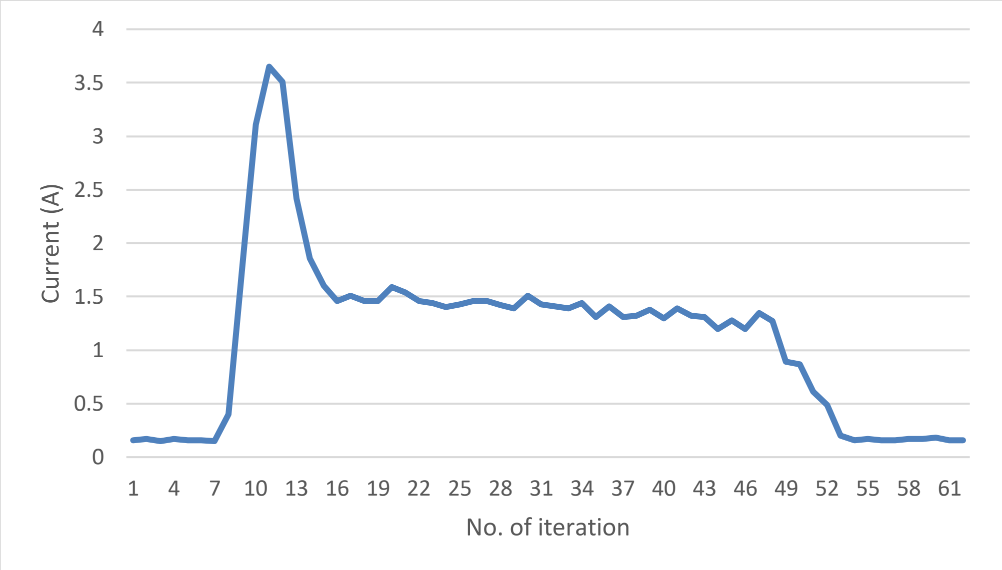

Figure 4.2: Current drawn out from LiPo set 2.

Another difference that can be observed from Figure 4.1 and Figure 4.2 was the current dropped when the AGV was stopped. From Figure 4.1, the current dropped sharply to 0A when the AGV stopped, while in Figure 4.2, the current dropped gradually to 0A instead of dropped sharply to stop the AGV. This was due to the control of the AGV was fine tuned to make the AGV stop gradually instead of stopping immediately to reduce the inertia of the AGV.

Overall, with these two sets of data we can conclude that regardless of the rated torque of DC motor, during the starting of motors on the AGV the current drawn out from the LiPo will experience a short internal of higher current discharge after that the current drawn to power the motors will only being drawn steadily.

4.3 Result and discussion

With the designed circuit integrated into the AGV’s energy storage system, supercapacitor will be connected parallel to the load, motor driver occasionally depending on the condition. The charge and discharge of the supercapacitor in the system was controlled by Arduino, with current sensor and voltage sensor as inputs. As the DC motors of the AGV replaced with a higher torque DC motor, there are two set of data collected one with the initial DC motors which have lower torque, and the other set was collected with the latest DC motors with higher torque.

4.3.1 Integration of proposed circuit into AGV with lower torque DC motors

Figure 4.3 shown the current drawn out from LiPo to power up the motors for the AGV move in the straight line, same as the scenario where Figure 4.1 was captured. But Figure 4.3 was captured with the proposed circuit integrated into the energy storage system of the AGV and the supercapacitor module was connected to the loads to power up the load along with the LiPo.

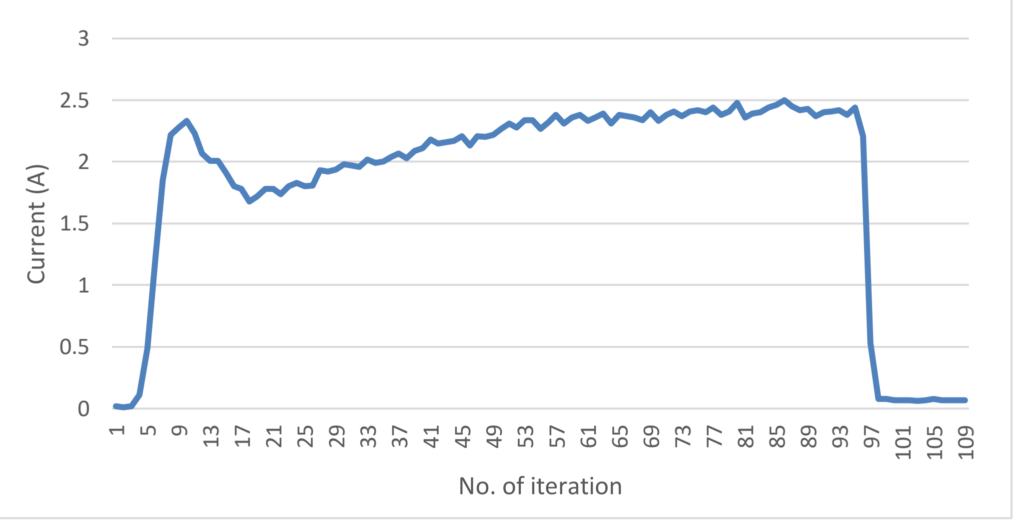

Figure 4.3: Current drawn out from LiPo with higher torque DC motors with supercapacitor connected.

From Figure 4.3, the current spike during the starting of motors, inrush current, was captured at a value below 2.5A. This inrush current value was lower compared to the inrush current captured with just LiPo powering the motors. After the inrush current, the current drawn from the LiPo slowly increased. As the AGV kept on moving in a straight line, the current provided by the LiPo battery is more than the inrush current provided by LiPo battery at the beginning of the movement of AGV. Even though the value of current kept increasing, but the highest value captured during this movement of AGV did not exceed 2.5A. While for the case of just LiPo providing power to AGV, the current drawn from LiPo for the constant moving AGV was captured around 3A as shown in Figure 4.1.

With the energy stored inside the supercapacitor has a finite amount and the fast discharge characteristics of supercapacitor, the voltage of supercapacitor will drop drastically as well as the current discharge to the loads. This will be further discussed in the upcoming section.

4.3.2 Integration of proposed circuit into AGV with higher torque DC motors

As the DC motors in the AGV changed to motors with higher torque, in this sub section results of the current drawn out of the LiPo during the moving of AGV will be discussed.

As mentioned in section above, even though the new motors having a higher torque than the previous motors, but the speed of the AGV has been tuned down to reduce the inertia. Data recorded in Figure 4.4 was recorded with supercapacitor was charge at 13.30V and connected to the output terminal of the HESS along with LiPo to power up the AGV to move in a straight line.

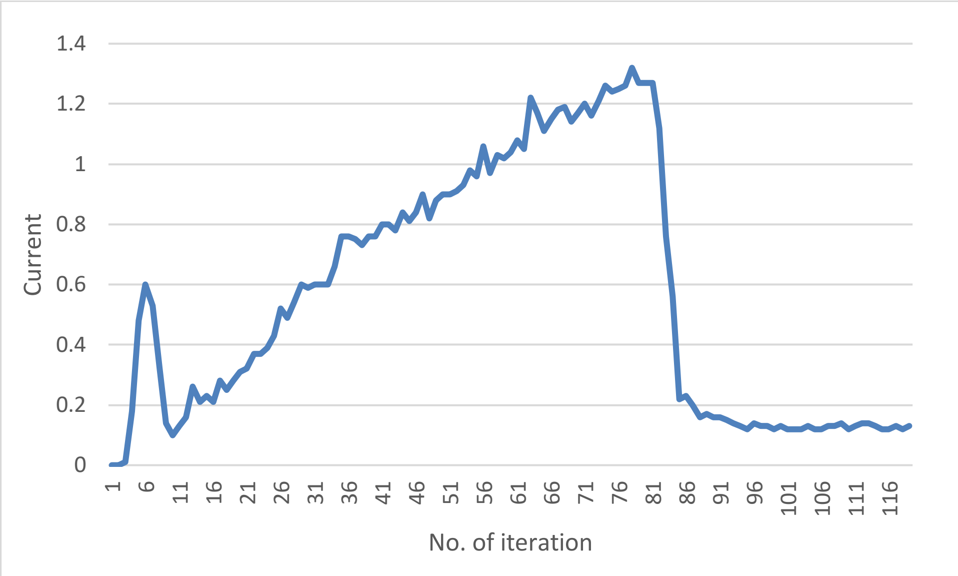

Figure 4.4: Current drawn out from LiPo with higher torque DC motors.

From Figure 4.4, it can be observed that once the AGV started moving, there was a current spike at the beginning of the current drawn out from the LiPo with the current reached the peak of spike at 0.6A. This was considered as the inrush current drawn out from LiPo to kick start the DC motors for rotation. Compared to Figure 4.2, when only LiPo powering the AGV with the same DC motors as used during the data collecting for Figure 4.4, the inrush current peak was lower than recorded in Figure 4.2. Thus, with the comparison of these two figures, connecting a fully charged supercapacitor parallel to LiPo to power up the AGV able to reduce the inrush current experienced by the LiPo.

Similar to the scenario of supercapacitor module connected parallel to LiPo to power the AGV with a lower torque, higher speed DC motors, which shown in Figure 4.3, the current drawn out from the LiPo slowly after the inrush current. This was due to the fast discharge characteristics of supercapacitor, as the energy of supercapacitor discharge very quickly, the output current from supercapacitor will be reducing as the voltage of supercapacitor dropped during discharge to motor drivers. This can be validated with Figure 4.5 and 4.6. As the current required for the AGV moving with the new DC motors is around 1.5A as observed in Figure 4.2, this explained why in Figure 4.5 current slowly increased to around 1.3A after the inrush current.

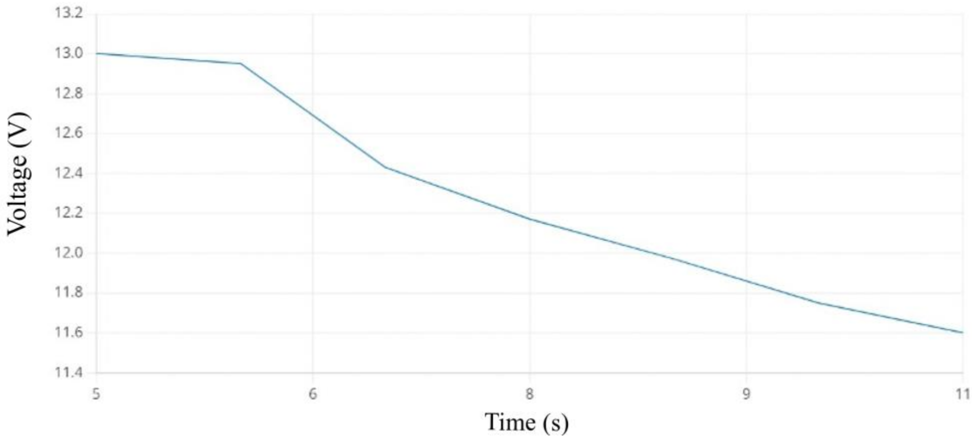

Figure 4.5: Voltage of supercapacitor discharging.

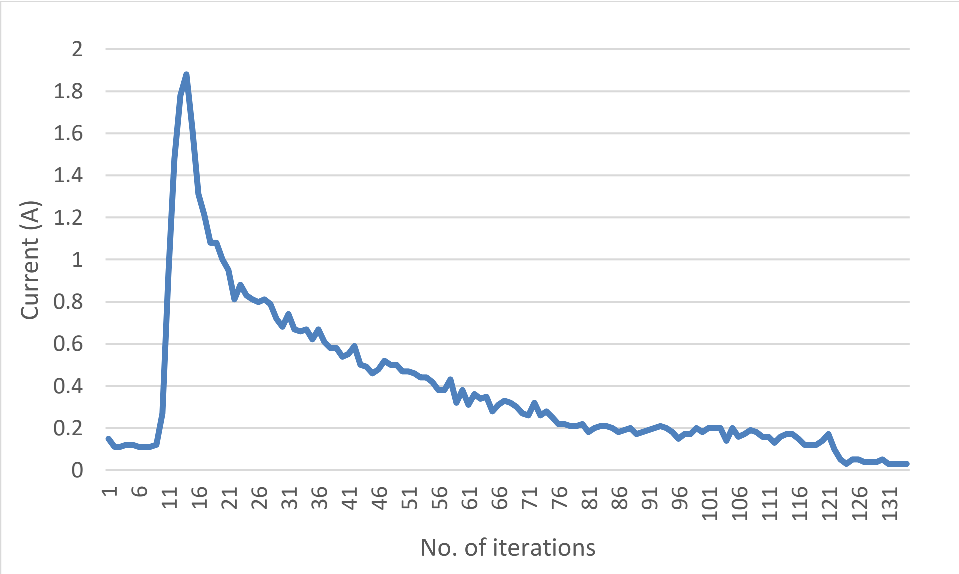

Figure 4.6: Current discharge of supercapacitor

Figure 4.5 shows the voltage drop of supercapacitor module during the running of AGV. As the AGV running it can observe that the voltage of supercapacitor initially was 13.0V and was dropping as the AGV running. As the voltage decreasing, the current discharge from supercapacitor was decreasing as well, this can be observed on Figure 4.6. Thus, is explained why the current drawn out from the LiPo slowly increasing to nearly 2.5A during the running of AGV in Figure 4.3.

Figure 4.6 shows the discharge current of supercapacitor when it was connected parallel to LiPo battery to power up the AGV to move in a straight line. During the starting of DC motors of AGV, inrush current occurred on both

LiPo and supercapacitor module. From the Figure 4.6, it can be observed that the current drew was spiked to around 1.9A once the AGV was moving, with this current from supercapacitor, the current draw from LiPo battery to kick start the motors was greatly reduced as seen from Figure 4.4. After the inrush current to kick start the movement of AGV, the current discharge from supercapacitor was reducing over time as seen from Figure 4.6, where there is an incline of the current discharge graph over time. Thus, the statement of supercapacitor discharge current reduces as voltage of supercapacitor dropped over time is valid.

4.3.3 Effect of supercapacitor module to the current drawn from LiPo

In order to show the effect of the supercapacitor module in reducing the current drawing out from LiPo, scenario of AGV run and stop in a straight line was carried out. Figure 4.4 shows the current drawn out from the LiPo during the scenario. Initially, LiPo was the only energy source to power up the motors of AGV for the first run of the AGV then the AGV stopped, the next round of running of the AGV was powered up by LiPo alongside with the supercapacitor.

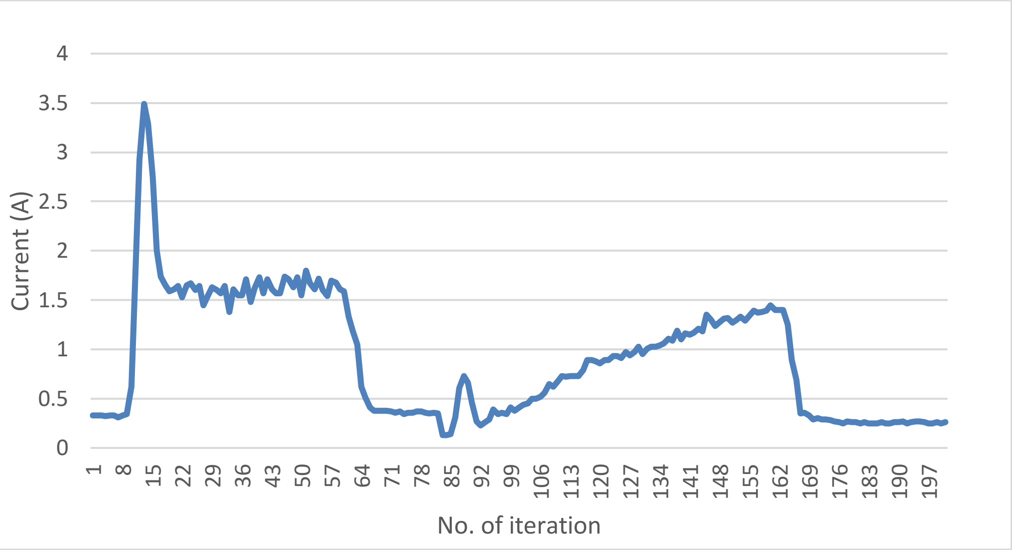

Figure 4.7: Effect of supercapacitor module to LiPo

From Figure 4.7, it can be observed that during the first running of the AGV, which was powered only by LiPo, the current drawn out from the LiPo behave similar to Figure 4.2. Where at the start of the AGV, there was high current drawn from LiPo, approximately 3.5A for a short interval. Once the motors of AGV gain sufficient current to kick start, the current drawn out from the LiPo dropped to around 1.5A for the duration of AGV running. The current dropped gradually for the stopping of the AGV.

While for the second half of the graph in Figure 4.7, where the AGV was powered by LiPo battery and supercapacitor module. The different between the starting of AGV on the first half and second half is very obvious. As the current drawn from LiPo battery to start the AGV on the second half was way lower to the first half of AGV running. The second peak in Figure 4.7 indicate the inrush current provided by LiPo battery while supercapacitor providing power to AGV too, the peak was lower than the peak during the first peak where only LiPo battery powering up the AGV.

4.3.4 Summary

In a nutshell, this chapter discussed the results of the characteristics of current discharge from LiPo to power up the AGV and how the implementation of proposed circuit affects the current drawn from LiPo battery to power up the AGV.

The implementation of the proposed circuit able to reduce the current discharge from LiPo battery to power up AGV. This is achieved by utilizing the high energy density and quick energy discharge of supercapacitor to compensate the current discharged by LiPo battery to power up the AGV. Due to the characteristics of supercapacitor, the energy released to the AGV does not last long. Thus, the current discharge from LiPo will slowly increases to compensate the reducing current provided by the supercapacitor. This conclude that supercapacitor only able to reduce the current discharged from LiPo battery for a short interval. But it is sufficient enough to reduce current stress experienced by LiPo battery during the inrush current to start the motors of AGV.

CHAPTER 5

CONCLUSION

5.1 Problem encountered.

During the design of the proposed circuit for HESS, the first problem encounter was the conductivity of MOSFETs in the circuit. Initially, the component to connect and disconnect LiPo battery, supercapacitor module, and output terminal was done by MOSFETs. The reason of selecting MOSFETs during the initial state was due to its smaller size and no external power source required. But during the testing of the circuit with MOSFETs in it, when condition of only LiPo battery powering up the DC motors, not only the MOSFET connecting LiPo battery to the output terminal was ON, the MOSFET connecting supercapacitor module to the output terminal was ON too, by referring back to the code in Arduino, the MOSFET connecting supercapacitor module and output terminal should be off. Thus, there was issue in the connection in circuit. This was later solved by redesigned the circuit to the final circuit design shown in this report.

The other problem encountered was the output voltage on the output terminal of the circuit was lower than then input voltage from the LiPo battery. This was later found out by using multi-meter to carry out connection checking on the circuit, where the voltage drop across the MOSFET was around 1.4V, and with the voltage drop of fast recovery diode, 0.7V connected in between the power source and output terminal, resulted the output voltage on the output terminal 2.1V lesser than the input voltage, which was not idea for the DC motors of the AGV, as the working voltage of DC motors was 12V, while the rated voltage of LiPo battery was just 12.6V before the voltage drop across MOSFET and fast recovery diode. This was the reason why in the final designed of the circuit, a 5V relay module was used, as no voltage drop across the relay, but an external power source is required, with the required power sources was just 5V, the relay module was powered by the 5V from Arduino.

5.2 Limitations

One of the limitations in this project is the data collection on the current discharge on both LiPo battery and supercapacitor module. In order to evaluate the effect of the proposed circuit in reducing the current stress on LiPo battery, the discharge current of LiPo battery and supercapacitor module needed to be captured. The ideal scenario for data collecting is to capture both discharged current of LiPo battery and supercapacitor module at the same time and same route of the AGV moving. Initially, oscilloscope and a shunt resistor were used to capture the current discharged from both power sources, but due the limited space on the AGV and the movement of AGV, oscilloscope was not suitable for the scenario. In the end, a current sensor, ACS712 was used to capture the current, the accuracy of ACS712 was inaccurate as compared to oscilloscope, thus the data collected may not be that accurate, but it still managed to capture the characteristics of discharging of LiPo battery and supercapacitor module, the inrush current might be higher than what the sensor captured.

Another limitation while collecting data was Arduino unable to capture data from two current sensors at the same time with great accuracy, As the current sensor senses current by using the input voltage from Arduino, 5V as reference, but in practical the voltage input to the current sensor is not exactly 5V. In order to ensure the voltage input to current sensor is very close to 5V, using two separate Arduino is the ideal case. But with the limited space on the AGV, it is hard to fit two laptops on it to perform data collecting. Thus, in the end the data of discharging of LiPo battery and supercapacitor module was done separately but not done at the same time.

5.3 Improvement

In this project, DC/DC converters used in final design of the circuit for HESS were ready made products, and lack of feedback system in these DC/DC converters. As the output voltage was set by turning the potentiometer, when the input voltage changes the output voltage will changes. Resulting in the output voltage of the converter is not stable, which was not idea for the charging of supercapacitor. Thus, the improvement of designing the DC/DC converters with feedback system to regulate the output voltage by adjusting the duty cycle of the MOSFETs according to the input voltage. With that, the charging and discharging of supercapacitor module able to fully utilize the energy stored in it.

5.4 Conclusion

In this report, the characteristics of LiPo battery and supercapacitor module has been reviewed. With the understanding of the characteristics of LiPo battery and supercapacitor, the proposed circuit in this report utilize both of these energy storage devices to make a HESS. The objective of this project is achieved with the integration of the HESS on the AGV, where the current discharged from LiPo battery able to be reduced. Thus, the current stress experienced by the LiPo battery on the AGV is reduced too.

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APPENDICES

Appendix A: Code

```
// Define the pin
const int VOLTAGE =A0;
const int ACS = A1;
const int SC = 8;
const int LIPO = 7;
const int charge = 6;

float sensitivity = 0.103; // Sensitivity of the ACS712 sensor, change this value
to adjust sensitivity
float zero_current_voltage = 2.509; // Voltage output of the ACS712 when there
is no current flowing
float voltage_reading = 0.0;
float current_reading = 0.0;
float sum_current_reading = 0.0;
int num_readings = 100; // Number of readings to average
int delay_time = 1; // Delay time between readings

// Floats for ADC voltage & Input voltage
float adc_voltage = 0.0;
float in_voltage = 0.0;


// Floats for resistor values in divider (in ohms)
float R1 = 30000.0;
float R2 = 7500.0;

// Float for Reference Voltage
float ref_voltage = 5.00;
```

```
// Integer for ADC value
int adc_value = 0;

float voltage_value() {

  adc_value = analogRead(VOLTAGE);
  adc_voltage  = (adc_value * ref_voltage)/1024.0;
   // Calculate voltage at divider input
  in_voltage = (adc_voltage / (R2/(R1+R2)))-0.34;//0.34 offset
  Serial.print("Input Voltage = ");
  Serial.println(in_voltage, 2);

  return in_voltage;
}

float calculateCurrent(){

  sum_current_reading = 0.0;
  for (int i = 0; i < num_readings; i++) {
    voltage_reading = analogRead(ACS) * (5.0 / 1023.0); // Read voltage from
ACS712
    current_reading = (voltage_reading - zero_current_voltage) / sensitivity; //
Calculate current reading based on sensitivity and zero voltage
    sum_current_reading += current_reading; // Add current reading to sum
    delay(delay_time); // Wait before next reading
  }
  float avg_current_reading = (sum_current_reading / num_readings); //
Calculate average current reading
  return avg_current_reading; // Return the calculated value*/
}
void setup() {
 pinMode(SC, OUTPUT);
 pinMode(LIPO, OUTPUT);
```

```
 pinMode(charge, OUTPUT);
 pinMode(VOLTAGE, INPUT);

 digitalWrite(LIPO, LOW);
 digitalWrite(SC, HIGH);
 digitalWrite(charge, HIGH);
 Serial.begin(9600);

}


void loop() {

  float current= calculateCurrent();
  float calculatedVoltage = voltage_value();
  if (current > 2.5 and calculatedVoltage > 12.5)  {
    digitalWrite(SC, LOW);
    delay(8000);

  } else {
    digitalWrite(SC, HIGH);
  }

  if(calculatedVoltage < 12.5){
    digitalWrite(charge,LOW);
    delay(5000);

  }
  else if(calculatedVoltage >=13.5) {
    digitalWrite(charge,HIGH);
  }

}
```