THE ANALYSIS ON BATTERY AND SUPERCAPACITOR ENERGY MANAGEMENT SYSTEM FOR EV

NUR QAMARINA BINTI AHMAD SHUKRI

BACHELOR OF ELECTRICAL ENGINEERING WITH HONOURS
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2024

THE ANALYSIS ON BATTERY AND SUPERCAPACITOR ENERGY MANAGEMENT SYSTEM FOR EV

NUR QAMARINA BINTI AHMAD SHUKRI

A report submitted
in partial fulfilment of the requirements for the degree of
Bachelor of Electrical Engineering with Honours

Faculty of Electrical Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2024

DECLARATION

I declare that this thesis entitled "THE ANALYSIS ON BATTERY AND SUPERCAPACITOR ENERGY MANAGEMENT SYSTEM FOR EV is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

Signature :

Name : NUR QAMARINA BINTI AHMAD SHUKRI

Date : 21/6/2024

APPROVAL

I hereby declare that I have checked this report entitled " THE ANALYSIS ON BATTERY AND SUPERCAPACITOR ENERGY MANAGEMENT SYSTEM FOR EV", and in my opinion, this thesis fulfils the partial requirement to be awarded the degree of Bachelor of Electrical Engineering with Honours

Signature : ....

Supervisor Name : NORHAZILINA BINTI BAHARI

Date : 21/6/2024

DEDICATIONS

To my beloved mother, father, and my family

ACKNOWLEDGEMENTS

Firstly, I would like to express my deep gratitude to my supervisor, Mrs. Norhazilina Binti Bahari, for her unwavering patience, unwavering inspiration, unwavering passion, and immense knowledge. The guidance provided me with assistance throughout the process of doing research and preparing this report. In addition to expressing gratitude towards my supervisor, I would like to extend my thanks to Universiti Teknikal Malaysia Melaka (UTeM) for giving me the opportunity to complete my studies in the field of Bachelor of Electrical Engineering.

Furthermore, I express my gratitude to all my fellow classmates for their invaluable assistance and dedication during the process of accomplishing this assignment. In addition, I would like to express my heartfelt gratitude to my family, including my mother, father, my brother, and my sisters, for their continuous support and constant encouragement. If it had been not for their assistance, I would not have successfully finished this project. Also, I would want to express my gratitude to an individual of great significance who has consistently shown unwavering belief in me and provided continuous encouragement throughout this project. Without of your presence, I might give up my efforts and surrender.

Lastly, I would like to express gratitude towards myself. I appreciate my constant faith in myself, my dedication to putting in great effort, my commitment to working tirelessly without taking breaks, my refusal to give up, and my consistent authenticity.

ABSTRACT

This abstract discusses the incorporation of a Hybrid Energy Storage System (HESS) that combines a battery and supercapacitor (SC) to overcome the limitations faced by individual storage systems in electric vehicle (EV) applications. Although batteries are effective in delivering improved mileage, their inability to achieve greater speeds and vulnerability to deterioration under demanding settings need regular replacements. In contrast, supercapacitor provide faster speeds but do not meet the expected level of fuel efficiency. It is necessary to install a HESS in order to synchronize these conflicting characteristics. The literature explores several topologies that define the interface between the two energy storage systems (ESS), intending to optimize the use of each component. This project provides a comprehensive review of different topologies, including a full comparative study based on cost, flexibility, control, efficiency, and the type of DC/DC converter. The publication utilizes current literature to provide a thorough comprehension of HESS topologies, allowing for educated choices depending on unique needs and factors. This initiative aims to further improve the effectiveness and long-term viability of electric transportation systems by using new energy storage techniques. This project will used MATLAB Simulink to analyse the performance of the whole EV by using a new topologies.

ABSTRAK

Abstrak ini membincangkan penggabungan Sistem Penyimpanan Tenaga Hibrid (HESS) yang menggabungkan bateri dan supercapacitor (SC) untuk mengatasi batasan yang dihadapi oleh sistem penyimpanan individu dalam aplikasi kenderaan elektrik (EV). Walaupun bateri berkesan dalam memberikan jarak tempuh yang lebih baik, ketidakupayaan mereka untuk mencapai kelajuan yang lebih tinggi dan terdedah kepada kemerosotan di bawah tetapan yang menuntut memerlukan penggantian tetap. Sebaliknya, supercapacitor memberikan kelajuan yang lebih pantas tetapi tidak memenuhi tahap kecekapan bahan api yang dijangkakan. Ia adalah perlu untuk memasang HESS untuk menyelaraskan ciri-ciri ini. Kesusasteraan meneroka beberapa topologi yang mentakrifkan antara dua sistem storan tenaga (ESS), yang bertujuan untuk mengoptimumkan penggunaan setiap komponen. Projek ini menyediakan semakan menyeluruh tentang topologi yang berbeza, termasuk kajian perbandingan penuh berdasarkan kos, fleksibiliti, kawalan, kecekapan, dan jenis penukar DC/DC. Penerbitan ini menggunakan kesusasteraan semasa untuk memberikan pemahaman menyeluruh tentang topologi HESS, membolehkan pilihan terdidik bergantung pada keperluan dan faktor unik. Inisiatif ini bertujuan untuk meningkatkan lagi keberkesanan dan daya maju jangka panjang sistem pengangkutan elektrik dengan menggunakan teknik penyimpanan tenaga baharu. Projek ini akan menggunakan MATLAB Simulink untuk menganalisis prestasi keseluruhan EV dengan menggunakan topologi baharu.

TABLE OF CONTENTS

		PAGE
DECLARATION		
APPROVAL		
DEDICATIONS		
ACKNOWLEDGEMENTS		**2**
ABSTRACT		**3**
ABSTRAK		**4**
TABLE OF CONTENTS		**5**
LIST OF TABLES		**7**
LIST OF FIGURES		**8**
LIST OF SYMBOLS AND ABBREVIATIONS		**11**
CHAPTER 1	**INTRODUCTION**	**12**
1.1	Overview	12
1.2	Motivation	12
1.3	Problem Statement	13
1.4	Objective	14
1.5	Scope	14
1.6	Report Outline	14
CHAPTER 2	**LITERATURE REVIEW**	**16**
2.1	Introduction	16
2.2	Drive Train Structure	16
	2.2.1 Series HEV	17
	2.2.2 Parallel HEV	18
	2.2.3 Series-Parallel HEV	19
2.3	Topology Of HESS	20
	2.3.1 Series SC/Battery Full Active	20
	2.3.2 Series Battery/SC Full Active	21
	2.3.3 Parallel Full Active	21
	2.3.4 Multiple Input Full Active	22
2.4	Energy Storage System	23
	2.4.1 Battery Energy Storage System	23
	2.4.1.1 Lead acid Battery	24
	2.4.1.2 Nickel-Cadmium Battery	25
	2.4.1.3 Lithium Ion Battery	26
	2.4.2 Supercapacitor	27
	2.4.3 Fuell Cell	28

2.5 Power Switching 28
2.5.1 Switching Device 30
2.5.2 Type of converter for EV 30
2.6 Type Of Motor 31
2.6.1 AC and DC Electrical Machines 33
2.6.2 BLDC MOTOR DRIVES 34
2.6.3 PMSM Motor Drives 35

CHAPTER 3 METHODOLOGY 37
3.1 Introduction 37
3.2 Research Methodology 37
3.2.1 Flowchart 37
3.2.2 Milestone 38
3.2.3 Gantt Chart 39
3.3 Battery Model 40
3.4 Supercapacitor Model 41
3.5 Battery and Supercapacitor Energy Management System for EV 42
3.6 Bidirectional Buck-Boost Converter 43
3.6.1 Boost Mode 44
3.6.2 Buck mode 45
3.7 BLDC Motor 46
3.7.1 Driving mode in switching technique 46
3.7.2 Regenerative mode in Switching technique 48

CHAPTER 4 52
4.1 Introduction 52
4.2 Simulation Result 52
4.2.1 Boost mode 52
4.2.2 Buck Mode 55
4.2.3 Performance Of Electric Vehicle by using BLDC motor 58
4.2.3.1 Boost mode 58
4.2.3.2 Buck mode 62

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS 67
5.1 Conclusion 67
5.2 Future Works 67

REFERENCES 69

LIST OF TABLES

Table 2.1 : Comparison type of HEV 19

Table 2.2 : Summary Of Battery System 27

Table 2.3 : Summary Of EMS 28

Table 2.4 : Comparison Of BLDC and PMSM 36

Table 3.1 : Gantt chart of Research Methodology 39

Table 3.2 : Parameter for resistor, Inductor and capacitor 42

Table 3.3 : Boost mode Parameter for battery and Supercapacitor 43

Table 3.4 : Buck mode Parameter for battery and Supercapacitor 44

Table 3.5 : Logical expression During Motoring Mode 48

Table 3.6 : Regeneration mode in switching pattern 51

Table 4.1 : Boost mode result for battery and supercapacitor 55

Table 4.2 : Buck mode result for battery and supercapacitor 57

LIST OF FIGURES

Figure 2.1 : Series drive train structure[3]. 17

Figure 2.2 : Parallel drive train structure[3]. 18

Figure 2.3 : Series-Parallel drive train structure[3]. 19

Figure 2.4 : Series SC/Battery Full Active[6]. 20

Figure 2.5 : Series Battery/SC Full Active[6]. 21

Figure 2.6 : Parallel Full Active[6]. 22

Figure 2.7 : Multiple Input Full Active[6]. 22

Figure 2.8 : Type of Automobile Vehicle[3]. 23

Figure 2.9 : Battery Used In Automobile Vehicle[3]. 23

Figure 2.10 : Lead Acid batteries during charge and discharge[10]. 24

Figure 2.11 : Nickel Cadmium battery[14]. 25

Figure 2.12 : Lithium Ion Battery[10]. 27

Figure 2.13 : Type of power Converter[3]. 29

Figure 2.14 : Bidirectional converter with single and dual source [3] 31

Figure 2.15 : Bidirectional DC-DC converter[3] 31

Figure 2.16 : Power control unit for hybrid electric vehicle[3] 31

Figure 2.17 : Utilisation selection of motor[27]. 33

Figure 2.18 : Types of DC Electrical motors[27]. 33

Figure 2.19 : Classification of AC Electrical motors[27]. 34

Figure 2.20 : Brushless DC Motor Drives[27] 35

Figure 2.21 : Motor Drives of PMSM[27]. 35

Figure 2.22 : Differences of BLDC and PMSM Drives[27]. 35

Figure 3.1 : Flowchart of research methodology 38

Figure 3.2 : Battery Model 40

Figure 3.3 : Supercapacitor model 41

Figure 3.4 : Battery and Supercapacitor EMS for EV circuit 42

Figure 3.5 : Bidirectional DC-DC Converter 43

Figure 3.6 : Bidirectional DC-DC Converter 43

Figure 3.7 : When S2 is activated 44

Figure 3.8 : When D1 is appear to be forward biased 44

Figure 3.9 : when S1 is ON 45

Figure 3.10 : when D2 is forward biased 45

Figure 3.11 : Circuit diagram of BLDC Motor 46

Figure 3.12 : BLDC motor Six-step commutation 47

Figure 3.13 : Waveform of the back emf and Hall output 48

Figure 3.14 : Circuit schematic representing in mode 1 49

Figure 3.15 : Circuit schematic representing in mode 2 50

Figure 4.1 : Battery voltage for boost mode 53

Figure 4.2 : Supercapacitor voltage for boost mode 53

Figure 4.3 : Battery current for boost mode 53

Figure 4.4 : Supercapacitor current for boost mode 54

Figure 4.5 : SOC of battery for boost mode 54

Figure 4.6 : SOC of supercapacitor for boost mode 54

Figure 4.7 : Battery voltage for buck mode 55

Figure 4.8 : Supercapacitor voltage for buck mode 56

Figure 4.9 : Battery current for buck mode 56

Figure 4.10 : Supercapacitor current for buck mode 56

Figure 4.11 : SOC of battery for buck mode 57

Figure 4.12 : SOC of supercapacitor for buck mode 57

Figure 4.13 : Performance of EV by using BLDC motor in Boost mode 58

Figure 4.14 : Waveform of voltage Back EMF with different phases 59

Figure 4.15 : Stator current waveform in different phases 60

Figure 4.16 : Waveform speed and its zoomed version 61

Figure 4.17 : Performance of EV by using BLDC motor in Buck mode 62

Figure 4.18 : Waveform of voltage Back EMF with different phases 63

Figure 4.19 : Stator current waveform in different phases 64

Figure 4.20 : Waveform speed and its zoomed version 65

LIST OF SYMBOLS AND ABBREVIATIONS

ICE	-	Internal Combustion Engine
EV	-	Electric Vehicle
HEV	-	Hybrid Electric Vehicle
HESS	-	Hybrid Energy Storage System
SC	-	Supercapacitor
DC	-	Direct Current
AC	-	Alternating Current
ESS	-	Energy Storage System
UPS	-	uninterruptible power supply
VSI	-	voltage source inverters
IGBT	-	insulated-gate bipolar transistors
MOSFET	-	metal-oxide-semiconductor field-effect transistor
DOD	-	Depth of discharge
SOC	-	State Of Charge
HV	-	High Voltage
LV	-	Low Voltage
Pout	-	Power out
Pin	-	Power in
Vo	-	Voltage output
Vs	-	Voltage supply
D	-	Duty cycle
L	-	Inductor
f	-	Frequency
C	-	Capacitor
R	-	resistor
ΔIl	-	Inductor ripple current
ΔV_c	-	Voltage ripple
I	-	Current

CHAPTER 1

INTRODUCTION

1.1 Overview

As part of this project, a battery-supercapacitor hybrid energy source that will power an electric car (EV) will be modelled and then put into use. The idea for the project came from the realization that electric vehicles will play a big part in transportation systems in the future. Because people around the world are becoming more concerned about protecting the climate and saving energy, automakers are constantly looking into options to traditional cars that run on carbon fuels. A possible answer is the rise of Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV). HEVs help lower pollution by using less petrol, but they don't solve all the problems facing the earth. On the other hand, electric vehicles use less energy, don't pollute the air, and need less upkeep than regular internal combustion engine (ICE) vehicles. This makes them a great choice for environmentally friendly transportation.

1.2 Motivation

In the present day, the consumers of EV face a significant issue with the system of HEV because of the functioning of EV may be completely disrupted by a single failure in the system. In order to overcome this constraint, the project seeks to improve the current design of the Hybrid Energy Storage System (HESS), guaranteeing the autonomous operation of its components and their ability to function as backups for one another. The goal is to create a system that reduces the chances of interruptions during crucial operating situations, ensuring the smooth and dependable operation of Electric Vehicles (EVs). The project aims to reduce the possible risks associated with the common semi-active series hybrid electric vehicle (HEV) designs. This will help improve electric transportation systems and promote efficiency, dependability, and sustainability in future vehicle technologies.

1.3 Problem Statement

The implementation of battery-supercapacitor The Hybrid Energy Storage Systems (HESS) used in Hybrid Electric Vehicles (HEV) provide a new active structure that aims to improve control and offer supplementary benefits to the vehicle. Both the battery and supercapacitor in this system are linked to the traction motor using two DC/DC converters, allowing for the supercapacitor to operate independently and flexibly with different voltage levels. Nevertheless, the present configuration of HESS shows limitations, including amplified power dissipation, elevated expenses, and a more extensive physical size. The need for advanced power electronics controls for both the supercharger and batteries adds extra intricacy to the system.

An important problem develops due to the widespread usage of semi-active series hybrid electric vehicle (HEV) designs in the majority of HEVs. This arrangement demonstrates inefficiencies at medium to high power and speeds, principally due to the need of several energy conversions - from mechanical to electrical energy and then back to mechanical energy. The inefficiencies are most noticeable during long-distance, high-speed journeys, when the engine functions with optimal efficiency. In contrast, the conventional gearbox provides more efficiency in such situations. Furthermore, the series hybrid electric vehicle (HEV) setup presents a potential hazard to the whole system, since any failure in a single element, whether it be the battery, converter, or supercapacitor, may result in the complete disruption of the vehicle's operation.

A new solution has been suggested to tackle these difficulties, which involves implementing a parallel active configuration in electric vehicles (EVs). This setup functions as an alternative for the primary storage system, guaranteeing uninterrupted operation in the case of a problem. Moreover, it ensures effective energy control by enabling the supercapacitor to provide a high power output to the system. This paradigm change seeks to overcome the constraints of the HEV series by offering a sturdier and more effective energy management system for Electric Vehicles.

1.4 Objective

I. To study the characteristic of charge and discharge of Electric Vehicle (EV).

II. To simulate Battery and Supercapacitor in EV by using parallel active topologies buck-boost converter using MATLAB simulink.

III. To analyse buck boost converter performance in Electric Vehicle (EV) application.

1.5 Scope

The purpose of this study is to explore how electric vehicles (EVs) charge and discharge in parallel full active topologies. Its goal is to investigate creative combinations of these topologies and ascertain how they affect EV power systems' ability to manage energy. Understanding the dynamic interactions between these systems' batteries and supercapacitors and how they impact EV performance under different driving scenarios is a major area of interest. MATLAB Simulink will be used to create battery and supercapacitor simulation models in order to do this. To control the energy flow between the battery and the supercapacitor, a buck-boost converter will be used. The study will model how an electric vehicle would operate in both driving and regenerative braking situations. Through the use of a complete simulation technique, the research will provide a thorough investigation of the performance of the EV, looking at the complex interactions between the energy storage devices, power converter, and the whole electric vehicle system.

1.6 Report Outline

Chapter 2: Literature Review – This chapter brief about background on electric vehicles, the topology of battery and supercapacitor configuration, the control strategy in switching. Not only that, the EMS also was explain detail as well as the battery technology that been used, supercapacitor and fuell cell. A thorough literature review is presented on the related on battery and supercapacitor with energy management system.

Chapter 3: Methodology – This chapter is detailed explained about the battery that been used, supercapacitor, power converter characteristic.

Chapter 4: Results and Discussion – The results of the simulation implementation of the battery supercapacitor combination are described and analysed by looking at the characteristic. The Lithium-ion battery pack and supercapacitor module was connected in parallel. The relationship of battery and supercapacitor also has been observed by seen the performance of the combination by using full active HEV configuration.

Chapter 5: Conclusion and recommendation – This chapter conclude the project that should be continue in FYP 2.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

EVs use rechargeable batteries to power electric motors. electric vehicles do not have internal combustion engines (ICEs). Instead, a master circuit powers the electric motor. In the 18th century, electric automobiles were proposed, but their batteries couldn't be recharged. EVs took off in the late 1800s when rechargeable batteries were accessible [1]. In the early 1900s, electric automobiles lost popularity due to cheap oil and self-starters for ICE cars became easier to find.

Even with their issues, electric automobiles were helpful as delivery and labor vehicles. Concerns about the environment have renewed interest in electric vehicles (EVs), leading to advances in their design, motors, control systems, and reuseable batteries. Electric automobiles are simpler to use than petrol and fuel-cell cars, even though experts worldwide are attempting to improve battery technology. Due to its fewer moving components, well-designed electric automobiles don't require oil, filters, spark plugs, or gas monitors. Regeneration systems improve stopping system, and tires only need to be examined every 100,000 miles[2].

Eco-friendly electric automobiles may be quicker than gas-powered ones. Electric motors provide a lot of torque from 0 rpm and maintain it until 6,000 rpm. Above 13,500 rpm, powerful will produce. This allows high-performance electric automobiles to hit incredible speeds without a gearbox or clutch. This implies even new drivers can drive them[2].

2.2 Drive Train Structure

The vehicle is called as a hybrid when it needs power from two or more different sources in order to move. A hybrid electric vehicle (HEV) is created by combining an internal combustion engine (ICE) with one or more electric motors. The classification of ICE and electric motors, as well as the battery connections, is often categorized as series, parallel, and series-parallel hybrid electric vehicles (HEV).

2.2.1 Series HEV

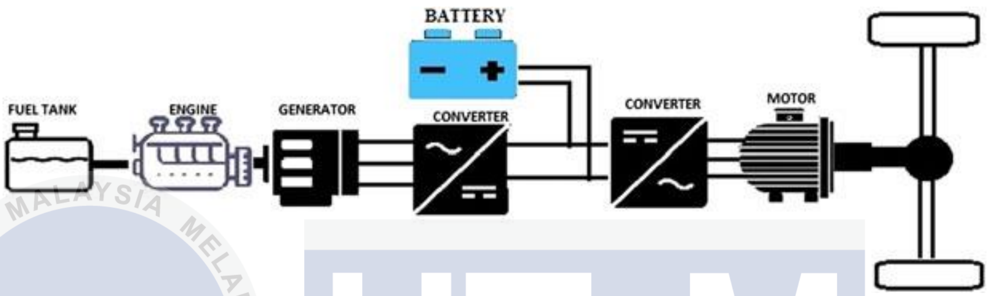

Figure 2.1 : Series drive train structure[3].

A series hybrid combines two sources of power to turn on a the electric motor to move a vehicle. A series hybrid electric vehicle (HEV) drive train includes an converters, electric traction motor, electric generator, battery, and ICE. Petrol tanks attached to electric generators feed the Internal Combustion Engine (ICE). A converter, which includes an inverter, is connected between a generator and a traction motor. Battery and inverter are connected. This means that the traction motor gets its power either from the internal combustion engine (ICE) to the electric generator or from the battery[4].

EV introduction set the groundwork for HEV fundamentals. Electric vehicles (EVs) have a restricted range. Battery charging is the problem, but a series hybrid electric car solves it. Sequential energy conversion happens in the drive train during a driving cycle. The internal combustion engine (ICE) creates mechanical power (PICE) that drives an electric generator's rotor, generating electrical power (P_{eg}). The electric traction motor receives power from both P_{eg} and the traction battery (P_{tb}), which may be expressed as $P_{em} = P_{eg} + P_{tb}$. The traction motor then powers the wheels. While braking, the traction motor generates. Braking recharges the battery. Recuperation uses braking kinetic energy to charge the battery.

2.2.2 Parallel HEV

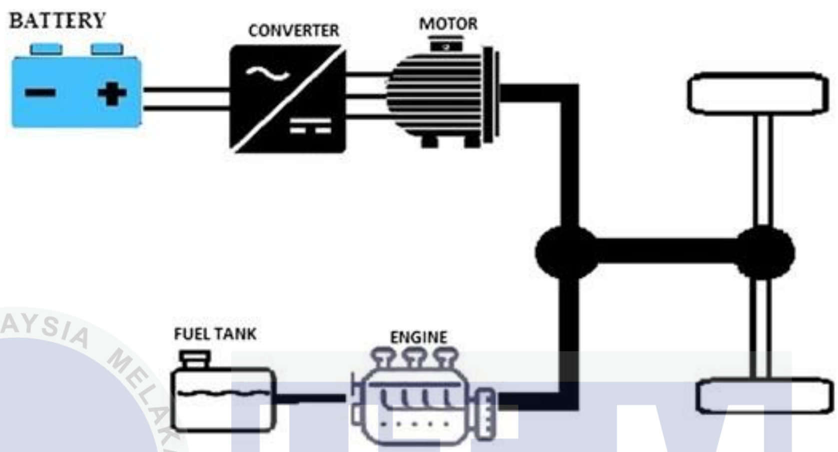

Figure 2.2 : Parallel drive train structure[3].

An Internal Combustion Engine (ICE), an electric driving motor, or both can power a parallel Hybrid Electric Vehicle (HEV). To drive the shaft, the driving powers of ICE and electric motor is PICE and $P_{em,}$ must connected in parallel. Parallel hybrid electric vehicles (HEV) are prevalent currently. The Internal Combustion Engine (ICE) powers the wheels of this vehicle.[5].

Wheels are connected to the electric motor. A parallel hybrid car, often called a power assist hybrid, uses an Internal Combustion Engine and a battery with a motor. The car briefly operates as an electric vehicle (EV) in electric mode. When the engine generates less power than required to propel the wheels, process of regenerative braking and cruising can recharge the battery. When decelerating, the motor generates energy to charge the battery. Accurate battery capacity selection and collaboration between the primary and secondary power sources may greatly reduce internal combustion engine (ICE) power consumption.

2.2.3 Series-Parallel HEV

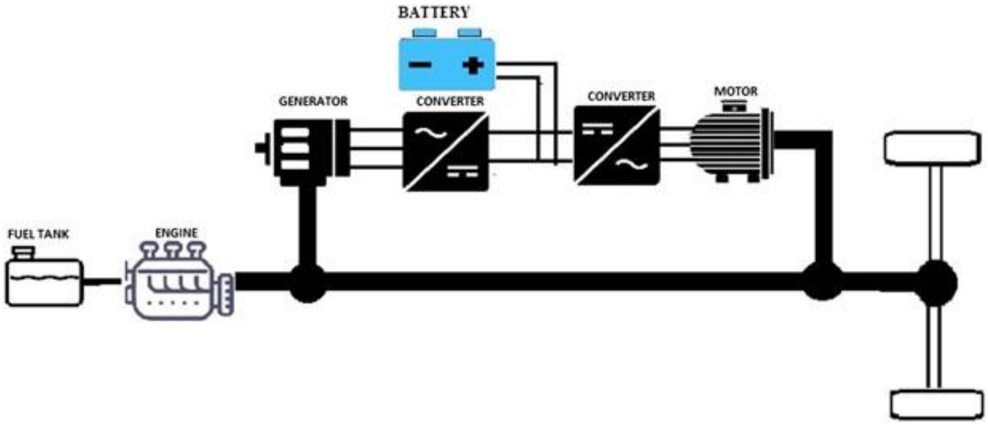

Figure 2.3 : Series-Parallel drive train structure[3].

A combined hybrid or series-parallel hybrids take the best parts of both series and parallel configuration and combine it. The wheels can be moved in two ways. The series and parallel are the 2 different pathways. The parallel path shows both the energy going from the engine to the wheels and the power from the motor that is attached to the same shaft. ICE and generator are connected via the series paths. This approach resembles series hybrid drive trains.

Table 2.1 : Comparison type of HEV

	Type	Series HEV	Parallel HEV	Series-Parallel HEV
Fuel economy	Idling Stop	Better	Better	Excellent
Advancement	Energy Recover	Better	Better	Excellent
	High Efficiency operation control	Better	Inconvenient	Excellent
	Total efficiency	Inconvenient	Better	Excellent
Driving Performance	Acceleration	Inconvenient	Better	Better
	Repeated high output	Inconvenient	Inconvenient	Better

2.3 Topology Of HESS

An active structure is presented to control the battery and supercapacitor Hybrid Energy Storage System (HESS) and give additional options. The battery and supercapacitor (SC) are coupled to DC through two DC/DC converters. By inverting, the DC connection is connected to the traction motor. SC operates with a broad variety of voltages since it is battery-independent.

The HESS design arrangement has more converters, which increases power loss and costs. It is also bigger, heavier, and takes up more space. The supercharger and batteries need complex power electronics controls.

Based on the connection of each Energy Storage System (ESS), HESS may be configured in parallel, with many inputs, and in flexible multilayer structures. All these pieces are essential to its active structure.

2.3.1 Series SC/Battery Full Active

The setup is shown in Figure 2.4. A power converter is used to connect the battery to the DC link and is responsible for regulating the output voltage of the ESS. The supercapacitor (SC), which is isolated by a converter, is activated once the demand for load current exceeds the permissible battery current. A DC/DC converter of significant magnitude, positioned close to the inverter, is necessary to effectively manage the surge in current demand. Therefore, the configuration resulting from two power conversions incurs significant losses in the converter and is more expensive.

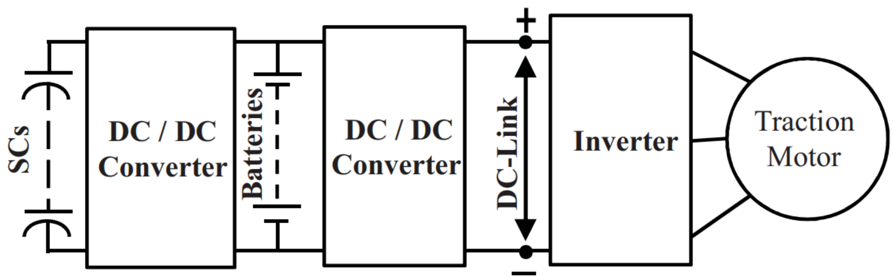

Figure 2.4 : Series SC/Battery Full Active[6].

2.3.2 Series Battery/SC Full Active

Figure 2.5 illustrates the structure of the battery/supercapacitor (SC) system. The supercapacitor (SC) can effectively manage unexpected changes in power requirements, in order relieving stress on the battery and thereby reduce its physical dimensions. This setup, developed in [5], aims at improving battery life while enhancing control over the topology. Due to the double transformation of power, the total efficiency is diminished. Furthermore, a converter that can manage the highest peak current is necessary, it can increase both the size and cost of the converter.

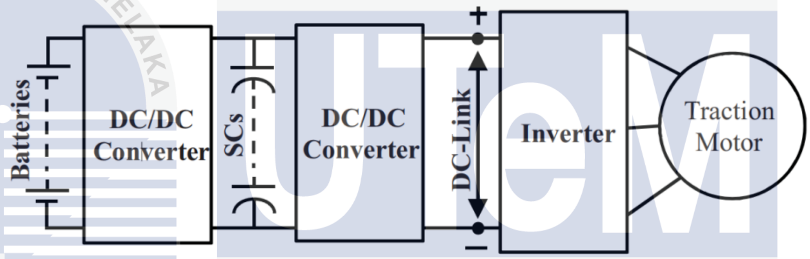

Figure 2.5 : Series Battery/SC Full Active[6].

2.3.3 Parallel Full Active

In a Hybrid Electric Vehicle (EV), Figure 2.6 shows the parallel full active HESS arrangement with a battery and supercapacitor (SC). Energy Storage Systems (ESS) may function independently based on voltage. To meet energy storage device power needs, the converters have a lower power rating. In [38-39], a unidirectional buck converter connects the battery to the DC-link. However, a bidirectional buck-boost converter links the supercapacitor (SC) and limits regenerative current for battery charging. However, it blocked the supercapacitor (SC) and battery from exchanging energy. In references [6], [9], [19], and [28-29], a bidirectional DC/DC converter connects the supercapacitor (SC) and battery to the DC-link. The supercapacitor (SC) stores and recharges the battery using regenerative braking power. Meanwhile, the traction motor consumes.

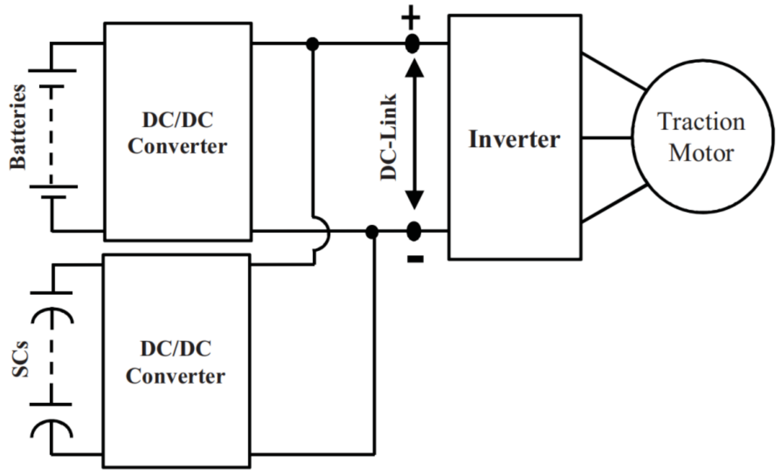

Figure 2.6 : Parallel Full Active[6].

2.3.4 Multiple Input Full Active

The arrangement shown in Figure 2.7 features a bidirectional multi-input DC/DC converter to connect both the battery and SC to the DC-link. This arrangement effectively reduces the cost and weight of the equipment. Nevertheless, the converter rating must be substantial in order to accommodate the overall current provided to the traction motor. Furthermore, the power management among the Energy Storage Systems (ESS) gets intricate.

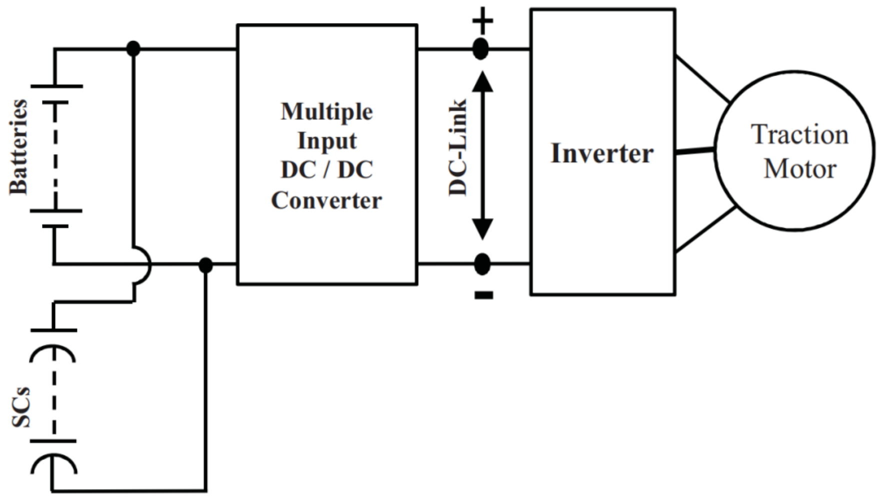

Figure 2.7 : Multiple Input Full Active[6].

2.4 Energy Storage System

Depending on the kind of energy storage used, the hybrid vehicle is categorized as an electric vehicle (EV), HEV, flywheel energy recovery hybrid vehicle, hydraulic hybrid vehicle (HHV), pneumatic hybrid vehicle or fuel cell EV. Figure 2.8 classifies hybrid automobiles and this part will go thorough about the different hybrid car.

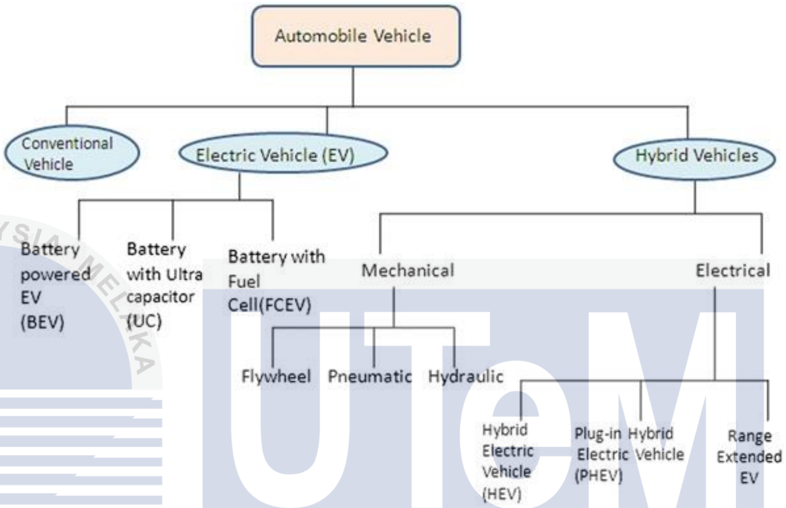

Figure 2.8 : Type of Automobile Vehicle[3].

2.4.1 Battery Energy Storage System

Batteries, supercapacitors, and flywheels store electrical energy from regenerative braking. Battery types include primary and secondary. The primary is disposable, while the other which is secondary is rechargeable. Automobiles employ secondary rechargeable batteries. Rechargeable batteries are classified as illustrated in Figure 2.9[7]. Lithium ion batteries do not contain lithium metal, but lithium polymer batteries do.

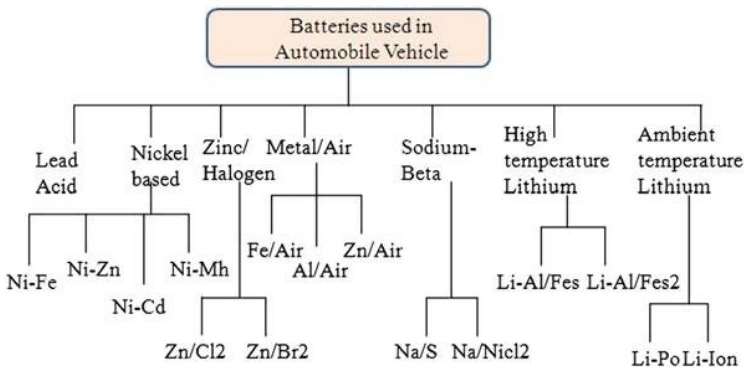

Figure 2.9 : Battery Used In Automobile Vehicle[3].

2.4.1.1 Lead acid Battery

For a long time, lead-acid batteries were used to store things. A lead-acid battery is made up of stacked cells that are submerged in a weak solution of sulfuric acid (H_2SO_4) [8]. Lead dioxide (PbO_2) act as positive electrode, and the negative electrode is sponge lead. During the discharge cycle, both the positive and negative electrodes will change into $PbSO_4$. Return to their previous condition throughout the charging cycle. [8].

$$Pb + PbO_2 + H_2SO_4 = 2PbSO_4 + 2H_2O$$

The battery has a lifetime of 5-15 years, depending on the operating temperature, and can undergo 1200-1800 cycles with an efficiency of 75-80%. An increase in temperature of around 45°C enhances the battery's performance and capacity, but at the expense of reducing the system's lifespan. Lead-acid batteries have a high capacity for holding power over extended periods of time, since they have a power loss of less than 0.1% each day[9].

Lead-acid battery storage is known for its poor performance in low and high temperatures and short lifespan[8]. As mentioned in[8], lead-acid battery storage technologies have significant drawbacks. The expense of flood maintenance and low specific energy of 30 Wh/kg and power of 180 W/kg [8], as well as a low specific energy of 30 Wh/kg and power of 180 W/kg[8] are among them. Setting up power cycling is difficult, especially with limited charging time. Sulphation failure may develop early in this case. Figure 2.10 shows a lead-acid battery schematic.

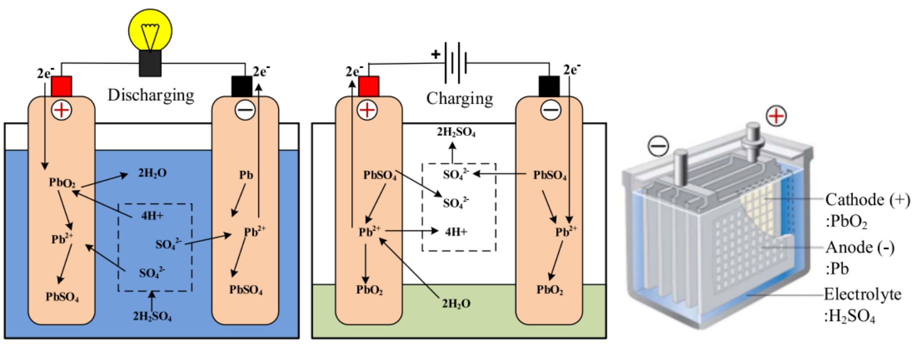

Figure 2.10 : Lead Acid batteries during charge and discharge[10].

2.4.1.2 Nickel-Cadmium Battery

The manufacturer has made alkaline recharge batteries since 1950[8], which recognizing their importance. This usage uses nickel and cadmium as positive and negative electrodes and alkaline fluid as the electrolyte [11]. $Ni(OH)_2$ and $Cd(OH)_2$ were two substances that are released from the positive and negative electrodes[8]. During charge cycles, positive and negative electrodes contain primarily NiOOH and solid Cd. The discharge electrolyte is usually an alkaline KOH solution[8].

It may happen with sealed, mobile equipment or with floods throughout the application[8]. Battery charging must be fast and high to perform effectively. Due to low internal resistance, they can pump electricity for two hours while working[11]. This allows them to swiftly complete a high-level discharge cycle. This application's lengthy cycle life (over 3500 cycles) and minimal upkeep are its finest features [12]. The lifespan relies on DOD, since it may last over 50,000 cycles at 10% DOD[13]. In industrial UPS, Ni-Cd batteries can store a lot of energy for green energy systems. Technology determines how effectively Ni-Cd batteries retain energy.

The application itself is harmful and can causes memory loss, making it unsafe for health[11]. Progress prompted the European Commission to propose new guidelines in November 2003. For this battery, recycling targets were 75%[8]. A nickel-cadmium battery design is shown in Figure. 2.11.

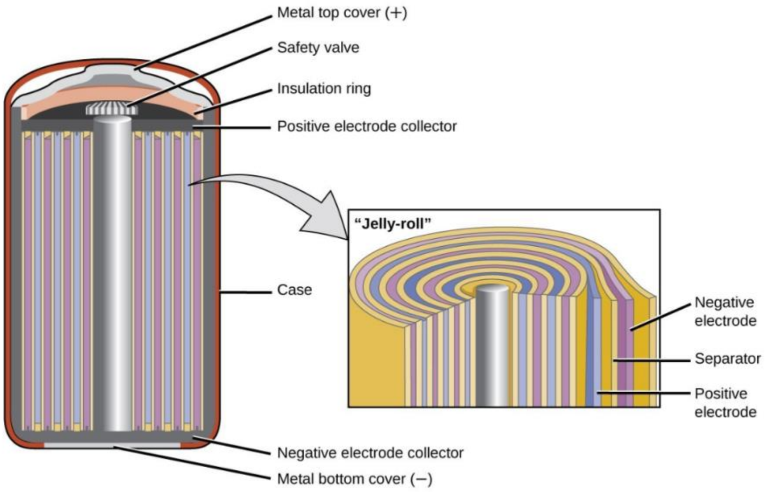

Figure 2.11 : Nickel Cadmium battery[14].

2.4.1.3 Lithium Ion Battery

Since it is still developing, this technology has not been employed to store uninterruptible power supply (UPS) system[8]. Due to its effectiveness, the technology may be employed in hybrid or electric automotive systems as well as mobile and laptop systems. The system uses lithium-ion and lithium-polymer cells[8]. Lits have 3.7V voltage and 80–150 Wh/kg energy density[8]. Lithium-polymer cells have 100–150 Wh/kg energy density. Energy efficiency is 90%–100% for the whole application[8]. Li* cells have 500–2000 W/kg power density, whereas lithium-polymer batteries have 50–250 W/kg. A battery's life cycle relies on temperature and self-discharges up to 5% every month. Useful up to 1500 times.

Li-ion batteries has 1–5% daily self-discharge rate makes them suitable for short-term usage[124]. Li-ion batteries have issues. This method isn't ideal for backups since the batteries might die due to the cycle DOD[13]. Due to their fragility, lithium-ion batteries need a safety circuit. Each battery pack has a safety circuit. It controls each cell's maximum charge voltage and prevents the battery from discharging too low. The cell's temperature is monitored to avoid overheating or cooling.

The power required to charge or discharge most packs is also limited. Safety steps must be made to prevent overcharge-induced metallic lithium plating. Temperature affects lithium-ion battery life. High temperatures accelerate ageing, which may shorten life due to long discharges. Since they share a metal ion, they won't combine. The system has been charged and discharged over 1,000 times at 100% DoD and will survive 15–20 years[13].

Even though ions don't require particular maintenance, the divider membrane should be changed every 5 years. The machine saves 78% of its energy this way [128], since storing a lot of energy for a long period is cheap. As energy storage increases, kW hour prices fall. The cost per kW hour for 8-hour energy storage systems may reduce below $150[8]. Returning to the system's issues, the battery's low specific energy and energy density (25–35 Wh/kg and 20–33 Wh/I) prevent non-stationary usage. Figure 2.8 shows lithium-ion battery components.

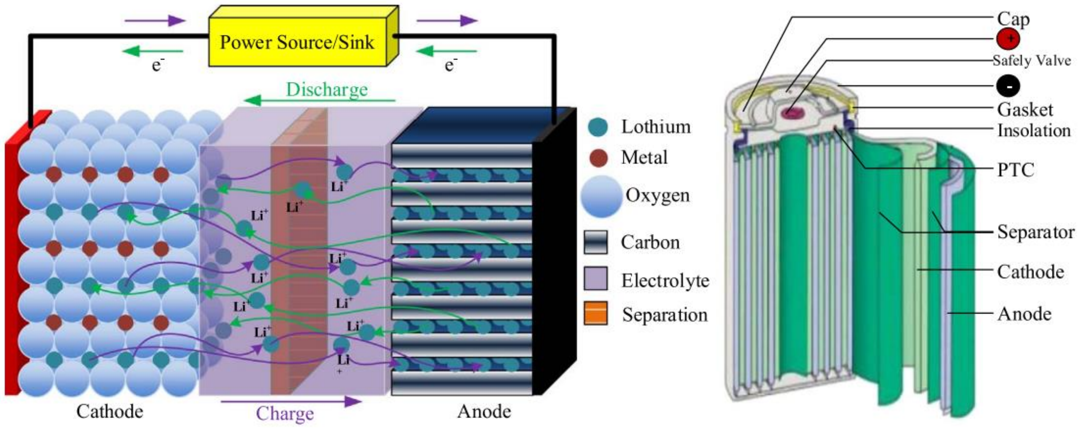

Figure 2.12 : Lithium Ion Battery[10].

Table 2.2 : Summary Of Battery System

Battery Type	Specific Energy (Wh/kg)	Peak Specific Power (W/kg)	Efficiency (%)	Cycle Life	Self Discharge (% per 48 h)	Cost
Lead Acid	35-50	150-400	>80	500-1000	0.6	144-180
Nickel-cadmium	50-60	80-150	75	800	1	300-420
Lithium-Ion	80-130	200-300	>95	1000+	0.7	240

2.4.2 Supercapacitor

Supercapacitors, which are efficient and long-lasting, are being investigated by automobile engineers and experts alongside batteries. A supercapacitor releases a lot of power quickly. It can also accept several charges, making it ideal for traction motor regenerative operation, which is an unique electric drivetrain feature[15]. As technology and research advance, supercapacitors are being utilized with batteries to improve performance and system efficiency. Normal capacitors store electricity by pulling long pieces of metal foil plates apart and separating them with an insulating film. Supercapacitors, on the other hand, separate charges on the order of ion size (-10A)[15].

2.4.3 Fuell Cell

Fuel cell technology can power automobiles when driving and when not, which attracts scientist Fuel cells are the most important components of ICE and batteries. An electrochemical process turns hydrogen's chemical energy into power. Fuel cells accomplish this. Fuel cells are produced and operate like batteries. Fuel cell machines generate power from fuel. Some parts of car fuel cell systems need to be the same as those in systems that use internal combustion engines (ICE). Fuel cell devices' weight, size, power efficiency, and response time are most significant.[15].

Battery and supercapacitors is a good match. The power converter can achieve this. Possibly a step-up or step-down converter. Batteries and supercapacitors also can provide backup power. The power converter may work as step-down or step-up based on the battery, and supercapacitor voltages.

Table 2.3 : Summary Of EMS

Characteristic	Mechanism	Technology	Energy Density	Power Density	Charging/ Discharging Time	Life	Efficiency
Battery	Chemical	Mature	High	Low	Hours	3-5y	75-85
SC	Electrostatic	Yet to mature	Low	Very High	Second	>10y	85-95
Fuell	Chemical	Yet to mature	Very High	Moderate	Unpredictable	10000-20000h	40-60

2.5 Power Switching

Power converters are important in HEV systems. Battery, power converter, and traction motor/generator are required in HEV. An inverter may be connected to an AC motor or be an inverter cum DC-DC converter. Power converters can regulate an unregulated DC voltage to an AC voltage level. They also transform electrical power voltage and current to meet car component needs.

DC-DC converters obtain the former conversion, and the latter is done by inverters (DC-AC converters) also known as frequency inverters. There are power topologies that either be isolated or non-isolated. DC-DC converters may operate in either a unidirectional or bidirectional manner.

In HEVs, converters do more than their basic functions. Regenerative braking and coasting depend on them recharging the battery pack from the fuel tank. Electric Vehicles (EVs) store energy in batteries or ultracapacitors, demonstrating the adaptability of power electronics technologies throughout the electric vehicle spectrum. Power electronics will speed the switch from conventional to HEVs and lead to a more sustainable and efficient automobile industry. Figure 2.13 shows the type of power converter in HEV.

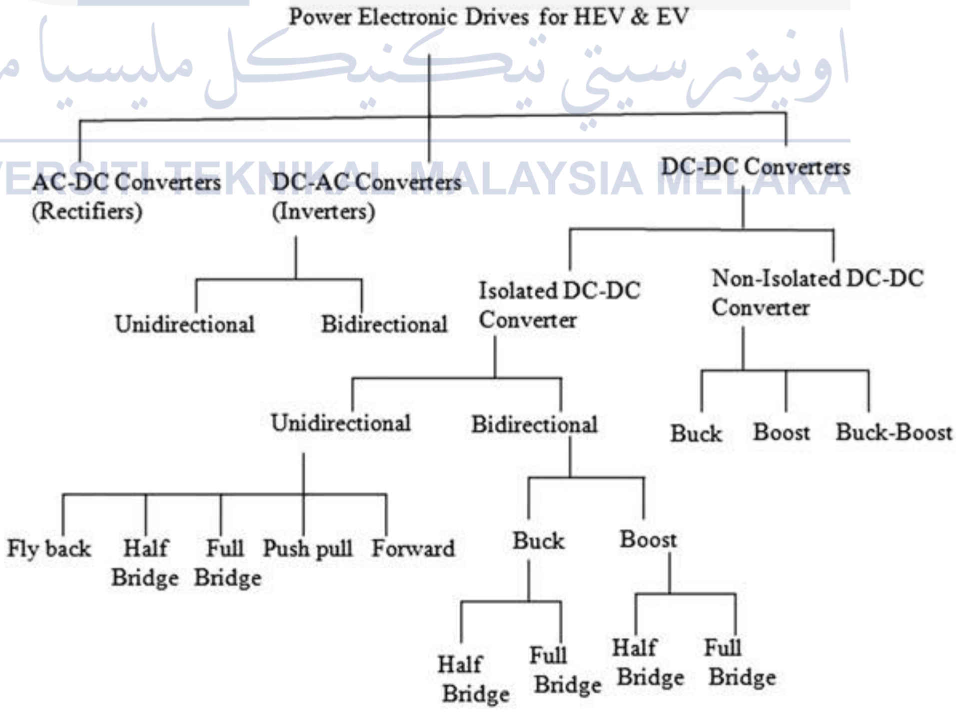

Figure 2.13 : Type of power Converter[3].

2.5.1 Switching Device

Drive systems need high power converters. These converters regulate high electric power and use power, voltage,and switching power electronic to switches such as insulated-gate bipolar transistors (IGBT) and MOSFETs for hybrid setups. IGBT controls high voltage and power. Use MOSFETs for low-to-moderate voltage and power or power design. n-channel used IGBT and MOSFETs to enhance power are widely employed. Due to considerable power loss, high-power electronics require cooling systems, a major downside. Power-switching devices with low resistance are expected. IGBT handle huge currents, while power MOSFET can switch quickly[16][17]. HEV, VSI control motors and generators.

2.5.2 Type of converter for EV

Boost converters output more voltage than its input voltage, whereas buck converters produce less. Buck-boost converters alter output level based on inputs by adjusting the duty cycle of the control signal transmitted to power semiconductor switches[18].

EV and HEV use DC and AC driving power electronic circuits with electric motor/generator. DC-DC boost converters match battery voltage to DC motor voltage for EV and HEV DC drives. Bidirectional buck-boost converters with DC motors are common DC drives but seldom energy management converters. This DC-DC converter connects batteries to the DC bus. The converter matches battery voltage to motor or generator voltage. This system requires AC drives and IM or PMSM motors for HEVs. PMSMs require dual inverter drive. Space vector pulse width modulation signals activate battery-motor inverters[19][20].

Figure 2.14 represents the variable DC-DC converter applied in HEV. Figure 2.15 represents a bidirectional DC-DC converter[21] with two power electronic switches, S1 and S2. Switch S1 is for boost mode and S2 for buck mode. During engine starving, this circuit uses buck converter mode. Regenerative braking uses wheel to charge the battery via motor/generator. The boost mode controls this[22][23]. The AC motor drives the HEV using voltage from the VSI. The DC voltage is converted by the VSI and enhanced by a DC-DC converter in Figure 2.16.

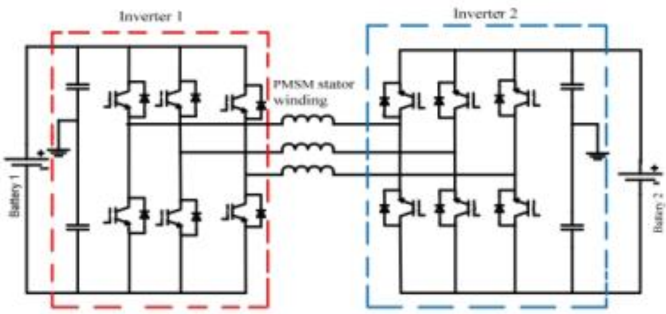

Figure 2.14 : Bidirectional converter with single and dual source [3]

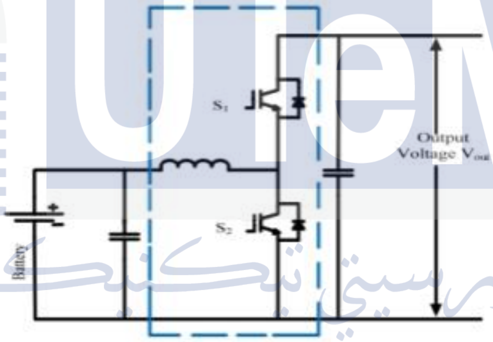

Figure 2.15 : Bidirectional DC-DC converter[3]

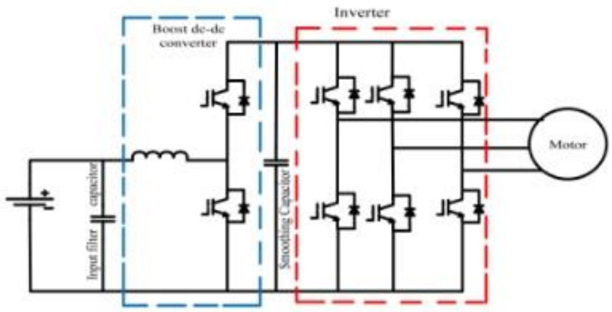

Figure 2.16 : Power control unit for hybrid electric vehicle[3]

2.6 Type Of Motor

This section provides an easily understood description and comparison of BLDC and PMSM drives. BLDC and PMSM electrical machinery share numerous similarities. Main distinction: Trapezoidal back EMF is present in BLDC, while sinusoidal back EMF is present in PMSM. Both devices possess a wide range of capabilities. There are numerous industrial applications for these two affordable electric instruments.

Both devices are similar. BLDC motors use an A.C. machine, an inverter, and position sensors to create a torque-speed electric motor drive [24][25]. In a permanent magnet motor with a fixed frequency A.C. source, the permanent magnets' constant rotor flux generates continuous stimulation emf. Excitation emf depends on magnet type, size and rotor shape. To design this machine, must ensure that normal or excessive power doesn't demagnetize magnets. Feedback devices, High power density, speed range, inverter rating, torque per current rating, and parameter function are examined[24], [25], [26].

According to various studies, modern permanent magnets (PM) with high energy density led to the creation of dc machines with PM Field excitation in the 1950. The replacement of electromagnets, which require an external power source and rotation, with permanent magnets resulted in the reduction of the size of DC machines. The rotor is excited by permanent magnets, as opposed to the field excitation of the synchronous machine. Mechanical commutators were replaced with inverters in the late 1950s, as switching power transistors and SCR devices were introduced. Both brushless DC machines and permanent magnet synchronous machines experienced growth as a result of these two modifications. The armature of a DC electrical machine is not required to be located on the rotor, as an electronic commutator can be employed in place of a mechanical one. The machine's armature can be located on the stator to increase the voltage and chill it, as it has shielding space. Energy is sent from the stator to the rotor via the permanent magnet (PM) poles.

AC drives come in several varieties; Figure 2.17 shows motor selection. Low-cost BLDC and PMSM motors with permanent magnets need less maintenance than others. Durability, improved torque, and speed bandwidths, and reduced maintenance expenses are among the most prevalent justifications for selecting brushless servo electric motor drives over brush-type DC motor drives[26].

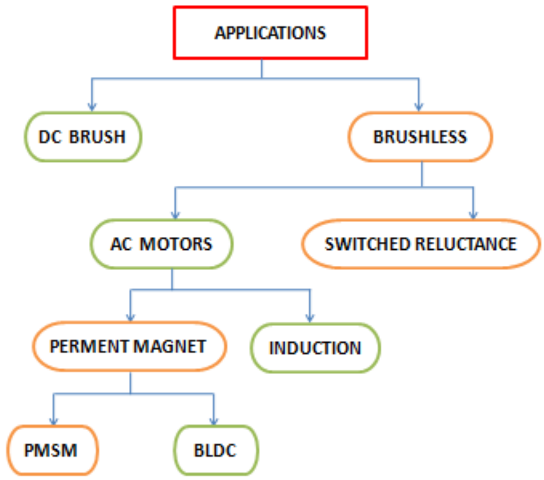

Figure 2.17 : Utilisation selection of motor[27].

2.6.1 AC and DC Electrical Machines

DC power is utilised by DC actuators. DC motors may be more portable by operating on rechargeable batteries. Brush DC motors use fixed magnets and an internal power source, whereas Brushless DC motors employ rotating permanent magnets. DC motor types are explained in Figure 2.18.

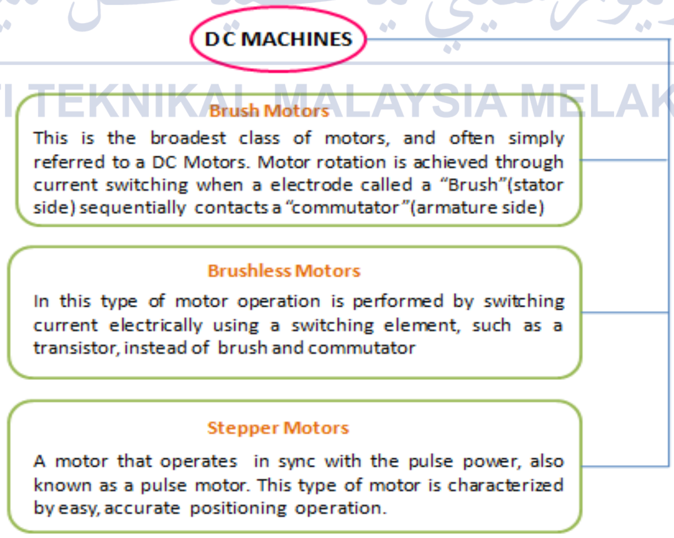

Figure 2.18 : Types of DC Electrical motors[27].

AC motors use alternating current. AC motor drives cost cheaper and need less maintenance than DC machines. Figure 2.19 describes AC motors in detail.

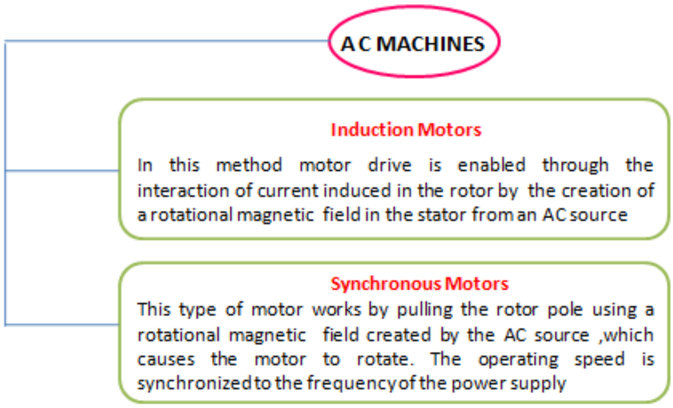

Figure 2.19 : Classification of AC Electrical motors[27].

2.6.2 BLDC MOTOR DRIVES

The trapezoidal induced electromotive force is a characteristic of permanent magnet brushless DC machinery. A permanent magnet brushless machine has advantages over a PMSM. Control simplicity is the reason why these devices are preferred over others. In order to initiate and modify the electric current, it is necessary to monitor the beginning and conclusion of the constant component of the induced emf. A three-phase machine has six locations during each electrical cycle. These signals may be generated by placing three hall sensors 120 electrical degrees apart. The rotor magnets are utilised to provide position details, or the excess magnet wheel can be distributed by enlarging the rotor behind the stator stack length. Hall sensors are facing a small magnet wheel that is anchored to the rotor and has the same number of poles as the PMBLDC rotor. These systems monitor the entire position of the rotor magnets and the form and direction of the induced electromotive forces in all phases of the electrical machine.

PMBLDC position-feedback requirement is simpler than the PMSM's continuous and instantaneous absolute rotor position: A three-phase electrical machine only needs six locations, saving money on the feedback sensor. PMSM drive control requires vector operations, although PMBLDC motor drive does not. Figure 2.20 shows the PMBLDC motor operation block diagram. These power converter converts power from the source to drive permanent magnet synchronous machines.

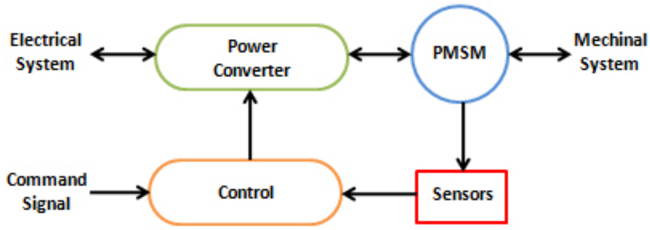

Figure 2.20 : Brushless DC Motor Drives[27]

2.6.3 PMSM Motor Drives

Figure 2.21 shows different parts of the electric drive system, like the PMS Motor. When the damper winding is not present, the PMS motor needs position indicators in the rotor shaft in order to work. To make sure the rotor is in the right place, devices for measuring position have grown in number. The potentiometer, LVD transformer, optical encoder, and resolver are the four most important devices for measuring position. A location monitor with the right level of precision can be chosen based on the motor's purpose and performance goals. Table 2.4 below explain about comparison of BLDC drives and PMS Motor [28],[29].

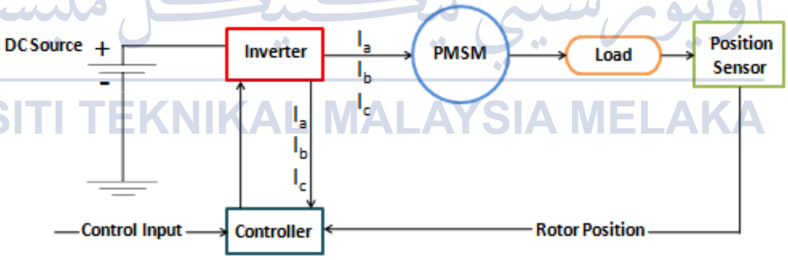

Figure 2.21 : Motor Drives of PMSM[27].

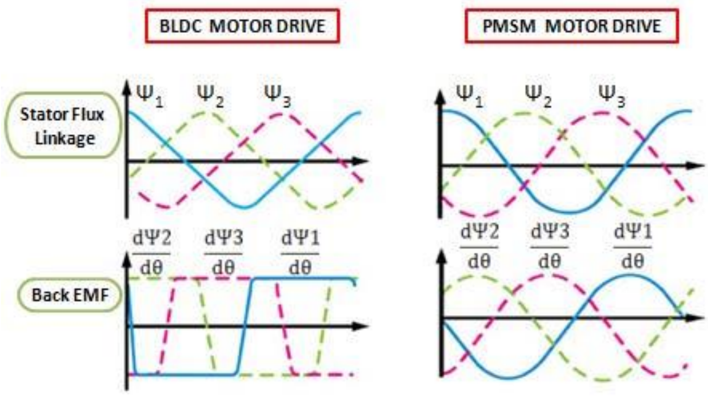

Figure 2.22 : Differences of BLDC and PMSM Drives[27].

Table 2.4 : Comparison Of BLDC and PMSM

BLDC	PMSM
Synchronous machine	Synchronous machine
Fed with direct currents	Fed with sinusoidal currents
Trapezoidal back emf	Sinusoidal back emf
Stator flux position commutation each 60º	Continuous stator flux position variation
Only two phases ON at the same time	Possible to have three phases ON at the same time
Torque ripple at the commutation	No torque ripple at the commutation
Low order current harmonics in the audible range	Fewer harmonics due to sinusoidal excitation
High core losses due to harmonic content	Less core loss
Less switching losses	High switching losses at the same switching frequency
Control algorithms are relatively simple	Control algorithms are mathematically intensive
Easier to control (six trapezoidal states)	More complex control (continuous 3ĭ sine wave)
Better for lower speed	Higher maximum achievable speed
Noisy	Low noisy
Doesn’t work with distributed winding	Work with low-cost distributed winding
Not as efficient, lower torque	Higher efficiency, higher torque
Low cost	Higher cost
Rectangular current waveforms	Sinusoidal or quasi- sinusoidal current waveforms

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter reviews the methodology used in this project. It covers all the methods used to design and analyse battery and supercapacitor in EV. This chapter also briefly explains the controller method and switching method. Detailed explanations have been presented in this chapter with supported block diagrams.

3.2 Research Methodology

The research methodology includes a flowchart, milestone, and Gantt chart to ensure this project is completed on time. This subtopic is going to assist in the explanation of the process and procedures for managing this project.

3.2.1 Flowchart

The project's progression is illustrated in the flowchart. Figure 3.1 shows the sequential progression of this project to ensure it can be complete in the given timeframe. The initial phase of this project involves collecting all relevant data and information associated with the project. Extensive literature reviews have been conducted, with a particular focus on full active topologies by using buck-boost converter on battery and supercapacitor. The performed simulation involves connecting a battery to power converter and it will connected to PI controller, same goes to the supercapacitor which must connected to power converter and PI controller. This battery and supercapacitor are then connected in parallel which is in full active topologies based on the information obtained from the literature reviews. In this project, MATLAB/Simulink was applied to model and analyse the result of the voltage, current, state of charge of the battery and the performance of EV. The inverter and motor will be chosen to create a whole EV system. Next, an analysis is conducted to see whether the supercapacitor can be influenced to the battery when the other part is not functioning. Finally, all the results and discussions of the data have been compiled and presented in this project.

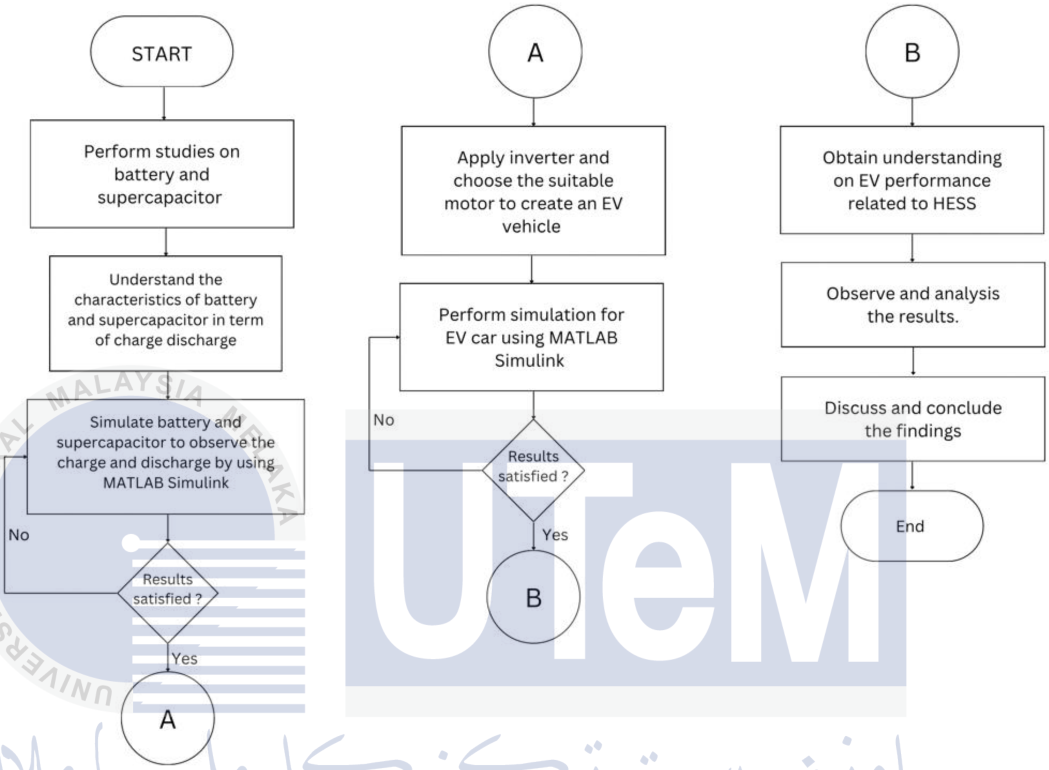

Figure 3.1 : Flowchart of research methodology

3.2.2 Milestone

Below is the research's milestone plan. This project has established six milestones to ensure its systematic progression.

Milestone 1: Research on battery and supercapacitor by using parallel full active topologies.

Milestone 2: Modeling and simulating the battery and supercapacitor to analysing the characteristic of charge and discharge on battery and supercapacitor.

Milestone 3: Implementation of parallel full active on battery and supercapacitor by using bidirectional buck-boost converter.

Milestone 4: Verify the accuracy of the data acquired from the simulation.

Milestone 5: Create a whole EV system, and analyse the performance of the EV .

Milestone 6: Report Writing.

3.2.3 Gantt Chart

Table 3.1 : Gantt chart of Research Methodology

Milestone	Task	Month/Year									
		2023			2024						
		10	11	12	1	2	3	4	5	6	7
1	Literature review on battery and supercapacitor Energy Management System For EV.										
2	Literature review on type of motor that suitable For EV.										
3	Modeling and simulating the battery and supercapacitor EMS for EV and analysing the characteristic of charge and discharge on battery and supercapacitor.										
4	Implementation of parallel full active on battery and supercapacitor by using bidirectional buck-boost converter.										
5	Continue modeling and simulating the whole EV										
6	Implementation the design in fyp 1 to fyp 2 to create a whole EV system.										
7	Analyse the performance of the EV.										
8	Verify the accuracy of the data acquired from the simulation.										
9	Report writing.										

3.3 Battery Model

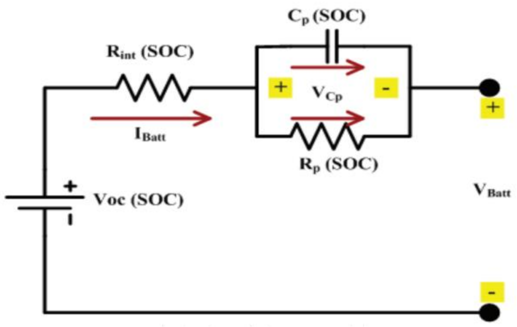

Figure 3.2 : Battery Model

The dynamic model for the Li-ion battery package implemented in MATLAB/Simulink as The Thevenin battery model, internal resistance (R_{int}), polarisation capacitance (C_p), overvoltage resistance (Rp, polarisation resistance), and open circuit voltage (V_{oc}) are explored within this report, outlining how each caters for the battery's state of charge (SoC) in its own unique manner. Every model component depends on the battery's state of charge (SoC). The battery system consists of a package with N_{batts} cells that are interconnected linked in series and N_{battp} cells connected in parallel.

$$V_{Batt} = N_{batts}\,[V_{oc} - I_{batt}R_{int} - V_{cp}] \tag{1}$$

$$SOC = SOC\ 0 + \frac{1}{3600}\int \frac{I_{Batt}}{C_b}\,dt \tag{2}$$

$$I_{Batt} = \frac{I_{Load}}{N_{battp}} \tag{3}$$

$$\frac{dV_{cp}}{dt} = \frac{-V_{cp}}{C_p R_p} + \frac{I_{Batt}}{C_p} \tag{4}$$

3.4 Supercapacitor Model

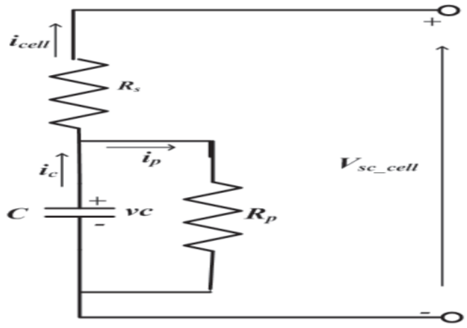

Figure 3.3 : Supercapacitor model

Supercapacitors are particularly suitable for sudden and transient surges in Power as is evident from their design. There are however have three integral components of the SC model, a capacitor ‘C’, resistor ‘R_S’ that is connected in series and known as which is the equivalent series resistance (ESR), and a parallel resistor ‘R_p’. The R_p resistor is the leaks currents in capacitors and it is the one which is in charge of self-discharges. It is structurally composed of a series connection of N_{scs} cells as well as a parallel connection of N_{scp} strings.

$$V_{SC_{cell}} = i_{cell} R_s + V_c \tag{5}$$

$$V_c = \frac{1}{C} \int i_c(t)dt + V_{cup}(t = 0) \tag{6}$$

$$i_c = i_{cell} + \frac{V_c}{R_p} \tag{7}$$

$$SOC_{sc} = (\frac{V_C}{V_{cell-max}})^2 \times 100 \tag{8}$$

$$V_{cup}(t = 0) = (\sqrt{\frac{SOC_{sc}0}{100}}) \times V_{cell-max} \tag{9}$$

3.5 Battery and Supercapacitor Energy Management System for EV

The concept of battery and supercapacitor EMS for EVs is to to make sure the EMS are not dependable to each other. The system comprises a battery that is connected to a buck-boost converter and supercapacitor also is connected to buck-boost converter. Which is the system will connected in parallel active configuration. The whole system is to create an EV by using inverter to convert the DC voltage from the EMS which is battery and Supercapacitor into AC voltage. The components of the circuit consist of MOSFET, inductor, resistor and capacitor. The buck-boost converter functions is to make sure the system can operate in bidirectional. Figure 3.4 shows the MATLAB/Simulink model of Battery and Supercapacitor EMS for EV.

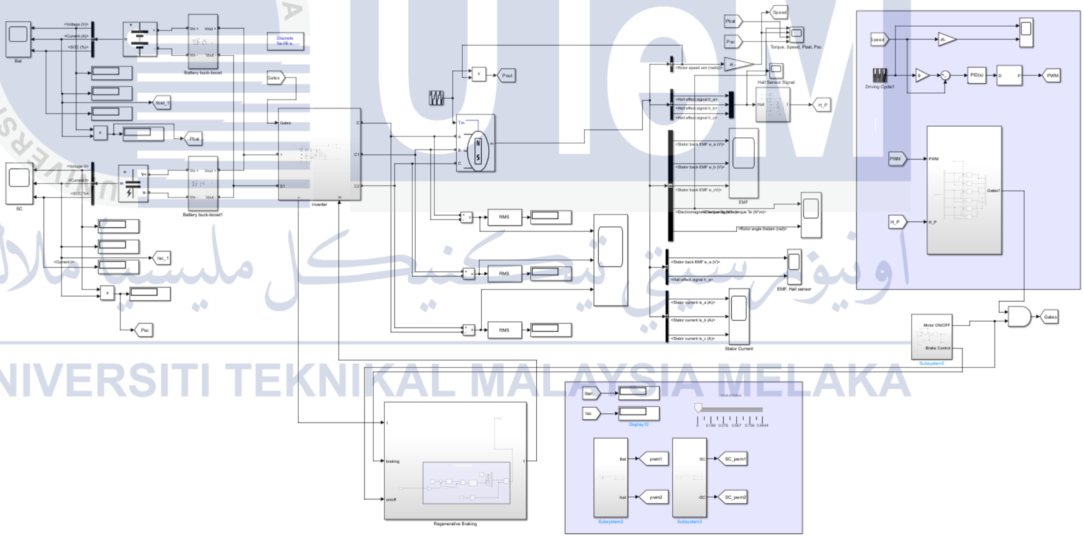

Figure 3.4 : Battery and Supercapacitor EMS for EV circuit

Table 3.2 : Parameter for resistor, Inductor and capacitor

Parameter	Value
Inductance	13e-6H
Capacitance	1000e-6
Resistor	1e-4 Ω

3.6 Bidirectional Buck-Boost Converter

Figure 3.5 show the basic DC-DC converter circuit while Figure 3.6 is simulation circuit from MATLAB simulink. This converter operates in two mode which is Forward and Backward. During Forward mode, the power is transferred from low voltage to high voltage, so the converter functions as a "Boost converter". During regenerative braking, the power will recharge the source, so it will transferred from high voltage to low voltage. The converter functions as a "Buck converter" in this process.

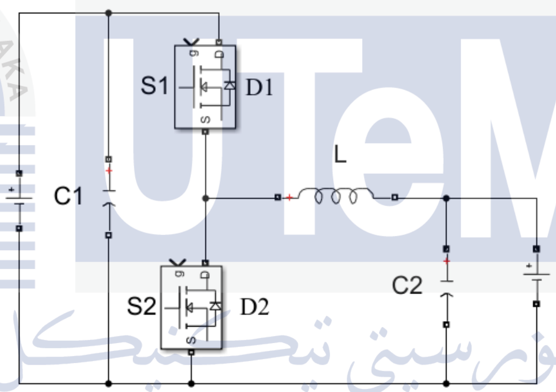

Figure 3.5 : Bidirectional DC-DC Converter

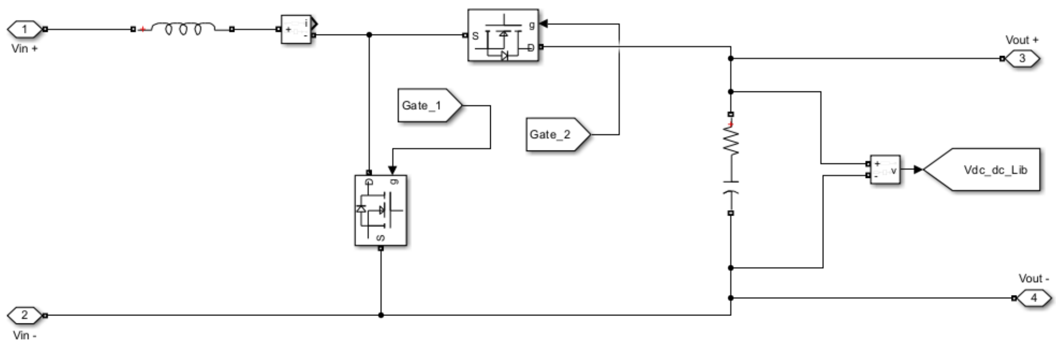

Figure 3.6 : Bidirectional DC-DC Converter

Table 3.3 : Boost mode Parameter for battery and Supercapacitor

Battery	Value
Nominal Voltage	300
Rated Capacity	15.5
SOC	20

Supercapacitor	Value
Rated Voltage	280
Initial Voltage	280
Capacitance Rated	50

Table 3.4 : Buck mode Parameter for battery and Supercapacitor

Battery	Value
Nominal Voltage	300
Rated Capacity	15.7
SOC	80

Supercapacitor	Value
Rated Voltage	280
Initial Voltage	0
Capacitance Rated	50

3.6.1 Boost Mode

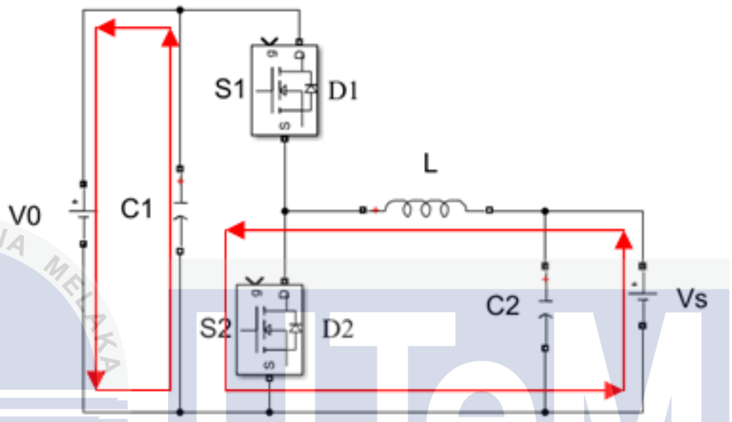

Figure 3.7 : When S2 is activated

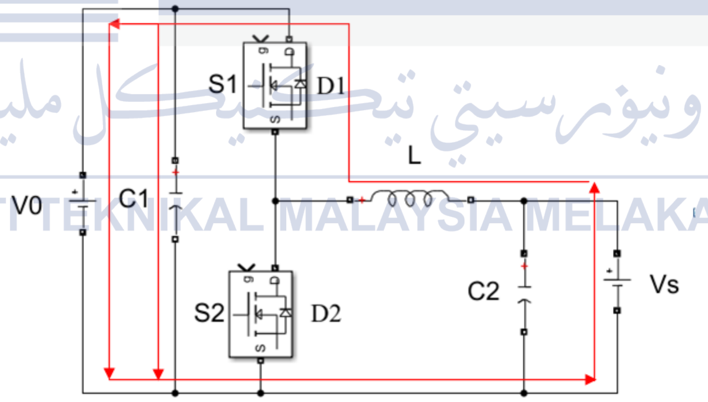

Figure 3.8 : When D1 is appear to be forward biased

Figure 3.7 illustrates the direction of current flow when switch S2 is turned on and switch S1 is turned off. An inductor accumulates charges, resulting in a linear rise in current. Figure 3.8 shows the state in which diode D1 is turning on, but switches S1 and S2 are not operating, and diode D2 is in reverse biased. The energy stored in the inductor will initiate discharge via diode D1. During this mode, the energy supplied from the source and inductor will be transferred to the load, increasing voltage level.

3.6.2 Buck mode

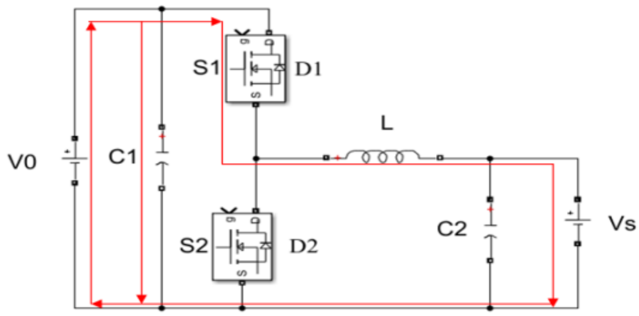

Figure 3.9 : when S1 is ON

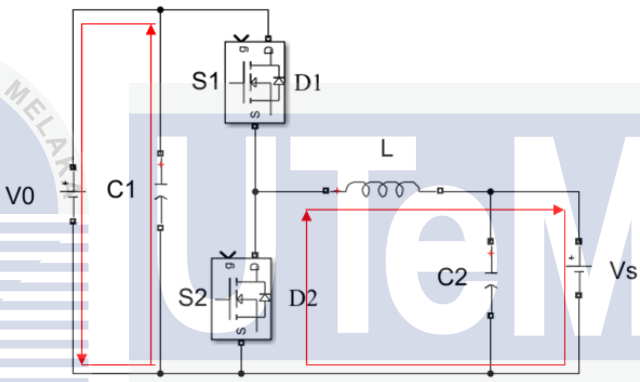

Figure 3.10 : when D2 is forward biased

Figure 3.9 illustrates the direction of current flow when switch S1 is in the ON state, switch S2 is in the state of OFF, and both diodes D1 and D2 are reverse biassed. The energy stored in the inductor will dissipate with a negative slope. Figure 3.10 illustrates the condition when diode D2 is in the ON state, diode D1 is in reverse biased, and switches S1 and S2 are in the OFF state. Regenerative braking use this operational mode to recharge the battery.

The equations related to bidirectional Buck/Boost is listed below:

$$\eta = \frac{P_{out}}{P_{in}} \quad (10)$$

$$V_o = \frac{V_s D}{Lf} \quad (11)$$

$$\Delta Il = \frac{V_s D}{Lf} \quad (12)$$

$$\Delta V_c = \frac{V_S D}{8Lf^2 c} \tag{13}$$

$$L = \frac{V_S D R}{2 f V_o} \tag{14}$$

$$C = \frac{D V_S}{16 L f^2 V_o} \tag{15}$$

3.7 BLDC Motor

A BLDC motor has a permanent magnet (PM) rotor and windings on the stator (armature). DC power enters the stator windings via a configuration of semiconductor switches. A comparable BLDC motor circuit design is shown in Figure 3.11. To power the stator windings in response to changes in the rotor shaft's position, the semiconductor switches must be adjusted, a trapezoidal back EMF is produced. This form of motor control is also known as trapezoidal commutation or the six-step commutation method. The stator windings are only switched on in two phases at a time when this technique is applied. The remaining phase continues to be de-energized. The switching order shifts every 60°. There are six flipping patterns in a cycle.

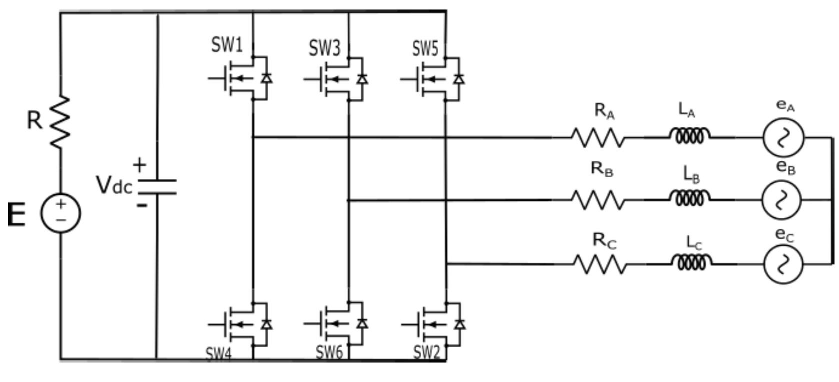

Figure 3.11 : Circuit diagram of BLDC Motor

3.7.1 Driving mode in switching technique

The attraction and repulsion of a permanent magnet and an electromagnet are used by both brushed DC motors and BLDC motors to create rotation in the motor.

The only difference is that electrical commutation is used in this case. The rotor's magnetic field constantly seeks to align with the stator's magnetic field due to the energizing of the stator coil. The rotor turns because of the forces of attraction and repulsion. The rotor's movement when the six-step commutation is applied is seen in Figure 3.12. As shown in Figure 3.13, the stator windings create Trapezoidal back EMF. The Hall Effect sensors are used to get important information about the position of the rotor.

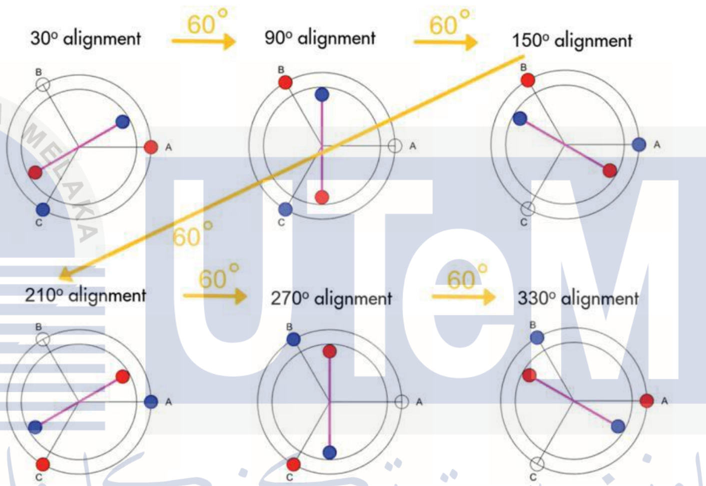

Figure 3.12 : BLDC motor Six-step commutation

Hall sensor outputs tells the inverter what pattern to use to turn on its switches. This case must be referring to Figure 3.13. Switch SW1 is on when Hall 1 is high and Hall 2 is low. SW2 will be turned on when Hall 1 is high and Hall 3 is low. Every 60°, one phase of the back EMF pattern changes, while the other two phases remain constant. Section 1 affects phase C, while phases-A and B stay the same. The phases A and B are energized when their back EMFs do not change.

As the back EMFs of phase C change, it is de-energized. Switches SW1 and SW6 are activated in sector 1. In Sector 2, back EMFs for phases A and C stay the same, while phase B back EMF changes, causing the activation of SW1 and SW2. In sector 4, phase-A changes, phase B remains constant, and phase C changes. However, A and C now have different polarities. Due to this, the switches must be properly set off to connect phase A to the battery's negative terminal and phase B to the battery's positive terminal. To do this, the switches SW4 and SW3 are turned on in sector 4.

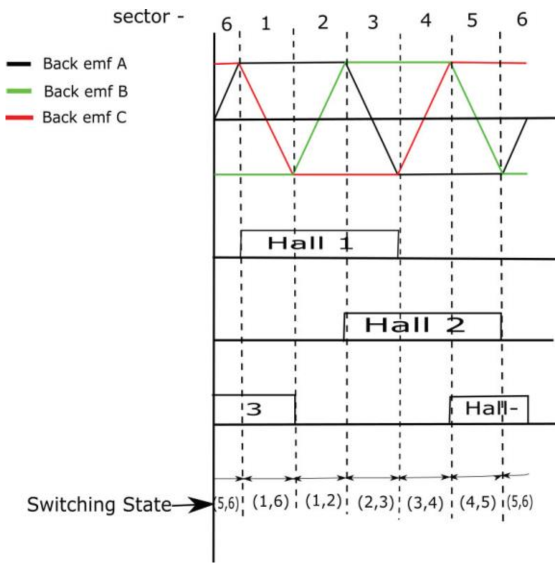

Figure 3.13 : Waveform of the back emf and Hall output

Table 3.5 displays the switching pattern for every switch in the driving mode. The symbols H1, H2, and H3 stand for the Hall outputs of Halls 1, 2, and 3, respectively. The complimentary of this signal are identified as H1´, H2´, and H3´. High-frequency pulse width modulation (PWM) may be used to control each switch within a 60° interval, adjusting the motor's voltage and therefore its speed.

Table 3.5 : Logical expression During Motoring Mode

Switch	Hall Logic
1	H1 , H2’
2	H1 , H3’
3	H2 , H3’
4	H1’ , H2
5	H1’ , H3
6	H2’ , H3

3.7.2 Regenerative mode in Switching technique

When the vehicle deceleration or stop, the moving energy is turned into electrical energy, this is called as regeneration mode. The motor's back EMF functions as a power source to recharge the battery when it is in the regeneration mode. Conversely, even when the motor is operating at its maximum speed, the back EMF is lower than the battery voltage. Recharging the battery is not possible with the back EMF power. The back EMF voltage must be increased in order to charge the battery.

Here, a buck-boost converter manages switches and boosts back EMF. The DCDC boost converter stores energy in an inductor and transfers it to the load side. In the first mode, the bottom switch of the inverter may be switched on for the phase with the highest positive back electromotive force (EMF) to store energy in the phase winding. In order to transition to the second mode, turn off every switch. Consequently, energy was saved to freewheel to the DC-link. Phase A of sector 1 has the greatest positive back EMF, illustrated in Figure 3.14. SW4 which is in the phase A winding's bottom switch, stores energy in mode 1. In mode 2, all switches are off to permit freewheeling across the anti-parallel diodes D1 and D6 of switches SW1 and SW6. Phase B has the lowest back EMF, which explains the reason.

During regenerative braking, the back EMF can charge the battery. This allows recovery without an supercapacitor or DCDC boost converter. The corresponding circuits for modes 1 and 2 are explained in Figures 3.14 and Figure 3.15.

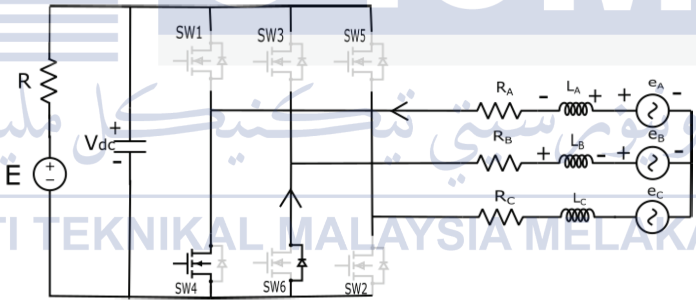

Figure 3.14 : Circuit schematic representing in mode 1

By applying Kirchhoff's voltage law in mode 1,

Assume $L_A = L_B = L_C = L$,

$$-V_{lB} - e_b + e_b - V_{lA} = 0$$

$$e_a - e_b = 2V_l$$

$$e_a - e_b = 2L\frac{di}{dt}$$

$$\Delta i = \frac{e_a - e_b}{2L} t_{on} \quad (16)$$

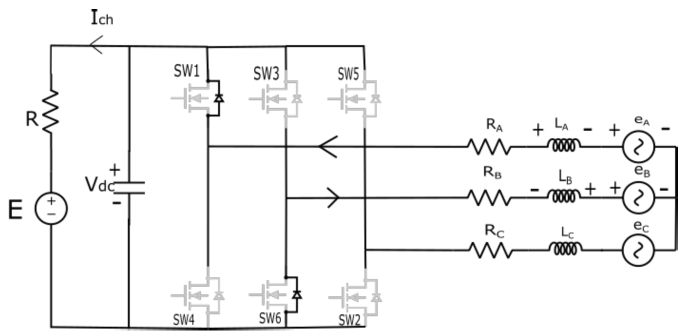

Figure 3.15 : Circuit schematic representing in mode 2

Applying Kirchhoff's voltage law in mode 2,

$$V_{lB} - e_b + e_a + V_{lA} = V_{dc}$$

$$2L\frac{di}{dt} = V_{dc} - (e_a - e_b)$$

$$\Delta i = \frac{V_{dc}-(e_a-e_b)}{2L} t_{off} \quad (17)$$

From Equation (1) and (2)

$$V_{dc} = \frac{(e_a-e_b)}{(1-d)} \quad (18)$$

Where $e_a = -e_b$ by referring to Fig 3.15 and charging current will be-

$$I_{ch} = \frac{V_{dc}-E}{R} \quad (19)$$

The variables e_a and e_b represent the back EMF of phase-A and phase-B correspondingly. v_l is the voltage across the motor's phase winding, R is represented as internal resistance, $t_{on}$and t_{off} are the switch's on and off times, d is the duty ratio and Δ_i is represented as ripple current. In the regeneration mode of operation, Table 3.6 displays the potential switching options for each section during the regeneration mode, determined by the back EMF.

Table 3.6 : Regeneration mode in switching pattern

Sector	Switch	Diodes
1	4	1,6
2	4	1,2
3	6	3,2
4	6	3,4
5	2	5,4
6	2	5,6

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter discusses the performance of Battery and supercapacitor energy management system for EV. The simulation circuit was conducted to analyse the performance of Battery and supercapacitor . Besides, this chapter focuses on the result of the power, voltage, current , SOC waveform, charge-discharge characteristic and the performance of EV.

4.2 Simulation Result

This subtopic presents the simulation result of the Battery and supercapacitor EMS for EV with parameter that indicate in chapter 3. All the values of Kp, Ki, and C were determined using the try-and-error method.

4.2.1 Boost mode

The voltage results during the activation of boost mode are apparent in the study. Figure 4.1 show the battery graph indicates a transition towards the charging process, as the starting voltage of 300V rises to 341.2V because of the activated charging mode. Conversely, the graph of the supercapacitor illustrates at Figure 4.2 show that a process of discharging, starting at 280V and gradually falling to 253V due to the active discharging mode. This finding highlights the contrasting behaviors of the battery and supercapacitor when subjected to boost mode which is the battery charges while the supercapacitor discharges.

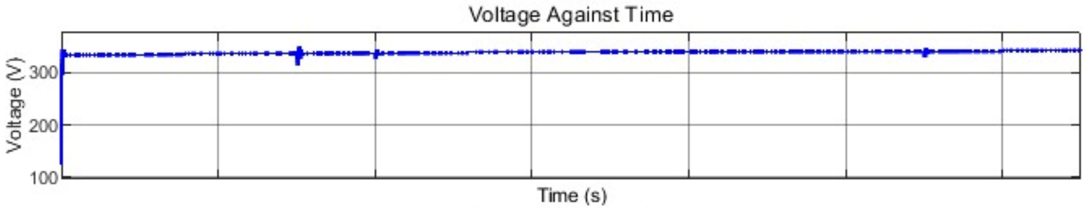

Figure 4.1 : Battery voltage for boost mode

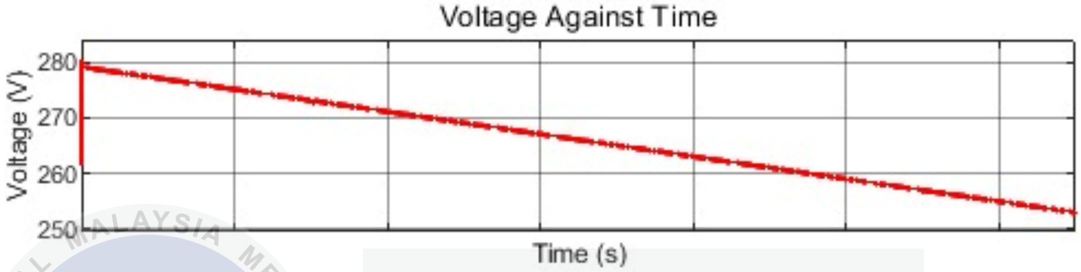

Figure 4.2 : Supercapacitor voltage for boost mode

An analysis of the electric current during the activation of boost mode reveals clear patterns in the graphs of both the battery and supercapacitor. In Figure 4.3, the current against time graph in the battery section displays a discharge pattern, which is distinct from the voltage graph shown at Figure 4.1. The inverse relationship suggests that, when in boost mode, the current for battery is undergoing discharge. The current detected during the discharging phase is reported as -71.64A. In contrast, the graph of the supercapacitor shows a charging pattern which is shown at Figure 4.4 that opposes the voltage graph in the supercapacitor in Figure 4.2. The current produced during this charging method is measured at 100.3A. The findings highlight the electrical characteristics of the battery and supercapacitor when subjected to boost mode, providing insight into the relationship between current and voltage in the system.

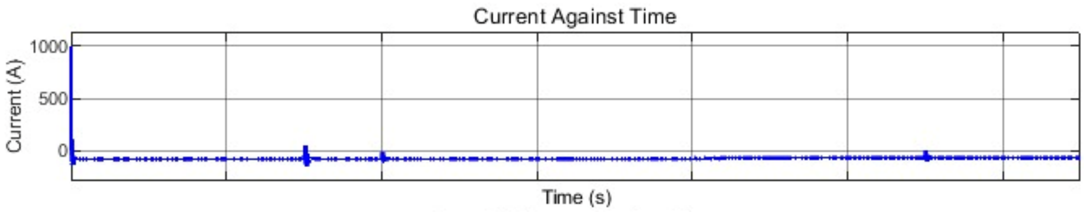

Figure 4.3 : Battery current for boost mode

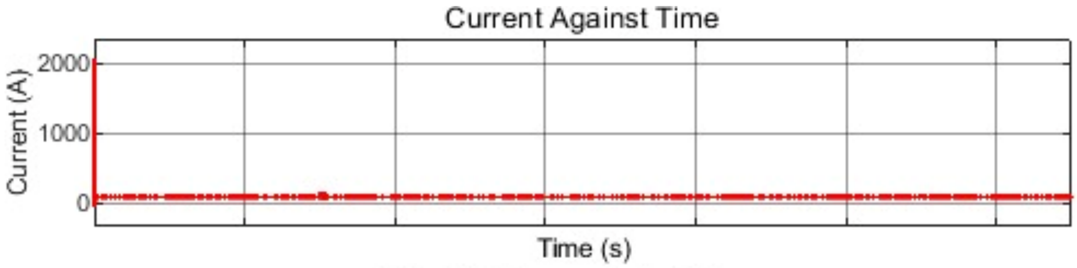

Figure 4.4 : Supercapacitor current for boost mode

Analyzing the state of charge (SOC) when the boost mode is in operation reveals clear patterns in the graphs of both the battery and supercapacitor. The battery graph displays the state of charge (SOC) over time, illustrating the charging pattern shown at Figure 4.5. During the charging mode, the State of Charge (SOC) also undergoes a charging phase. The battery's initial state of charge (SOC) is recorded as 20%, and because of the charging mode, it rises to 21.76%. In contrast, the graph of the supercapacitor shown at Figure 4.6 demonstrates a reduction in state of charge (SOC) when discharging, which corresponds to a fall in voltage. The initial state of charge (SOC) for the supercapacitor is recorded at 100%. However, due to the discharging mode, it lowers to 88.77%.

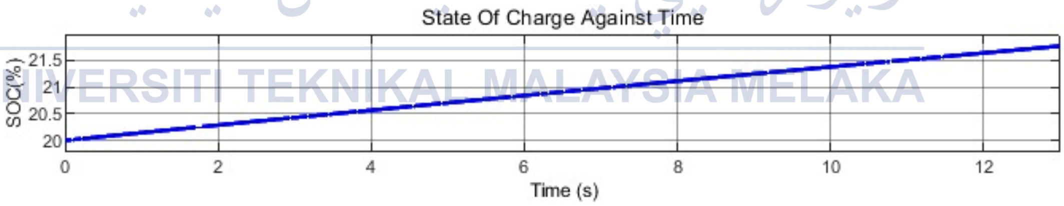

Figure 4.5 : SOC of battery for boost mode

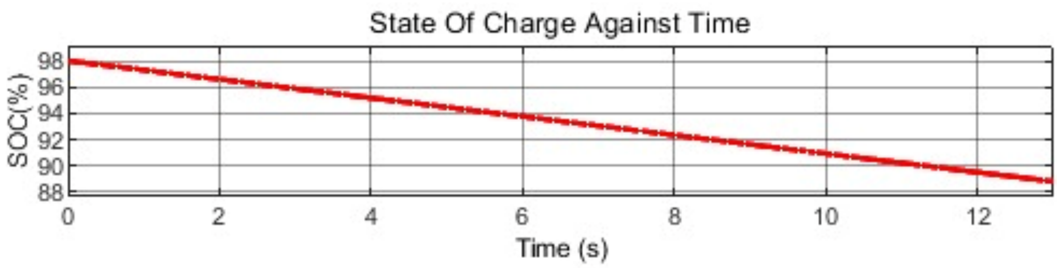

Figure 4.6 : SOC of supercapacitor for boost mode

Table 4.1 : Boost mode result for battery and supercapacitor

Result For Battery	Value
Voltage	341.2
Current	-71.64
SOC	21.76
Power	-2444

Result for Supercapacitor	Value
Voltage	253
Current	100.3
SOC	88.77
Power	2537

Based on the result that been obtained from simulation, the power for the battery is negative, so the battery will be in boost mode and supercapacitor will be in buck mode because the power for Supercapacitor is positive. This means the battery will be in charging mode and the supercapacitor will be in discharging mode.

4.2.2 Buck Mode

The voltage results during the operation of the buck mode are clearly apparent in the study. Upon analyzing the voltage against time graph of the battery, a distinct change is seen, indicating the presence of a discharging process. The battery's voltage shown at Figure 4.7, which was initially set at 300V, falls to 77.67V because of active discharge. Conversely, Figure 4.8 show the graph of the supercapacitor demonstrates a pattern of charging. The initial voltage is 0V and it rises to 9.286V due to the executed discharge process. This discovery emphasizes the different behaviors of the battery and supercapacitor when subjected to buck mode which is the battery discharges while the supercapacitor charges.

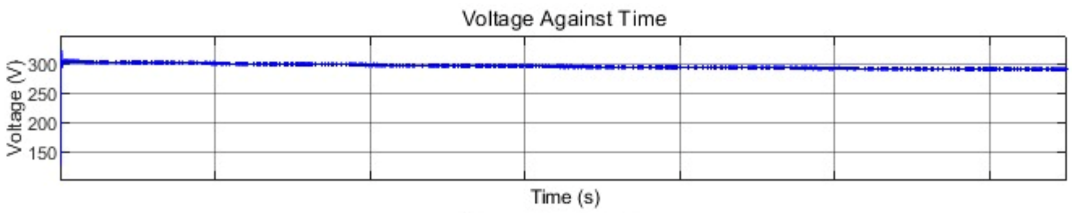

Figure 4.7 : Battery voltage for buck mode

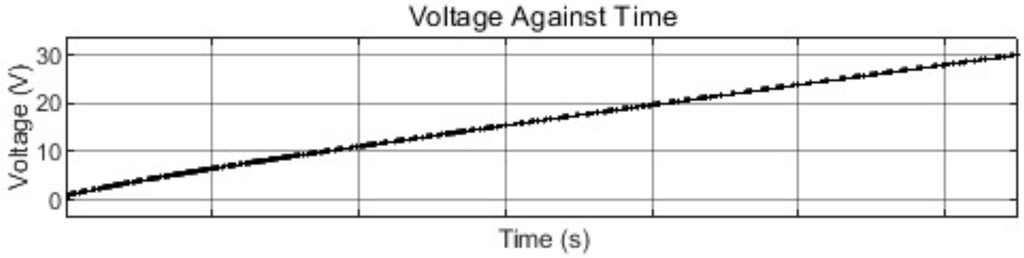

Figure 4.8 : Supercapacitor voltage for buck mode

The analysis of electric current during the functioning of the buck mode exposes clear patterns in the graphs of both the battery and supercapacitor. In Figure 4.9, the current against time relationship in the battery graph represents the charging process, contrasting with the voltage graph's behavior in the battery section shown at Figure 4.7. The current produced during this charging method is precisely measured at 99.39A. In contrast, the supercapacitor graph displays a trend of discharging shown at Figure 4.10, which is opposite from the voltage graph in the supercapacitor section at Figure 4.8. The current generated during this discharge mode is recorded as -101.1A.

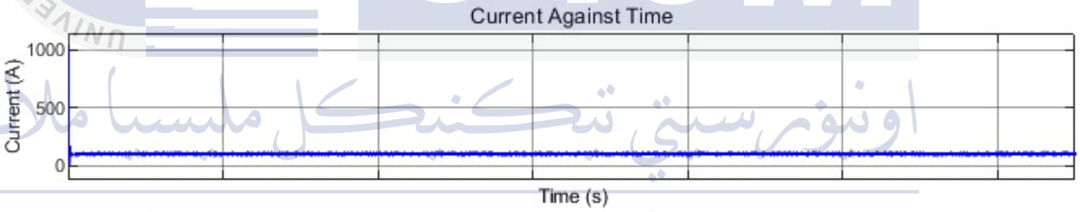

Figure 4.9 : Battery current for buck mode

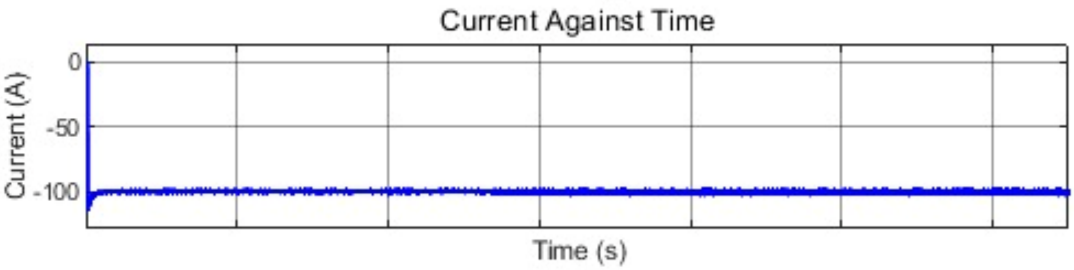

Figure 4.10 : Supercapacitor current for buck mode

The battery graph displays the state of charge (SOC) over time, indicating a phase of discharge that differs from the voltage graph but follows its overall pattern. During the discharging mode, the state of charge (SOC) decreases in along with the voltage. The initial state of charge (SOC) for the battery is recorded as 80%. However, as a result of the discharging mode, it lowers to 77.67%. In contrast, the graph of the supercapacitor demonstrates a correlation between the state of charge (SOC) and the charging process, as shown by the voltage graph where an increase in charging voltage corresponds to a rise in SOC. The initial state of charge (SOC) for the supercapacitor is documented as 0%. Through the process of charging, the SOC subsequently rises to 9.286%. The charge and discharge of the SOC is shown at Figure 4.11 and Figure 4.12.

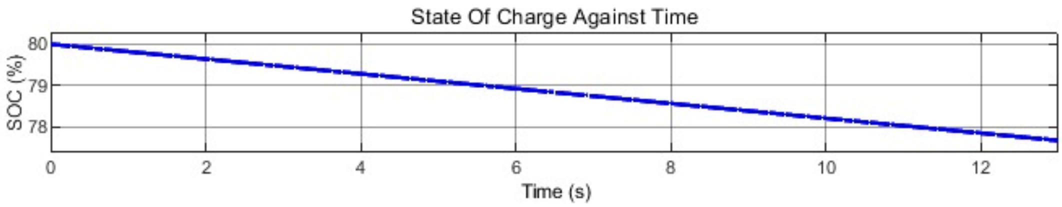

Figure 4.11 : SOC of battery for buck mode

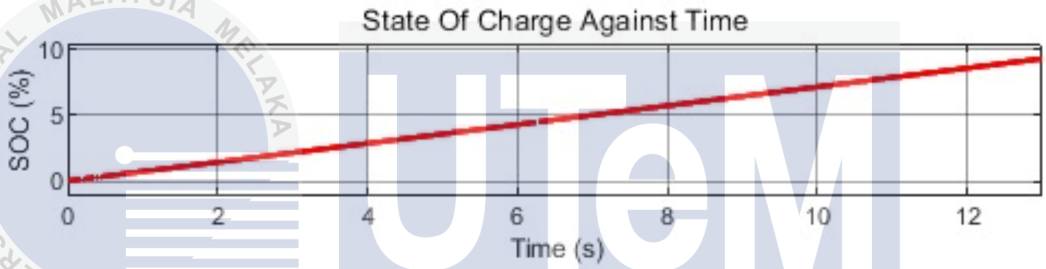

Figure 4.12 : SOC of supercapacitor for buck mode

Table 4.2 : Buck mode result for battery and supercapacitor

Result For Battery	Value
Voltage	292
Current	99.39
SOC	77.67
Power	2902

Result for Supercapacitor	Value
Voltage	30.19
Current	-101.1
SOC	9.286
Power	-3051

Based on the result that been obtained from simulation, the power for the battery is positive, so the battery will be in buck mode and supercapacitor will be in boost mode because the power for Supercapacitor is negative. This means the battery will be in discharging mode and the supercapacitor will be in charging mode.

4.2.3 Performance Of Electric Vehicle by using BLDC motor

4.2.3.1 Boost mode

Figure 4.13 show performance motor that operates in boost mode. The following figure show how the BLDC motor works when it changes from driving mode to regenerative mode and regenerative braking to driving mode. During the 13 second, the brake pedal is pressed at points 1, 2, and 3. As shown in Figure 4.13, each time the brakes are applied, the speed drops. Whenever the motor slows down, the electromagnetic force turn to negative, which means it is working as a generator. Simultaneously, the battery experiences a negative power flow, indicating that the power is being used to charge the battery. Simultaneously, the supercapacitor's power becomes positive, indicating that power is being discharged from the supercapacitor. This way that power flow and torque combine shows how the BLDC motor system works dynamically in boost mode under different circumstances.

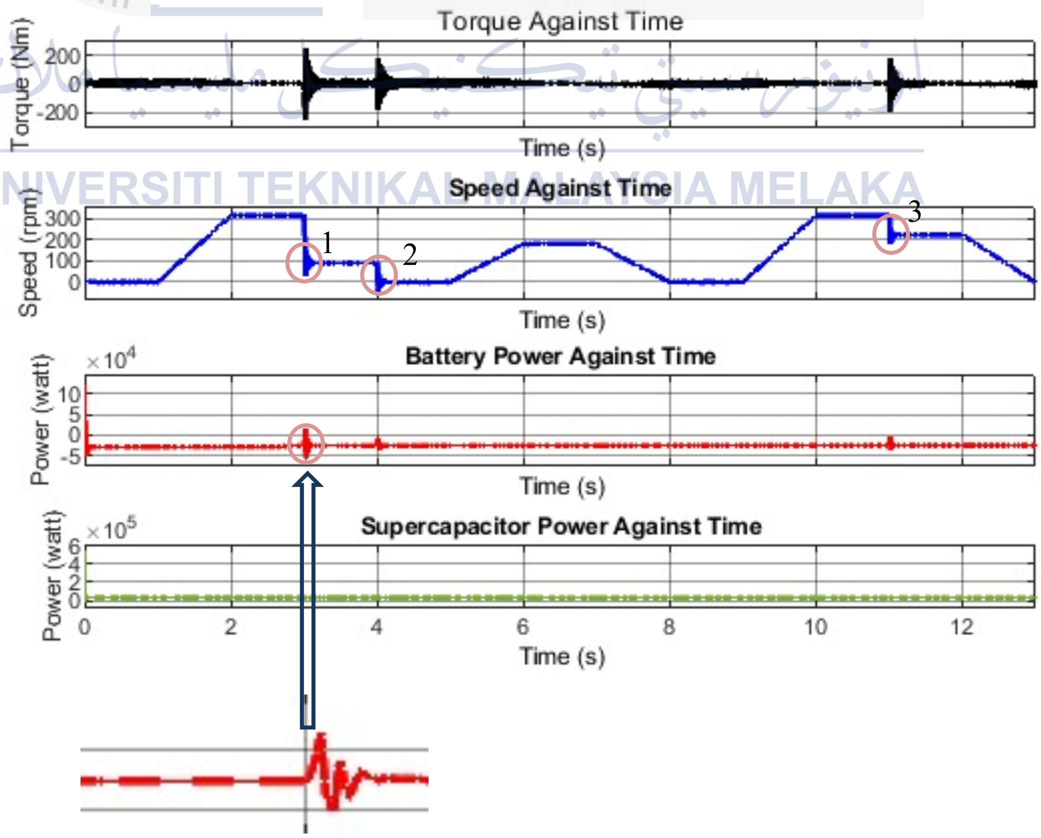

Figure 4.13 : Performance of EV by using BLDC motor in Boost mode

Figure 4.14 displays the waveforms of the back EMFs, whereas Figure 4.15 shows the waveforms of the stator currents for phases A, B, and C. These figures are used to demonstrate the fluctuations at the corresponding braking points. Since speed and back EMF are strongly correlated, a drop in speed also causes a decrease in back EMF. Figure 4.14 provides a clear example of this connection. Furthermore, Figure 4.15 shows that in regenerative mode, the stator current increases immediately following the braking points, suggesting that is appears to be a boosting action. This increase in stator current signifies that energy is being recuperated and fed back into the system, enhancing efficiency during braking events. The detailed waveforms thus provide a comprehensive view of the dynamic behavior of the motor's electrical characteristics under different operational states.

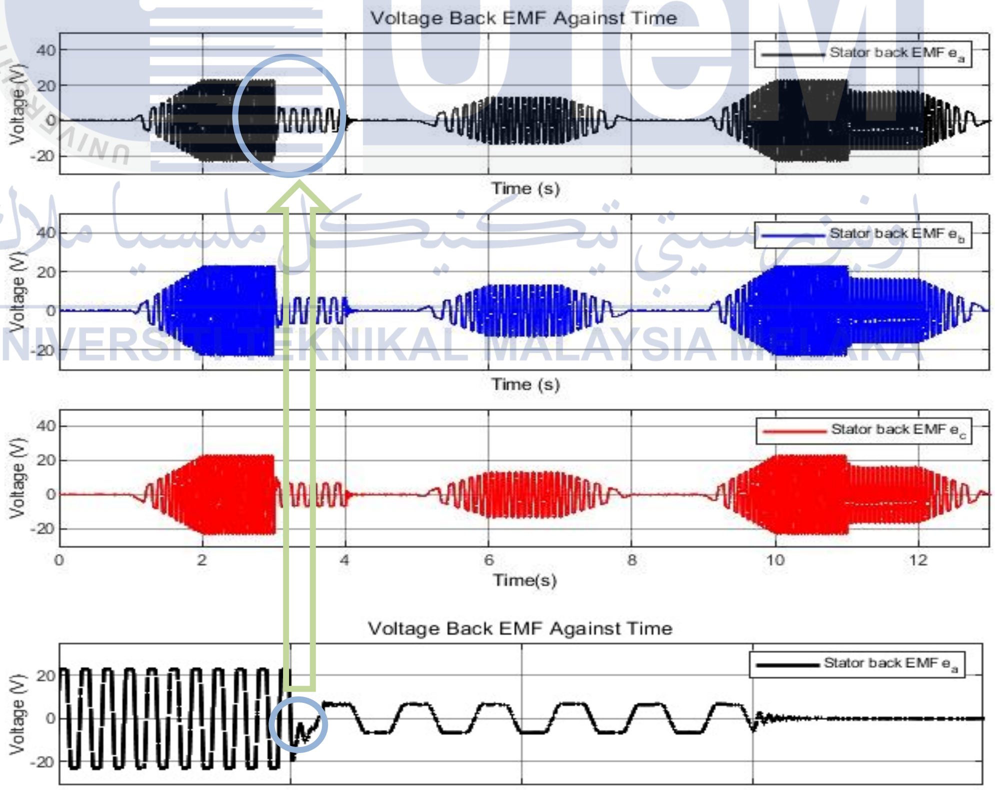

Figure 4.14 : Waveform of voltage Back EMF with different phases

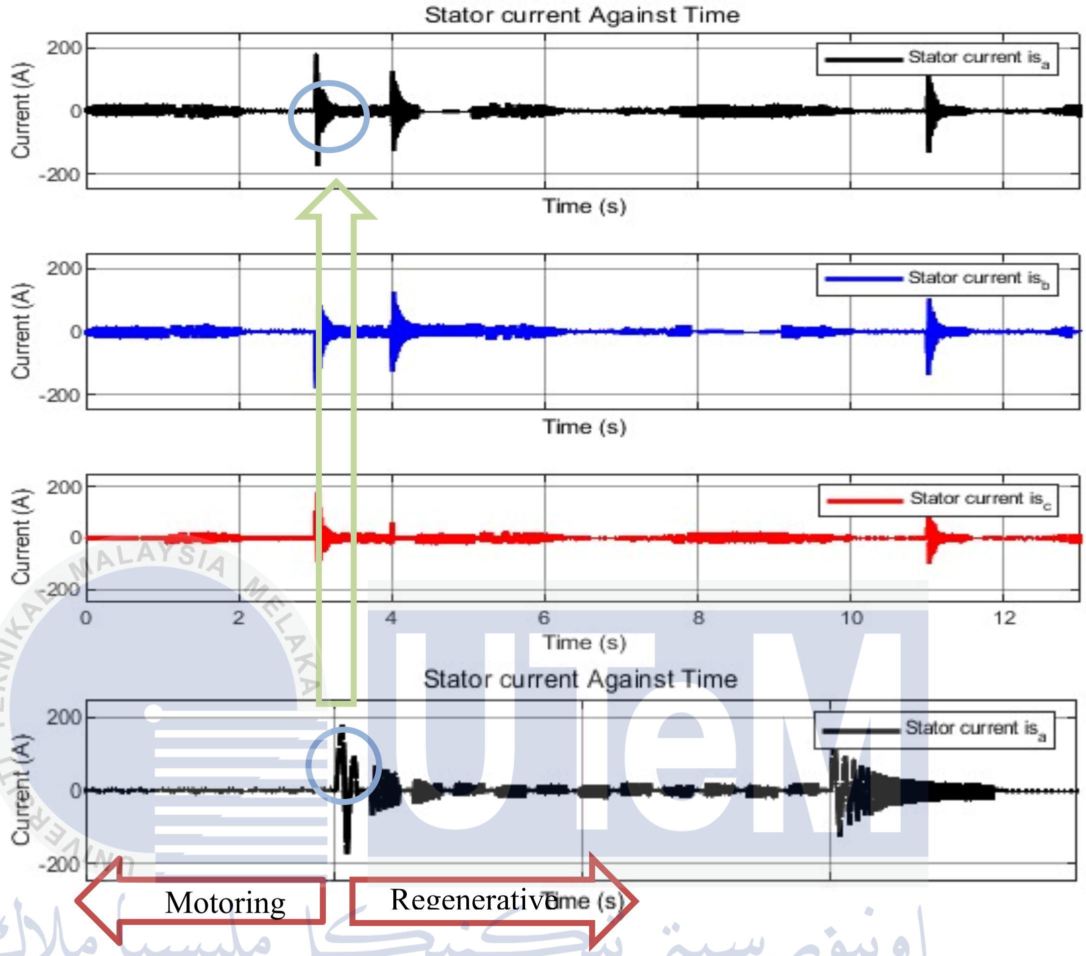

Figure 4.15 : Stator current waveform in different phases

This graph in Figure 4.16 is comparing the reference speed and the actual speed of this simulation. The actual speed is almost the same as the reference speed, which shows that the actual speed is nearly accurate. At point 1, point 2, and point 3, regenerative braking occurs due to the immediate brake application. Consequently, the actual speed decreases and ramps slightly before aligning with the reference speed. This close alignment between the actual and reference speeds, despite the brief deviations caused by braking, demonstrates the effectiveness of the simulation in maintaining speed accuracy.

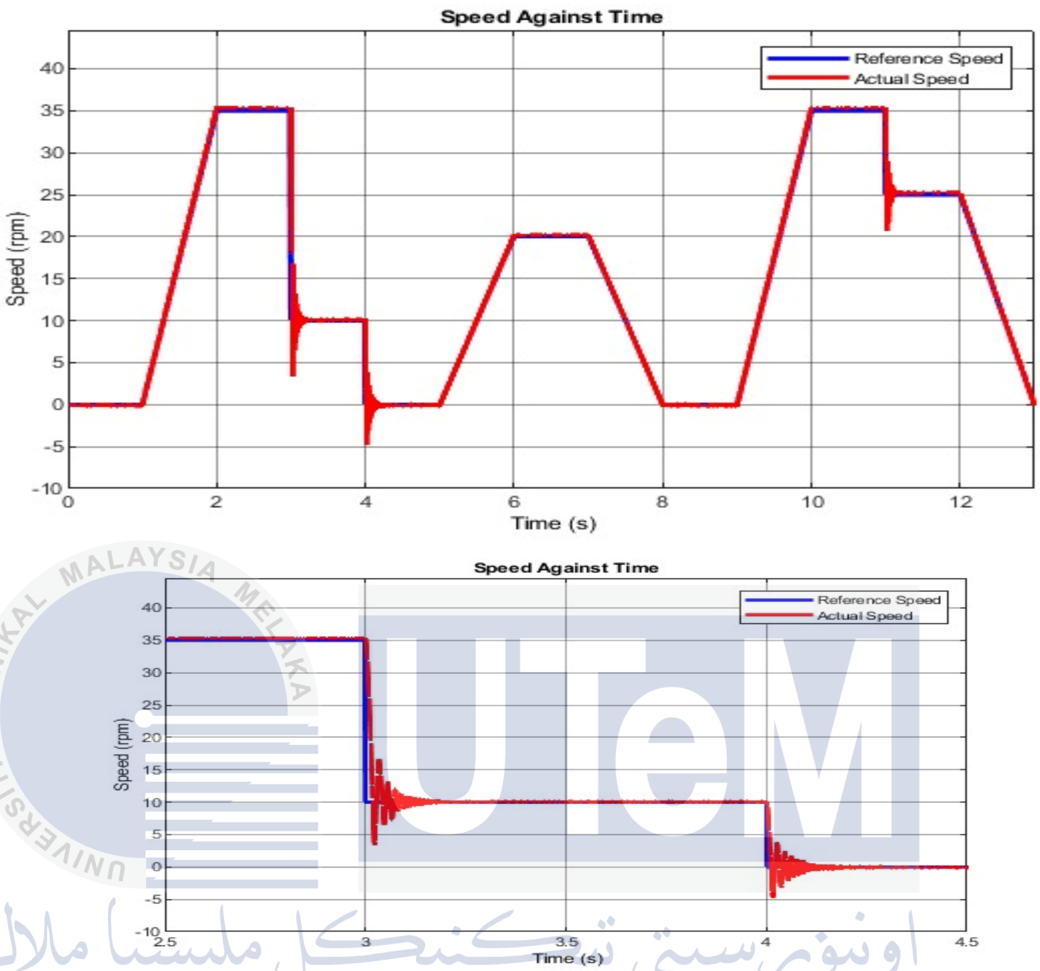

Figure 4.16 : Waveform speed and its zoomed version

During boost mode, the supercapacitor releases its stored energy with a consistent and steady flow of electric current, which is made possible by its little internal resistance. The steady discharge leads to a reliable and uninterrupted flow of electric current to the converter. Moreover, the process of charging the battery entails the use of lower electrical currents and carefully regulated patterns to avoid deterioration, resulting in less fluctuations in current and a more seamless transmission of power to the motor. The stable current supply from the supercapacitor in boost mode results in smaller ripples in motor speed, torque, and current, ensuring more consistent and efficient motor operation.

4.2.3.2 Buck mode

The BLDC motor's activity during the switch from driving mode to regenerative mode and vice versa is shown in Figure 4.17 below. In this instance, the system is operating in buck mode. The brake pedal decreases at points 1, 2, and 3 for 13 seconds throughout the simulation. The speed decreases with each braking event, as Figure 4.17 illustrates. The electromagnetic torque becomes negative during braking times, meaning the motor is operating like a generator. At the same time, there is a positive battery power, which indicates that the battery is losing power. In the meanwhile, the supercapacitor's power goes negative, signifying that it is receiving power input for charging. The dynamic functioning of the BLDC motor system under different situations is effectively shown by the interaction between torque and power flow.

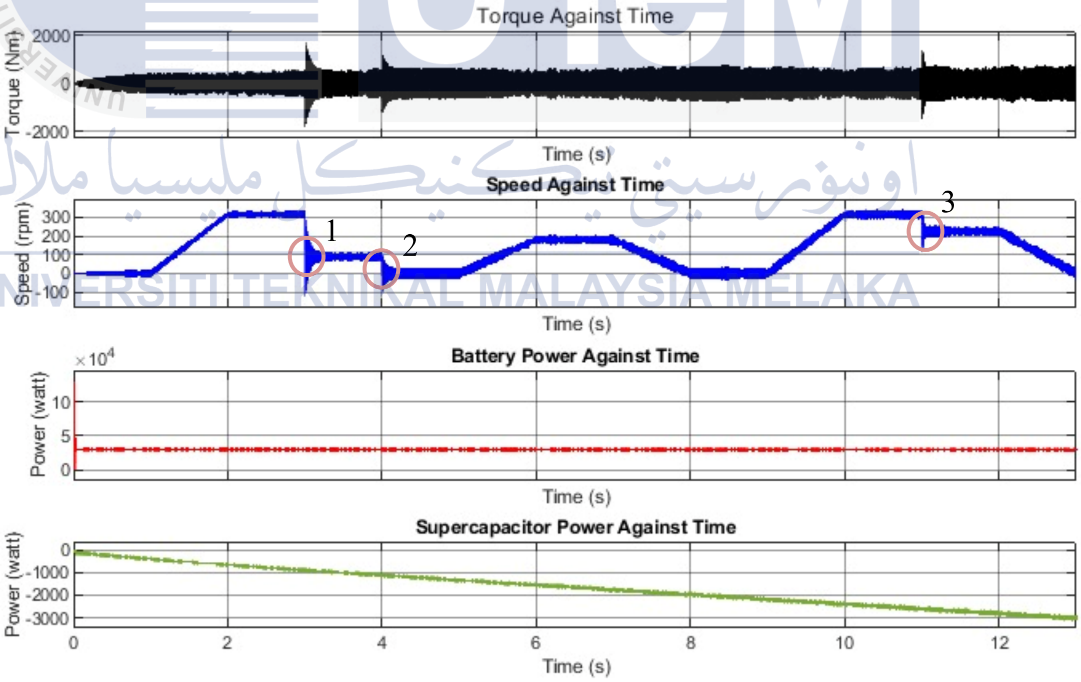

Figure 4.17 : Performance of EV by using BLDC motor in Buck mode

Figures 4.18 and 4.19, respectively, show the waveforms of the stator currents and back EMFs for different phases, illustrating the fluctuations at the corresponding braking points in buck mode. Back EMF is precisely related to speed, thus when you reduce speed, back EMF also decreases, as Figure 4.18 illustrates. Figure 4.19 makes it clear that in regenerative mode, the stator current rises immediately after the braking points, suggesting that a boosting action takes place. This figure also provides a clear comparison between motoring mode and regenerative mode, highlighting the different behaviors in each state. The stator currents in buck mode are notably has bigger ripple than in boost mode, highlighting the higher current need during energy recovery and the operational efficiency of energy conversion at this stage.

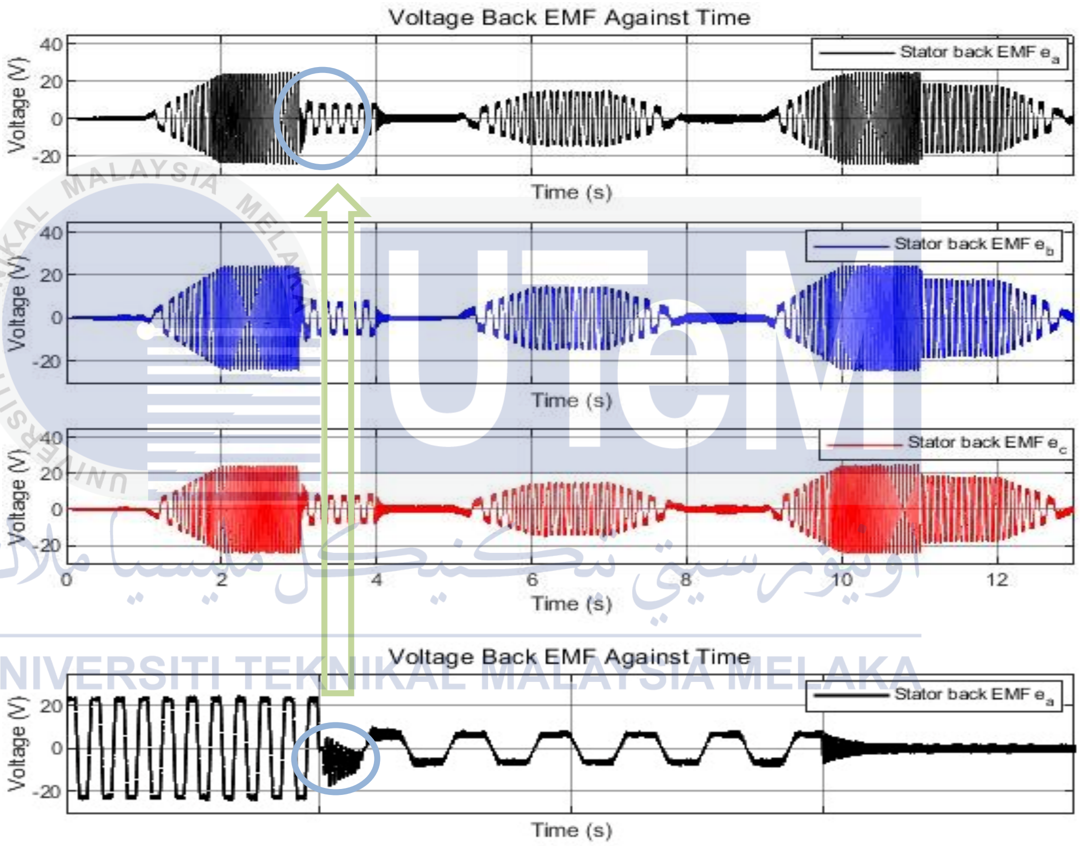

Figure 4.18 : Waveform of voltage Back EMF with different phases

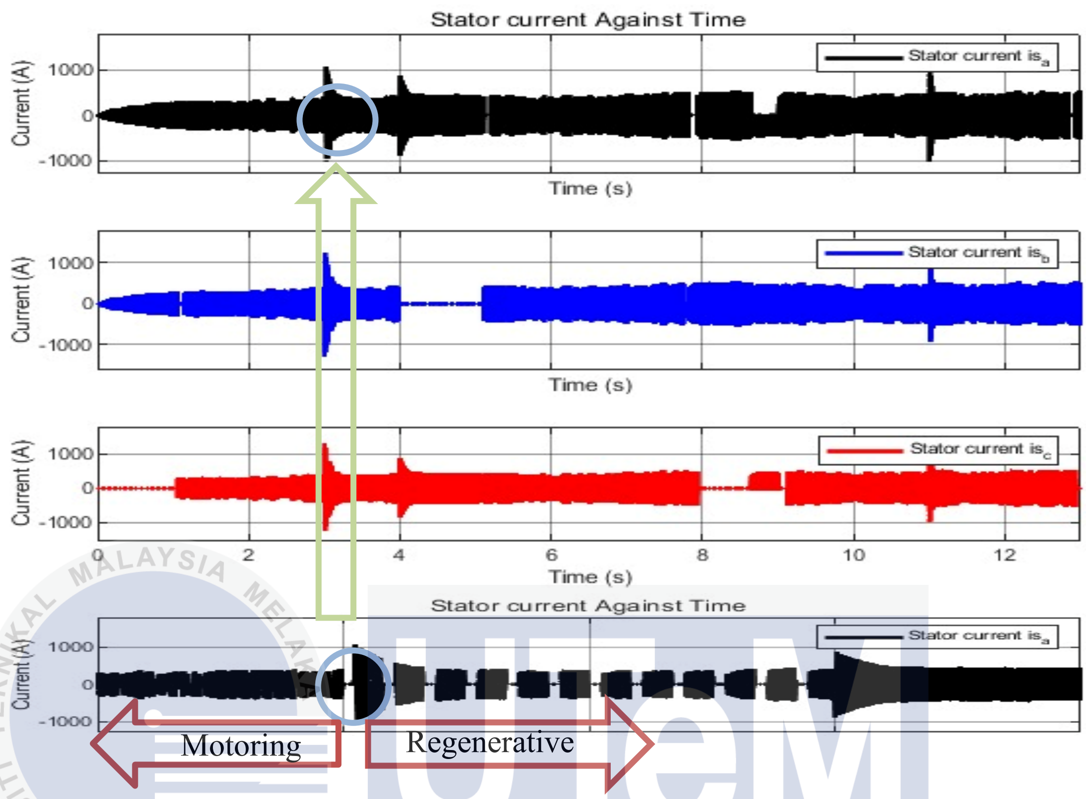

Figure 4.19 : Stator current waveform in different phases

The speed waveform and its zoomed version are shown in Figure 4.20, which compares the simulation's real speed to the reference speed. High precision is shown by how closely the real speed matches the reference speed. However, in buck mode, the actual speed is slightly higher and ramps more compared to boost mode. At points 1, 2, and 3, regenerative braking occurs due to immediate brake applications, causing the actual speed to decrease before ramping up and realigning with the reference speed. This close alignment between the actual and reference speeds, despite brief deviations caused by braking, highlights the effectiveness of the simulation in maintaining speed accuracy and responding dynamically to changes in braking conditions. The ability to closely track the reference speed in varying modes and conditions underscores the robustness of the control system employed in this simulation.

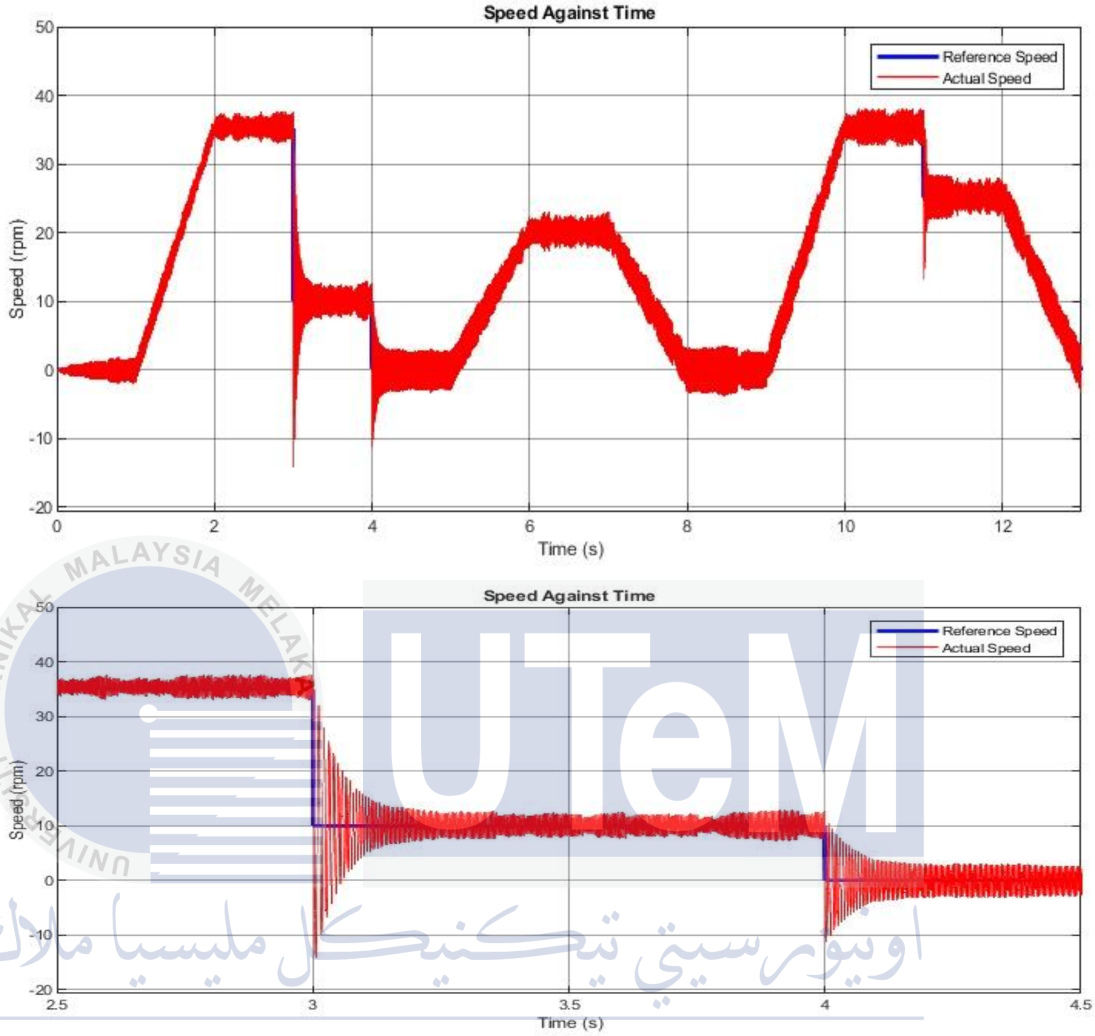

Figure 4.20 : Waveform speed and its zoomed version

The system has significant current variations while it is in buck mode, which is when the battery is draining and the supercapacitor is charging. Supercapacitors may quickly draw large currents while charging since they have a low internal resistance. The current that the battery supplies via the buck converter varies significantly as a consequence of this high current demand. Moreover, batteries have a larger internal resistance by design than supercapacitors. This resistance increases the overall ripple in the system by causing noticeable fluctuations in voltage and current changes while discharging. The motor's input power is immediately impacted by these variations, which result in obvious differences in the motor's torque, speed, and current. As a result, the motor performs inconsistently, which lowers overall efficiency and has a negative impact on drivability.

The converter's inductive element behaviour has a big impact on how big the ripples are. When the converter is in buck mode, it lowers the battery voltage to the level needed to charge a supercapacitor. Because of the significant voltage differential between the input and output, the buck converter's inductor stores energy during the on-state and releases it during the off-state, resulting in noticeable current waves. The inductor's current ripple increases with voltage differential, which has an impact on the motor's power supply stability.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The conclusion of this section reviews the accomplishments in relation to the original study goals. Beyond the set aims, this study has added to the knowledge reservoir by providing direct insights into parallel battery-supercapacitor electric vehicle operations. Real-world driving data analysis was used to demonstrate the system's practicality, departing from simulation research. On a bright note, this study and other tiny but progressive contributions should spark various new ideas.

The main goal of studying EV charge and discharge was achieved. Parallel supercapacitor integration, enabled by high-power contactors, aimed to improve acceleration and range. Real-world driving data analysis confirmed the parallel battery-supercapacitor configuration's gains, which were supported by simulation tests.

Secondary and tertiary goals included modeling EV batteries and supercapacitors by using parallel active topologies buck-boost converter using MATLAB Simulink and analyzing the performance of buck-boost converter in electric vehicle (EV). These components' dynamic interactions in the electric vehicle system were revealed by extensive simulation research. This enhances theoretical knowledge and informs justification for parallel battery-supercapacitor system design and execution in electric vehicle applications. This study allows for the gap between theoretical simulations and real-world performance, furthering electric car technology.

5.2 Future Works

In order to improve the performance of battery and supercapacitor energy management systems, future research and development should concentrate on several important areas. It is possible to create sophisticated control algorithms that minimise ripples in both the boost and buck modes and dynamically adapt to changing load circumstances by using machine learning and artificial intelligence. By predicting and reducing variations before they have an impact on motor performance, predictive control systems may further improve system stability. Another crucial area is optimising inductor design, where studies on specialised inductors and cutting-edge magnetic materials may boost effectiveness and lessen ripple effects. Investigating hybrid capacitor systems, which combine the advantages of supercapacitors and batteries, may provide a more reliable energy storage option by balancing performance throughout cycles of charging and discharging. Furthermore, to effectively dissipate heat produced during high current operations in buck mode and maintain ideal operating temperatures for batteries and supercapacitors, sophisticated thermal management techniques are required. Predictive maintenance techniques and real-time health monitoring systems may guarantee reliable operation and increase the energy storage system's lifetime. By addressing these issues, EV motor performance will be greatly increased, which will result in more dependable, efficient, and sustainable energy management systems.

REFERENCES

[1] A. A. Parker, "Electric power-assisted bicycles reduce oil dependence and enhance the mobility of the elderly," in *29th Australasian Transport Research Forum, ATRF 06*, 2006.

[2] M. Ortúzar, J. Moreno, and J. Dixon, "Ultracapacitor-based auxiliary energy system for an electric vehicle: Implementation and evaluation," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 4, 2007, doi: 10.1109/TIE.2007.894713.

[3] V. Krithika and C. Subramani, "A comprehensive review on choice of hybrid vehicles and power converters, control strategies for hybrid electric vehicles," *International Journal of Energy Research*, vol. 42, no. 5. 2018. doi: 10.1002/er.3952.

[4] Q. Xu, F. Wang, X. Zhang, and S. Cui, "Research on the Efficiency Optimization Control of the Regenerative Braking System of Hybrid Electrical Vehicle Based on Electrical Variable Transmission," *IEEE Access*, vol. 7, 2019, doi: 10.1109/ACCESS.2019.2936370.

[5] P. T. Chen, P. H. Pai, C. J. Yang, and K. D. Huang, "Development of transmission systems for parallel hybrid electric vehicles," *Applied Sciences (Switzerland)*, vol. 9, no. 8, 2019, doi: 10.3390/app9081538.

[6] K. Jayasawal, A. K. Karna, and K. B. Thapa, "Topologies for Interfacing Supercapacitor and Battery in Hybrid Electric Vehicle Applications: An Overview," in *2021 International Conference on Sustainable Energy and Future Electric Transportation, SeFet 2021*, 2021. doi: 10.1109/SeFet48154.2021.9375802.

[7] J. Cao and A. Emadi, "A new battery/ultra-capacitor hybrid energy storage system for electric, hybrid and plug-in hybrid electric vehicles," in *5th IEEE Vehicle Power and Propulsion Conference, VPPC '09*, 2009. doi: 10.1109/VPPC.2009.5289744.

[8] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, and R. Villafáfila-Robles, "A review of energy storage technologies for wind power applications," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 4. 2012. doi: 10.1016/j.rser.2012.01.029.

[9] J. B. Greenblatt, S. Succar, D. C. Denkenberger, R. H. Williams, and R. H. Socolow, "Baseload wind energy: modeling the competition between gas turbines and compressed air energy storage for supplemental generation," *Energy Policy*, vol. 35, no. 3, 2007, doi: 10.1016/j.enpol.2006.03.023.

[10] M. A. Hannan, M. M. Hoque, A. Mohamed, and A. Ayob, "Review of energy storage systems for electric vehicle applications: Issues and challenges," *Renewable and Sustainable Energy Reviews*, vol. 69. 2017. doi: 10.1016/j.rser.2016.11.171.

[11] M. Huang, M. Li, C. Niu, Q. Li, and L. Mai, "Recent Advances in Rational Electrode Designs for High-Performance Alkaline Rechargeable Batteries," *Advanced Functional Materials*, vol. 29, no. 11. 2019. doi: 10.1002/adfm.201807847.

[12] J. McDowall, "Integrating energy storage with wind power in weak electricity grids," *J Power Sources*, vol. 162, no. 2 SPEC. ISS., 2006, doi: 10.1016/j.jpowsour.2005.06.034.
[13] L. Szablowski, P. Krawczyk, K. Badyda, S. Karellas, E. Kakaras, and W. Bujalski, "Energy and exergy analysis of adiabatic compressed air energy storage system," *Energy*, vol. 138, 2017, doi: 10.1016/j.energy.2017.07.055.
[14] A. G. Olabi, C. Onumaegbu, T. Wilberforce, M. Ramadan, M. A. Abdelkareem, and A. H. Al – Alami, "Critical review of energy storage systems," *Energy*, vol. 214, 2021, doi: 10.1016/j.energy.2020.118987.
[15] A. F. Burke, "Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, 2007, doi: 10.1109/JPROC.2007.892490.
[16] S. Chakraborty, H. N. Vu, M. M. Hasan, D. D. Tran, M. El Baghdadi, and O. Hegazy, "DC-DC converter topologies for electric vehicles, plug-in hybrid electric vehicles and fast charging stations: State of the art and future trends," *Energies (Basel)*, vol. 12, no. 8, 2019, doi: 10.3390/en12081569.
[17] S. Yoshihara, H. Hamano, H. Yamada, and K. Nakajima, "Development of technology for electrically driven powertrains in hybrid electric vehicles," *Hitachi Review*, vol. 58, no. 7, 2009.
[18] A. Kumar and P. Gaur, "Operation of DC/DC Converter for Hybrid Electric Vehicle," *International Journal of Electronic and Electrical Engineering*, vol. 7, no. 4, 2014.
[19] S. Mehta and S. Hemamalini, "A Dual Control Regenerative Braking Strategy for Two-Wheeler Application," in *Energy Procedia*, 2017. doi: 10.1016/j.egypro.2017.05.135.
[20] B. V. Kumar, R. K. Singh, and R. Mahanty, "A modified non-isolated bidirectional DC-DC converter for EV/HEV's traction drive systems," in *IEEE International Conference on Power Electronics, Drives and Energy Systems, PEDES 2016*, 2016. doi: 10.1109/PEDES.2016.7914???
[21] D. R. Northcott, S. Filizadeh, and A. R. Chevrefils, "Design of a bidirectional buck-boost dc/dc converter for a series hybrid electric vehicle using PSCAD/EMTDC," in *5th IEEE Vehicle Power and Propulsion Conference, VPPC '09*, 2009. doi: 10.1109/VPPC.2009.5289583.
[22] G. Subramanian and J. Peter, "Integrated Li-Ion Battery and Super Capacitor based Hybrid Energy Storage System for Electric Vehicles," in *Proceedings of CONECCT 2020 - 6th IEEE International Conference on Electronics, Computing and Communication Technologies*, 2020. doi: 10.1109/CONECCT50063.2020.9198317.
[23] J. S. Lai and D. J. Nelson, "Energy management power converters in hybrid electric and fuel cell vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, 2007, doi: 10.1109/JPROC.2006.890122.
[24] R. Krishnan, "Selection Criteria for Servo Motor Drives," *IEEE Trans Ind Appl*, vol. IA-23, no. 2, 1987, doi: 10.1109/TIA.1987.4504902.
[25] R. Krishnan and A. J. Beutler, "PERFORMANCE AND DESIGN OF AN AXIAL FIELD PM SYNCHRONOUS MOTOR SERVO DRIVE.," in *Conference Record - IAS Annual Meeting (IEEE Industry Applications Society)*, 1985.

[26] T. M. Jahns, "Torque Production in Permanent-Magnet Synchronous Motor Drives with Rectangular Current Excitation," *IEEE Trans Ind Appl*, vol. IA-20, no. 4, 1984, doi: 10.1109/TIA.1984.4504490.

[27] S. Sakunthala, R. Kiranmayi, and P. N. Mandadi, "A study on industrial motor drives: Comparison and applications of PMSM and BLDC motor drives," in *2017 International Conference on Energy, Communication, Data Analytics and Soft Computing, ICECDS 2017*, 2018. doi: 10.1109/ICECDS.2017.8390224.

[28] A. Weschta, "DESIGN CONSIDERATIONS AND PERFORMANCE OF BRUSHLESS PERMANENT MAGNET SERVO MOTORS.," in *Conference Record - IAS Annual Meeting (IEEE Industry Applications Society)*, 1983.

[29] G. Pfaff, A. Weschta, and A. F. Wick, "Design and Experimental Results of a Brushless Ac Servo Drive," *IEEE Trans Ind Appl*, vol. IA-20, no. 4, 1984, doi: 10.1109/TIA.1984.4504491.