Design, modeling and simulation of electric vehicle powertrain components with DC motor drive

By

Getnet Admasu Getahun

A THESIS SUBMITTED TO THE

DEPARTMENT OF MECHANICAL SYSTEMS AND VEHICLE ENGINEERING

SCHOOL OF MECHANICAL, CHEMICAL AND MATERIAL ENGINEERING

Presented in Partial Fulfillment of the Requirement for the Award of the Degree of Master of Science in Automotive Engineering

Office of Graduate Studies

ADAMA SCINECE AND TECHNOLOGY UNIVERSITY

ADAMA; ETHIOPIA

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Advisor: Ramesh Babu Nallamothu (PhD)

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APPROVAL OF BOARD OF EXAMINERS

We, the undersigned, members of the Board of Examiners of the final open defense by Getnet Admasu Getahun have read and evaluated his thesis entitled "Design, modeling and simulation of electric vehicle powertrain components with DC motor drive" and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master of Science in Automotive Engineering.

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CANDIDATE'S DECLARATION

I hereby declare that the work which is presented in the thesis entitled "Design, modeling and simulation of electric vehicle powertrain components with DC motor drive" in partial fulfillment of the requirements for the award of the degree of Master of Science in automotive engineering is an authentic record of my own work carried out from October 2019 to January 2021 under the supervision of Ramesh Babu Nallamothu (PhD), Department of Mechanical system and vehicle Engineering, at Adama science and technology university, Ethiopia. Any portion embodied in this thesis has not been submitted by me for the award of any other degree or diploma. All relevant sources of information used in this thesis have been acknowledged.

Name	Signature	Date
Getnet Admasu Getahun		
(Candidate)	______________________	______________________

This is to certify that the above statement made by candidate is correct to the best of my knowledge and belief. This thesis has been submitted for examination with my approval.

Name	Signature	Date
Dr. Ramesh Babu Nallamothu		
(Advisor)	______________________	______________________

ADVISOR’S APPROVAL SHEET

To: SoMCM Engineering Automotive Engineering Department

Subject: Thesis Submission

This is to certify that the thesis entitled “**Design, modeling and simulation of electric vehicle powertrain components with DC motor drive**” submitted in partial fulfillment of the requirements for the degree of Master’s in Automotive Engineering, the graduate program of the department of Automotive Engineering, and has been carried out by Getnet Admasu Getahun Id.No. A/PE16408/10 under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence hereby he can submit the thesis to the department.

______________________________	____________________	________________
Advisor	Signature	Date

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ACRONYMS

AC	Alternative Current
BEV	Battery electric vehicle
C_d	Aerodynamic drag coefficient
$C.G$	Center of gravity
C_r	Coefficient of rolling resistance
CV	Conventional vehicle
CVs	Conventional cars
DC	Direct Current
EV	Electric Vehicle
FCV	Fuel cell vehicle
F_{a_e}	Aerodynamic resistance force
F_g	Grade resistance force
F_r	Rolling resistance force
F_{re}	Resistance force
P_r	Resistance power
GHG	Greenhouse gas
HEV	Hybrid electric vehicles
ICE	Internal combustion engine
NEDC	New European Drive Cycle
PHEV	Plug in hybrid electric vehicles
RPM	Revolution per minute
RWD	Rear wheel drive
VOC	Volatile organic compounds
ZEV	Zero emission vehicles

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ABSTRACT

The automotive industry has been in a period of energy transformation from fossil fuels to a clean energy economy due to the economic pressures resulting from the energy crisis and the need for stricter environmental protection policies. Among various clean energy systems, electric vehicles, with lithium-ion batteries have the largest market share because of their stable performance and they are a relatively mature technology. However, electric vehicles still have critical issues which need to be solved. The three main challenges are limited driving range, long charging time, and high cost. The three main challenges are all related to the battery package of the car. The battery package should both contain enough energy in order to have a certain driving range and it should also have a sufficient power capability for the accelerations and decelerations. In order to be able to estimate the energy consumption of an electric vehicles it is very important to have a proper model of the vehicle. The drive train components consist of a battery, a motor, a motor controller with H Bridge and a transmission. The design or rating of each component is a difficult task as the parameters of one component affect the power level of another one. There is therefore a risk that one component is rated inappropriately which may make the vehicle unnecessary expensive or inefficient. In this work the power train components of the electric vehicle is simulated using MATLAB (Simscape) simulation software, and the electric motor performance is simulated using C++ software. The battery pack is properly modeled in the Simscape environment since it is the heart of the electric vehicle, but the other components are taken simply from Simscape block diagrams. The vehicle is tested in theoretical drive cycle, which is travelled for a distance of 11 km and a duration of 1180 seconds. The result shows the vehicle speed follows the path of the drive cycle reference speed. All simulation results are plotted and discussed.

Keywords: Electric machine, Electric vehicles, lithium-ion batteries, Power electronics Transmission.

CHAPTER ONE

INTRODUCTION

1.1 Background

The massive use of ICE cars has led to the dependence on fossil fuels. The exploitation of fossils fuels brings up big environmental costs since it constitutes one of the major contributions to the greenhouse gas effect. The different means of transport cause almost 14% of global greenhouse gas emissions and as it is predicted it will reach the 50% by 2030. The high percentages of carbon dioxide and the rest of climate-altering emissions threatens both the environment and the people. To limit the impact of these emissions cleaner fuels and fuel catalysts have been introduced to the conventional cars. Nevertheless, these measures have not managed to restrict the carbon dioxide emissions which contribute majorly to the greenhouse effect [1].

The aforementioned results and predictions of other researches indicate that a more sustainable transportation system is needed. Shifts in fuel characteristics or the provision of alternative energy sources can reduce the emissions and promote the substitution of conventional gasoline and diesel fuel. These concerns have necessitated the adoption and use of alternative fuel vehicles such as hybrid and battery electric vehicles. This thesis refers to the electric vehicles only (those electric cars which are 100% powered by electric battery). Electric cars operate by one or more electric motors which are powered by rechargeable electric batteries. Due to electric cars' ability to operate using clean energy sources, an alteration to electric cars contributes to an independent, cleaner and more secure energy future [2].

Electric vehicles are by many seen as the cars of the future as they are high efficient, produces no local pollution, are silent, and can be used for power regulation by the grid operator. However, electric vehicles still have critical issues which need to be solved. The three main challenges are limited driving range, long charging time, and high cost. The three main challenges are all related to the battery package of the car. The battery package should both contain enough energy in order to have a certain driving range and it should also have a sufficient power capability for the accelerations and decelerations. In order to be able to estimate the energy consumption of an electric vehicles it is very important to have a proper model of the vehicle [3-5].

Beside the benefits an electric car can offer, it still has some drawbacks that make it look inferior to the conventional car. Although improvements in energy efficiency have been made so as to achieve sustainability in personal transportation, low emission vehicles such as electric cars still present a lot of disadvantages that make their comparison with conventional car inevitable. Present batteries' capacity does not offer unlimited driving range, instead they require long recharging times and high initial purchase price agrees that technical issues such as driving range, cost and charging procedure cause uncertainty to potential customers. The main problem is that the initial costs of an electric car are much higher than those of a conventional car while in the long term this is not true. High purchase price, limited driving range, absence of recharging stations and the duration of recharging procedure are important deterring factors in the purchase of electric cars. On the one hand electric cars deprive time and money (as it is perceived at first), on the other hand they offer inexpensive fuel, electric motors with bigger lifecycle than the internal combustion engine of the conventional cars and cheaper maintenance costs [1, 2].

The model of an electric vehicle is very complex as it contains many different components, e.g., transmission, electric machine, power electronics, and battery. Each component needs to be modeled properly in order prevent wrong conclusions. The design or rating of each component is a difficult task as the parameters of one component affect the power level of another one. There is therefore a risk that one component is rated inappropriate which might make the vehicle unnecessary expensive or inefficient. In this thesis a method for designing the power system of an electric vehicle is presented. The focus in this thesis will be on the modeling and designing of the power system of a battery electric vehicle. Less attention will therefore be put on the selection of each component (electric machines, power electronics, batteries, etc.) of the power system as this is a very big task in itself. This thesis will therefore concentrate on the methodology of the modeling and design process. However, the method presented here is also suitable for other architectures and choice of components.

1.2 Statement of the problem

Battery electric vehicles (BEVs) do not consume fuels or produce tailpipe carbon emissions, silent technology and better efficiency than ICE vehicles. Battery electric vehicles (BEVs) are clean and efficient way of using energy in comparison with internal combustion engines. Therefore, there is a great potential of saving energy and reduce emissions when the BEV is being introduced on a large scale. However todays BEV challenges are battery-related issues; the high initial cost, limited driving range, and long charging time. The efficiency as well as the emissions of the BEV already have been subject of research and numerous can be found in literature. The development of battery technology and the future costs of advanced batteries are uncertain but are utmost important for the success of the BEV. The battery technology is considered to be the most critical factor in the commercialization of the BEV. The battery technology has made considerable progress since then as a result of the success of the mobile phone and notebook technology. The improvement of the technology is still going on but the battery price, range and charging time remains a big obstacle. Therefore in order to solve those problems, to estimate the energy consumption of the battery and performance of the power train components, developing a proper model was important for the commercialization of the BEV. Understanding the limits of the actual BEV power train components now allow us to correctly model and to simulate the real world driving environment. The computer models and simulations can be run for multiple variations of the key parameters that may affect the system performance, and then it will be satisfactory to determine the optimum operating points without building multiple prototypes, and running actual field tests, which can be time consuming and costly.

1.3 Objective of Study

1.3.1 General Objective

The general objective of this thesis is to design the dynamics of battery electric vehicle (BEV), model and simulate the power train components in MATLAB (Simscape) environment and to simulate electric motor performance using C++ software which helps to have a propel model as well as to know and discuss the electric motor performance of the vehicle.

1.3.2 Specific Objectives

The specific objectives are:

- To model BEVs power train components; DC Source (Battery), Traction Motor, Transmission and Vehicle body using MATLAB with Simscape software.
- To study BEV dynamics and simulate the performance of the vehicle using C++ and MATLAB/Simscape software.
- To select which batteries, traction motors, and controllers suitable for battery electric vehicles, have the potential to compete with internal combustion engine fuels considering the battery lifetime, specific energy, specific power and costs.
- To test the functionality of the modeled system and compare the effectiveness with the theoretical driving cycle using MATLAB/Simscape.

1.4 Significance of the thesis

Due to increasing market of EVs in transportation sector around the globe, the motivation to use EVs is necessary to reduce air pollution released from ICE particularly in Ethiopia is the potential solutions and the foundation of this study.

The purpose of this thesis is to model and simulate powertrain components and to design vehicle dynamics of BEV and quantify the relation between vehicle performance, component selection, and energy consumption, while accounting for a large number of drive cycles as well as vehicles designed based on an extensive number of existing BEVs. Moreover, a target was to use a clean and renewable energy source vehicle that have high performance using and producing as much as possible in an adequate way, which brought a preferable vehicle in the transport industry of Ethiopia. The significance of the proposed thesis work is the following

- Reducing greenhouse gas (GHG) emissions.
- Improving acceleration because the electric motor allows the vehicle to accelerate immediately from an idle position without the need to wait for the engine.
- BEV features can improve safety because EVs tend to have a lower center of gravity that makes them less likely to roll over.
- Maintenance cost is low because it has less moving parts than a conventional car.

1.5 Beneficiaries

Automotive industries, researchers, teacher’s society and country as a whole get benefitted with this work.

1.6 Delimitation (Scope)

The development of electric vehicles has become a large discipline over the course of time. Due to both time constrains and the necessity to conduct an in-depth analysis, the scope of this research is limited by the following criteria:

- In this thesis, it is considered only battery electric vehicle (BEV). Hybrid electric vehicle (HEV), Plug in Hybrid electric vehicle (PHV) and Fuel cell vehicle (FCV) are excluded, because it mainly needs another study.
- The research is limited to passenger cars (light vehicles) and exclude trucks, busses, etc.
- Modeling of Battery, Controller, Traction Motor and Vehicle Body has been conducted, however, designing of these component itself needs another research which was a difficult task as the parameters of one component affect the power level of another one and it is not included in this work.

1.7 Organization of the thesis

The thesis is organized in to five chapters. The first chapter is an introduction to the study. It includes, statement of the problem, objectives, significance, scope, objectives and organization of the thesis. The second chapter focuses on different kinds of literature that emphasize on previous investigation, deals literature survey on the electric vehicle (EV) design, modeling, principles, types electric vehicles (EVs) and components with the objective of revealing contributions, weaknesses and gaps. Chapter Three describes about materials and methods that I have used during Battery electric vehicle (BEV) design, modeling and simulation. Fourth chapter presented Result and discussion, Deals the Conceptual design, analysis, result and discussion of the proposed work. The final chapter consists Summary, Conclusion, Recommendation and Future works.

CHAPTER TWO

LITERATURE REVIEW

2.1 Previous research arts

A novel propulsion system design scheme for BEVs requiring high power density was developed. The theory analysis mathematical models of BEV are first set up based on the vehicle dynamic characteristics, then the whole system is divided into seven function blocks according to power flow, the simulation models are formed in the MATLAB language. The simulation results are verified in an AC-AC converter, which shows that the suggested method is suitable for EV but a drive cycle test is not considered [10].

A design methodology for BEV and HEV propulsion systems based on the vehicle dynamics was presented. This methodology is aimed at finding the optimal torque-speed profile for the electric powertrain. The study reveals that the extended constant power operation is important for both the initial acceleration and cruising intervals of operation. The more the motor can operate in constant power, the less the acceleration power requirement will be. Several types of motors are studied in this context. It is concluded that the induction motor has clear advantages for the EV and HEV at the present. A brushless dc motor must be capable of high speeds to be competitive with the induction motor. However, more design and evaluation data is needed to verify this possibility [11].

The first step toward an assessment by estimating the impact of battery second use on the initial cost of PHEV/BEV batteries to automotive consumers and exploring the potential for grid-based energy storage applications to serve as a market for used PHEV/BEV batteries was studied. It was found that although battery second use is not expected to significantly affect today's PHEV/BEV prices, it has the potential to become a common component of future automotive battery life cycles and potentially to transform markets in need of cost-effective energy storage. Based on these findings, the author's advice further investigation focused on forecasting long-term battery degradation and analyzing second-use applications in more detail but this study did not study the limitation of the battery [12].

The importance of vehicle simulations in designing the hybrid electric vehicles was studied. A series hybrid electric vehicle simulation with the simulation language Modelica was developed. They explained the simulation approach and they concluded with some of the simulation results emphasizing the simulation importance but not conducted on BEV [6].

A powertrain dynamic simulation model of an integrated starter/generator (ISG) hybrid electric vehicle (HEV) was established using Simulink. The parallel electric assist control strategy (PEACS) was researched and designed. The analysis of dynamics performance and fuel economy of the model was carried out under the FTP drive cycle, which can provide a design reference for the setup of the powertrain test bench. The results show that the fuel consumption can be effectively reduced by using the designed PEACS with the state-of-charge of the battery maintaining in a certain scope but not simulated vehicle body and dynamics [7].

A mathematical modelling, analysis and simulation of a novel hybrid powertrain used in a scooter was described. The primary feature of the proposed hybrid powertrain is the use of a split power-system that consists of a one-degree-of-freedom (dof) planetary gear-train (PGT) and a two-dof PGT to combine the power of two sources, a gasoline engine and an electric motor. Detailed component level models for the hybrid electric scooter are established using the Matlab/Simulink environment. The performance of the proposed hybrid powertrain is studied using the developed model under four driving cycles. The simulation results verify the operational capabilities of the proposed hybrid system only [8].

Plug-in hybrid electric vehicle technology holds much promise for reducing the demand for petroleum in the transportation sector. Its potential impact is highly dependent on the system design and the energy storage system. They discussed on the design options including power, energy and operating strategy as they relate to the energy storage system. They studied the design options including power, energy, and operating strategy as they relate to the energy storage system. Expansion of the usable state-of-charge window will dramatically reduce cost but it will be limited by battery life requirements. Increasing the battery power capability will provides the ability to run all-electrically more often but it will increase the cost. Increasing the energy capacity from 20-40 miles of electric range capability provides an extra 15% reduction in fuel consumption but also nearly doubles the incremental cost [9].

The evaluation of driving power and energy requirements for automotive vehicle was provided. A survey of most promising applications of electric and hybrid vehicles in cities with commercial line solutions was given. Evaluation of vehicle's energy, when is referred to urban driving cycles, reflects an important diversification of the average and maximal power requirements. Simulation results of a small car equipped with advanced fuel cell converter and super capacitor storage bank have indicated the power flow between these sources at normalized urban driving conditions but theoretical driving cycle test is not performed [13].

2.2 Historical overview of electric vehicles (EVs)

The first EV was built by Frenchman Gustave Trouvé in 1881. It was a tricycle powered by a 0.1 hp DC motor fed by lead-acid batteries [74].

In the 1890s ten times more EVs were sold than gasoline cars and the EVs dominated roads and dealer showrooms and remained more popular until mid-1910s. Some well-known car manufacturers like Studebaker and Oldsmobile actually started out as successful EV companies before switching to combustion engine vehicles [16].

The power given to the vehicle to operate was sourced by a rechargeable lead battery. While around 4000 automobiles were produced in the United States in 1900, 38 % of them were electric which proves that the electric car trend was at its prime during this period. Electric cars had experienced their "golden age" in the 1920s. This period was characterized by a lot of technological developments and improvements like networks of charging stations [14].

EVs, like other vehicles, were at that time much of a novelty item and almost exclusively used in urban areas as electricity was available there. The reason for the early popularity of EVs was due to them being quieter and less dangerous as well as being easier to drive than the combustion engine driven cars. One of bestselling EVs at that time was the Columbia Runabout which could go as fast as 15 mph and as far as 40 miles on a single charge. The peak production for early EVs was in 1912 when 34,000 cars were registered [15].

After a while though, the innovative battery technology was put off because oil became cheaper and more than sufficient. In this way electric vehicle lost ground due to the competitive conventional vehicles.

EVs were a common sight until the mid-1910s until the combination of cheap oil and the non-electrification of rural areas assured the victory of combustion engine vehicles over EVs. Other reasons include the fact that volume production of combustion engine vehicles was achieved in 1910 with the motorized assembly line and the addition of an electric motor to combustion engine cars which removed the need for dangerous and difficult crank to start the engine. Due to these factors the manufacturing of the early EVs had stopped by the end of World War I [15].

In the 60s though, electric technology gained interest again since semiconductors were invented and various changes in motors and controllers were introduced [1]. The increased popularity of electric vehicles in that period is also attributed to the fact that the first regulation regarding the environment was introduced.

The Air Quality Act of 1967 toward vehicle emissions that was applied in the United States, in combination with the oil crises in 70s and 80s helped the development of electric vehicles to move further. Determining factor though in the investment of electric vehicles was a strict command from the California Air Resources Board, which demanded that all manufacturers should sell a big amount of zero emissions vehicle. The defined percentage of zero emissions vehicle began at 2% in 1998, increased to 5% in 2001 and was doubled by 2003 [1].

In the 90s some legislative and regulatory actions renewed EV development, most notably the zero emission vehicles (ZEV) program that was enacted by the Californian government to promote the use of ZEVs by requiring carmakers to make 10% of the cars they produce by 2003 ZEVs. In response to this the car manufacturers soon developed and released EV models. The ZEV program was eventually removed resulting in almost all EV models being withdrawn from the market. In most cases the withdrawn cars were destroyed which proved a highly controversial decision [15].

When the Zero Emission Act was dismissed, partial zero emissions cars started being of more preference and this is when Toyota developed hybrid cars (Toyota Prius) which have both electric and combustion engines. The increasing popularity of hybrid cars led to a parallel increasing interest in the electric cars in general. Adjacent to the hybrid cars, 100% electric cars are powered exclusively by an electric motor. Another peculiarity of the 100% electric car compared to the hybrid is the car size. On the one hand battery size must grow so as to offer bigger capacity and consequently longer range but this affects the total weight of the car. In the future electric cars are planned to be mainly small or medium-size cars. The sizes are defined this way because the weight restricts the range of operation and also because bigger cars require bigger batteries which increases the cost of the battery and at the end the initial purchase price of the electric car [17].

In the late 90s a technology very closely related to the battery EVs was introduced to the market, the hybrid. Hybrids are cars which mainly run on gasoline or diesel but are equipped with a battery that allows recapture of energy released by breaking and shutdown of the combustion engine when driving under certain speed, resulting in a one third reduction in fuel consumption. Toyota announced the Prius in 1997 which has proved a huge market success. The first hybrid to enter the U.S. market was Honda‘s Insight in 1999. Only a month after that Toyota entered the U.S. market with an upgraded version of the Prius. The Prius was in the beginning considered as an experiment with only 5% chance of succeeding. Although sales were slow in the beginning they gradually increased and soon it was clear that Toyota´s leadership and perseverance paid off as it was selling very well, and in 2005 it sold 180,000. In 2007 Toyota Prius was the 7th bestselling car in the U.S. Since then many large automakers have released hybrid models as consumers called for cars that could free them from fluctuations in fuel price. Many carmakers have scheduled releases of plug-in hybrid electric vehicles (PHEV). Plug in hybrids have smaller combustion engine but larger battery packs and electric motors and can be plugged to the electronic grid for most of their energy. Many see the hybrids and especially PHEV as a stepping stone towards full electric vehicles [18].

Tesla Motors is rightfully considered to be one of the leaders in production of electric automobiles, as evidenced by the report data for the first half of 2015, published by the Internet community of EV Sales. The company ranks second in the number of sold electric cars (21.6 thousand hatchbacks of Model S), being ahead of the world leader Nissan (25,000 Nissan Leaf) in sales in the USA [19].

In 2003 Tesla Motors Company was established by Martin Eberhard, Marc Tarpenning, JeffreyB. Straubel and Ian Wright [20]. In the first major sale of shares a successful businessman Elon Musk joined it as a Chairman of the Board in February 2004. Elon Musk wanted to demonstrate to the whole world that beautiful, dynamic electric vehicles with a large range on one battery charge are not a fiction. The presentation of high-class electric vehicle (fashionable, stylish and cutting edge kitsch) was necessary for the rapid development from zero level and entry to the world consumer market. Therefore, the first model has become a two-seater electric sports car Tesla Roadster, introduced in August 2006, which design was borrowed from another, more famous model Lotus Elise. However, all the components were developed by the company staff with Elon Musk taking part in designing of each element [21].

To start up mass production of Tesla Roadster initially scheduled for September 2007, Tesla Motors had been continuously looking for new investors, including Compass Technology Partners, SDL Ventures, Valor Equity Partners, cofounders of Google Sergey Brin and Larry Page, the former president of eBay, Jeffrey Skoll and others. The amount of investment in Tesla Motors by 2007 has exceeded $ 105 million, and by the time the first production version left the assembly line in 2008, has reached $ 140 million (instead of the planned $ 25 million). In early August 2009, the company announced the overall profitability for the month of July and making a profit of 1 million dollars, and 4 years later in May 2013 the company was the first and the only one of the automobile companies to repay a loan of 465 million dollars, obtained from the US Department of Energy [20, 21].

Currently, the vehicle line of the electric car manufacturer consists of three different not only in their appearance, but by function and purpose cars: sport car Tesla Roadster, hatchback Tesla Model S and crossover Tesla Model X. By the technical characteristics two versions of a sports car can be distinguished: Tesla Roadster (2008) and Tesla Roadster Sport (2009). The electric vehicle is driven by three-phase four-pole electric motor. Thrust is transmitted to the wheels of the rear axle via a single-stage transmission developed by BorgWarner Company. Upgrading concerned the engine, increasing the torque and acceleration time of 0.2 s. In the passenger compartment of Tesla Roadster Sport the aluminum gearbox lever gave way to key operated mechanism; the color touch screen appeared on the center console, and high-quality leather and carbon fiber insertions were used in the interior trim [22].

Tesla Roadster model release was completed in 2012, but already in late 2014 the manufacturer issued an update package, which received the designation 3.0. It encompassed: increased range up to 640 kilometers through installation of battery packs with new cells, capable of storing 31% more power than preceding counterparts; an aerodynamic body kit, providing a reduction in aerodynamic drag from 0.36 to 0.3; tires with reduced rolling resistance. At the same time, in spite of the increased capacity, the size of the battery pack (its capacity is 70 kW·h) remained unchanged [22-24].

The second model of the Tesla Motors electric car was the Tesla Model S, presented by company in 2009 and subsequently recognized (according to the «Motor Trend» magazine, the USA) as the "Car of the Year 2013". In the USA, the first deliveries of Tesla Model S were launched in June 2012, in Europe - in August 2013 and in 2014 they started to be supplied to China. On September 29, 2015 in California, the official presentation of the family crossover Tesla Model X took place [20, 21].

2.3 The Benefits from electric vehicle (EV) Utilization

Electric vehicles have number of advantages over the dominating internal combustion engine vehicles. The following section explores these benefits. The challenges of EVs will be described later in the section.

2.3.1 Lower Energy Consumption

It is debated whether a switch to EVs from conventional cars (CVs) would reduce energy consumption from the worlds transport sectors. If one considers only the vehicle itself EVs are far more energy efficient than CVs. For the Tesla Roadster 86% of the electricity used to charge the battery is used to power the cars motor, thus giving the car itself 86% energy efficiency [25]. Most CVs however convert only about 20% of the energy in gasoline into engine energy. But that does not tell the whole story as in order to determine the system-wide energy efficiency the primary source of the energy must be taken into consideration. The loss of energy from generating electricity from a primary source of energy (such as hydroelectric plant or a coal plant) and transporting it to an electrical outlet is much greater than the energy loss from extracting, refining and delivering petroleum fuel to a car. If the electricity is generated by a combined cycle natural gas-fired power plant the electricity generating efficiency can be as high as 60% [26] and hydroelectric production reaches generating efficiency as high as 90%. Natural gas recovery and processing are both 97.5% efficient and the transport of electricity over the grid is 92% on average [25] giving a 52.2% well-to-outlet efficiency. Charging a Tesla Roadster with electricity generated by a “top of the line” combined cycle power plant would result in a

45% well-to-wheel efficiency. It must still be noted that the EV technology is nowhere as developed as the CV technology and the efficiency could well increase with further research and development.

In addition to higher efficiency, if it is possible to charge EVs during off-peak periods, it could help load-balance the electric grid. Otherwise, the generator would just sit idle and waste excess. Furthermore, in some areas, there is no need to build more power plants to supply the electricity for EVs. In the U.S. the existing electricity infrastructure can comfortably charge tens of millions of plug-in hybrids without additional generating resources [27].

2.3.2 Reducing Oil Dependence

For many nations the key promises of EVs and PHEV, from a policy point of view, is the potential to reduce dependency on foreign oil. The economies of many nations depend heavily on oil which creates both economic and energy security problems. In the U.S. 40% of energy comes from petroleum and daily consumption of oil is 20.8 million barrels of which 40% goes to automobiles. The situation is similar for many countries. As oil and fossil fuels are scarce energy resources and with increasing consumption these resources will eventually run out. Until then the prices are likely to rise steadily with oil purchasing taking a larger piece of the cake for economies around the world. As well as having negative economic effects this situation is a source for political tension. Electrification of transport would help reduce this dependency and the negative effects that follow. In many countries the only sector relying on oil is the transport sector and although ocean and air transport solutions are not around the corner, the electrification of road transport is a promising possibility [15].

2.3.3 Environmental Impacts

The increasing use of EV would have significant positive impact on the environment because of the reduction of overall energy consumption and air pollution. Study performed in the U.S. For the nation as a whole, the total GHG (greenhouse gases) are expected to be reduced by maximum of 27% from the projected penetration of PHEV [28]. Besides, total volatile organic compounds (VOC) and carbon monoxide (CO) emission would improve by 93% and 98%, respectively and the total NOx emissions are reduced by 31% due to the elimination of the use of internal combustion engines [28]. However, electricity resource and the efficiency along the electricity generation path is the key issue in this case. A number of studies have been done on the impact of using EVs powered by electricity generated by coal power plants. A literature review of the subject (well to wheels emissions comparisons) and compared different studies was done [29]. The results of the studies ranged from 0%-59% less GHG emissions compared with ICE vehicles (two studies found 0% change; seven found 17% - 59% change [29]. So even if EVs were to be powered by electricity generated using coal the emissions of GHG would still be lower although the degree of change varies with different studies.

Conversely, the use of EVs could bring few slight negative impacts to environment, such as increasing amount of waste batteries, and increasing of energy demand for extracting lithium and production battery. Fortunately, the most promising lithium ion battery is more environmentally friendly than lead-acid, and Nickel–cadmium [31]. One can not only think about the emissions from the vehicle itself as obviously there are many polluting steps in the lifecycle of each vehicle. The lithium battery offers the main difference between EVs and other vehicles. A detailed lifecycle inventory of a Li-ion battery and produced a rough lifecycle analysis (LCA) of electric vehicles was Compiled [30]. The main finding of that study was that the impact of a Li-ion battery used in EVs for transport is relatively small. It showed that the negative environmental effect of mobility is dominated by the operation phase regardless of whether an internal combustion engine vehicle (ICEV) or an EV is used. When an EV was compared to an ICEV, the use of an EV in transport results in lower environmental burdens. The share of total environmental impact of EVs caused by the battery is 15%. The impact of lithium extraction for the battery is less than 2.3% while the highest burden related to the battery was the supply of copper and aluminum for anode and cathode production and cables required for the battery management system [30].

Apart from the before mentioned benefits of EVs on social level, using EVs has many upsides for users. Most regard home plugging a comfortable experience and some prefer it to the fueling of gasoline cars and most people enjoy driving EVs because of the high acceleration at low speeds due to the high torque of the motor [32]. Other positive aspects for users include low noise levels and lower repair requirement than CVs.

2.4 Challenges to the development of the electric vehicle (EV)

EVs have many advantages over conventional vehicles. But, why have EVs not become widespread around the world to date? Obviously, there are some challenges to overcome.

2.4.1 Range

Despite the fact that researches have shown that the limited range of electric cars is enough to satisfy the needs of a considerable amount of people, many car buyers still tend to choose cars with higher possible range [33].

If manufacturers want to achieve higher available range then they have to increase the capacity of this range which in turn brings higher purchase price and loses the advantage of being affordable and cost-effective compared to the conventional cars [33].

Three new decision factors regarding the limited range was came up [34]. The first one is the "safety buffer" which refers to peoples' need to leave at least 20 miles of range on the vehicle at all times. The second one relates to the "routine activity space" which consists of the places of the activities the families reach on everyday basis such as commuting to work. The last factor is called "critical destination" and refers to the furthest reachable distance someone driving the electric car expects to be available in case of an emergency or for main activities related to their lifestyle.

A majority of people has still a little knowledge and understanding towards the electric cars. Their lack of understanding leads to the creation of false perceived inadequacies such as the reduced range [35]. A lot of people are not willing to buy an electric car because they are afraid that the available range will not be enough and it will be incapable of satisfying their needs. In line with [35] are the findings of [36] who argue that the driving range is one of the most important factors that influence the consumer's behavior. To emphasize the importance of a sufficient range of the electric cars, a UK survey showed that 70% of 500 consumers were afraid that the charge of the electric car would finish faster than expected and they would not be able to reach their destination. This perception makes them choose conventional cars over electric so as to enjoy the security and convenience the first offer [37].

Conventional cars have a range of 500-600 km while the range of electric cars is 150-200km and in order to fully charge may take more than an hour compared to gasoline. In order to test if the limited range of an electric car affects the individual mobility, the authors compare the relative frequency of directions of a specific length. The study shows that the trajectories for 99% of the electric cars and for 90% of the conventional cars are less than 50km. Since these trajectories are comparable, the limited range of electric cars does not seem to be a substantial problem. This result though does not prove that electric cars can satisfy all the demands of users. An argument is that an electric car can fully satisfy your requirements if you can commute to and from work without recharging during the day. The authors compared the everyday total distance driven for electric and conventional cars. The results showed that only a small percentage of the respondents would be able to cover the everyday total distance days with an electric car, since the rest of the respondents had to cover longer total distances than the electric car can cover without recharging. Consumers' insecurity regarding the limited range constitutes an important obstacle in their decision to buy an electric car [38].

2.4.2 Recharge and Recharging Times

There are a lot of different types of batteries for different electric cars and a variety of recharging outlets with varied costs depending on the location, time and the size of electrical service. In houses, where the lifestyle requires only the available distance that an electric car can offer, there is no need for extra recharging station facilities since the home recharging is enough [34].

The concern of users regarding the available range is linked also to the high recharging times. According to [2] the duration of recharging a battery of an electric car with standard outlets may take 8 to 16 hours and the fact that there are not so many available recharging stations make things more complicated. On the contrary the abundance of gas service stations and the extremely fast refueling time gives a competitive advantage to the conventional cars. Nevertheless [34] found out in their study that charging times might be an obstacle but not as important as the range. The households tested in their research were more vulnerable to the available range than the recharging time. Most of them would rather solve the problem of optimal range rather than decreasing charging time.

The difference between conventional and electric cars is how energy is stored in order for the vehicle to operate and the actions required transmitting power to the vehicle. Electric cars use electrical energy to operate and this energy is stored in batteries while a conventional car uses liquid fuel which is stored in a compact fuel tank. When you want to power an internal combustion engine (conventional car) you just have to visit a petrol station and in few minutes its full but electric cars have to be plugged in to external electricity supply. Electric cars' charging procedure takes more time than refueling a conventional car but the benefit it offers is that it can be recharged overnight at home and the cost of this consumed energy is included in the domestic electric supply. The operating costs of electric cars are cheaper for a standard range of 100 miles compared to petrol or diesel that will cover the same distance [37].

2.4.3 Costs (purchase and maintenance)

Critics claim that battery electric cars (BEV) can be very costly and they need subsidies or other kinds of promotion in order to be more attractive to clients. Various studies have shown that that BEVs appear to cost much more than conventional cars in the short-term, but according to other studies BEVs' costs can reach comparable levels of costs with the conventional cars very fast. Future predictions suggest that BEVs' purchase costs and lifecycle costs will exceed those of conventional cars [39].

Electric cars present low operating costs compared to conventional cars because the price of electricity is usually lower than petrol's price (although this is not always the case , since the price of petrol is not stable). Maintaining an electric car is also cheaper than maintaining a conventional car but the initial purchase cost of the first needs at least 10 years to balance with the initial and ownership cost of a conventional car [40].

Although the basic EV (excluding battery) is probably slightly cheaper than the CV, battery pack would add much cost to EV at this moment. According to the California Air Resources Board Expert Panel the cost of lithium ion battery ranges from $340 to $420 per kWh (500MWh/year production rate) and $240-280/kWh (2500MWh/year) based on different production amounts [41].

2.4.4 Battery limitation

Due to breakthrough in material science, lithium batteries have made great progress since the 90s. The energy specificity and power specificity (100-150Wh/kg; 2000-4000 W/kg) of Li-ion batteries could satisfy the requirement of EVs [41]. Due to the more stable crystal structure, the lithium-ion battery has longer cycle life. The Freedom CAR program estimated lithium-ion calendar life at 10 years, while several commercially available batteries achieve > 1000 cycles for deep discharge (BEV) profiles and 150,000 cycles for shallow-cycle (HEV) operation [42].

However, the test data derived from laboratories are unproven under real world circumstances. The temperature, humidity, and various discharging situations would affect the capacity and performance of the battery. Another critical issue is battery safety. Concerns about Li-Ion battery safety can be limited based on the tolerance of cells and batteries to “abuse”, either electrochemical (shorting, high rate and extensive overcharging), thermal (heating to temperatures above the cell tolerance limit) and/or mechanical (destruction of physical integrity). The degree of tolerance to various abuses is serving as a relative measurement of safety as well as a guide to the development of adequately safe Li Ion cells and batteries [43].

2.4.5 Electric vehicles (EVs) infrastructure

It is clear that sufficient EV infrastructure is required to make charging battery become as convenient as possible for everyone and everywhere. According to a recent research report, the average infrastructure installation cost is from $4,000 per charger) to $6,300 (commercial charger) including (charger, installation labor, permits, tax) [44]. This is clearly a very large investment and nobody knows if or when they will start to get profit.

2.5 Electric vehicle (EV) Powertrains

As it has been already pointed out, the necessity of introduction of alternative electric vehicles derives from the lack of fuel resources, from the greenhouse gas emissions that keep rising and the noise pollution. The reasons for the implementation of alternative fuel vehicles are mainly environmental concerned and this emphasizes the importance of this implementation.

Until now the most common alternative fuel cars are the electric vehicles. Electric vehicles is the general category of these alternative fuel vehicles and the sub-categories are battery electric vehicles (BEVs) or else called pure-electric vehicles that operate on electric power, hybrid electric vehicles (HEV) that have both internal combustion engine (ICE) and electric battery and hydrogen fuel cell electric vehicle (FCEV).

2.5.1 Hybrid Electric Vehicles (HEV)

Conventional Hybrids, that have both a gasoline engine and electric motor cannot be plugged in and recharged. Their batteries are recharged when braking while kinetic energy is converted into electricity.

2.5.2 Plug in Hybrid Electric Vehicles (PHEV)

Plug in-hybrid electric vehicles differ from conventional hybrids in that they can be plugged into an outlet to recharge the battery. The superiority of plug-in hybrid electric vehicles compared to the conventional hybrids is that they can substitute electricity from the grid for gasoline. For instance, the 2014 Chevy Volt can drive 38 miles before the gasoline motor starts working.

2.5.3 Fuel Cell Electric Vehicles (FCEV)

Fuel cell electric vehicles (FCEVs) have only an electric motor like a BEV but the way energy is stored differs. FCEVs do not recharge battery but they store hydrogen gas in a tank. The combination of hydrogen and oxygen from the air produces electricity in the fuel cell which in turn powers the electric motor which powers the whole vehicle at the end. Like BEVs there is no production of tailpipe since the only byproduct is water. The biggest pron of this type of vehicle is that since they do not need recharging, the refilling with hydrogen lasts around 5 minutes at a filling station.

2.5.4 Battery Electric Vehicles (BEVs)

Pure-electric vehicles operate solely with electric power via on-board batteries that are charged when plugged into an outlet or charging station. The battery can be charged either when plugged in the electric grid via a charging device or during braking through recuperation (regenerative braking) [17]. Examples of pure-electric cars are the Nissan Leaf, Fiat 500e and Tesla Model S. These models have achieved longer driving ranges in comparison with PHEVs and produce zero gas emissions. The fact that pure EVs do not have a gear box it makes users feel they drive an automatic car. The BEVs at the present offer a range of up to 80 miles per charge with the exception of Tesla which can offer 200 miles driving distance on a single charge. Battery technology though improves all the time and at some point BEVs will be able to offer a wider range and attract more customers. A typical BEV drive system, which is also the type of system studied in this theses, is depicted in Figure 2.1 below.

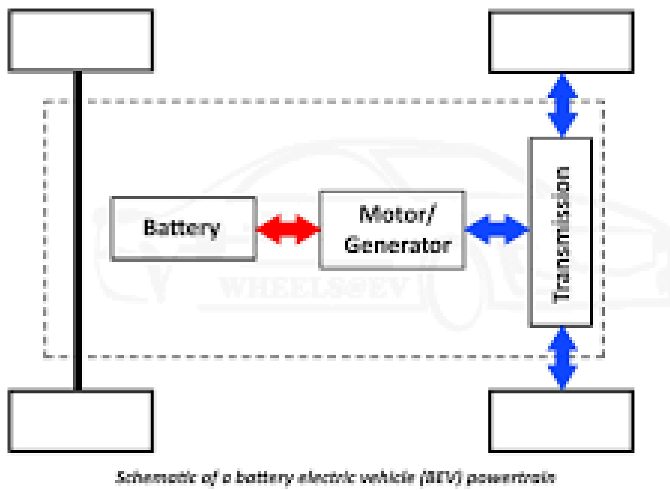

Figure 2.1. BEV drive system [17]

Within the following the term ‘electric vehicle’ is used to describe full battery electric vehicles. Relevant aspects of BEVs are presented in the following sub-section. First the components and basic functioning of BEVs are described. Then, the composition of the energy consumption of BEVs are explained.

The basic version of an electric drivetrain consists of the battery, an inverter (power electronics), controllers and the electric motor. The battery provides a direct current which is passed on to the inverter. The inverter turns the direct current into an alternating current and provides it to the electric motor. Then the electric motor turns the electric energy into mechanical energy (i.e. into a torque with a specific rotational speed). This process can be turned around and the electric motor can serve as an electric brake. The electric motor then works as a generator and turns braking energy into electric energy which is stored in the battery via the inverter. This process is referred to as regenerative braking [45].

For the non-propulsion electrical system a high voltage and a low voltage branch can be distinguished. Heating and cooling auxiliaries are connected to the high-voltage branch. The low voltage branch is supplied by a DC/DC converter. It ensures a sufficient charging of the 12 Voltage battery as well as energy supply for all 12 Voltage auxiliaries like light, radio and navigation [45, 46].

2.6 Electric vehicle (EV) Motors

The ideal characteristic of vehicle's traction motor is constant power output over full speed range, in other words torque varies hyperbolically with speed as shown in Figure 2.2a. Wide constant power characteristics provide high tractive effort at low speeds where it is needed for acceleration, grade ability and drawbar pull [74].

The use of ICE as vehicle's power plant requires a multi-speed transmission because the torque characteristics of ICE are far from ideal described above. With electric motor the case is opposite as can be seen from the Figure 2.2(b). The Figure 2.2(b) presents typical characteristic of electric motor. The motor starts with zero speed and it increases until base speed, where voltage reaches its rated value while flux remains constant. Beyond this point the increase in speed is achieved by keeping the voltage constant but weakening the flux [74]. This constant power zone is also referred as flux-weakening zone [47].

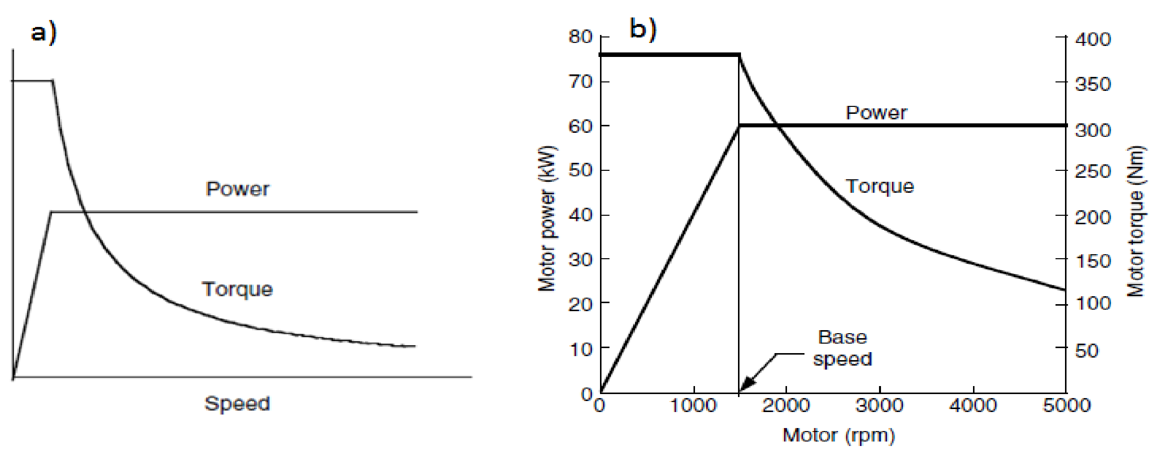

Figure 2.2. Ideal characteristics of traction motor (a) and typical electric motor characteristics (b) [74].

Industrial electric motors are designed to be used in typical operating point. Typical motor can supply continuous torque from zero to rated torque and this variable torque can be delivered at all speeds up till rated speed. These rated conditions can be exceeded but typically with industrial motors the overload torque and maximum speed are only twice the rated value and the maximum operating efficiency is optimized to be achieved at rated conditions. Industrial motors do not provide sufficient characteristics for traction motor use and this is why traction motors are considered as an individual class [48].

One of the important characteristic of variable speed electric motor is a speed ratio. The speed ratio is defined as ratio of motor's maximum speed versus the base speed. Importance of speed ratio, especially with traction motors, is illustrated in Figure 2.3 where 60 kW motor's torque-speed characteristics with different speed ratios are shown.

As it can be seen, the maximum torque, and thus vehicle's acceleration and gradeability, is increased with motor that have long constant power region i.e. high speed ratio. High speed ratio motor also enables the use of single-gear transmission in EV's powertrain making it more simple and robust [74].

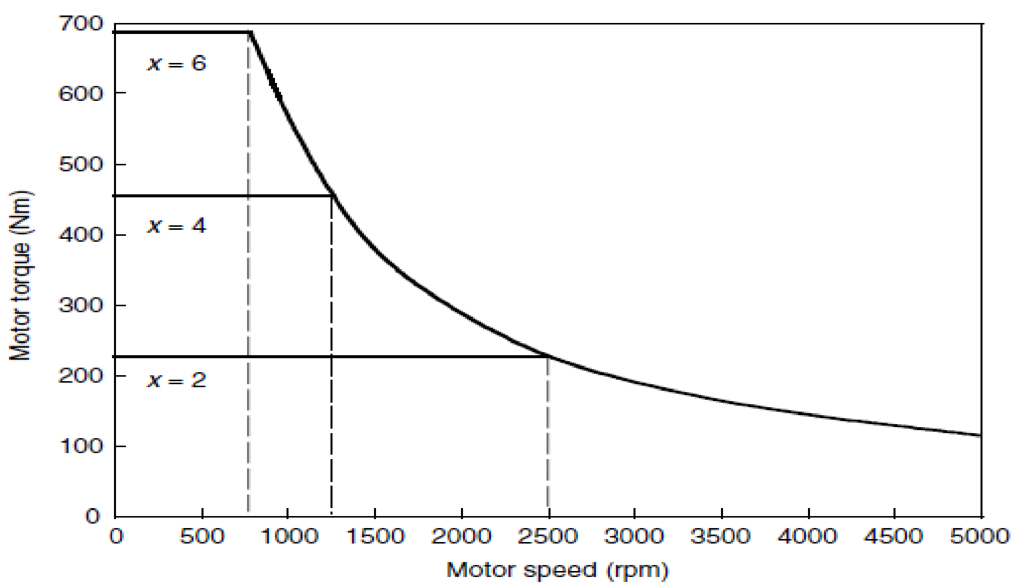

Figure 2.3. The 60 kW electric motor's characteristics with different speed [74].

Electric motors commonly consist of a moving (i.e. rotor) and stationary (i.e. stator) component. They generate movement through the interaction of a magnetic field and conductors which carry current, using the so called Lorentz force [49]. Different types of electric motors exist: direct current (DC) and asynchronous and synchronous alternating current (AC) motors. The names are derived from the required input current.

In addition to above mentioned characteristics electric traction motors should also fulfil some other demands. The use in vehicle application requires good overall efficiency over wide speed range and high power density to reduce total vehicle weight. Vehicular application also means installation in harsh conditions so tolerance against high temperatures, weather and vibrations are required [48].

The overall efficiency over wide speed range is usually expressed in torque-speed plane as show in Figure 2.4 [74]. As earlier stated in this work the driving conditions or driving cycles effect on the operating points of the electric motor. Different electric motor types have different optimal operating points, which means that when single-speed transmission is used, the most efficient speed region cannot be utilized in all driving cycles.

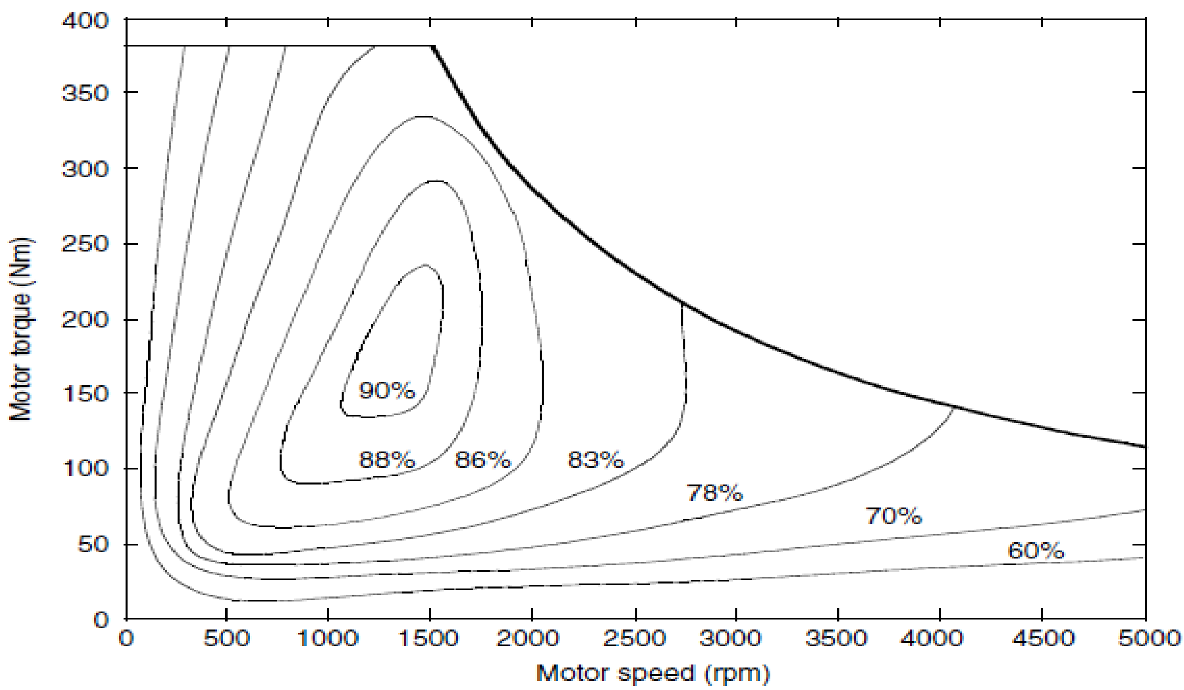

Figure 2.4. Example of electric motor's efficiency map [74].

In DC motors the rotor carries the conductors and rotates in the magnetic field of a permanent magnet (stator). In AC motors the stator creates a rotating magnetic field in which the rotor moves. Due to their constructions, the rotor of synchronous motors moves with the speed of the magnetic field (synchronous), in asynchronous motors the rotor moves slower (asynchronous) [50]. Today’s EVs are usually equipped with AC motors. Asynchronous AC motors are simpler and therefore less expensive than synchronous AC motors.

There are a few possible electric motors that are suitable for a BEV. A distinction can be made between a DC motor and an AC motor. The possible AC and DC motors for EVs are described.

2.6.1 Brushed DC motor

The simplest motor that can be used in automotive applications is the brushed DC motor. This motor is used in all sorts of domestic electric appliances like hairdryers and fans. In Figure 2.5 a two-pole brushed DC motor is shown with one coil. The motor consists of a stator with two permanent magnets and brushes and a rotor (coil) with commutator and windings. The force on the left side is upwards where the force on the right side is downwards, causing the coil to turn clockwise. When the wires of the coil with the commutator are clear of the magnets momentum carries the rotor halfway around until it connect with the brushes again. The commutator is constantly changing the direction of the current to assure that the forces are pushing the coil clockwise.

A real DC motor however is using a rotor with multiple coils and a stator with more than one pair of magnets but the principle remains the same. There are three basic brushed DC motors; a parallel, series and separately excited brushed DC motor. For use in electric vehicles the one that can be used is the separately exited motor. The required torque can be controlled at any angular speed giving the motor great flexibility [51].

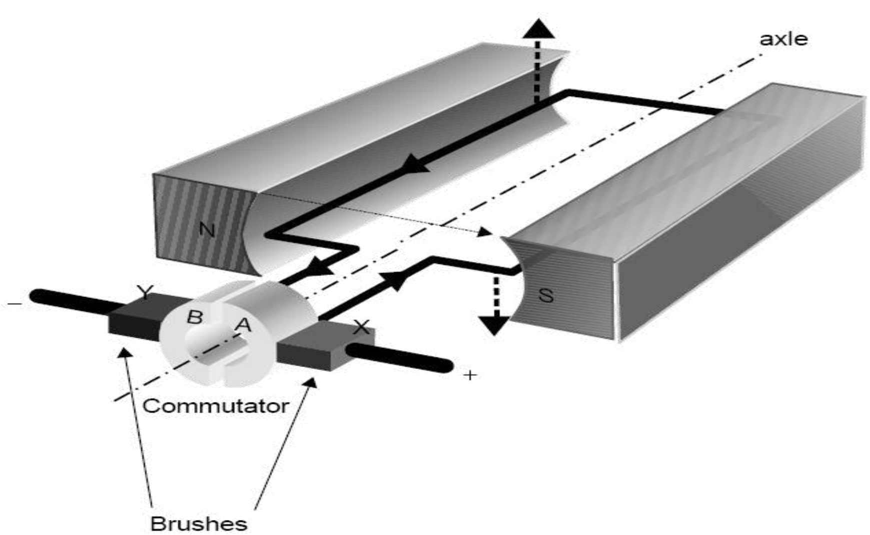

Figure 2.5. The brushed DC motor [51].

2.6.2 Brushless DC motor

A brushless DC (BLDC) motor actually is not a DC but an AC motor. The motor needs an alternating current but must have variable frequency. Therefore the current have to be derived from a DC power supply. The BLDC motor is given different names by manufacturers and users of which the most common are permanent magnet synchronous motor (PM synchronous), self-synchronous AC motor, variable frequency synchronous motor and electronically commutated motor (ECM) [51].

The motor has a three-phase stator with a number of coils and a rotor with surface mounted permanent magnets. The stator and the rotor are reversed compared to the brushed DC motor where the permanent magnet are mounted on the stator see (Figure 2.6).

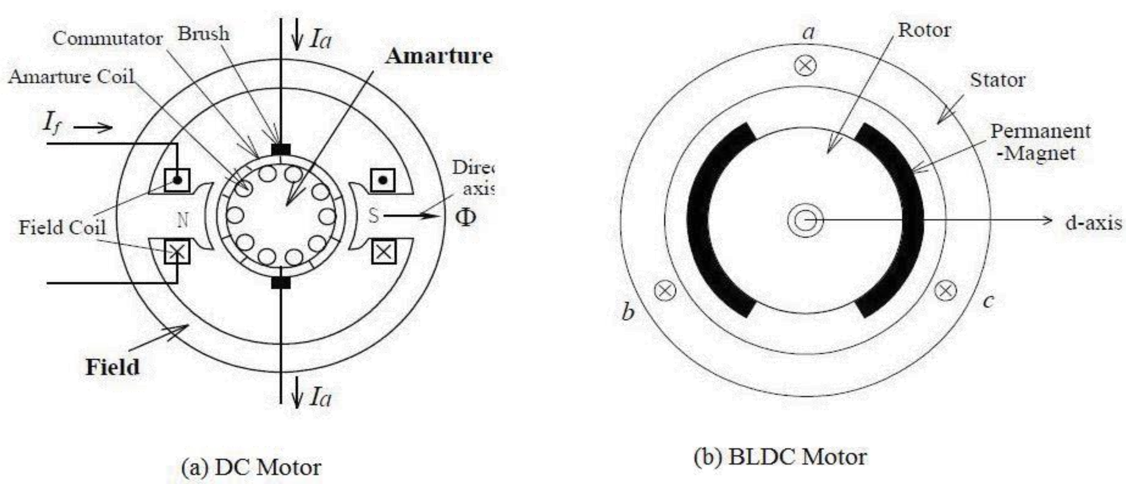

Figure 2.6. The brushed DC motor (left) and the 'Brushless' DC motor (right) [51].

The way a BLDC motor works is that the poles on the stator are alternating, in such a way that the rotor is turning clockwise. The pole on the stator pulls the pole on the rotor clockwise and when the poles are in line with each other the current is switched off. Momentum then carries the rotor further and the current is reversed, changing the magnetic field and the poles in the stator. To make sure the motor keeps on turning sensors are needed to determine the position of the rotor. This is often done using Hall Effect sensors. BLDC motors are very efficient. Torque is high under low speeds and goes down as the speed goes up. A drawback of this type of motor is the price compared to the other possible EV 3 motors. A BLDC motor needs a strong permanent magnet that can influence the total price of the motor.

2.6.3 Permanent magnet synchronous motor

Most car manufacturers rely on PMSM as electric traction motor. This selection is due to their reduced overall volume and weight i.e. high power density. These motors are also more efficient than IMs which makes them an attractive choice as traction motor [74].

In PMSM the rotor permanent magnets (PM) provide the excitation field of the rotor. The stator is essentially similar to induction machines and the applied 3-phase voltage creates rotating magnetic field. As induction machine rotor was dragged by the rotating magnetic field, in the synchronous machines the rotor speed synchronizes with the rotating stator field and thus it is the same as synchronous speed [52].

The torque produced by PMSM is generated with two different components, which are PM torque and reluctance torque. The magnitudes of these components are dependent on the rotor structure and different rotor topologies are presented in the Figure 2.7.

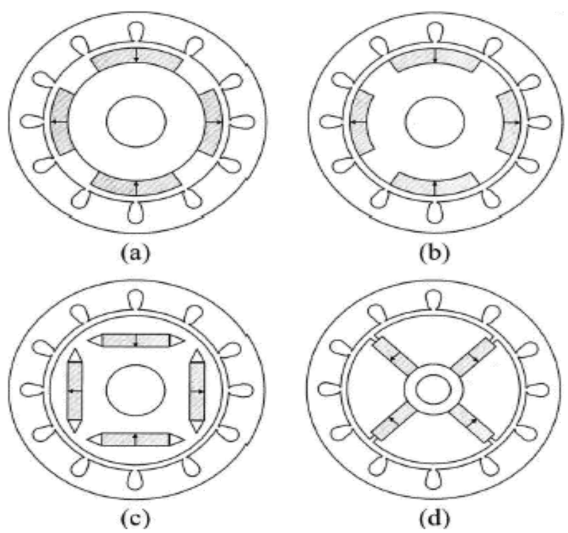

Figure 2.7. PMSM rotor structures: a) Surface mounted. b) Surface inset. c) Interior radial. d) Interior circumferential [48].

Hence controlling PMSM requires control of torque and flux component of the stator current, the PMSM drives are very similar to IM drives. The drive is supplied from voltage source inverter and the currents are controlled via the voltage [52].

2.6.4 Switched reluctance motor

The SR motor is a fairly simply motor with an iron rotor and stator (see Figure 2.8). The stator is magnetized and attracts the rotor. When the rotor is aligned with the stator (magnetic field is symmetrical) the current is switched off and momentum carries the rotor further and the current is switched on again.

The stator and control electronics of a SR motor are similar to those of a BLDC and induction motor. The rotor of a SR motor however is much simpler, making it cheaper and more rugged than the BLDC and induction rotor. The SR motor does not create back EMF because it has no permanent magnets. It therefore can reach higher speeds. Back EMF is the voltage that is generated when an electric motor with permanent magnets is spinning. The speed of a BLDC motor is limited because of this back EMF.

Also the current in the coil of a SR motor does not need to alternate. It needs an advanced control systems and sensors to adjust the speed and make sure the current is switched on and off on time. Another back draw of the motor is that it is known to be a bit noisy. SR motors are not used in commercial EVs and HEVs yet, but because of the good properties and possible low costs of the motor they will become more widespread in the future [51-53].

Figure 2.8. Three-phase Switched Reluctance motor [74].

Two typical constructions of SRM are presented in Figure 2.9. The structure of SRM is doubly-salient, which means that it has projecting poles in rotor and stator as well. The stator consists of laminations and it has no windings or magnets, which makes it simple and easy to manufacture. The stator has coils on each pole and they are grouped to form three phases to be energized independently by 3-phase inverter [52].

As the motor name suggest, the torque is produced with reluctance method. The working principle is same as the behavior of an iron bar in a magnetic field. If the bar is suspended to rotate freely, it will align itself with the field and it will turn if the direction of the field is changed. The rotor of SRM acts like the iron bar and when the stator coils are energized in right sequence it will rotate [52] .

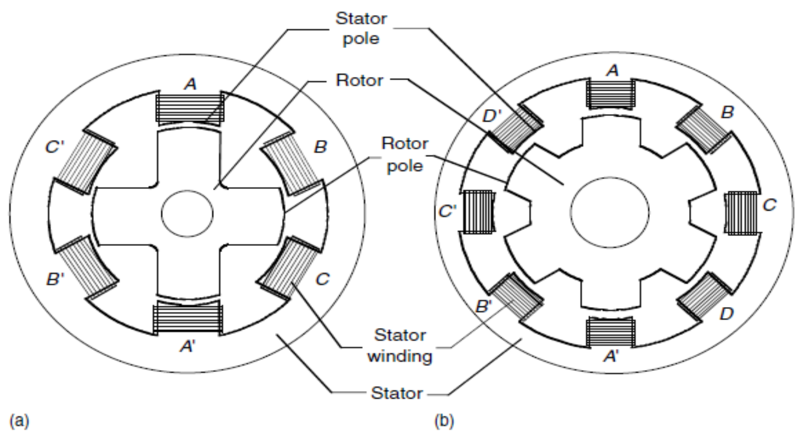

Figure 2.9. SRM motor with configurations 6/4 (a) and 8/6 (b) [74].

As in Figure 2.9, SRM has usually unequal number of poles in rotor and stator. This construction is crucial, because by this way it can be prevented that all the rotor poles are aligned with stator poles and no torque can be produced [54]. The Figure 2.10a motor is operated clockwise by energizing the coil in sequence A-C-B and anticlockwise with sequence A-B-C. The sequential operation causes torque ripple, vibration and noise [47].

2.6.5 AC Induction motor

Instead of using a permanent magnet in the rotor (as in the BLDC motor), it is also possible to induce a current in the rotor to create a temporary magnet. This is done in an AC induction motor.

IMs can be categorized into two types according to their rotor construction: wound-rotor and squirrel-cage motor. Wound-rotor type motor requires maintenance, it has high cost and it suffers lack of sturdiness, thus it is not as attractive for EV propulsion [74].

The rotor type (Figure 2.10) that is most common in an IM is the ‘squirrel cage’ [55]. The rotor consists of a stack of steel laminations with evenly spaced conductor bars around the shaft.

The conductor bars are forming a kind of cage. The conductor bars are electronically linked with end rings.

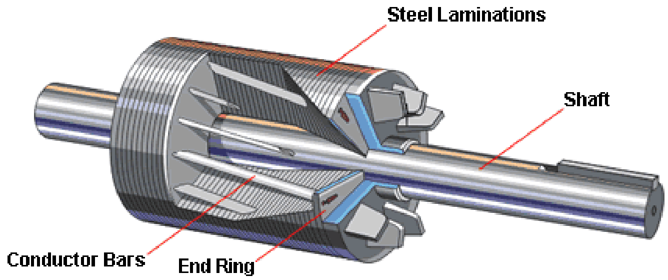

Figure 2.10. Squirrel cage rotor [55]

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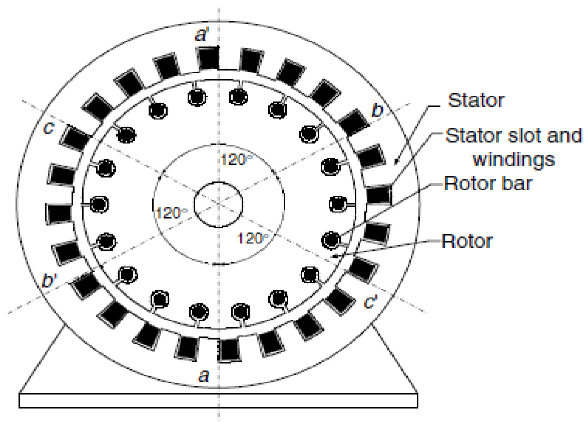

Figure 2.11. Two-pole IM construction [74]

In Figure 2.11, a cross section of IM is shown. IM consist of two parts, rotor and stator. Three phase windings are inserted into slots of stator inner periphery and the turns of each winding are distributed to create approximately sinusoidal flux density to the air gap when current is applied to windings [74]. Rotor core consist of stacked silicon steel laminations. These laminations have evenly spaced slots on the outer periphery in which typically aluminum or copper conductor bars are inserted. These conductor bars are joined together in both ends which gives the name squirrel-cage, Figure 2.12 [52].

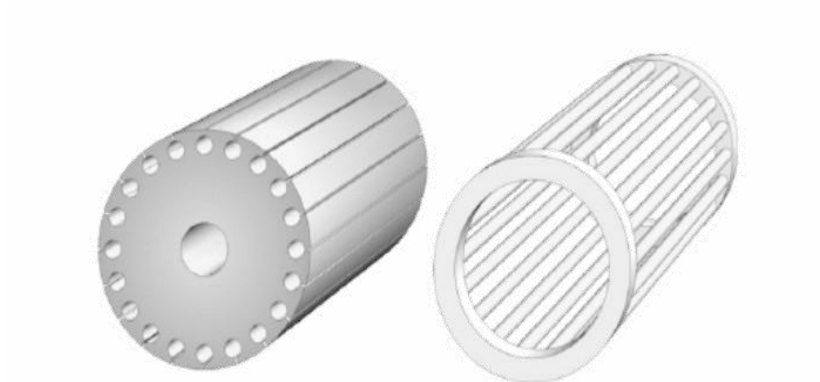

Figure 2.12. Squirrel-cage rotor construction [52].

The basic operating principle of IM relies on the currents that are induced to the rotor by the rotating magnetic field of the stator. Each of the stator phase is fed with sinusoidal current with frequency ω and phase difference 120º between each current. Each phase creates moving magnetic field and together they produce resultant moving magnetic field of the stator which is rotating at angular velocity of ω in case of two pole stator, Figure 2.11 [74].

The total flux in the machine is the sum of the three fluxes. The summation of the three AC fluxes results in a rotating flux, which turns with constant speed and has constant amplitude. Such a magnetic flux produced by balanced three phase currents flowing in three-phase windings is called a rotating magnetic flux or rotating magnetic field (RMF). RMF rotates with a constant speed (Synchronous Speed). Existence of a RMF is an essential condition for the operation of an induction motor.

- An AC current is applied in the stator armature which generates a flux in the stator magnetic circuit.
- This flux induces an emf in the conducting bars of rotor as they are “cut” by the flux while the magnet is being moved (E = BVL (Faraday’s Law))
- A current flows in the rotor circuit due to the induced emf, which in term produces a force, (F = BIL) can be changed to the torque as the output.

The torque production of the IM depends on the slip. Slip speed is the relative velocity between the rotor and the stator field, which is also referred as synchronous speed. Usually slip S is expressed as ratio as presented below, where N is the speed of the rotor and N_S is the synchronous speed. If slip is 0, the rotor speed is same as synchronous speed and corresponding slip of 1 means that rotor is stationary [52].

$$S = \frac{N_S - N}{N_S}$$

The slip in torque production of IMs is important because the induced electro motive force (e.m.f.) of the rotor is directly proportional to slip. If slip is 0, no e.m.f. is produced and when the rotor is stationary, at slip of 1, induced e.m.f. is at its maximum. The voltages that are induced in the short-circuited rotor bars, drive currents in the bars. These axial currents of rotor bars create the driving torque of the motor by interacting with the radial flux wave. The rotor is rotating to the same direction as the rotating field so it is dragged by the field. The expression asynchronous with induction machines comes from the fact that motor action is only possible if the rotor speed is less than synchronous speed [52].

To achieve torque-speed characteristics applicable for traction, the characteristics of IM can be enhanced. The characteristics can be enhanced by simultaneously varying the voltage and frequency. This control is also known as constant volt/hertz control [74]. In constant volt/hertz control the voltage/frequency (V/f) ratio, the flux, is kept constant until the rated voltage and frequency of the motor i.e. until the base speed. Beyond the base speed, at the constant power region, voltage is kept constant and the flux is weakened by increasing the frequency.

Inverter is used to vary the voltage and frequency, but it also limits the current. The current limit of the inverter is set at the rated current of the motor to prevent overheating. With modern control, which is presented later, the current limits the permissible torque and it allows some controlled exceeding of current limit for peak torque demand. In the constant torque region rated torque is usually half of the pull-out torque that the motor can provide [52].

Although, IM speed range can be extended with constant volt/hertz control, it does not provide suitable characteristics for EV application. The main reasons for this are poor response to frequent and fast speed varying. Field oriented control (FOC) has been developed to overcome the limitations of constant volt/hertz control [74].

The technology of the IM is very mature and is used in all sorts of appliances like washing machines, pumps and industrial machines. Therefore it is a popular choice and most used in EVs and HEVs of today. The Th!nk city electric vehicle and the Tesla Roadster and Model S which are already on the market uses a 3-phase AC induction motor.

Table 2.1. Comparison of EV motors [56]

Type of Motor	Advantage	Disadvantage	Vehicles Used In
Brushed DC motors	➢ Maximum torque at low speed	➢ Bulky structure ➢ Low efficiency ➢ Heat generation at brushes	➢ Fiat Panda Elettra (Series DC motor) ➢ Conceptor G-Van (Separately excited DC motor
Permanent Magnet Brushless DC Motor (BLDC)	➢ No rotor copper loss ➢ More efficiency than induction motors ➢ Lighter and Smaller ➢ Better heat dissipation ➢ More reliability ➢ More torque density ➢ More specific power	➢ Short constant power range ➢ Decreased torque with increase in speed ➢ High cost because of PM	➢ Toyota Prius (2005)
Permanent magnet Synchronous Motor (PMSM)	➢ Operable in different speed ranges without using gear systems ➢ Compact ➢ Efficient ➢ Suitable for in-wheel application ➢ High torque even at very low speeds	➢ Huge iron loss at high speeds during in-wheel operation	➢ Toyota Prius ➢ Nissan Leaf ➢ Soul EV
Induction Motor	➢ The most mature commutator less motor drive system ➢ Can be operated like a separately excited DC motor by employing field orientation control	➢ No draw backs	➢ Tesla Model S, X & Y ➢ Toyota RAV4 ➢ GM EV1
Switched Reluctance Motor	➢ Simple and robust construction ➢ Low cost ➢ High speed ➢ Less chance of hazard ➢ Long constant power range ➢ High power density ➢ Robust ➢ Fault tolerant ➢ Small and Efficient	➢ Low efficiency ➢ Larger and heavier than PM machines ➢ Complex design and control ➢ Problems in controllability and manufacturing ➢ Low power factor	➢ Chloride Lucas

Even though induction motor have many advantages over the other electric motors that have discussed in the above Comparison table, it needs inverters and controllers and difficult for simulation. For this reason I have used the simplest brushed DC motor for this thesis.

2.7 Electric vehicle (EV) Batteries

A typical battery consists of two or more electrochemical cells joined together. The battery converts stored chemical energy into electric energy. A single battery cell is made of a negative electrode and a positive electrode which are connected by an electrolyte. The chemical reaction between the electrodes and electrolyte generates electricity. Rechargeable batteries can reverse the chemical reaction by reversing the current. This way the battery can be recharged [57]. The kind of material used for the electrodes and electrolyte determines the battery specifications. A number of batteries available or under development are suitable for EVs. These batteries are described here.

2.7.1 Lead/acid batteries

Lead/acid (Pb/A) batteries are the oldest type of battery used in vehicles. The battery negative electrodes contain elementary lead (Pb) while the positive plates have lead dioxide (PbO_2) as active material in charged state. The electrodes are immersed in an electrolyte of sulphuric acid (H_2SO_4). When being discharged the lead of the negative electrodes and the lead dioxide of the positive electrode reacts with the sulphuric acid. Lead sulphate is formed on the electrodes and the electrolyte loses its dissolved sulphuric acid and becomes water. Energy is released during the chemical reaction and when energy is added the process will reverse. The overall reaction is:

$$\text{Pb} + PbO_2 + 2H_2SO_4 \longleftrightarrow 2\text{Pb}SO_4 + 2H_2O$$

Most ICE vehicles use a SLI (start, lightning, and ignition) Pb/A battery. The Pb/A battery is the most mature technology of the EV batteries and the prices are the lowest. However their specific energy also is low compared to the other battery technologies. A typical Pb/A battery for an EV has a specific energy of around 35 Wh/kg and a specific power of 250 W/kg [59]. The number of lifecycles than can be achieved by a Pb/A battery is 100 cycles for a normal SLI car battery [58]. The reason for the short lifetime of a car SLI battery is corrosion of the active material on the positive plate (anodic corrosion). Means to reduce corrosion on the battery plates are mechanical compression.

The more advanced valve regulated Pb/A (VRLA) batteries can achieve around 800 cycles, while with compression realized in tubular-plate positive electrodes the Pb/A batteries can achieve around 1500 cycles (80% DOD) [58]. Charging and discharging SLI batteries goes slow and are not suited for use in a BEV.

2.7.2 Nickel Metal Hydride batteries

There are four types of nickel based batteries that use nickel in the positive electrode of the battery; the nickel iron (Ni-Fe), nickel zinc (Ni-Zn), nickel cadmium (Ni-Ca) and nickel metal hydride (Ni-MH). The Ni-Zn and Ni-Fe batteries are not considered to be an option for EVs because of their short lifecycle and low specific power [60]. Ni-Ca is the most mature technology of the cadmium based batteries. It has similar specifications compared to the Ni-MH [51]. The advantage of the Ni-MH battery is that it uses no cadmium and is therefore environmental friendlier. The battery uses hydrogen absorbed in a metal hydride at the positive electrode. Nickel oxyhydroxide becomes nickel hydroxide during discharge. At the negative electrode hydrogen is released from the metal producing water and electrons during discharge. The overall reaction is written as:

$$MH + NiOOH \longleftrightarrow M + Ni(OH)2$$

Nickel-metal hydride batteries have developed rapidly since the introduction in 1991. They are being used in hybrid vehicles like the Honda Civic hybrid and the Toyota Prius because of their high specific power. The lifetime of a NIMH battery can be as high as 3000 cycles if the battery operates between 20% and 80% SOC (State of Charge) and could well meet the projected lifetime requirements of full-function battery EVs and plug-in HEVs [42].

The number of deep cycles that can be achieved today are already over 1000 cycles (80% DOD). The technology will be the dominant battery technology in hybrid and electric vehicles the next five to ten years because of their safety and lifecycle advantages over lithium batteries [42].

Ni-MH does not deteriorate over time, like lithium-ion batteries, and when temperature and usage is being controlled the battery can be designed to last the life of the vehicle. However, the Ni-MH battery is not expected to improve in specific energy as the 75 Wh/kg is close to its fundamental practical limits.

2.7.3 Lithium-ion batteries

Lithium-ion batteries are state of the art for EVs. The term describes a group of batteries which possesses a high specific power and a high specific energy [49, 61 & 62]. Lithium-ion batteries have the potential to become the dominant battery technology in BEVs and HEVs. They rapidly developed the last years for the use in small consumer electronics like cell phones and notebooks. Most BEVs are equipped with lithium-ion battery packs. Examples of BEVs that use lithium-ion batteries are the Tesla Roadster, Tesla Model S, Tesla Model X, the Th!nk City and the Mitsubishi iMiev.

Lithium-ion batteries are very suitable as high performance EV batteries because of the main characteristics of lithium metal. Of all the different metals lithium has the highest standard potential and electrochemical equivalent. This indicates it has the highest specific energy potential (in Wh/kg) of all metals and on a volumetric energy basis (Wh/l) it is only inferior to aluminum and magnesium [64]. Lithium is also very light, the lightest of all metallic materials.

In general, a battery consists of cells, a battery management system, packing and a cooling system [63]. The cells are the most defining element of the battery. They are available in different forms: pouches, prismatic and cylindrical cells. The cell contains the anode (negative electrode), cathode (positive electrode), separator and electrolyte. The anode often consists of graphite. The cathode consists of a lithium-metal oxide or a metal phosphate. Common cathode materials are lithium cobalt oxide, lithium iron phosphate or lithium manganese oxide. The direction in which the lithium-ions cross the separator depends on whether the battery is being charged or discharged. The lifetime is mainly defined by two parameters: the time passing and the number of charging and discharging cycles. Typical life time's range from 8 to 12 years and are close to 3000 cycles [66]. According to [65] Battery cell properties are briefly discussed as follows;

- **Terminal cell voltage:** The voltage measured across the terminals of cell is known as cell voltage when the cell is applied to any application with certain load. Thus, Open circuit voltage is higher than the nominal cell voltage. It is because during discharge, as the chemical energy is transformed into electrical energy the open circuit voltage also drops to the nominal voltage due to the losses in cell. Polarization or over potential occurs when a load current is passing through the cell. The dominant cause of loss in the cell is due to internal resistance resulting into ohmic losses In addition to it, causes voltage drop, when load current is passed through during discharge which is referred as ohmic polarization, which is directly proportional to discharge current applied.

- **Cut-off voltage:** Voltage level at the terminals of the battery at which battery is said to be empty or zero state of charge. And prohibited to use in the application in order to prevent permanent loss in capacity of the battery.
- **State of Charge (SOC):** It is a percentage of instantaneous battery capacity left out of total battery capacity. SOC can be calculated by integrating battery current over a period of time.
- **Depth of Discharge (DOD):** the percentage of battery capacity discharged in the terms of total capacity is known as depth of discharge. Generally, DOD can be related to SOC as follows;

  DOD = 1−SOC; (when expressed in fraction)
- **Capacity:** Also known as coulometric capacity, absolute Ah (ampere hours) available at a certain C-rate, when battery goes from 100% SOC (state of charge) to 0% SOC.
- **Charge and discharge rates:** The charging and discharging of the battery is termed as C-rate. The discharge and charge rate depends upon the electrochemical reaction and movement of ion in the electrolyte of cell. Also, it depends upon internal resistance of cell. As we change our discharge and charge rate, other parameters such as State of Charge (SOC), lifetime period, life cycle, etc. Charge and discharge rate is governed by the C-Rate. The capacity of the battery is rated as 1C, which implies that fully charged battery of 1Ah rating is going to deliver 1 Ampere for 1 Hour.
- **Battery lifetime**: the time when battery is unable to meet 80% of rated capacity after certain number of charge and discharge cycles. Conditions like rate of discharge, depth of discharge, temperature, humidity, etc. are responsible for determining battery operating life.
- **Specific Energy:** Specific energy depends upon the battery chemistry and packaging. It is primarily ratio of energy battery holds to the total weight of the vehicle with unit

of Watt-hour/kg. It is one of most vital information, as it is used to determine the size of battery required to go up to a certain range.

- **Specific Power:** Specific power also depends upon chemistry and packaging. It is defined by the ratio of available maximum power over the mass. Specific power has a unit of watt/kg. It is vital to know about the battery capability to deliver power to meet high power application, such as start, acceleration and climbing a slope.
- **Energy Density**: The battery energy per unit volume is known as energy density. It is required to determine the range of vehicle. Its unit is watt-hour/L.
- **Power Density**: It is the maximum available power per volume of battery. Its unit is watt/L.

Table 2.2. Common battery types, their basic construction components, advantages and disadvantages [56].

Battery type	Components	Advantage	Disadvantage
Lead acid	➢ Negative active material: spongy lead ➢ Positive active material: lead oxide ➢ Electrolyte: diluted sulfuric acid	➢ Available in production volume ➢ Mature technology as used for over fifty years	➢ Cannot discharge more than 20% of its capacity ➢ Has a limited life cycle if operated on a deep rate of SOC (state of charge) ➢ Low energy and power density ➢ Heavier ➢ May need maintenance
NiMH (Nickel-Metal Hydride	➢ Electrolyte alkaline solution ➢ Positive electrode nickel hydroxide ➢ Negative electrode alloy of nickel, titanium, vanadium and other metals.	➢ Double energy density compared to lead-acid ➢ Harmless to the environment ➢ Recyclable ➢ Safe operation at high Voltage ➢ Can store volumetric power and energy ➢ Cycle life is longer ➢ Operating temperature range is long ➢ Resistant to over-charge and discharge	➢ Reduced lifetime of around 200–300 cycles if discharged rapidly on high load currents ➢ Reduced usable power because of memory effect

Lithium -Ion	➢ Positive electrode: oxidized cobalt material ➢ Negative electrode: carbon material ➢ Electrolyte: lithium salt solution in an organic solvent	➢ High energy density, twice of NiMH ➢ Good performance at high temperature ➢ Recyclable ➢ Low memory effect ➢ High specific power ➢ High specific energy ➢ Long battery life, around 1000 cycles	➢ High cost ➢ Recharging still takes quite a long time, though better than most batteries
Ni-Zn (Nickel-Zinc)	➢ Positive electrode: nickel oxyhydroxide ➢ Negative electrode: zinc	➢ High energy density ➢ High power density ➢ Uses low cost material ➢ Capable of deep cycle ➢ Friendly to environment ➢ Usable in a wide temperature range from −10 °C to 50 °C	➢ Fast growth of dendrite, preventing use in vehicles
Ni-Cd (Nickel-Cadmium)	➢ Positive electrode: nickel hydroxide ➢ Negative electrode: cadmium	➢ Long lifetime ➢ Can discharge fully without being damaged ➢ Recyclable	➢ Cadmium can cause pollution in case of not being properly disposed of ➢ Costly for vehicular application

Due to many advantages over the other Batteries that have discussed in the above Comparison table Lithium ion battery is selected for this thesis.

The energy storage of EV is usually an electrochemical battery, often referred only as battery. During charging the energy from the grid is converted to a potential chemical energy and during discharging the chemical energy is converted back to electric energy. The specific energy, the energy capacity per unit battery weight (Wh/kg), is dependent on the battery type. The battery discharge and charge efficiency is dependent on the type, but also on the state of charge (SOC) of the battery. Usually the discharging efficiency is at its highest at high SOC values and it decreases with the SOC [74]. Nissan Leaf uses Lithium-ion batteries (Nissan Motor 2017) and according to [74], these batteries have specific energy of 80-130 Wh/kg and efficiency above

95%. The future of the EV depends a lot on the battery technology development. The lithium-ion technology is the most promising technology for the future EVs. Indeed, the energy density of a Lithium battery is much higher than the other current technologies, and this is why this type of battery is highly used for portable devices (digital cameras, laptops, cell phones…).

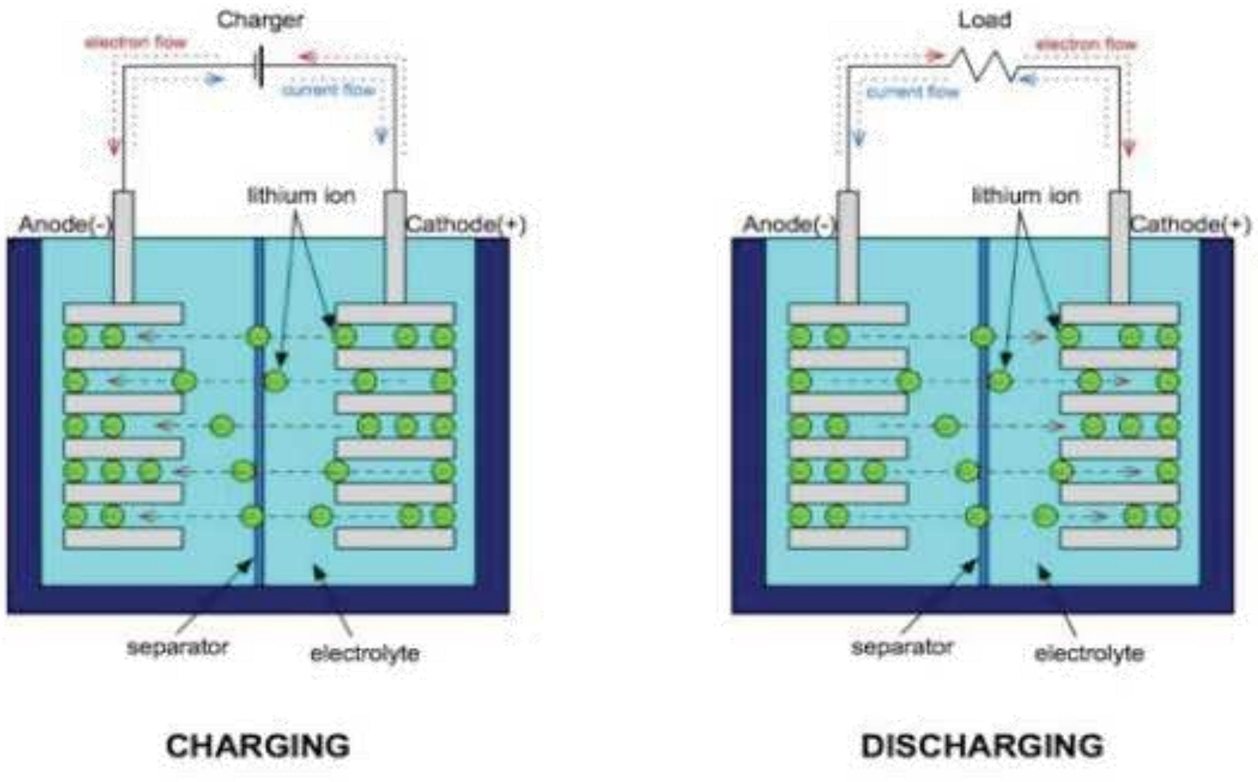

Figure 2.13. Principle of a lithium-ion battery [67]

The negative electrode (anode) of Li-Ion battery cell is graphite and the positive electrode (cathode) is a lithium-bearing metal compound. Li-ion batteries have a good cycling aptitude due to the stable electrode structure: charging and discharging involves exchange of lithium ions between the electrodes via the electrolyte [67].

While charging, the electrons are pumped from the cathode to the anode. Positively charged lithium ions move from the cathode through the separator via the electrolyte to the anode. While discharging, positively charged lithium ions move from the anode through the separator via the electrolyte to the cathode. Electrons move through the external load from the anode to the cathode, resulting in a current that provides power to the load [67]. For a problem of safety, the charge intensity and the charge voltage must be correctly adapted for a Li-ion battery. An important overload can induce the destruction of the battery.

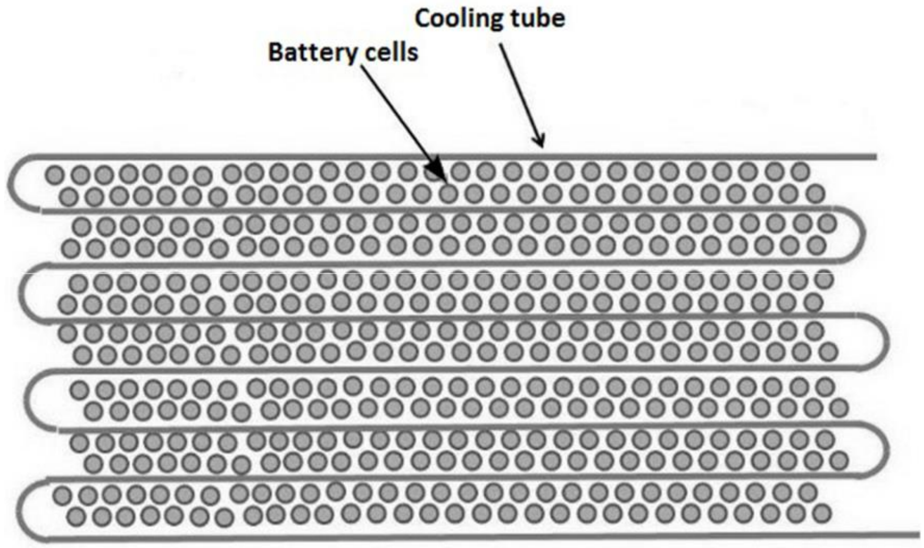

Figure 2.14. Lithium ion Battery Pack [67]

Lithium ion (Li-ion) battery shows high nominal voltage around 4.0 V/cell, different for different variant of Li-ion battery. Some of them are being compared in the table below,

Table 2. 3 Types of lithium ion battery [60]

Cell Parameters	Type of Li -Ion cell		
	$LiCoO_2$	$LiMn_2O_4$	$LiFePO_4$
Nominal Voltage / cell	3.6 - 3.7	3.6 - 3.7	3.2-3.3
End Charging Volt / cell	4.2	4.35	4.25
End discharging Volt / cell	2.75	2.2	2.5
Charging Current(max)	0.3-0.5 CA	0.3-1CA	0.3-3CA
Discharging Current (max)	2-5CA	5CA	3CA (10CA Pulse)
Service life	80% DOD - 1000cycles	80% DOD -300 cycles	80% DOD -2000 cycles
Self-discharging	2% / month	3% / month	3% / month
Operating temp (°C)	(-20 to 75)	(-25 to 75)	(-25 to 75)

Due to many benefits discussed on the above table lithium ion battery ($LiMn_2O_4$) was selected for this thesis.

2.7.3.1 Charge of a Lithium Battery

Currently, we can charge a vehicle with two types of charge: conductive and inductive charge. Inductive charging is one kind of short distance wireless energy transfer. The conductive charge requires direct electrical contact between the battery and the charger. The load with inductive charge might be a little bit higher than a conductive load since there might be more losses. In this thesis, we will focus on the conductive charge, since it is the type of charge that is more likely to be developed. We can charge a Lithium Ion battery with different current. The different terms used in this report are expressed in table 2.3.

Table 2.4. Different types of charge

	Load	Charge time
Slow charge	< 6kVA	> 4 hours
Standard charge	between 6 kVA and 22 kVA	between 1 and 4 hour
Fast charge	between 43 kVA and 125 kVA	less than 1 hours

2.8 Ultra capacitors

Ultra-capacitors are different from batteries. Batteries store their energy chemically where an ultra-capacitor stores it physically. A single ultra-capacitor cell has two plates (collectors) that are separated by a separator in an electrolyte. The capacitor stores energy electro statically on the collectors. The collectors are made of a material with a very high surface area. Ultra-capacitors can be charged and discharged much faster than batteries and are very suitable for storing the energy from regenerative braking, for climbing hills or sudden acceleration. The ultra-capacitor has high specific power up to 5000 W/kg and cycle life of over 300,000 cycles but a low energy density of 5 Wh/kg [60]. Therefore the ultra-capacitor cannot solely be used as energy storage for a BEV. The ultra-capacitor is not part of this research as it is not a battery but is mentioned because it can be a part of the total energy storage system in a BEV.

2.9 Electric vehicles (EVs) Energy Consumption

The range of EVs is determined by the state of charge of the battery and the energy consumption of the vehicle. Even though the state of charge of the battery is known at the beginning of each trip, the range of the vehicle is uncertain as it depends on the upcoming, uncertain energy consumption. The energy consumption depends on the vehicle itself and variables like the ambient temperature and the driving behavior. Therefore, it is variable. To understand which elements lead to the total energy consumption of EVs and what influences the final result, its composition is described in the following. As an aid to determine the energy consumption of vehicles, driving cycles are described subsequent to the description of the energy consumption.

The energy consumption of EVs is influenced by five aspects [68]:

- The driving resistances must be overcome to put the vehicle into movement.
- Energy is lost in the process of transforming the electric energy of the battery into mechanical energy at the wheels of the vehicle. Hence, each drivetrain has a specific efficiency.
- Auxiliaries that are particularly the high voltage devices for heating and cooling but also low voltage auxiliaries such as light, radio or navigation.
- The charging process is affected of energy losses. In addition, the battery loses energy when in still stand.
- The electric motor can serve as a generator and charge energy into the battery while braking. Hence, recuperation recovers energy and reduces the total energy use.

2.10 Driving Cycles

Driving cycles are predefined schedules to operate a vehicle under reproducible conditions and to achieve comparable results. These cycles are mainly used for the measurement of emissions and for type approval [69]. A cycle is defined by its speeds over time. They can cover urban and rural roads as well as highways. A variety of different driving cycles exist like the EU legislative, the US and the Japanese testing cycles or the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) [69].

Figure 2.15 shows the example of the New European Driving Cycle (NEDC). The NEDC is a stylized driving cycle with constant speed and acceleration. The NEDC is a stylized driving cycle with constant speed and acceleration. It consists of four identical urban cycles and one extra-urban cycle. Currently, the NEDC is the standard driving cycle for type approval of passenger cars in Europe. Such a stylized type of driving cycle can underestimate the energy consumption achieved when driving in real traffic situations. In contrast, real-world cycles are derived from real data of one or multiple trips.

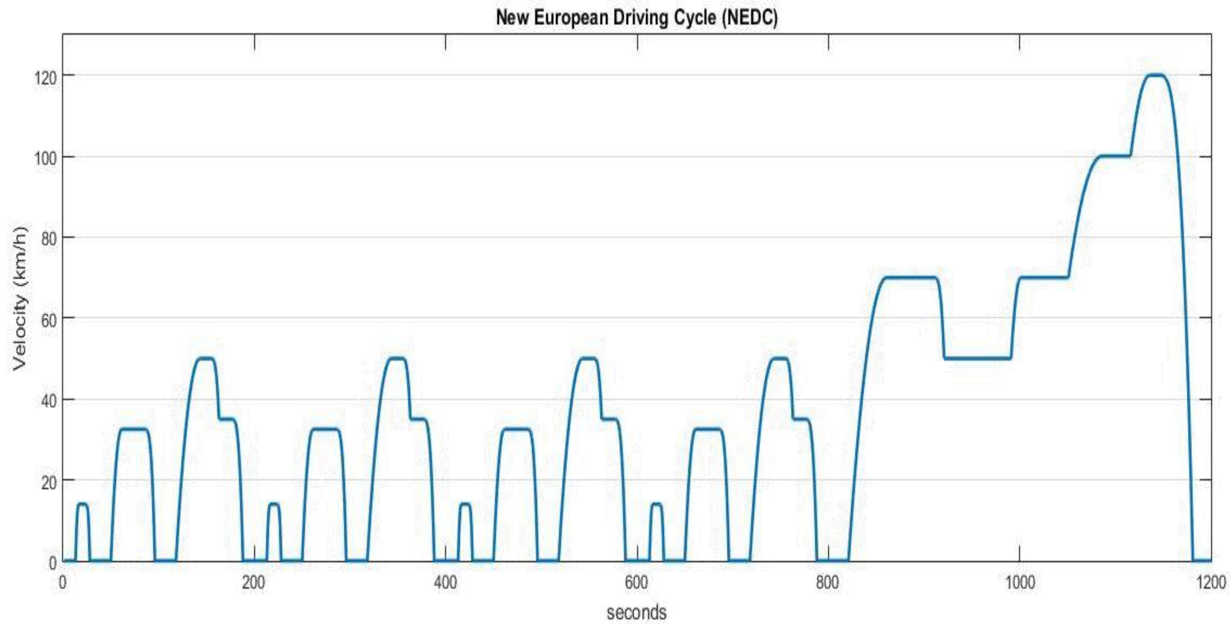

Figure 2.15. NEDC driving cycle [69]

2.11 Summery of the Literature review

In this work, previous research arts related to this work and an introductory information of power train types, advantage and limitation or challenges of Electric Vehicles with historical developments until today was discussed. In addition to it, which type of electric motor and batteries are suitable for BEV was studied, which in this work the actual speed was tested by predefined data NEDC represented by theoretical driving cycles.

2.12 Literature gap

The gaps in the literature are the following;

- The battery pack was not properly modeled in the MATLAB/Simscape environment.
- BEV was not tested in theoretical drive cycle.
- Finally all were not conducted a propel model of BEV.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Methods

The thesis work consists of DC source (Battery), H Bridge, DC motor as a load, controller and transmission. The proposed work is expressed in Figure 3.1 below.

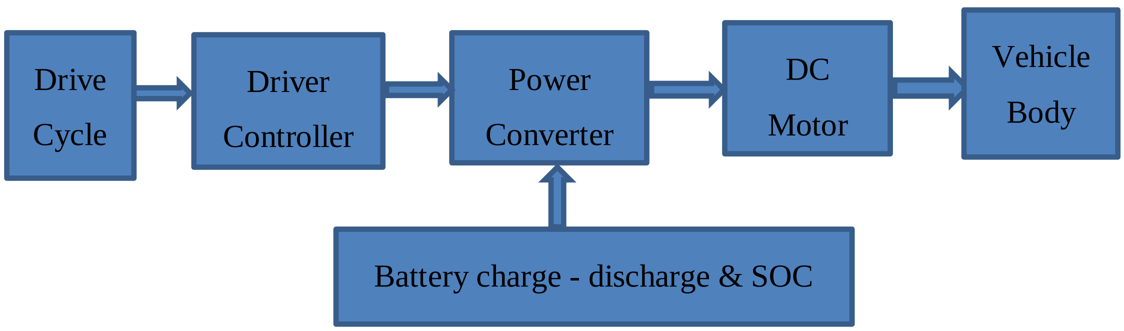

Figure 3.1. Block diagram of the thesis

Literature survey of the existing electric vehicles and the previous works done related to electric vehicle design and modeling was the key methodology of this thesis which help gaining enough knowledge about what others done and identify where the problem does exist and identifying the research gap existing.

After reviewing the literature, designing of the vehicle dynamics and physical modeling of each component of the power system and the vehicle body in MATLAB/Simscape and the electric vehicle performance in C++ was performed. After designing vehicle dynamics and physical modeling of each components a model of the battery electric vehicle was obtained so that the system can perform its function well.

3.1.1 Methods of Data Collection

- The necessary data for the electric vehicle design and modeling is collected by Primary and Secondary Data Collection method , i.e. by visiting and searching various websites, published books, journals and/or online portal in the area of electric vehicle design, modeling, simulating & BEV dynamic analysis, SAE and other publications.

3.2 Materials

In this section selection materials of power train components that I have been used for design and modeling and vehicle dynamics have been discussed. Each and every power train components have its own semiconductor, controller, protective and amplifying devices and also it has its own working and operation principles under certain circumstances to perform a particular functions. Before the design and modeling have performed first the functions of power train components have been discussed below.

3.2.1 DC source (Battery)

Also known as electric batteries in general, are made by connecting individual cells in order to get a specific standard voltage at their terminals. Batteries are energy devices which converts chemical energy to electrical energy. Batteries now a days plays an important role in as an energy producing source as well as energy storage devices.

3.2.2 DC Motor

The function of DC motor is to convert direct current electrical energy into mechanical energy. The electrical machine which uses the direct current as power input (Motoring mode) and generating direct current (generation mode) are termed as DC motor.

3.2.3 DC motor controller (H Bridge)

The term H-bridge is derived from the typical graphical representation of such a circuit. An H-bridge is built with four switches (solid-state or mechanical). The H-bridge arrangement is generally used to reverse the polarity/direction of the motor, but can also be used to 'brake' the motor, where the motor comes to a sudden stop, as the motor's terminals are shorted, or to let the motor 'free run' to a stop, as the motor is effectively disconnected from the circuit.

3.2.4 Final drive transmission

The final drive consists basically of a pair of gears which provide a permanent gear reduction thereby multiplying the torque being transmitted from the gearbox.

3.2.5 Electric vehicle dynamics

Vehicle designs fundamentals are a direct implementation of Newton’s Second law of motion which relates force and acceleration. Vehicle dynamics aim to describe how a vehicle moves on a road surface while it is under the influence of forces between the tire and the road, as well as aerodynamics and gravity. During the powertrain design phase, basic knowledge in vehicle dynamics is essential, since it reveals what loads and load levels that the powertrain needs to cope with during driving. The understanding of vehicle dynamics is equally important while evaluating the powertrain’s impact on the vehicle’s performance (usually assessed through simulations), whether it may be time to accelerate, or average energy consumption per driven distance. As with modeling of any object, a rolling vehicle can be modeled with various levels of detail depending on what main phenomena that is targeted to be studied. For the type of dynamical studies in this thesis, where powertrain load levels and energy consumption will be analyzed, it is reasonable to assume that the vehicle body is rigid, hence it can be modeled as a lumped mass at the vehicle’s center of gravity [93]. Furthermore, only dynamics in one direction, i.e. the longitudinal forward direction, is of interest while under the assumption that vehicle stability is not under any circumstances violated.

According to Newton’s second law of mechanics, the dynamical movement of a vehicle in one coordinate axis is entirely determined by the sum of all the forces acting on it in that same axis of direction, as described in the translational form equation 3.1 [93].

$$F = ma = m \frac{d}{dt} v(t) = Ftractive(t) - Fresistive(t) \tag{3.1}$$

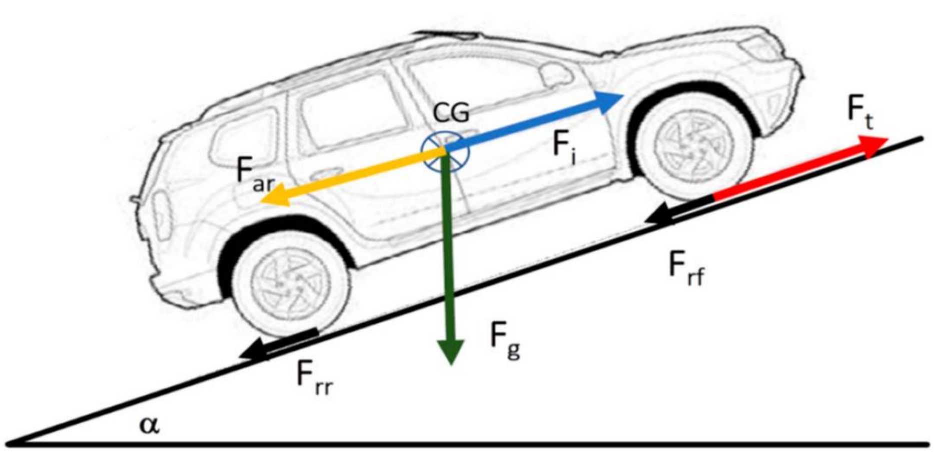

Figure 3.2. Free body diagram of the forces (thick arrows) acting on the vehicle [93].

where m (kg) is the equivalent mass to be accelerated including possible rotating inertias in the powertrain, a (m/s^2) and $\frac{d}{dt}$v (t) is the time rate of change of vehicle speed v(t)(m/s), i.e. acceleration a(m/s^2), F tractive(t)(Nm) is the sum of all the tractive forces acting to increase the vehicle speed and F resistive(t) is the sum of the resistive forces acting to decrease the speed. The main tractive force is the one exerted from the powertrain via the gear, differential and the wheel shaft to the contact area between the wheels and the road. During downhill driving gravity may also serve as a major tractive force, however during uphill driving it may instead be a large resistive force. Other major resistive forces are aerodynamic drag and rolling resistance, as well as regenerative braking using the electric power train and braking using conventional friction brakes. To conclude, a vehicle will accelerate when the sum of the tractive forces is larger than the sum of the resistive forces, and thus will decelerate when the opposite applies. To keep a constant speed, the net resistive force must be exactly matched by the net tractive force. Finally, if (F_t) = 0 and the friction brake is disengaged, the vehicle is said to be coasting, that is onlyF_a, F_r and possibly F_g are acting on the vehicle [93].

3.2.5.1 Aerodynamic drag

The aerodynamic drag that any vehicle unavoidably is exposed to during driving, springs from the flow of air around and through the vehicle.

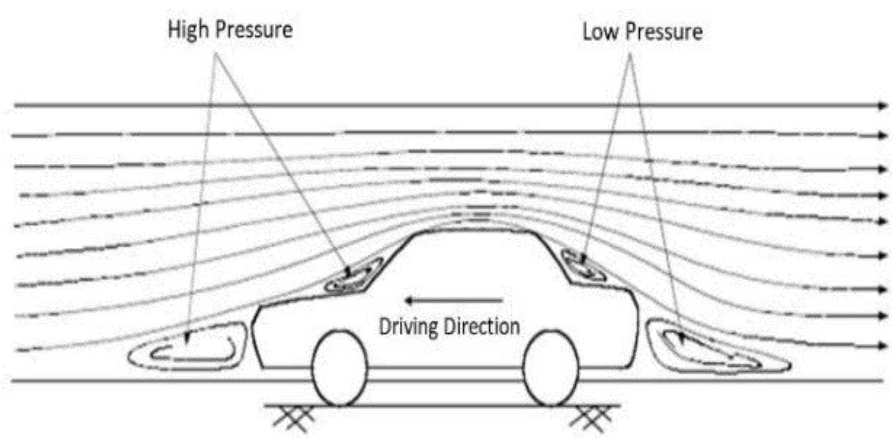

Figure 3.3. Aerodynamics drag [5]

Due to the complex shape of automobiles, along with the even more complex nature of fluid dynamics, accurate reliable analytical models of aero dynamical drag are very difficult to develop. A compromise often used to model the aero dynamical drag force, $F_{A_e}$is the partly empirical model, partly based on the expression of dynamical pressure, which is showing a strong dependence on the square of the vehicle speed as equation 3.2.

$$F_{A_e} = \frac{1}{2}\rho_a C_d A_f (v_{car} - v_{wind})^2 \quad (3.2)$$

Table 3.1. vehicle type and $\boldsymbol{C_d}$ [5]

Vehicle type	Drag coefficient(C_d)
Cabriole	0.5 - 0.7
Car	0.3 - 0.4
Bus	0.6 - 0.7
Truck	0.8 – 1.5
Optimal Design	0.2 - 0.3

$$\mathrm{F}_{\mathrm{A_e}} = \frac{1}{2} \times 1.3 \frac{kg}{m^3} \times 0.34 \times \; 2.4\, m^2 \times \left(61.11 \frac{m}{s}\right)^2$$

$$F_{A_e} = 1.98 \text{ kN}$$

Where ρ_a (kg/m^3) is the air density, C_d is the aerodynamic drag coefficient, A_f (m^2) is the effective cross sectional area of the vehicle, v_{car} (m/s) is the vehicle speed and v_{wind} (m/s) is the component of wind speed moving in the direction of the vehicle [93].

3.2.5.2 Rolling resistance

Rolling resistance is caused by a number of different phenomena taking place in and around the car tires during rolling. One of the major effects is that the repeated deflection of the tire causes a hysteresis within the tire material, which gives rise to an internal force resisting the motion. According to [5], Tire rolling resistance coefficient varies according to the road surface.

Table 3.2. Road surface and $\boldsymbol{C_r}$ [5]

Road surfaces	Rolling resistance Coefficient (C_r)
Concrete or Asphalt	0.013
Small gravel ground	0.02
Macadamized road	0.025
Soil road	0.1 - 0.35

The rolling resistance force, F_r acting on a vehicle in the longitudinal direction, is usually expressed as the effective normal load of the vehicle multiplied by the dimensionless rolling resistance coefficient, Cr as equation 3.3.

$$\mathrm{F_r} = C_r m_v g \cos\theta \tag{3.3}$$

Where C_r coefficient of rolling resistance m_v (kg) is the vehicle mass, g (m/s^2) is the gravity constant, θ (degree) is the road inclination angle [93].

The maximum road inclination angle that can climb the vehicle taking rolling resistance into consideration is given as equation 3.4.

$$\theta = \tan^{-1}\left(\frac{\mu a_1 - C_r}{l - \mu h}\right) \tag{3.4}$$

Where μ is the coefficient friction between the tire and the road, a_1 the distance from center of gravity ($C.G$) to the center of front wheel, l is wheel base distance, C_r coefficient of rolling resistance and h is height from ground to the $C.G$ therefore first we should know the maximum road inclination angle that can climb the vehicle.

$$\theta = \tan^{-1}\left(\frac{(0.8 \times 1.4208) - 0.01)}{2.96 - (0.8 \times 0.46)}\right)$$

$$\theta = 23.5°$$

Therefore now we can easily find, F_r as

$$\mathrm{F_r} = 0.01 \times 2240\ kg \times 9.81 \frac{m}{s^2} \times cos 23.5°$$

$$\mathrm{F_r} = 0.202\ \ \mathrm{kN}$$

3.2.5.3 Grading force

In case of a road grade (or inclination), the vehicle's dynamics will be affected by the component of the gravitational force F_g that is parallel with the road as equation 3.5 [93].

$$F_{\ g} = m_v g \sin\theta \tag{3.5}$$

$$F_g = 2240kg \times 9.81\frac{m}{s^2} \times sin23.5°$$

$$\mathrm{F_g} = 8.762 \text{ kN}$$

Since the vehicle may be traveling uphill or downhill this force may either be resisting or contributing to the net tractive force on the vehicle, i.e. it will either be positive or negative. From an energy perspective, driving on a non-level road will cause buffering and draining of potential energy in the vehicle. However, since passenger cars are usually displaced only temporarily over a day or so, from its starting position (e.g. at home), whatever the route traveled the potential energy when coming back remains the same. As with deceleration, a BEV is normally able to recuperate some of the energy from going downhill [93].

3.2.5.4 Resistive force

The resistive force at certain speed level, road grade and neglecting acceleration can be found as in equation 3.6.

$$F_{re} = F_{A_e} + F_r + F_g \tag{3.6}$$

$$F_{re} = (1.981 + 0.202 + 8.762)\text{KN}$$

$$\mathrm{F_{re}} = 10.95 \text{ kN}$$

3.2.5.5 Resistive power

The resistive power P_r at certain speed level, road grade and neglecting acceleration is determined by the resistive force and the vehicle speed as equation 3.7.

$$P_r = F_{re}V \tag{3.7}$$

The maximum speed at maximum inclination angle $\frac{220}{3}km/hr \approx 75km/hr$

$$P_r = 10.95\ kN \times 20.83\frac{m}{s}$$

$$\underline{P_r = 228.09 \text{ kW}} \text{ @ Maximum } \theta$$

3.2.6 Power train design

3.2.6.1 Transmission

The torque, angular velocity, and power of the transmission system are given by the following equations:

$$\tau_t = F_{re}R_w \tag{3.8}$$

$$\tau_{re} = 10.95\ KN \times 0.35m$$

$$= 3.83 \text{ kNm}$$

$$\tau_w = \frac{3.83}{2} = 1.92\ KNM,\ for\ each\ wheels.$$

$$\omega_w = \frac{v}{r_w} = \frac{20.83\frac{m}{s}}{0.35\ m} = 59.51\frac{rad}{s}$$

Where $\tau_{re}(NM)$ resistive torque, $\tau_w(NM)$ torque of each driving wheel $\omega_w(\frac{rad}{s})$ angular velocity of the wheels, r_w (m) wheel radius.

3.2.6.2 Electric Motor

The efficiency of the DC motor is given by

$$efficency\ (\eta_m) = \frac{mechanical\ output\ power}{electrical\ input\ power} \times 100\% \tag{3.9}$$

Therefore the power from the shaft of the electric motor to the two driving wheels has an efficiency of η_m = 0.88. The motor torque, angular velocity, *RPM* and power are therefore

$$\tau_m = \frac{\tau_{re}}{\eta_m \times \text{G}} = \frac{3.83KNm}{0.88*9} = 0.48 \text{ kNM}$$

$$\omega_m = G\omega_w = 9 \times 59.51\frac{rad}{s} = 535.59\ rad/s$$

$$RPM = \frac{Total\ distance\ covered\ per\ hour * Gear\ ratio}{Linear\ distance(2\pi r)} \tag{3.10}$$

$$= \frac{2200 \times 1000m \times 9}{60min \times 2.2m}$$

$$RPM = 15000$$

And the motor power is $P_m = \tau_m \omega_m = 0.48\ KNM \times 535.59 \frac{rad}{s}$

$$\underline{P_m = 257.08 \text{ kW}}$$

Where $\tau_m(NM)$ motor torque, $\omega_m(\frac{rad}{s})$ Shaft angular velocity of the motor, RPM (Speed in revolution per minute), P_m(W) Shaft power of the motor and(G) Gear ratio of differential.

$$efficency\ (\eta_m) = \frac{mechanical\ output\ power}{electrical\ input\ power} \times 100\% = \frac{228.09KW}{257.08KW} \times 100\% = 88\%$$

3.2.6.3 Battery pack

Estimation of the battery pack size was useful during modelling of the battery electric vehicle (BEV). The battery size was calculated by multiplying the energy consumption by the range of the car divided by the specific energy of the battery used in the vehicle.

The vehicle has consumption of 0.308 kWh/km. The range of the car is 153 km based on the NEDC. Therefore the battery capacity is given by;

Battery capacity = 153km × 0.308 kWh/km = 47 kWh.

The battery used in the car is the lithium ion with a specific energy of 100 Wh/kg.

The total weight of the battery system is =47/0.1 = 470 kg

3.3 Modeling and simulation

The desired battery electric vehicle (BEV) model was modeled in MATLAB 2019b. During the MATLAB simulation wind speed (v_{wind}) and road angle (θ) have set to zero for simplicity. The input to the simulation model is a driving cycle (that was explained in testing) and the output of the model was all the distance, speed, state of charge, current, voltage, power, torque, etc., inside the vehicle.

Here are the block sets that was used to simulate the required electric vehicle that has been taken from MATLAB/Simscape software with screen shoot.

3.3.1 Drive cycle source

The physical modeling of drive cycle which is taken from Simscape block diagram is shown in Figure 3.4 below. The reference speed port of the drive cycle is connected to the vehicle reference speed of the longitudinal driver.

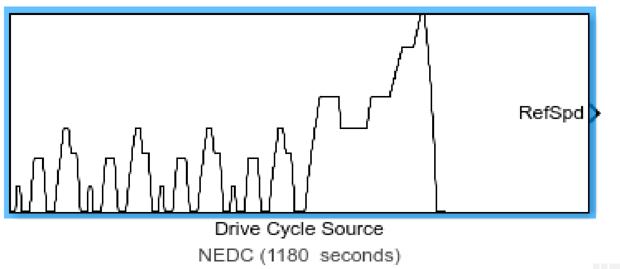

Figure 3.4. Drive cycle source from MATLAB /Simscape

3.3.2 Longitudinal driver

The vehicle speed is controlled by the longitudinal driver by accelerating and decelerating command is shown in Figure 3.5 below.

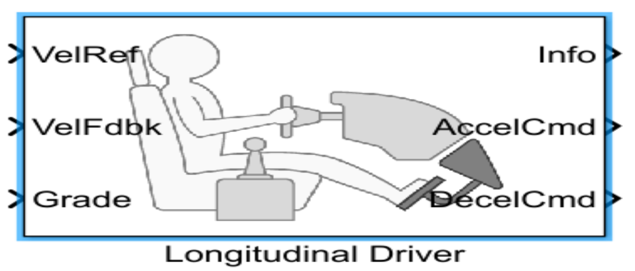

Figure 3.5. Longitudinal driver from MATLAB /Simscape

Where:

VelRef = Vehicle reference

VelFdbk = Vehicle feedback

AcelCmd = Accelerator command

DecelCmd = Decelerator command

3.3.3 Electric motor

In this thesis the electric motor is used DC motor and the MATLAB/Simscape physical model is shown in Figure 3.6 below. The rotor (R) of the motor is connected with gear box input shaft and the C port is grounded to the mechanical rotational reference.

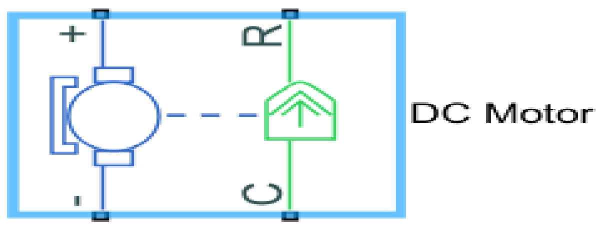

Figure 3.6. DC motor from MATLAB /Simscape

3.3.4 Battery pack

The battery pack is the heart of the electric vehicle. It consists of the series and/or parallel association of elementary cells. The overall battery pack configuration is modelled in MATLAB/Simscape software starting from battery cell.

3.3.4.1 Battery cell

The modeling of battery cell electrical circuit diagram is given in Figure 3.7 below. It has dc voltage source, capacitor and resistors.

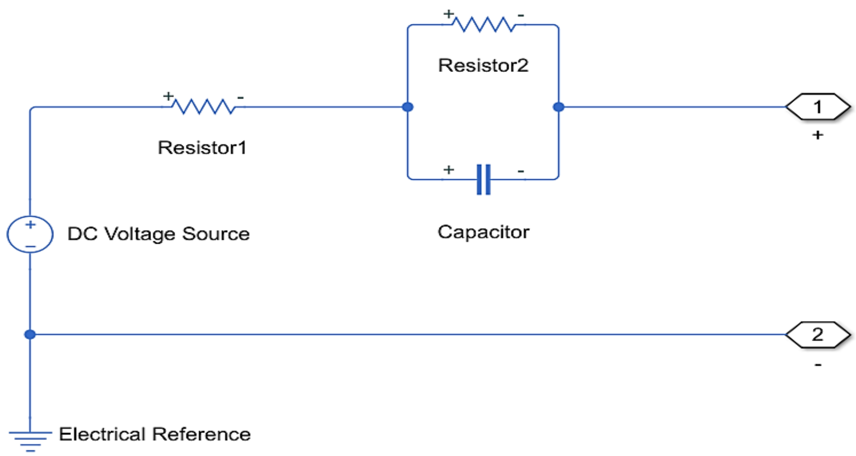

Figure 3.7. Battery cell model

3.3.4.2 Battery cells in series connection

Battery cells connected in series are modeled as shown in Figure 3.8 below. Each cell have a nominal voltage of 3.6 volt. When a battery cells are connected in series the battery voltage increases but the battery capacity Ah remains constant leads to have poor range performance.

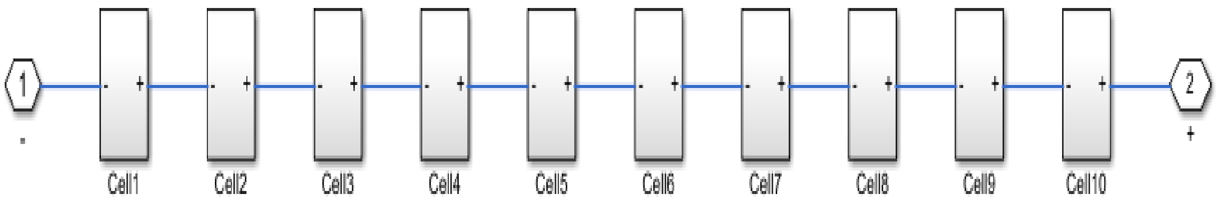

Figure 3.8. Battery cell in series connection

3.3.4.3 Battery cells in parallel connection

Battery cells connected in parallel are modeled as shown in Figure 3.9 below. When a battery cells are connected in parallel the battery capacity (Ah) increases leads to have good range.

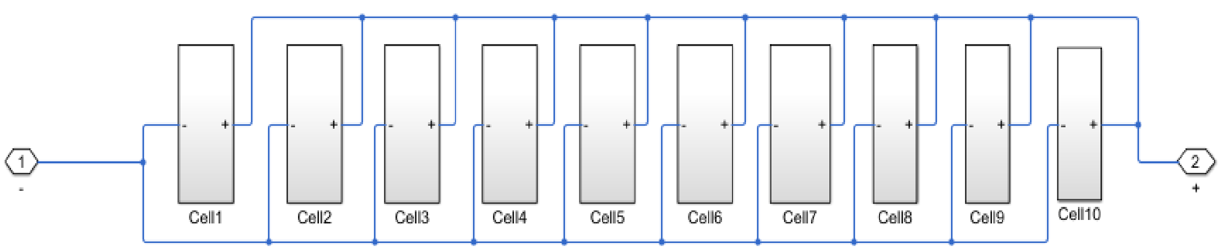

Figure 3.9. Battery cell in parallel connection

3.3.4.4 The battery pack module

The battery pack has 14 modules (10 cells per module), 5 modules connected in parallel and the rest are connected in series to get 360 V system voltage as shown in Figure 3.10 below.

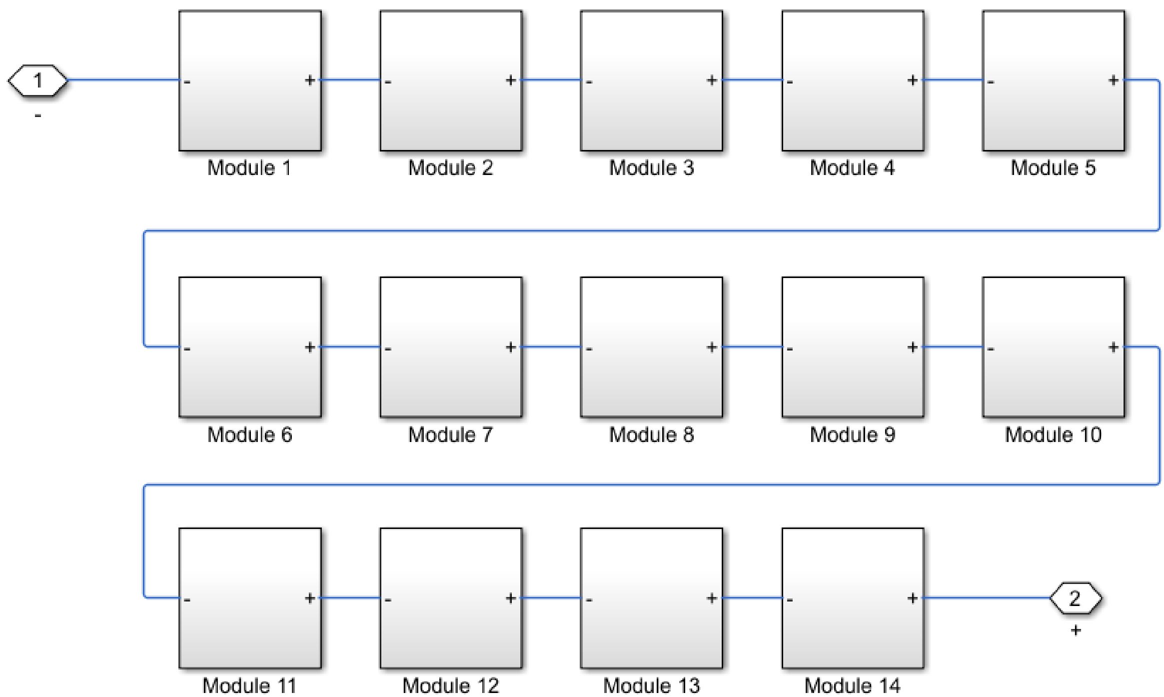

Figure 3.10. Battery module modeled from MATLAB/Simscape

3.3.5 Gear box, differential and tyre

The physical modeling of simple gear box, differential and tire which taken from simscape is shown in Figure 3.11 below. The DC motor rotor shaft is connected to the gear box input shaft (B) port and the gear box output shaft (F) port is connected to the differential input shaft port D and the Differential S1 and S2 ports are connected to the left and right wheels respectively.

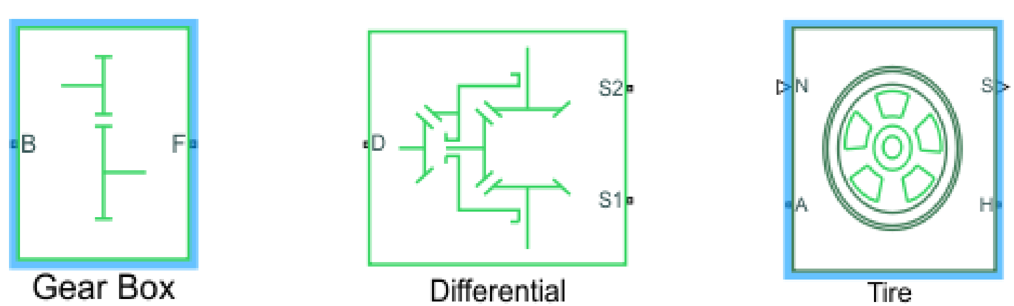

Figure 3.11. Gear box, differential and tire from MATLAB/Simscape

3.3.6 Vehicle Body

The vehicle body which is taken from Simscape physical modeling is shown in Figure 3.12 below. It has velocity, wind, slope, wheel hub, front and rear normal forces port and also used to feed vehicle dynamics parameters.

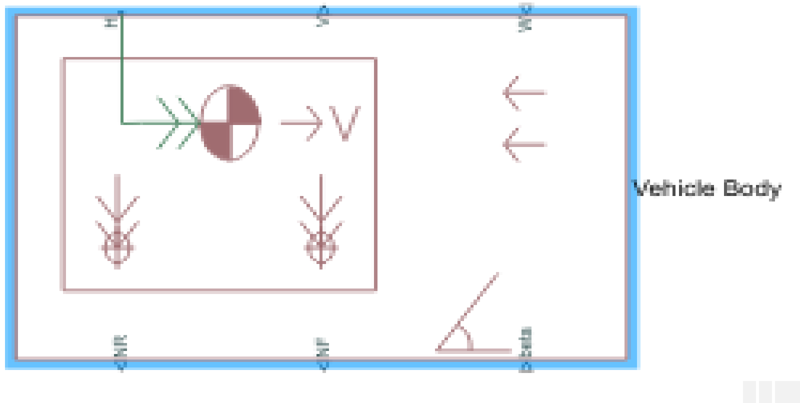

Figure 3.12. Vehicle body from MATLAB/Simscape

3.3.7 Motor controller sub system

In figure 3.13 a motor controller with H Bridge is shown below which is used to control the DC motor by the longitudinal driver accelerator and decelerator command.

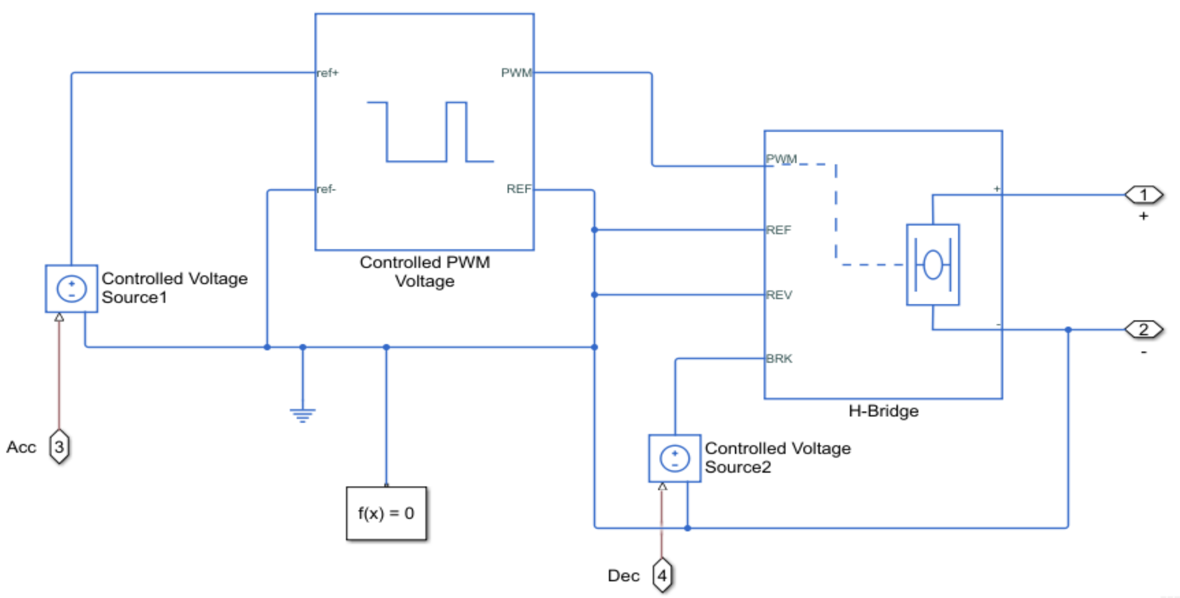

Figure 3.13. Motor controller with H Bridge

3.3.8 Vehicle Body sub system

The following figure 3.14 is the screenshot of Simscape model which represents an assembly of a gear box, differential, tire and a vehicle body.

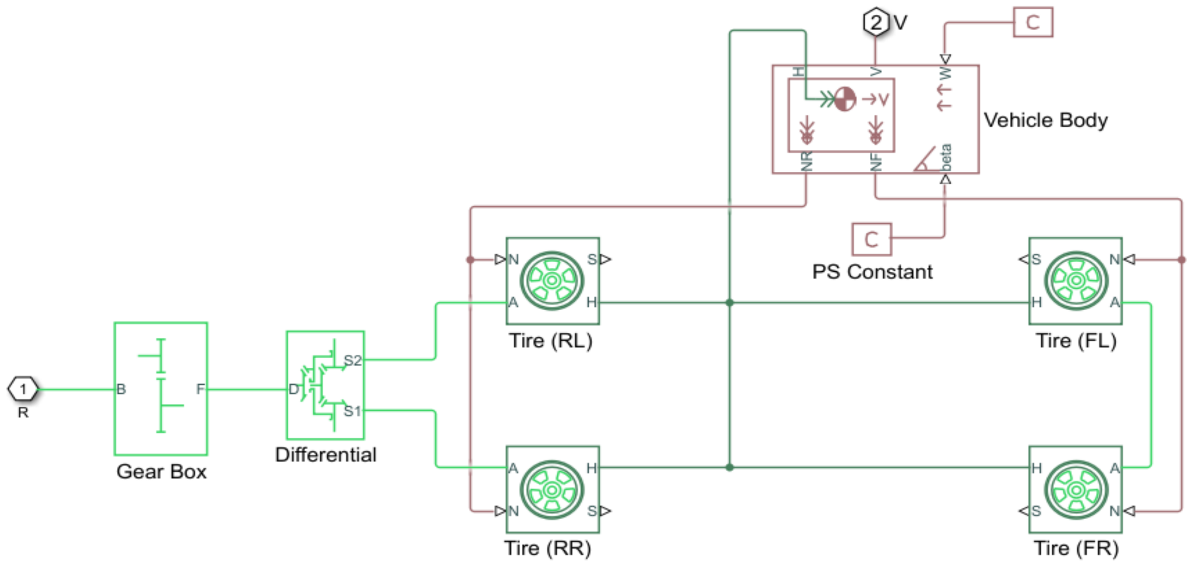

Figure 3.14. Vehicle sub system

3.3.9 BEV with DC motor drive over all modeling

The principle of operation of the BEV shown in Figure 3.15 is simple and easily understood. The DC motor is powered from the battery pack and the speed of DC motor is controlled by H Bridge when accelerated or decelerated by the longitudinal driver. After the motor get powered, the motor output shaft transfers power to the drive shaft then to the wheels leads the vehicle to run either forward or backward depending on the command of the driver. The consumption or regenerating of current and the remaining battery voltage in terms of SOC after travelling a distance of 11 km for 1180 seconds was analyzed.

Please note that the energy consumption is just the result of the vehicle dynamics and powertrain components not include auxiliary power consumptions, such as heating, air conditioning, and other facilities.

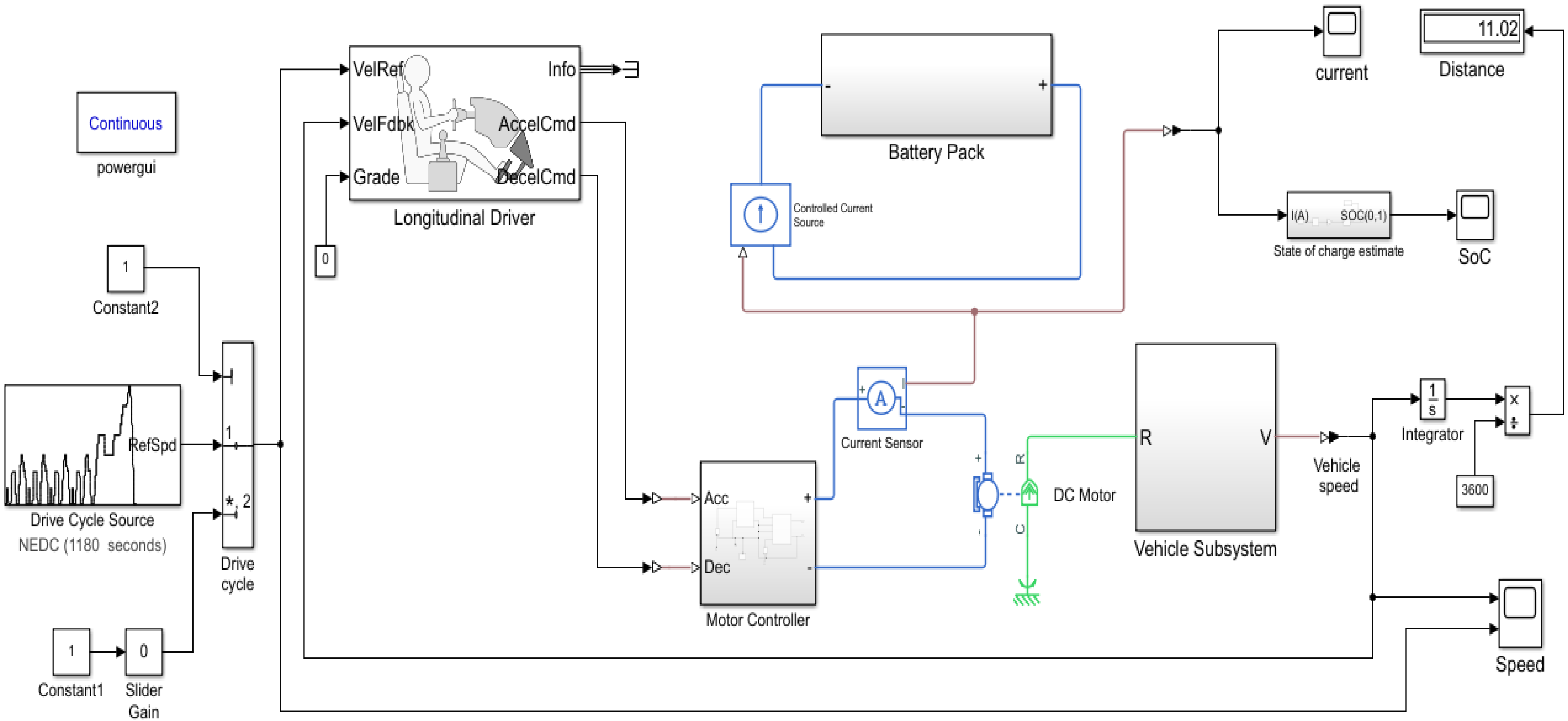

Figure 3.15. BEV with DC motor drive

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Introduction

The ICE power and torque as functions of speed are far from the ideal constant power characteristic. The engine cannot operate at speeds below a minimum (idle) speed. The available output power reaches a maximum at relatively high speed. In contrast, an electric motor can produce maximum torque starting from zero speed, and has the desirable constant power characteristic starting from a base speed (vb) up to a maximum speed limit. To match the engine capabilities with the traction power requirements over a wide range of vehicle speeds, a conventional ICE driven vehicle must include a multigear transmission. In contrast, an electric vehicle can operate with a simpler, more efficient single-gear transmission.

4.2 Electric Motor Performance

Using a computer Programming Language (C++) and Application Software's (MS-Excel), the expected '**Electric motor** Performance Curves' can be plotted as shown in Figure 4.1 below.

Table 4.1. Electric motor performance

Speed	Power	Torque
N (rpm)	P (kW)	T (Nm)
0	0	185.37
500	25.71	185.37
1000	51.42	185.37
1.50E+03	77.12	185.37
2.00E+03	102.83	185.37
2.50E+03	128.54	185.37
3.00E+03	154.25	185.37
3.50E+03	179.96	185.37
4.00E+03	205.66	185.37
4.50E+03	231.37	185.37
5.00E+03	257.08	185.37
5.00E+03	257.08	185.37
5.50E+03	257.08	168.52
6.00E+03	257.08	154.48
6.50E+03	257.08	142.59
7.00E+03	257.08	132.41
7.50E+03	257.08	123.58
8.00E+03	257.08	115.86
8.50E+03	257.08	109.04
9.00E+03	257.08	102.98
9.50E+03	257.08	97.56
1.00E+04	257.08	92.69
1.05E+04	257.08	88.27
1.10E+04	257.08	84.26
1.15E+04	257.08	80.6
1.20E+04	257.08	77.24
1.25E+04	257.08	74.15
1.30E+04	257.08	71.3
1.35E+04	257.08	68.66
1.40E+04	257.08	66.2
1.45E+04	257.08	63.92
1.50E+04	257.08	61.79

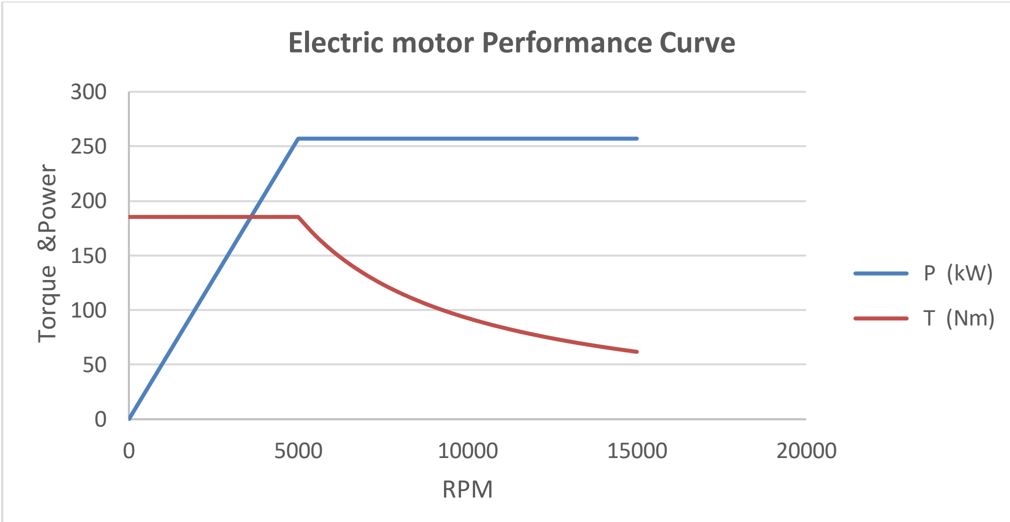

Figure 4.1. Electric motor Performance Curve of Battery Electric Vehicle

In the above Figure 4.1 it shows that, the electric motor starts from zero speed. As it increases to its base speed, the voltage increases to its rated value while the flux remains constant. In this speed range of zero to base speed, the electric motor produces a constant torque. Beyond the base speed, the voltage remains constant and the flux is weakened. This results in a constant output power while the torque declines hyperbolically with speed. Since the speed–torque profile of an electric motor is close to the ideal, a single-gear or double-gear transmission may be employed to meet the vehicle performance requirement, as shown in Figure 4.2.

4.3 Traction force

The expected 'Traction force (F_w)' as shown in Figure 4.2 below.

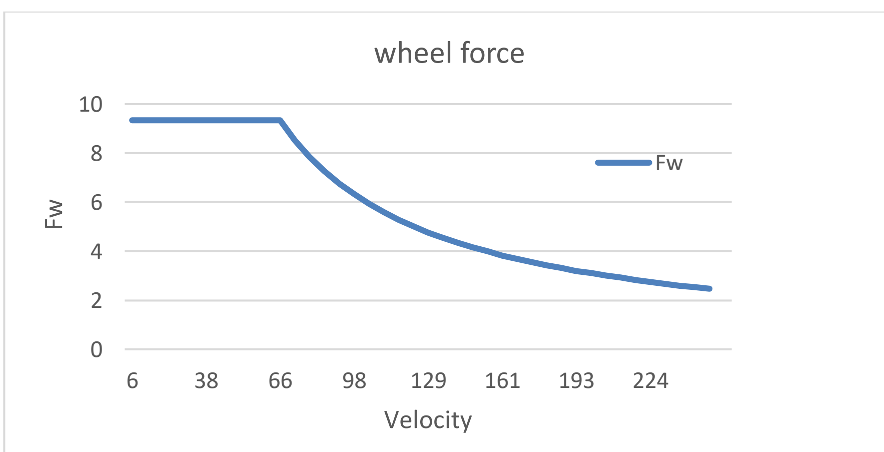

Figure 4.2. BEVs Wheel force

4.4 Resistance Power

The expected 'resistance Power (P_r)' of a rear wheel drive (RWD) Battery electric vehicle, accelerating from rest (v = 0) to a maximum velocity ($v = v_{max}$), can be plotted using a computer Programming Language (C++) as shown in Figure 4.3 below. As the velocity increases resistance power also increases exponentially.

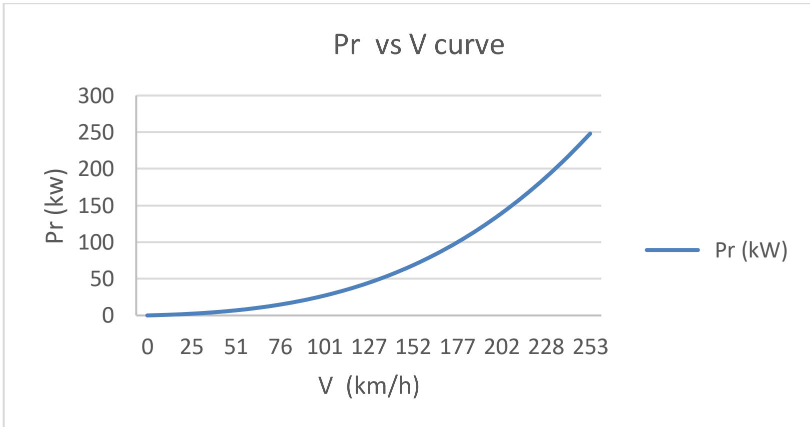

Figure 4.3. Resistance Power on a BEV accelerating on a Level Road

4.5 Drive cycle

The proposed vehicle driving tests and vehicle driving simulations was performed to support the design process and to determine if the design is appropriate for the desired application. The proposed drive cycle has a maximum speed 120 km/hr for 1180 seconds duration. The vehicle was travelled for a distance of 11 km and a duration of 1180 seconds. As we can see in the Figure 4.4 below the vehicle speed follows the path of the drive cycle reference speed which implies the simulation was correct.

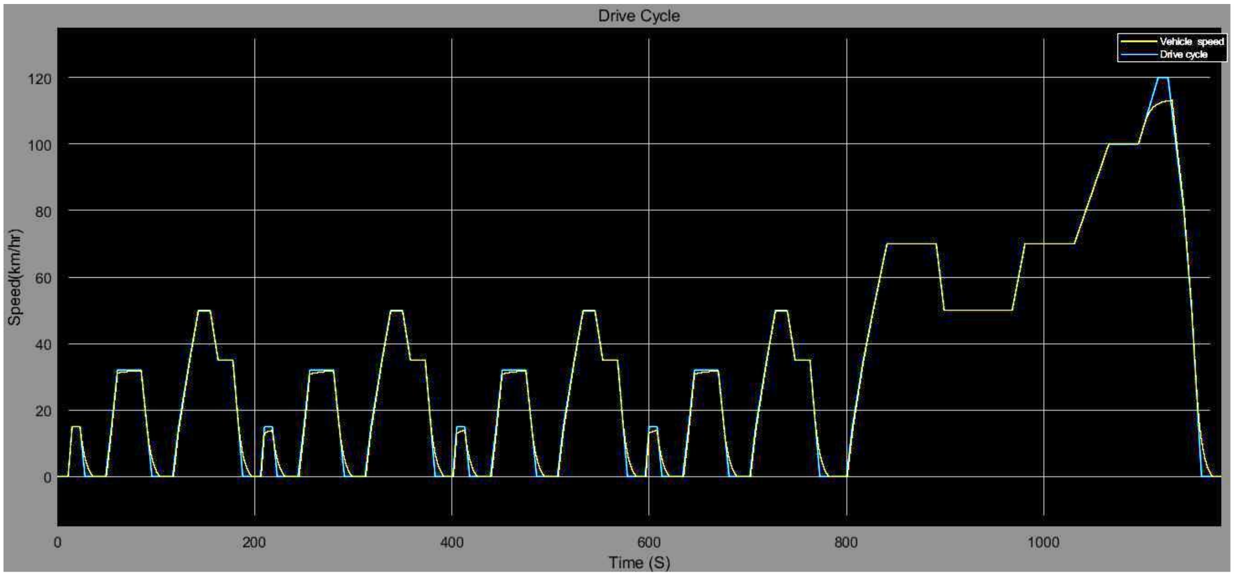

Figure 4.4. Drive cycle

4.6 Battery current

As we can see from Figure 4.5 the battery current varies from positive to negative values. The positive value indicates consumed current whereas the negative current indicates the battery is charged from regenerative braking.

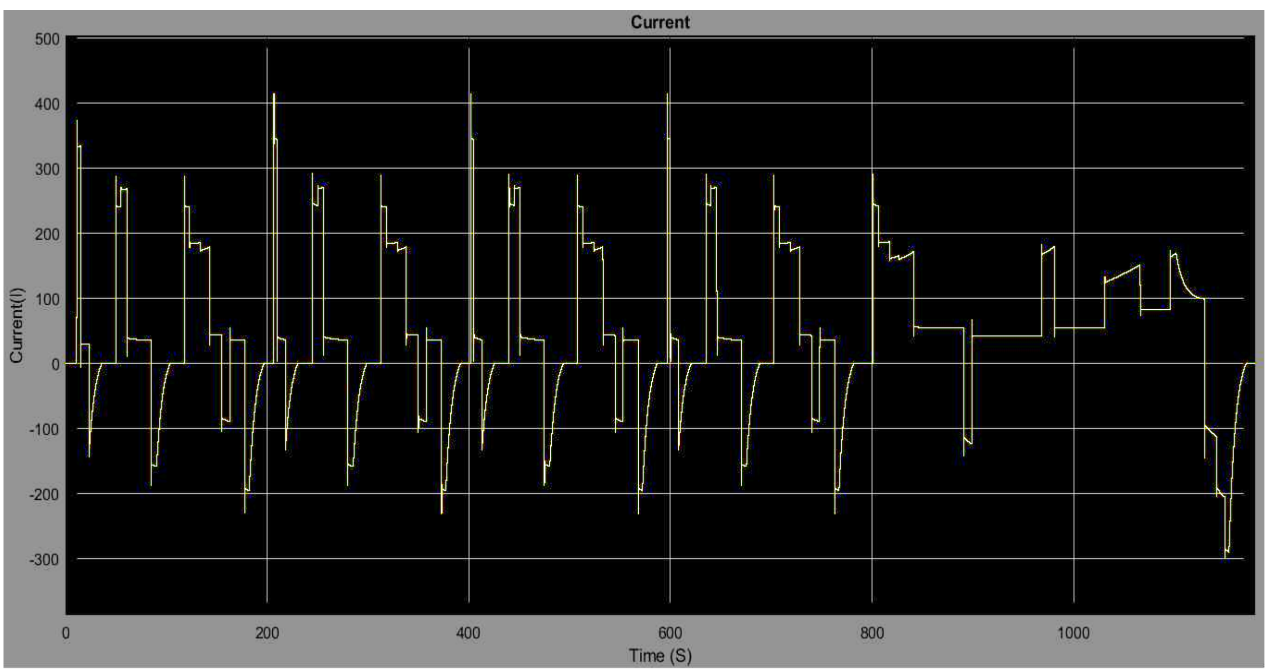

Figure 4.5. Battery current

4.7 State of charge (SOC)

After traveling for a distance of 11.2 km and a duration of 1180 seconds. The battery drops 12% SOC that means it remains SOC of 88% plotted in Figure 4.6 below. As we can see from the figure 4.6 below during acceleration the battery losses a voltage. In contrast the battery was charged from regenerative braking when the vehicles decelerates.

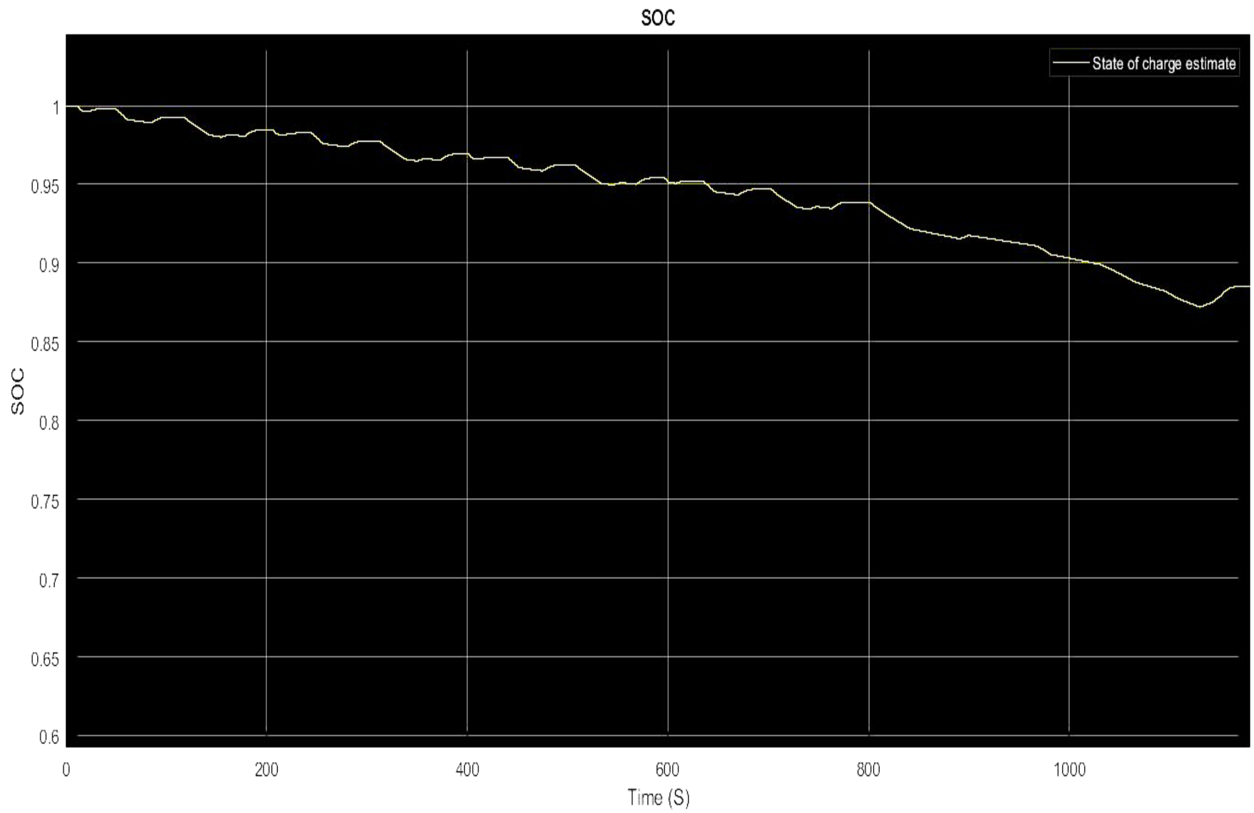

Figure 4.6. Battery SOC in percentage

4.8 BEV over all modeling Simscape result

The proposed battery electric vehicle (BEV) over all modeling result From MATLAB/simscape result explorer is given below.

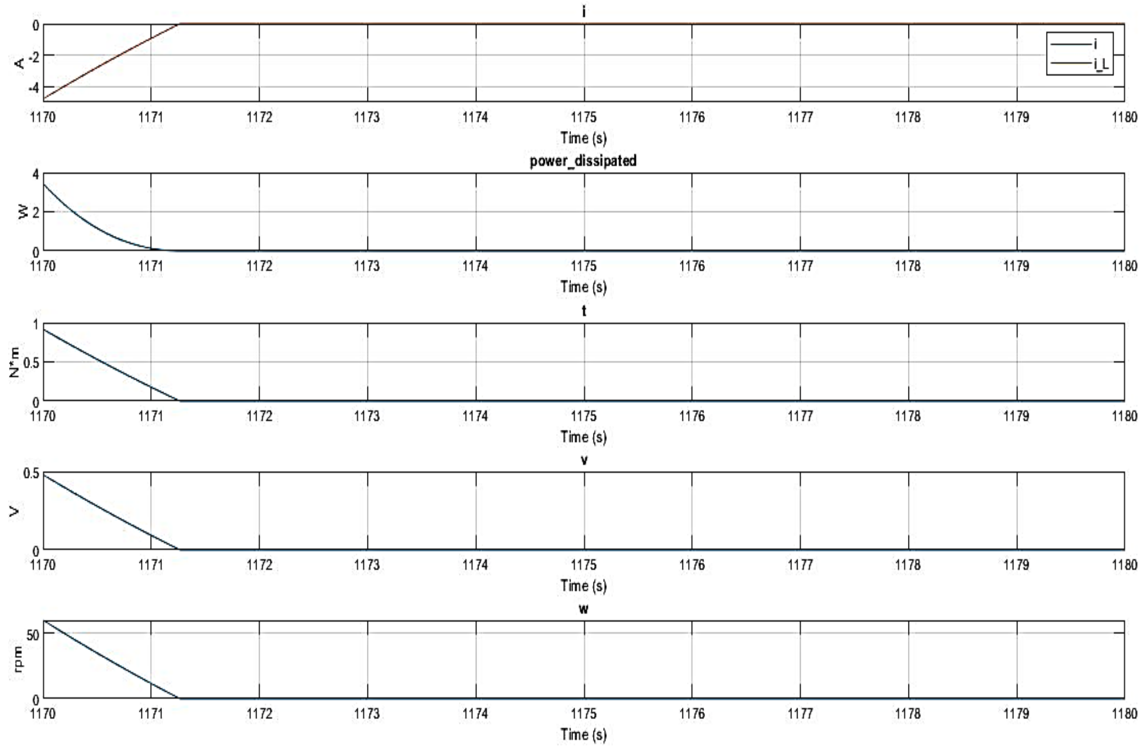

Figure 4.7. DC motor Simscape result

After the vehicle was decelerated from 1170 up to 1180 seconds due to braking the power, torque and voltage dissipated becomes zero starting from 1171 second in the DC motor and the H Bridge that is given in the above and below figure 4.7 and 4.8 respectively.

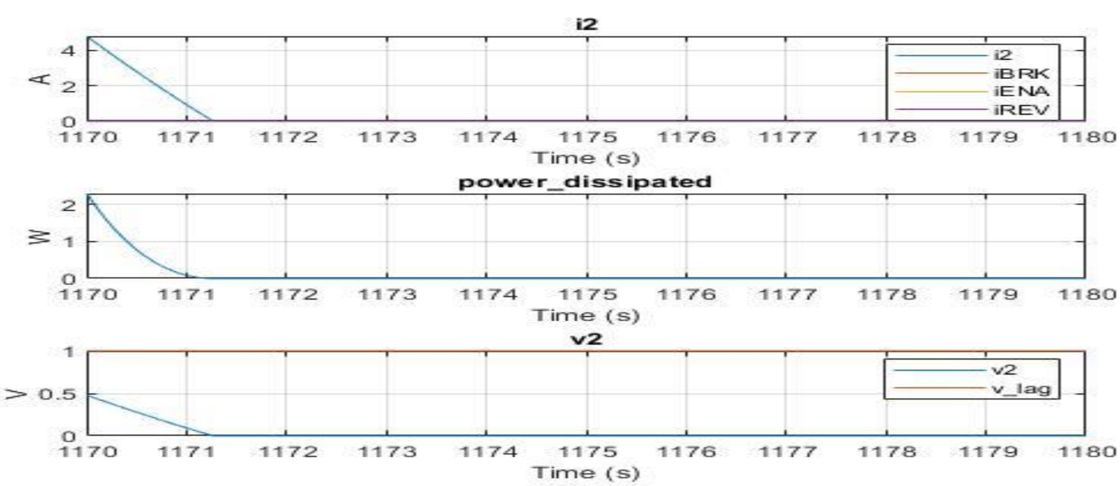

Figure 4.8. H Bridge Simscape result

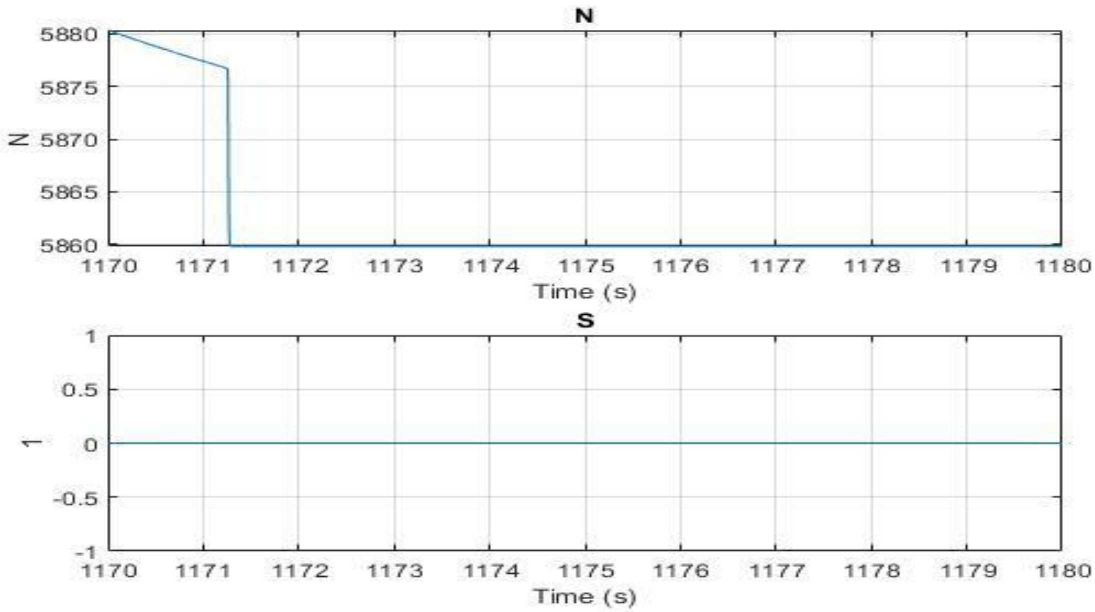

Figure 4.9. Front tyres Simscape result

As we can see from the above Figure 4.9 when the vehicle was decelerated from 1170 up to 1180 seconds the normal force at the front tyre has begun declining to 5860 N whereas the slip was zero due to no traction at front wheels. And in the below Figure 4.10 we can see that the rear tyre has a negative slip. Hence the vehicle was rear wheel drive (RWD), slip was occurred in the rear wheel and the negative slip indicates that the vehicle was skidding due to braking.

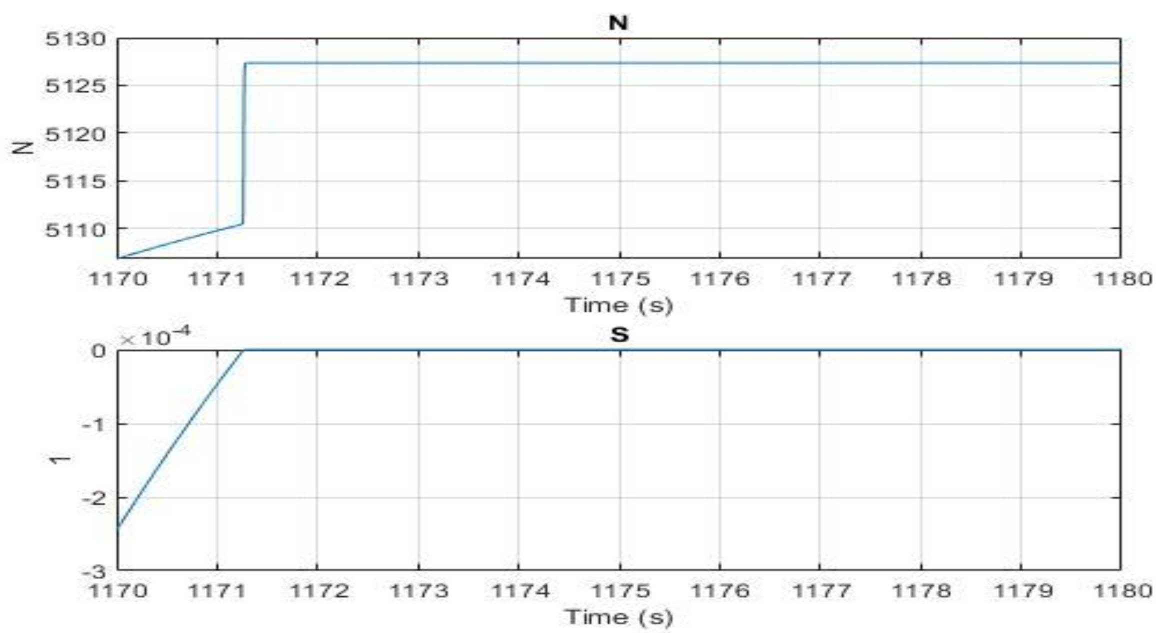

Figure 4.10. Rear tyres Simscape result

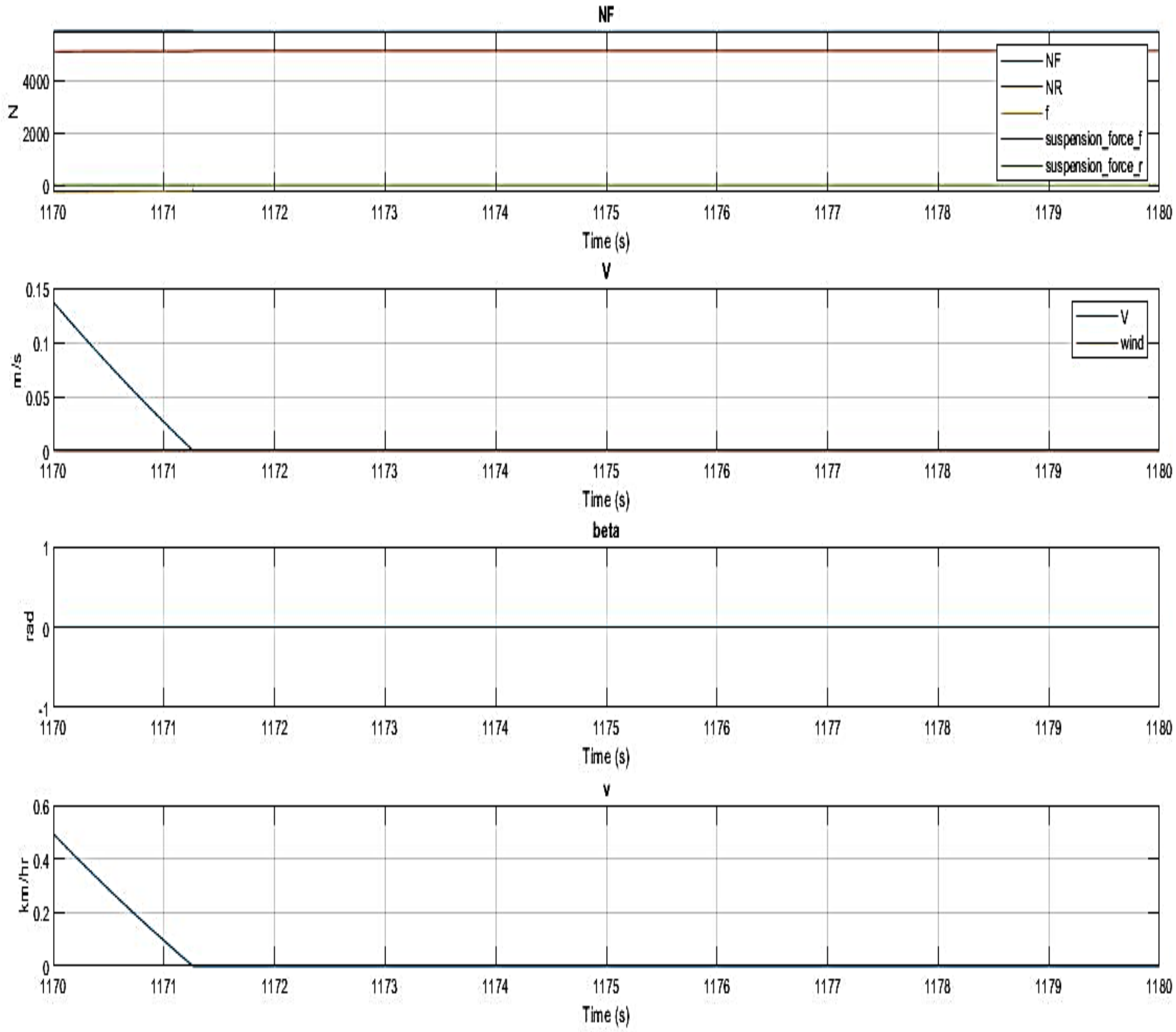

Figure 4.11. Vehicle body Simscape result

As we can see from the above Figure 4.11 when the vehicle was decelerated from 1170 up to 1180 seconds the wind and inclination angle becomes zero since the vehicle was travelled at horizontal surface and the suspension forces was zero because it was not considered in the proposed parameters.

CHAPTER FIVE

CONCULUSION AND RECOMMENDATIONS

5.1 Summary

This thesis work deals with the designing, modeling and simulating of a BEV power train components with DC motor drive. A detailed model of Battery pack and the overall model of powertrain components of the vehicle was developed in MATLAB/Simscape environment. Motor and drive parameters were chosen to be close to the 2016 Tesla model S system. A 360 Voltage battery pack was modeled using Simscape and the other power train components were taken from Simscape physical modeling.

After the designing and modeling of the vehicle was done with an attachment of a longitudinal driver to ensure proper operation during acceleration and deceleration by comparing the command from the drive cycle reference speed and an actual speed of the vehicle. Results were very satisfactory in terms of showing how the vehicle was moving with the drive cycle distance covered, the battery state of charge (SOC), current can be tested and then evaluated for optimum points to minimize energy loss which is the achievement in the proposed model. Maximizing the mileage from a battery is just one application where this technique can be used very effectively.

5.2 Conclusion

Cars powered by internal combustion engines have been the technological solution that dominated the automotive industry and coined the way that transport systems have been organized globally. Given the urgent need to decarbonize the world economy, however, alternative powertrain technologies are now gaining competitive advantages, and industries have to adapt. Hybrid and fully electric powertrains attract considerable investments, and so do new mobility concepts and services at the interface of the transport and the energy system. How industries adapt, which alternatives emerge, how rapidly they become competitive.

In this work, an introductory information of Electric Vehicles was covered with historical developments until today. In addition to it, one can find sufficient information of the resistive forces acting on the vehicle while subject to different driving conditions, which in this work is being represented by theoretical driving cycles.

The model created in this work is quite simple to understand and gives a fine idea of different BEV power train components. When going through observations obtained via simulations at driving cycles, we can see that battery's state of charge depends on speed, acceleration, deceleration and slope on which vehicle is subjected.

5.3 Recommendations

To further improve this model, there are several areas that can be considered. One major area that would greatly enhance this model is the do further optimization to capture the regenerative braking energy. Switching points of down-shifting can be optimized to yield the highest recapture of the energy during braking. Other areas that can be further developed to be more realistic would be the battery, the dc-dc converter, and the inverter. These components also add multiple non-linear effects and were beyond the scope of this project. However, in order to get more accurate results for the energy optimization, these models can be taken into account. Actual components used to realize these sub-systems (inductors, power MOSFETs. IGBTs, etc.) Can add complexities to modeling and simulation, but may provide other insights into the behavior of the overall simulation.

This model also can be further studied with different power sources and energy storage devices, such as ultra-capacitors, Fuel cells, Flywheels and more. Thermal modelling for batteries with the effect of ambient temperature can also be included for further work. This model is flexible and easy to modify with the basic knowledge of MATLAB. One can change data inputs from the specification sheets obtained from manufacturer.

5.4 Future work

Most of battery electric vehicle (BEV) manufacturers including Tesla Motor Corporation are producing BEVs with Three phase AC induction motor drive, Inverter, DC-DC converter and PID controller. Therefore a battery electric vehicle with induction motor drive and with different drive cycles test will be my future work.

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APPENDIX A: VEHICLE SPECIFICATION

BEV Specification	
Vehicle Model	Tesla Model S
Length (**L**)	4980 mm
Width (**W**)	1964 mm
Height (**H**)	1440 mm
Wheelbase ($\boldsymbol{W_b}$)	2960 mm
Centre of gravity	460 mm
Mass of the vehicle (m_v)	2240 kg
Maximum velocity of the vehicle (v)	220 km/h
Front wheel distribution	48%
Rear wheel distribution	52%
Type of drive	RWD
Tire size	235/35R21
Wheel radius	350 mm
Drag coefficient (C_d)	0.34
Rolling resistance coefficient (C_r)	0.01
Frontal area (A_f)	2.4 m^2
Density of air (ρ_a)	1.3 kg/m^3
Battery type	Lithium ion ($LiMn_2O_4$)
Battery capacity	360 v
Traction motor type	DC motor
Motor efficiency	88%
Gear ratio	9:1

APPENDIX B: VEHICLE PERFORMANCE USING C++ CODE

```
// Electric Vehicle Design (EVD).
#include<iostream.h>
#include<conio.h>
#include<math.h>
#include<fstream.h>
#include<iomanip.h>
 void main()
  {
 Start:
   clrscr();
    char ch1;
   float
L,W,H,wb,rw,Wv,v_max,PHI_max,PHI_min,WD_FWper,bmep_Pbmax,bsfc_Pbmax;
   float
Zs,Zc,N_min,FN_TbPb,GR_P,GR_B,GR_T,GR_F,ETA_Gtper,Cd,SF,OptG,RHOa;
   float g,Factv,RN_TbPb,ETA_Gt,WD_FW,FzF,FzR,Apf,radsin_PHImin,Pr_vmax;
   float
radsin_PHImax,v_min,v_Pbmax,v_maxL,delv,v_mps,v_mpsPbmax,Ra,Rg,RrlF;
   float Rtr,Pr,Pw,RrlR,Pw_max,Pb_max,v,v_Pbmaxmps,v_maxmps,v_maxmpsL;
   float OMEGAw_Pbmax,OMEGAw_max,Nw_Pbmax,N_Pbmax,OMEGAw_maxL,Nw_maxL;
   float
Nw_max,N_max,N_Tbmax,OMEGA_Tbmax,xii,Pb_Tbmax,Tb_max,Zrpc,N,bmep_Pa;
   float
ncps_Pbmax,ncps_Tbmax,Ec,Ec_cc,delN,x,Pb,OMEGA,Tb,ncps,bmep,bsfc;
   float ETA_vMmax,ETA_vMmin,ZMmin,ZMmax,dd_iv,dd_ivsqr,ZMa,ZM,ETA_v,AF;
   float
ETA_vper,Vs_cc,Vcl_cc,Vt_cc,powd,d,d_mm,s,s_mm,d_iv,Vs,Kfl_iv,Rsd;
   float nRTs,Cs,RHOim,div,Csa,ddiv,ZMb,ETA_vPbmax,ZM_Pbmax,RNv_GBmax;
// Vehicle Performance:
   float
Tw,Fw,Rg_1,Rtr_1,Fw_GT,v_GBmin,v_GBmax,v_GTmin,v_GTmax,Tw_GB,Fw_GB;
   float
Rg_GB,Rtr_GB,Tw_GT,Rg_GT,Rtr_GT,Rrl,v_GBPbmax,v_GBmps,GR_tT,GR_tB;
   float
ETA_GtT,ETA_GtB,N_vmax,OMEGA_vmax,xiii,Pb_vmax,Tb_vmax,ncps_vmax;
   float
Pr_vPbmax,ETA_vPbmaxper,bsfc_Tbmax,bmep_Tbmax,ETA_vTbmax,Tb_Pbmax;
```

```
   float ETA_vTbmaxper,bsfc_vmax,bmep_vmax,ETA_vvmax,ETA_vvmaxper,delv2;
   float OMEGA_Pbmax,N_maxL,N_GBvmax,bsfc1,bmep1,Tb1,GR_t,Pm_vmax;
// Electric Motor:
   float
Pm_max,Nm_bs,GRi_ed,GRt,OMEGA_bs,Tm_a,v_bs,Ftr_stat,Ftr_dyn,mv_lb;
   float
Whpmile,kWhpkm,Ftr,Nm,OMEGAm,Tm,Nm_max,vm_max,Nv_ratio,PHI_maxm;
   float
ETA_GtBm,v_bsmps,Ra_bs,Rrl_bs,Rtr_bs,Rg_bs,radsin_PHImaxm,vm_bs;
   const float PI = 3.14; g = 9.81;
 ofstream outfile ("EVD.dat");
 clrscr();
  cout << "\n\n\t\t  Adama Science and Technology University (ASTU) ";
  cout << " \n\t       Mechanical Systems and Vehicle Engineering ";
  cout << " \n\t\t         Getnet Admasu (MSc Student) ";
  cout << "\n\t\t\t       ****************** ";
  cout << " \n\n\t\t       Electric Vehicle Design (EVD) " ;
  cout << "\n -----------------------------------------------------------
-------------------- ";
  outfile << "\n\n\t\t  Adama Science and Technology University (ASTU) ";
  outfile << " \n\t       Mechanical Systems and Vehicle Engineering ";
  outfile << " \n\t\t         Getnet Admasu (MSc Student) ";
  outfile << "\n\t\t\t       ****************** ";
  outfile << " \n\n\t\t       Electric Vehicle Design (EVD) " ;
  outfile << "\n -------------------------------------------------------
----------------------- ";
  cout <<"\n  Enter the 'vehicle Length (L)' in 'm': ";
  cin >> L;
  cout <<"\n  Enter the 'vehicle Width (W)' in 'm': ";
  cin >> W;
  cout <<"\n  Enter the 'vehicle Height (H)' in 'm': ";
  cin >> H;
  cout <<"\n  Enter the 'length of wheelbase (wb)' in 'm': ";
  cin >> wb;
  cout <<"\n  Enter the 'effective tyre or wheel radius (rw)' in 'm': ";
  cin >> rw;
  cout <<"\n  Enter the 'vehicle Weight (Wv)' in 'N': ";
  cin >> Wv;
```

```
  cout <<"\n  Enter the 'Weight Distribution on the Front Wheels' (40% to 60%): ";
  cin >> WD_FWper;
  cout <<"\n  Enter the 'maximum vehicle velocity (v_max)' in 'km/h': ";
  cin >> v_max;
  cout <<"\n  Enter the 'vehicle velocity at maximum gradient (v_GB)' in 'km/h': ";
  cin >> v_GBPbmax;
  cout <<"\n  Enter the 'total gear ratio (GR_t)' (5 to 15): ";
  cin >> GR_t;
  cout <<"\n  Enter the 'total transmission efficiency (ETA_Gt)' (80 to 90 %): ";
  cin >> ETA_Gtper;
  cout <<"\n  Enter the 'drag Coefficient (Cd) of the vehicle' (0.2 to 0.6): ";
  cin >> Cd;
  cout <<"\n  Enter the 'Shape Factor (SF) for the vehicle's frontal area' (0.5 to 0.9): ";
  cin >> SF;
   Factv = 1.15; PHI_min = 0.0; RHOa = 1.2; GR_tT = GR_t; GR_tB = GR_t;
   radsin_PHImin = PHI_min*(PI/180.0); Apf = W*H*SF;
   ETA_Gt = ETA_Gtper/100.0; ETA_GtT = ETA_Gt; ETA_GtB = ETA_Gt;
   WD_FW = WD_FWper/100.0; FzF = WD_FW*Wv; FzR = (1.0-WD_FW)*Wv;
  clrscr();
  cout << "\n\n\t\t  Adama Science and Technology University (ASTU) ";
  cout << " \n\t       Mechanical Systems and Vehicle Engineering ";
  cout << " \n\t\t          Getnet Admasu (MSc Student) ";
  cout << "\n\t\t\t       ****************** ";
  cout << " \n\n\t\t       Electric Vehicle Design (EVD) " ;
  cout << "\n -------------------------------------------------------------------------------- ";
  cout << "\n\n  'Vehicle Resistance' ";
  cout << "\n ________________________ ";
  cout << "\n\n Select the 'type of Drive' for the Vehicle, \n";
  cout << "\n   1. Front Wheel Drive (FWD) ";
  cout << "\n   2. Rear Wheel Drive (RWD) ";
  cout << "\n   3. Four Wheel Drive (4WD) ";
  cout << "\n\n Enter your choice (1 or 2 or 3): ";
```

```
cin >> ch1;
 v_min = 0.0; v_Pbmax = v_max; v_maxL = Factv*v_max;
 delv = (v_maxL-v_min)/20.0;
   if ( ch1 == '1' )
    goto Perform1;
    else if ( ch1 == '2' )
    goto Perform2;
    else if ( ch1 == '3' )
    goto Perform3;
cout << "\n\n  Press 'Enter' twice, to 'proceed'.... ";
getch();
getch();
getch();
clrscr();
Perform1:
cout << "\n\n 'Pr' versus 'v' ";
cout << "\n __________________";
cout << "\n\n\t  v\t  Pr ";
cout << "\n\t(km/h)\t (kW) \n";
outfile << "\n\n\n\t 'Pr' versus 'v' ";
outfile << "\n\t ____________________";
outfile << "\n\n\t\t  v\t  Pr ";
outfile << "\n\t\t(km/h)\t (kW) \n";
for(v = v_min; v <= v_maxL; v = v+delv)
 {
   v_mps = v/3.6;
   Ra = 0.5*RHOa*Cd*Apf*(v_mps*v_mps); Rg = Wv*radsin_PHImin;
   Rrl = (0.01+(0.00016*v))*Wv; Rtr = Rrl+Ra+Rg;
   Pr = (Rtr*v_mps)*1.0e-3;
cout << setprecision(2)<<"\n\t "<<v;
cout << setprecision(2)<<"\t "<<Pr;
outfile << setprecision(2)<<"\n\t\t "<<v;
outfile << setprecision(2)<<"\t "<<Pr;
getch();
 }
goto Perform4;
```

```
Perform2:
cout << "\n\n\n 'Pr' versus 'v' ";
cout << "\n ____________________";
cout << "\n\n\t  v\t  Pr ";
cout << "\n\t(km/h)\t (kW) \n";
outfile << "\n\n\n\t 'Pr' versus 'v' ";
outfile << "\n\t ____________________";
outfile << "\n\n\t\t  v\t  Pr ";
outfile << "\n\t\t(km/h)\t (kW) \n";
for(v = v_min; v <= v_maxL; v = v+delv)
 {
   v_mps = v/3.6;
   Ra = 0.5*RHOa*Cd*Apf*(v_mps*v_mps); Rg = Wv*radsin_PHImin;
   Rrl = (0.01+(0.00016*v))*Wv; Rtr = Rrl+Ra+Rg;
   Pr = (Rtr*v_mps)*1.0e-3;
cout << setprecision(2)<<"\n\t "<<v;
cout << setprecision(2)<<"\t "<<Pr;
outfile << setprecision(2)<<"\n\t\t "<<v;
outfile << setprecision(2)<<"\t "<<Pr;
getch();
 }
goto Perform4;
Perform3:
cout << "\n\n\n 'Pr' versus 'v' ";
cout << "\n ____________________";
cout << "\n\n\t  v\t  Pr ";
cout << "\n\t(km/h)\t (kW) \n";
outfile << "\n\n\n\t 'Pr' versus 'v' ";
outfile << "\n\t ____________________";
outfile << "\n\n\t\t  v\t  Pr ";
outfile << "\n\t\t(km/h)\t (kW) \n";
for(v = v_min; v <= v_maxL; v = v+delv)
 {
   v_mps = v/3.6;
   Ra = 0.5*RHOa*Cd*Apf*(v_mps*v_mps); Rg = Wv*radsin_PHImin;
   Rrl = (0.01+(0.00016*v))*Wv;
```

```
      Rtr = Rrl+Ra+Rg;
      Pr = (Rtr*v_mps)*1.0e-3;
   cout << setprecision(2)<<"\n\t "<<v;
   cout << setprecision(2)<<"\t "<<Pr;
   outfile << setprecision(2)<<"\n\t\t "<<v;
   outfile << setprecision(2)<<"\t "<<Pr;
   getch();
    }
   goto Perform4;
  Perform4:
    cout <<"\n\n  Enter the resistance Power at: v = "<<v_max<<" km/h : ";
    cin >> Pr_vmax;
      Pw_max = Pr_vmax; Pm_vmax = Pw_max/ETA_GtT; Pm_max = Pm_vmax;
      Nm_max = ((2.65*GR_tT)/rw)*v_max;
     cout <<"\n\n\t  * Pm_max = "<<setprecision(2)<<Pm_vmax<<" kW  at  N
 = "<<Nm_max<<" rpm ";
   cout << "\n\n  Press 'Enter' twice, to 'proceed'.... ";
   getch();
   getch();
   getch();
   clrscr();
   cout << "\n\n  'Vehicle Performance' (EV) ";
   cout << "\n ___________________________________ ";
   outfile << "\n\n  'Vehicle Performance' (EV) ";
   outfile << "\n ___________________________________ ";
   cout << "\n\n\t v\t Fw_m ";
   cout << "\n\t(km/h)\t (kN) \n";
   outfile << "\n\n\t v\t Fw_m ";
   outfile << "\n\t(km/h)\t (kN) \n";
        Nv_ratio = (2.65*GR_t)/rw;
        Nm_bs = 0.3*Nm_max; vm_max = Nm_max/Nv_ratio;
        OMEGA_bs = (2.0*PI*Nm_bs)/60.0; Tm_a = (Pm_max*1.0e3)/OMEGA_bs;
        v_bs = Nm_bs*(rw/(2.65*GR_t)); v_bsmps = v_bs/3.6; vm_bs = v_bs;
        Ra_bs = 0.5*RHOa*Cd*Apf*(v_bsmps*v_bsmps);
        Rrl_bs = (0.01+(0.00016*v_bs))*Wv;
        Rtr_bs = (Pm_max*1.0e3*ETA_Gt)/v_bsmps;
```

```
     Rg_bs = Rtr_bs-(Rrl_bs+Ra_bs); radsin_PHImaxm = Rg_bs/Wv;
     PHI_maxm = radsin_PHImaxm*(180.0/PI);
     Ftr_stat = (0.02*Wv)/1000.0; Ftr_dyn = (0.015*Wv)/1000.0;
     mv_lb = (Wv/g)*2.2; Whpmile = mv_lb/10.0;
     kWhpkm = (Whpmile/1.6)*1.0e-3; delv2 = (v_maxL-v_min)/40.0;
for (v = v_min; v <= v_bs; v = v+delv2)
 {
    Ftr = ((Tm_a*GR_t*ETA_Gt)/rw)*1.0e-3;
    cout << setprecision(2)<<"\n\t "<<v;
    cout << setprecision(2)<<"\t "<<Ftr;
    outfile << setprecision(2)<<"\n\t "<<v;
    outfile << setprecision(2)<<"\t "<<Ftr;
    getch();
     }
for (v = v_bs; v <= v_maxL; v = v+delv2)
 {
    Nm = ((2.65*GR_t)/rw)*v; OMEGAm = (2.0*PI*Nm)/60.0;
    Tm = (Pm_max*1.0e3)/OMEGAm; Ftr = ((Tm*GR_t*ETA_Gt)/rw)*1.0e-3;
    cout << setprecision(2)<<"\n\t "<<v;
    cout << setprecision(2)<<"\t "<<Ftr;
    outfile << setprecision(2)<<"\n\t "<<v;
    outfile << setprecision(2)<<"\t "<<Ftr;
    getch();
     }
getch();
cout << "\n\n\t GR_t = "<<GR_t<<":1";
cout << "\n\t Pm_max = "<< setprecision(2)<<Pm_max<<" kW";
cout << "\n\t Nm_max = "<< setprecision(3)<<Nm_max<<" rpm";
cout << "\n\t v_max = "<<v_max<<" km/h";
cout << "\n\t vm_bs = "<<vm_bs<<" km/h";
cout << "\n\t PHI_maxm = "<<PHI_maxm<<" deg.";
cout << "\n\t Ftr_stat = "<<Ftr_stat<<" kN";
cout << "\n\t Ftr_dyn = "<<Ftr_dyn<<" kN";
cout << "\n\t Range = "<<kWhpkm<<" kWh/km";
outfile << "\n\n\t GR_t = "<<GR_t<<":1";
outfile << "\n\t Pm_max = "<< setprecision(2)<<Pm_max<<" kW";
```

```
 outfile << "\n\t Nm_max = "<< setprecision(3)<<Nm_max<<" rpm";
 outfile << "\n\t v_max = "<<v_max<<" km/h";
 outfile << "\n\t vm_bs = "<<vm_bs<<" km/h";
 outfile << "\n\t PHI_maxm = "<<PHI_maxm<<" deg.";
 outfile << "\n\t Ftr_stat = "<<Ftr_stat<<" kN";
 outfile << "\n\t Ftr_dyn = "<<Ftr_dyn<<" kN";
 outfile << "\n\t Range = "<<kWhpkm<<" kWh/km";
 cout << "\n\n  Press 'Enter' twice, to 'proceed'.... ";
 getch();
 getch();
 clrscr();
 cout << "\n\n  'Electric Motor Performance' ";
 cout << "\n ------------------------------- ";
 cout <<"\n  Enter the 'motor rated Power (Pm_max)' in 'kW': ";
 cin >> Pm_max;
 cout <<"\n  Enter the 'maximum motor speed (Nm_max)' in 'rpm': ";
 cin >> Nm_max;
 cout <<"\n  Enter the 'motor base speed (Nm_bs)' in 'rpm': ";
 cin >> Nm_bs;
 cout << "\n\n  Press 'Enter' twice, to 'proceed'.... ";
 getch();
 getch();
 getch();
 clrscr();
 cout << "\n\n  'Electric Motor Performance' ";
 cout << "\n ------------------------------- ";
 cout << "\n\n\t  Pb\t  Tb\t   N ";
 cout << "\n\t (kW)\t (Nm)\t (rpm) \n";
 outfile << "\n\n  'Electric Motor Performance' ";
 outfile << "\n ------------------------------- ";
 outfile << "\n\n\t  Pb\t  Tb\t   N ";
 outfile << "\n\t (kW)\t (Nm)\t (rpm) \n";
     OMEGA_bs = (2.0*PI*Nm_bs)/60.0; Tm_a = (Pm_max*1.0e3)/OMEGA_bs;
     delN = 500.0;
for(N = N_min; N <= Nm_bs; N = N+delN)
 {
```

```
   OMEGA = (2.0*PI*N)/60.0;
   Tb1 = Tm_a; Pb = (Tb1*OMEGA)/1000.0; Tb = Tb1/2.65;
    cout << setprecision(2)<<"\n\t "<<Pb;
    cout << setprecision(2)<<"\t "<<Tb;
    cout << setprecision(2)<<"\t    "<<N;
    outfile << setprecision(2)<<"\n\t "<<Pb;
    outfile << setprecision(2)<<"\t "<<Tb;
    outfile << setprecision(2)<<"\t    "<<N;
    getch();
     }
for(N = Nm_bs; N <= Nm_max; N = N+delN)
{
   OMEGA = (2.0*PI*N)/60.0; Tm_a = (Pm_max*1.0e3)/OMEGA;
   Pb = Pm_max; Tb1 = (Pb*1.0e3)/OMEGA; Tb = Tb1/2.65;
    cout << setprecision(2)<<"\n\t "<<Pb;
    cout << setprecision(2)<<"\t "<<Tb;
    cout << setprecision(2)<<"\t    "<<N;
    outfile << setprecision(2)<<"\n\t "<<Pb;
    outfile << setprecision(2)<<"\t "<<Tb;
    outfile << setprecision(2)<<"\t    "<<N;
    getch();
     }
cout << "\n\n  Press 'Enter' twice, to 'proceed'.... ";
getch();
getch();
getche();}
```