Escola Politècnica Superior
d'Enginyeria de Vilanova i la Geltrú
UNIVERSITAT POLITÈCNICA DE CATALUNYA

EPS - PROJECT

TITLE:	Design and creation of different simulation architectures for hybrid and electric vehicles
STUDENTS:	Josep Maria Fabrega Vedat Kilickaya Xavier Laxague Patrick Satchell Ioan Tudosa
SUPERVISORS:	Angels Hernandez Pere Andrada
DATE:	10 June 2010

TITLE: Design and creation of different simulation architectures for hybrid and electric vehicles

FAMILY NAME: Fabrega **FIRST NAME:** Josep

HOME UNIVERSITY: Universitat Politecnica de Catalunya

SPECIALITY: Electronics and Automatics Engineering

FAMILY NAME: Kilickaya **FIRST NAME:** Vedat

HOME UNIVERSITY: Dumlupinar University

SPECIALITY: Electrical-Electronic Engineering

FAMILY NAME: Laxague **FIRST NAME:** Xavier

HOME UNIVERSITY: Technical School of Tarbes

SPECIALITY: Electrical and Electronic Power Systems Engineering

FAMILY NAME: Satchell **FIRST NAME:** Patrick

HOME UNIVERSITY: South Dakota School of Mines and Technology

SPECIALITY: Industrial Engineering, Engineering Management, Process Design

FAMILY NAME: Tudosa **FIRST NAME:** Ioan

HOME UNIVERSITY: Technical University of Iasi

SPECIALITY: Electrical Engineering

Abstract

Development of electric vehicle architectures requires complex analysis and innovative designs in order to produce a highly efficient mode of personal transportation acceptable to the target demographic. Using computer-aided modeling and simulation has been proven to decrease the development time of conventional vehicles while increasing overall success of the product design. Computer-aided automotive development also allows a fast response to the testing and inclusion of developing technologies in individual systems. Therefore, it follows to use this technique in the research and development of electric vehicles for consumer markets.

This paper presents a system level model development and simulation for an electric vehicle using the Matlab-Simulink platform and its associated process. The current state of the art technologies for electric and plug-in hybrid electric vehicles are given to provide an introduction into the subject. Following, the project development is briefly described, detailing the specific goals for the project and the methods by which results were achieved. Next the paper discusses the analytical and simulation models for each key component as divided by the following systems: battery, charging, and traction. Model assembly and the development of a graphic user interface follows. Finally, the testing procedures for model validation, along with results, and future project works are provided.

Key words: Electric vehicle, Matlab, Simulink, Modeling, Simulation

Contents

List of Figures 6

List of Tables 8

1. Introduction 1

  1.1 Subject 1

  1.2 Purpose 2

  1.3 Plan of Development 2

2. State of the Art 2

  2.1 Electric Vehicles 3

    2.1.1 New EV Architecture Examples 4

  2.2 Plug-in Hybrid Vehicles 6

    2.2.1 New PHEV Technology Examples 6

  2.3 Key Technologies 8

    2.3.1 Batteries and Ultracapacitors 8

    2.3.2 Control Systems 12

    2.3.3 Engines and Motors 13

  2.4 Software Benchmark 17

    2.4.1 Software Overview 17

    2.4.2 Decision matrix 19

3. Project Development 20

  3.1 Project Approach 20

  3.2 Initial Goals 21

  3.3 Revised Goals 22

  3.4 Responsibilities 22

4. Electric Vehicle Model Development 23

  4.1 Systems Design 23

    4.1.1 EV Global System Architecture 23

    4.1.2 Battery and Battery Management 23

    4.1.3 Charging 29

4.1.4 Traction 32
4.1.5 Graphic User Interface 38
4.2 Model Assembly 41
4.2.1 Functionality of the final assembly 41
4.3 Model Validation 42
4.3.1 Component Testing 43
4.3.2 Assembly Testing 44
5. Results 45
5.1 Charging System 45
5.1.1 Battery 45
5.1.2 On-board Charger 45
5.1.3 Generator 46
5.3 Traction system results 48
5.4 Model assembly results 49
6. Project Extensions 52
6.1 Further Model Revisions 52
6.1.1 Assembly improvements 52
6.2 Project Expansion 53
7. Conclusion 54
7.1 Summary 54
7.2 Closing Comments 54
Appendix A: Work Breakdown Structure 55
Appendix B: Software Decision Matrix Template 56
Appendix C: Graphic User Interface Variables 57
Works Cited 59

List of Figures

Figure 1 - Mitsubishi "i" components 3
Figure 2 - Lampo² vehicle components. 4
Figure 3: Tesla Roadster 5
Figure 4: Torque and power relation 5
Figure 5: Toyota Prius PHEV 6
Figure 6: Range Extender 7
Figure 7: Audi A1 e-tron 8
Figure 8: Battery energy chart 9
Figure 9: Chevrolet Volt architecture 10
Figure 10: Cylindrical Li-Ion battery cell 11
Figure 11: Prismatic Li-Ion battery cell 11
Figure 12: BMS role in vehicle management 12
Figure 13: AC induction motors 14
Figure 14: Cross section of a PMSM 15
Figure 15: PMSM vector control block diagram 15
Figure 16: Wave disc engine/generator 17
Figure 17: EV architecture 23
Figure 18: Simulink battery 24
Figure 19: Internal structure of battery model 24
Figure 20: Equivalent circuit of the battery 25
Figure 21: Typical discharge characteristics 25
Figure 22: Discharge characteristics 27
Figure 23: Controller for cooling system 28
Figure 24: State of charge logic diagram 29
Figure 25 : On-board charger model 30
Figure 26. Buck-boost DC converter model 31
Figure 27: Generator management block 32
Figure 28: Traction system overview 33
Figure 29 Traction system overview in Matlab 34
Figure 30: PM synchronous motor drive subsystem 35
Figure 31 : Electrical motor parameters 36
Figure 32: Vehicle dynamics subsystem 37
Figure 33: Graphic user interface screenshot 39
Figure 34: Simulation tab of the graphic interface 39
Figure 35: PMSM block mask 40

Figure 36: Simplified model assembly 41
Figure 37: Output values of battery 45
Figure 38: Output voltage of the charger 46
Figure 39 : Motor/Generator results of the generator validation 47
Figure 40: Battery results of the generator validation 48
Figure 41 First simulation’s result 48
Figure 42 Second simulation's result 49
Figure 43: Requested driving cycle 50
Figure 44: Real speed of the car 50
Figure 45: Electrical motor Power and Torque 50
Figure 46: Electrical motor’s rotor speed 51
Figure 47: Battery characteristics 51

List of Tables

Table 1: Model and simulation softwares 19
Table 2: Output signals delivered by *m*........ 24
Table 3: Battery pack setup parameters........ 26
Table 4: Parameters obtained from simulation 27
Table 5: Charging modes........ 30
Table 6: PM synchronous motor outputs 34
Table 7: Vector controller values 36
Table 8: Tire characteristics........ 38
Table 9: Longitudinal vehicle dynamics values 38

1. Introduction

Development of global perspectives in engineering has become the focus of much academic debate in recent years. An increasingly complex network of communications and resources has led to a global economy and a means of collaborating to develop the technologies of tomorrow. In order prepare students to work on an international scale, the European Project Semester (EPS) was created in 1994 by Dr. Arvid Andersen in Helsingør, Denmark. The project based program focuses on expanding the capacities of students in areas of teamwork, project management, innovation, and several other faculties. Currently, the EPS at the Escola Politecnica Superior d'Enginyeria de Vilanova I la Geltru, Universitat Politecnica d'Catalunya is in its third edition. Of the five projects being conducted, this paper is written in response to the collaborative project between the University and SEAT Automotive entitled *Design and creation of different simulation architectures for hybrid and electric vehicles.*

1.1 Subject

In recent years, the driving force for development and production of mainstream electric vehicles has increased significantly. Environmental concerns and a focus on energy conservation lead this drive with concerns over climate change as the center of discussion. Currently, fossil fuels supply 95% of all transportation related energy, producing 23% of all green house gas (GHG) emissions in 2004 (1). Nearly three-quarters of this contribution is attributed to road vehicles, including personal transport, with predicted increases in transport energy usage at 2% per year (1). As economies continue to grow and developing nations expand at unprecedented rates, the amount of transportation activity only continues to grow proportionally, compounding concerns over transportation related emissions.

Originally invented in 1834, electric vehicles were produced by many companies throughout America, Britain, and France in the last decade of the 19th century (2). Unfortunately, substantial advancements in internal combustion engines, along with a lower price point and greater convenience of use, soon pushed electric vehicles to near existence (2). It was not until interest in environmental issues and reducing dependence on foreign oil after the energy crisis that electric vehicles saw resurgence in the 1960's and 1970's. Today, electric vehicles are used primarily for small vehicle and short distance applications. Technology limitations, specifically batteries, restrict greater market application and are the target of the largest research directives. Overall however, the greatest obstacle to overcome in electric vehicle development is the integration of constantly developing technologies into a viable market alternative for consumers. One way to ensure short development periods, with the flexibility to respond to these developing technologies, is with use of computer based models and simulations in the design process.

This report presents the development of a computer based model in the Matlab-Simulink platform for the purpose of simulating real-world driving cycles to assess different vehicle specifications. Model development is presented based upon the three subsystems used to classify an electric vehicle: battery, charging, and traction. In addition, a graphic user interface was created to allow quick and convenient modifications of the common parameters present in electric vehicles. The overall function of this model is to identify new technologies worth utilizing in future electric vehicles or signaling further research of technologies by assessing their viability when incorporated into a vehicle system.

1.2 Purpose

This document is a technical report written to detail the construction of an electric vehicle model in a computer based simulation program. State of the art technologies are presented to provide a brief description of the current areas of research and development as well as provide the reader with a small amount of background knowledge regarding the components of an electric vehicle.

In order to effectively present the current technologies and development of a computer-based model for electric vehicles, the following questions will serve as a framework for report structure and communication style:

I. What are the current state of the art technologies in electric and plug-in hybrid vehicles;
II. What process is followed for model development;
III. What are the requirements and components of the model, and;
IV. How is a computer-based model of an electric vehicle created.

1.3 Plan of Development

To address the aforementioned questions, the report is structured in the following sections:

I. State of the Art. This section will present an overview of the current state of the art technologies in electric and plug-in hybrid electric vehicles.
II. Project Development. Contained in this section is a description of the process, goals, and responsibilities associated with the final project outcomes.
III. Electric Vehicle Model Developments. In this section, the final model developed will be presented along with sections for the assembly, graphic user interface, and model validation.
IV. Results. Relating to model validation and overall design, the results for the model development will be presented in this section.
V. Project Extensions. As the final subject, future works for the project will be identified.

2. State of the Art

Research and development of new technologies in alternative fuel vehicles is taking place at unprecedented rates. Their subsequent implementation into mainstream transportation solutions is paramount in order to achieve a significant reduction in transportation related GHG emissions. Provided in the text following is an overview of the current state of the art technologies available, specifically targeted at electric vehicle and plug-in hybrid electric vehicle applications.

2.1 Electric Vehicles

An electric vehicle (EV) is a vehicle which is propelled by an electromotive force from an electrical motor. As illustrated in Figure 1, the main components of an EV are the motor, battery system, and on-board charging system. Also seen in the figure are power converters, such as the inverter, which functions to modify the electrical current from the battery before supplying the motor with the required power.

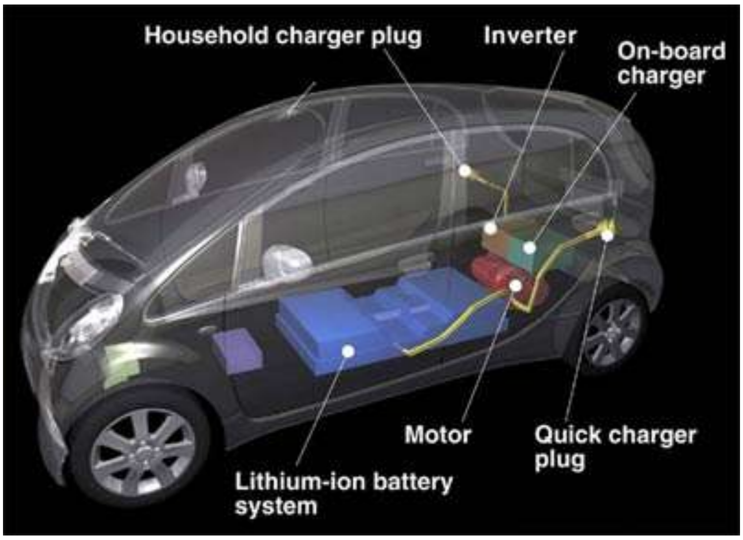


Figure 1 - Mitsubishi "i" components source: www.japanesesportcars.com

Generally, electrical vehicles are composed of only one motor, but some manufacturers implement several motors in order to improve the driving performance of the vehicle. Regardless of the number of motors present, the quantity of electrical power necessary to provide an acceptable driving experience is substantial. Therefore, battery packs are used and can be recharged by two different ways:

When the car is stopped, the only way to recharge the battery is to plug the EV into an electrical source. The recharging time depends on the vehicle's charging system, battery, and the electric source power. In the above case, a household and quick charger system is present.

In the case that the car is in motion and the motor is not needed to supply a propulsion force, such as during a hill descent, the electrical motor can work like a generator. Furthermore, the energy from braking can be recovered and used to recharge the battery in a process called regenerative braking. In this case, the on-board charger is used.

Currently, batteries do not have the capacity to produce a large driving range and their recharge time is long. For city driving however, there are some electric vehicles in the market which become more and more efficient. The next chapter will present two examples of state of the art technology.

2.1.1 New EV Architecture Examples

The objective of EV manufacturers is to produce a method of personal transportation that utilizes electricity rather than fuel for power. Because of the widespread design focus on EVs, new electrical vehicles are developed often and the market is undergoing rapid change. The following presents two example electrical vehicles.

a) Lampo² electrical vehicle:

At the 80th International Motor Show in Genève, Switzerland, new electrical vehicle prototypes were showcased. The Swiss Protoscar company presented their development of an electric sport vehicle called LAMPO². This vehicle has 2 electrical motors, one supplying the front axle with torque and the other at the back axle in order to improve the driving performance. This car has a total output of 300 KW (408hp), a 640N.m (472Lb-ft) of torque, supplied by two 32 KWh lithium-ion batteries. Weight reduction, aerodynamics enhancements, and component efficiency have been employed, resulting in consumption of less than 100Wh/Km. The vehicle accelerates from 0 to 100km/h in 5 seconds with a maximum speed of 200km/h and a range of 200km. Finally, the battery can be recharged with 4 different charging modes. Figure 2 shows the components used in this vehicle.

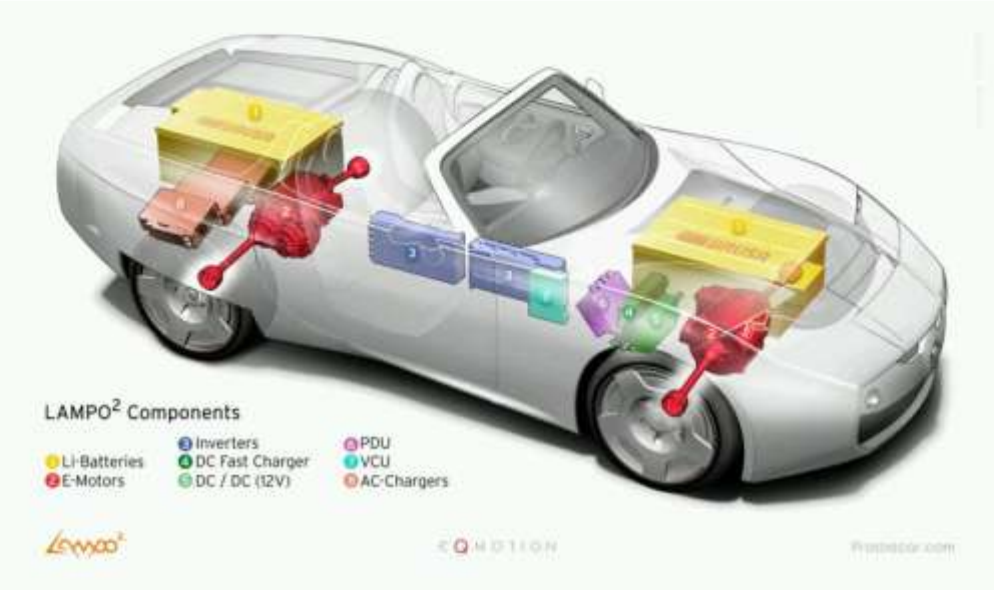


Figure 2 - Lampo² vehicle components. www.unstage.com

b) Tesla Roadster Electrical Vehicle:

The California-based company, Tesla Motors, has sold a very efficient sports car since 2008 called the Tesla Roadster. This EV uses electricity from a Li-ion battery exclusively, resulting in zero CO_2 emissions. The range of the Roadster is 350km and it can accelerate from 0-100km/h in less than 4 seconds. The maximum speed is 200km/h and the battery can be charged in 3h 30min. Of course, this vehicle caries a high price tag, prompting the company to consider producing another less expensive model in the future.

Figure 3: Tesla Roadster

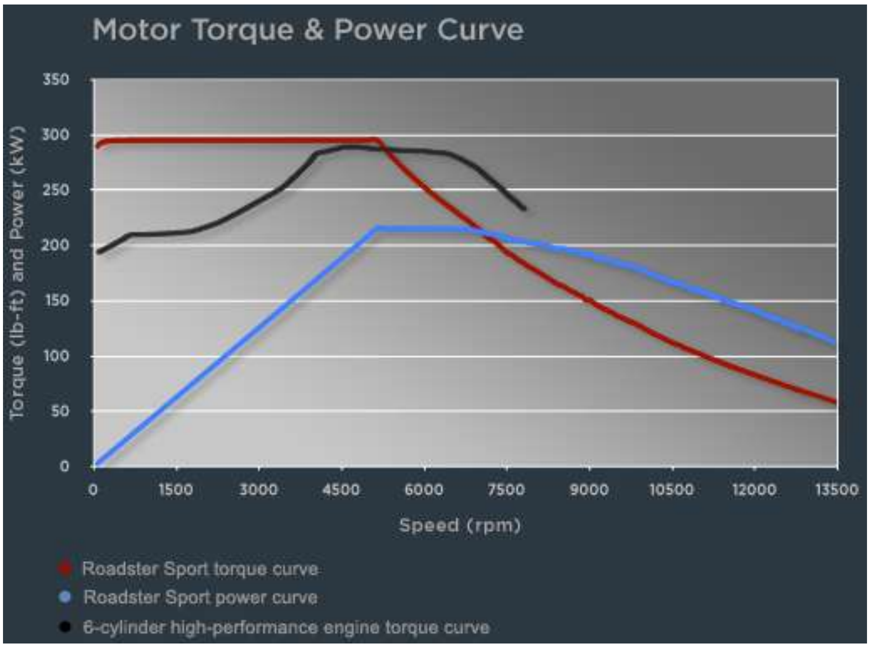


Figure 4: Torque and power relation

In the above chart, the black line represents the torque value during car acceleration in conventional gasoline engines. At low speeds, the torque is very low; becoming important only at high speeds. However, the Tesla electrical motor (in red) has a high torque which is about 300 lb-ft at low speed with a gradual decrease from 6000 until 14,000 rpm. In electrical motors, the evolution of the torque always follows this characteristic plot. It is very important because this evolution adequately meets vehicle requirements. The blue line represents the power increase, without interruption, to a peak of 275kw at 5133 rpm.

2.2 Plug-in Hybrid Vehicles

Figure 5: Toyota Prius PHEV (3)

Plug-in hybrid electric vehicles (PHEVs) are a merger of the benefits found in both pure electric and traditional hybrid vehicles. Utilizing one of the common hybrid vehicle architectures, PHEVs differ in their increase reliance on batteries for stored energy and emphasis on smaller, highly efficient internal combustion engines. The capacity to run in an all electric mode, supplied with power from the grid, coupled with the ability to utilize energy from an internal combustion engine (ICE) offers increased driving range, large fuel and cost savings, emissions reductions, and other benefits. Furthermore, the plug-in capability can also supply energy back to the power grid should it be needed in an emergency. Although PHEVs are still in the pre-commercial stage of development, the current research and development being conducted is bringing them ever closer to widespread commercialization.

The future of PHEVs is directly dependent on innovation taking place in energy storage, super-efficient ICEs, and the architecture employed in the overall system. Although several other technologies play a critical role in the development of new PHEV architectures, it could be argued that the previous three are the most significant. In effort to present the cutting edge technologies in PHEV architecture, the importance of the energy storage, super-efficient ICEs, and new concepts in architectures will be discussed.

2.2.1 New PHEV Technology Examples

With the focus of increased distance and performance in an all-electric mode, energy storage is a critical element in determining the feasibility of PHEVs as mainstream automobiles. Previously, technologies did not exist to allow adequate storage of energy to produce a reasonable electric-only distance without incurring excess weight from large batteries, cost, and safety concerns. Recent developments in both batteries and ultracapacitors have helped to alleviate some of these issues. Lithium-ion batteries are the current solution to many of the downfalls found in more traditional nickel metal hydride cells. With advanced battery technologies, Li-ion offers a light weight solution with higher power and higher energy. This directly translates into increased driving distance in an all-electric mode and better driving performance. Ultracapacitors are also of importance due to their ability to release and capture large amounts of energy quickly. With a primary function of providing additional power during acceleration and hill climbing in addition to recovering energy when braking, the use of ultracapacitors in PHEVs supplements the large energy storage capability of batteries with power performance. Further explanation of new technology in batteries and ultracapacitors can be found in the Key Technologies section.

Beyond energy storage devices, most PHEV applications also rely significantly on ICEs to extend the driving range and performance of the vehicle. The architecture utilized in the PHEV dictates which of many new engines can be utilized. Series hybrid systems are able to utilize much smaller ICEs when compared to parallel or series-parallel architectures that also must utilize the engine to propel the vehicle. Generally speaking, however, new engines focus on single to four cylinder blocks with advanced combustion cycles and other controls to minimize consumption while maximizing power output. The end result is smaller and lighter engines with better performance than those currently available, which are larger, use more fuel, and produce more emissions. Diesel and rotary engines are also being subject to notable research. Again, further discussion and examples can be found in the Key Technologies section.

The last individual section that is critical to the development of state of the art PHEVs is the overall architecture employed in parallel and series-parallel hybrids with plug-in functionality. One of the most common concepts in this field is known as range extension. Essentially, range extenders incorporate a small, efficient engine to supplement an electric motor as the main propulsion drive of the vehicle. Additional electronics and controls accompany the propulsion unit, along with unique transmissions, to create an advanced vehicle architecture. In Figure 6, the GETRAG Boosted Range Extender is shown. This system utilizes a two-cylinder combustion engine, electric motor, alternator, and power-shiftable two-speed transmission to propel the vehicle (3). Electric drive is used for a majority of driving with the combustion engine used only when extra power or range is required. In the case of using the combustion engine, the electric motor works to help maintain optimum efficiency of the engine. The transmission is actuated by a compact control module/hydraulics unit to smoothly transition between the two driving modes and maintain optimum engine speeds.

Figure 6: Range Extender (3)

Another example is the Audi A1 e-tron, introduced at the 2010 Geneva Motor Show. With a 50km electric range, the main application for this vehicle is metropolitan areas of Europe and North America. The A1 e-tron features a synchronous electric motor rated at is rated at 45 kW (61 hp) continuous output with peak power of 75 kW, 150 N·m of continuous torque, and a peak torque of 240 N·m (177 lb-ft). A small single-rotor Wankel engine is used to extend the range of the vehicle by running at a constant speed of 5,000 rpm in its peak efficiency window (3). The most important component of the A1 e-tron lies however, within the power electronics. A new pulse-controlled inverter, DC converter, and breaker unit work in tandem to provide high levels of system efficiency and work side by side with the 380V lithium-ion battery. Additionally, a proprietary thermal management system and refinements in accessory systems, such as power steering, have led to the A1 e-trons fuel consumption rating of 1.9 L/100 km, corresponding to CO_2 emissions of 45 g/km over the expected 200km range (3).

Figure 7: Audi A1 e-tron

2.3 Key Technologies

While overall system architectures of electric and plug-in hybrid electric vehicles are of significant importance, their success is directly depended on the research and development taking place in the individual technologies of which they are comprise. The following sections present these key technologies by providing background information on their function, as well as the new technologies, theories, and concepts being researched.

2.3.1 Batteries and Ultracapacitors

Today, there are many manufacturers that produce advanced batteries for alternative fuel vehicles. Batteries types such as Pb-acid, NiMH, and Lithium-Ion are the more commonly known examples.

EV battery needs can be summarized as requiring:

- High energy density
- Stable power during discharge
- Long cycle life and safety mechanisms
- Accepted as a recyclable battery

Battery performance and cost are essential factors for the development of electric vehicles.

Target Applications in Automotive Industry are:

- Power-Assist Hybrid Electric Vehicles (HEVs)
- Plug-in Hybrid Electric Vehicles (PHEVs)
- Battery Electric Vehicles (EVs)

For automotive applications, an important criterion is to assess battery energy use. In Figure 9, the current state of the automotive battery industry is represented. Note that new battery technology is based on lithium-ion (Li-Ion), the best current solution. There are other types of batteries based on lithium compounds, such as lithium-air batteries or Li-Polymer, but these are still under development and are not ready for market implementation. Nevertheless, Tesla has developed a battery pack that contains 6831 Li-Ion batteries and is equipped with a cooling system to allow cooling of batteries. This system also regulates the speed of ion flow to keep them in recharging conditions properly.

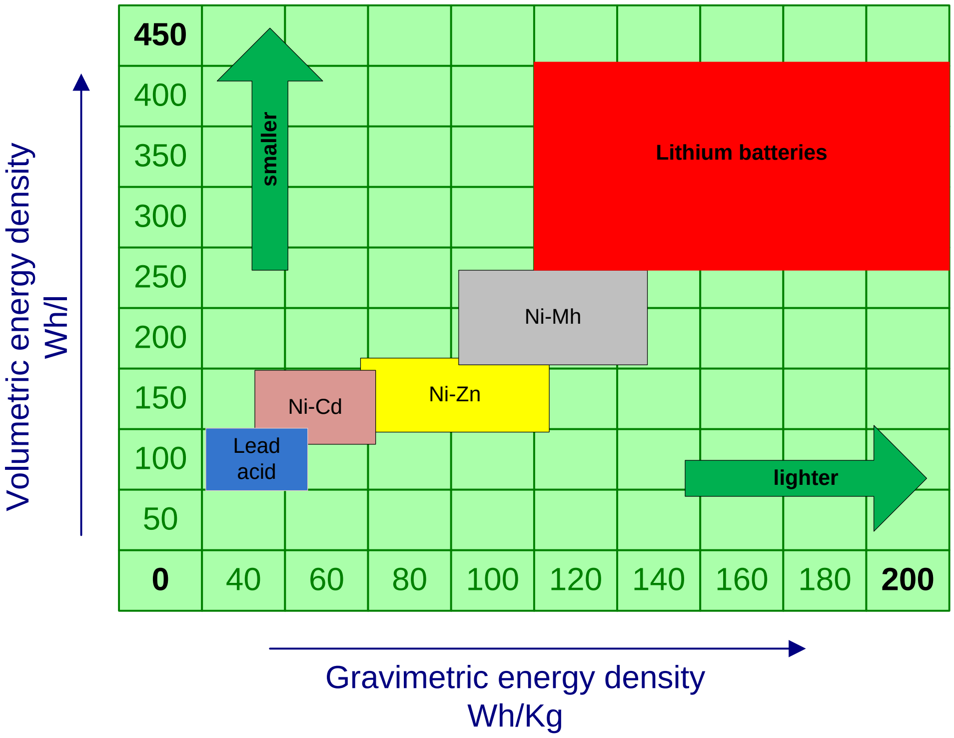


Figure 8: Battery energy chart

Car companies have dedicated considerable time to research and develop technologies that incorporate this Li-Ion battery in EV/HEV/PHEVs, as well as creating the accompanying safety systems. Battery longevity is measured in cycle lives; the number of times that one can charge/discharge the battery. A reduction of the total number of charge/discharge cycles can occur if batteries are maintained at 100% charge. For car batteries, recharging of more than 95 percent is not allowed as is also depletion of less than 5 percent. Batteries based on Li-Ion have higher volumetric and gravimetric energy densities than competing battery technologies. Thus allowing to create smaller and lighter battery packs. In regards to safety, today's nanotechnology has improved battery safety, helping to prevent dangerous explosions.

An important worldwide research center on battery technologies is Argonne National Laboratory, US Department of Energy. Argonne National Labs has an experience in battery research and development for more than 40 years, and for the past ten years, they have focused their research on Li-Ion batteries, especially for EV applications. The future EV will rely almost exclusively on Li-Ion batteries, while HEV/PHEV will slowly switch from NiMH technology to this new type of battery. However, a negative aspect of Li-ion batteries is the increase of vehicle cost, roughly 30-50%, limiting the attractiveness of the vehicle.

Lithium-ion batteries are popular because of a series of important advantages over competing technologies:

- Lighter than classical types of batteries at the same size
- High energy density
- Hold charge with maximum loses of 5% per month from initial charge
- No memory effect
- Durable

However, current disadvantages include:

- Battery cell degradation occurs upon leaving the factory
- Extreme sensitivity at high temperatures
- Complete discharging destroys the battery
- On-board a computer management is necessary

In 2007 Chevy Volt developed the concept vehicle chassis that includes the vehicle's lithium-ion battery pack shown in Figure 11. The Chevy Volt model is expected to start the production in 2011. Efficiency is expected to be 230 mpg and batteries from LG Chem will supply the power. The first 40 miles will be provided by the Li-Ion battery pack.

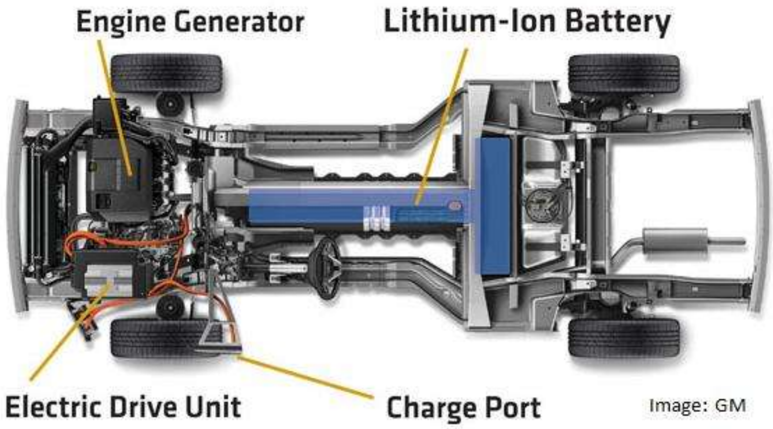
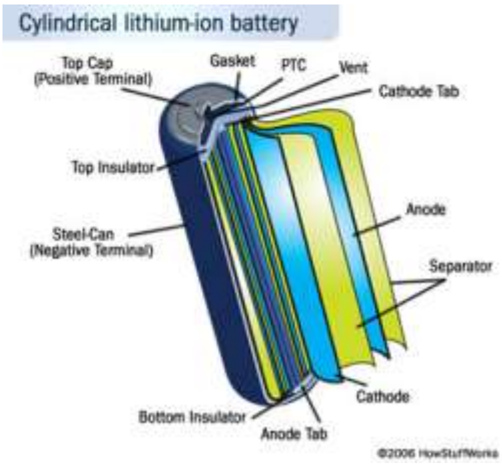


Figure 9: Chevrolet Volt architecture

GM has designed the battery to charge to 80 percent of its theoretical capacity and never discharge the battery pack less than 30 percent. With these considerations, they will extend the battery life over 10 years or 150000 miles without serious deterioration of batteries cells.

2.3.1.1 Cylindrical and Prismatic Lithium-Ion battery cells

There are two types of batteries based on Li-Ion technologies which are used in EV/HEV/PHEV applications. They are known as prismatic and cylindrical form batteries. Figure 9 represents a cylindrical battery cell and its main components. Also, in Figure 10, a prismatic battery cell is shown.



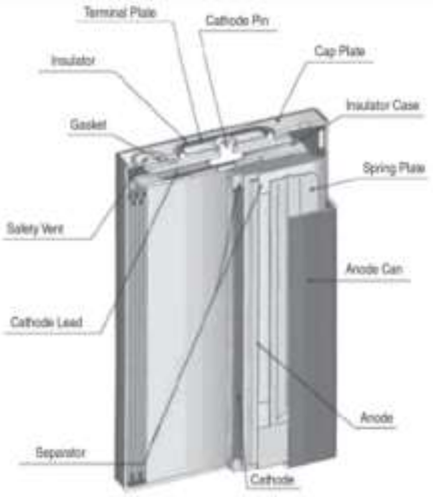


Figure 10: Cylindrical Li-Ion battery cell

Figure 11: Prismatic Li-Ion battery cell

2.3.1.2 Battery management systems

Automotive battery management systems (BMS) interface with a number of different on-board systems, working in real time with rapidly changing conditions as the electric vehicle accelerates and brakes. An important consideration is that every car company produces a proprietary battery management system. In practice, these BMSs incorporate more vehicle functions than simply battery management. They can determine the vehicle's desired operating mode, whether it is accelerating, braking, idling or stopped, and implement the associated electrical power management actions.

One of the first functions of the BMS is to provide the necessary monitoring and control to protect the cells of the battery. As well as individual cell protection, the automotive BMS system must be designed to respond to external fault conditions by isolating the battery as well as addressing the cause of the fault. If the battery overheats, cooling systems can be activated, and if the overheating becomes excessive then the battery can be disconnected. The primary BMS functions are presented in the diagram in Figure 12. The diagram is derived from three main BMS building blocks: the Battery Monitoring Unit (BMU), the Battery Control Unit (BCU) and the CAN bus vehicle communications network. Also shown is how it interfaces with the rest of the vehicle energy management systems. The BMS may also be coupled to other vehicle systems which can communicate with the BMS via the CAN bus, such as the Thermal Management System or to anti-theft devices that can disable the battery system to ensure that the car not be stolen.

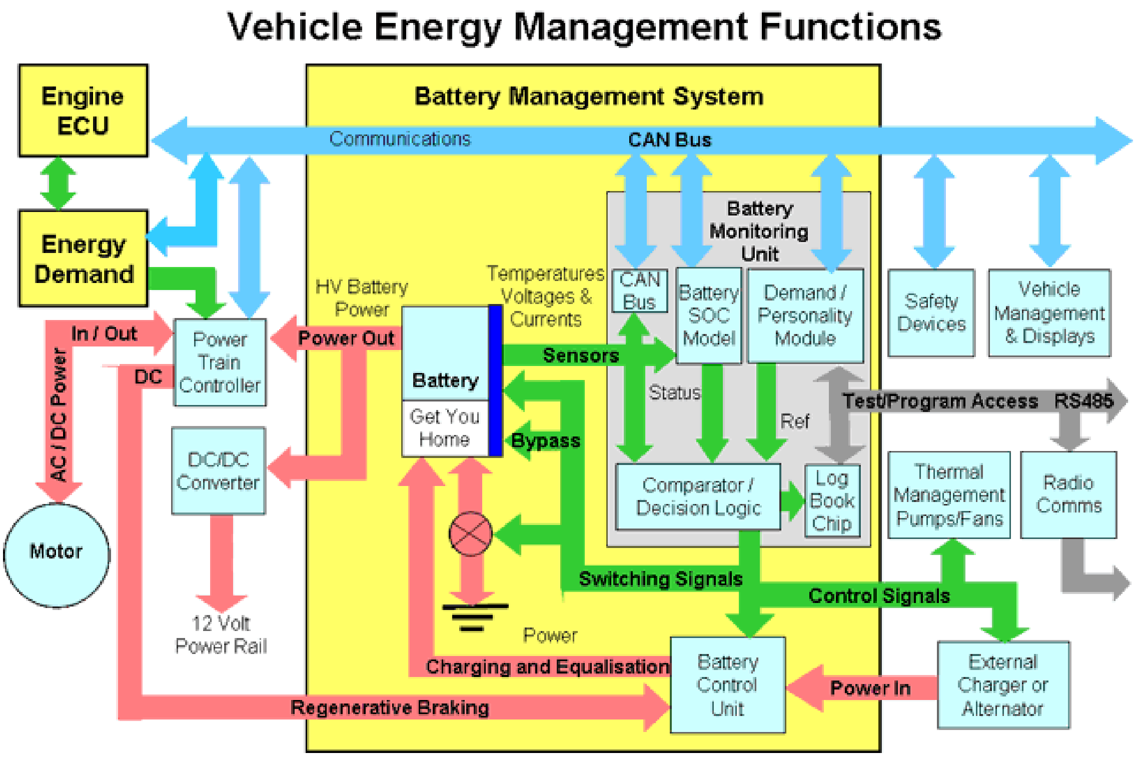


Figure 12: BMS role in vehicle management

2.3.1.3 Ultracapacitors

A new ultracapacitor structure that offers a capacitance density on the order of 100 to 200 Farads per cubic centimeter; versus the current state of the art capacitance density of 1 F/cm3, is a significant development in the area of power storage for EVs and PHEVs.

The principle behind the new ultracapacitor structure is the insertion of a few nanometers-thick layer of barium strontium titanate as an interface between an activated carbon electrode and a suitable electrolyte, such as acetonitrile or propylene carbonate. This mega-Farad ultracapacitor allows more cycles of charging and discharging and wide temperature range of operation.

Ultracapacitors are highly needed in vehicle applications because they can provide a significant increase in the energy storage capability leading to substantial improvement in the fuel efficiency of electric and hybrid vehicles.

2.3.2 Control Systems

A control system for EV/PHEVs ensures the best possible utilization of on-board energy resources for different operating conditions of the vehicle. This can be accomplished by controlling the output level of the primary power unit to ensure the highest possible combined efficiency of primary energy generation and energy exchange with the storage device. The overall energy management can be viewed as a global optimization problem. The performance index is linked to minimizing the fuel consumption and emissions outputs. The control system utilizes a strategy modified in real time depending on the inputs and the outputs from the sensor's continuous monitoring.

Although it is clear that many different control techniques have been applied, the overall conclusion is that only three generic types are likely to have a future in the short to mid term:

1. The rule based approach is often described as a heuristic control strategy. In the development of practical prototype vehicle systems, the majority have used rule-base controllers, although details are rarely published because of commercial aspects. It is based on a set of rules, usually implemented as nests of 'if-then-else' statements. The system components can be described by parametric or empirically derived maps, and the controller largely controls the switching between different modes, e.g. engine power, motor power, battery charging or energy regeneration

2. Equivalent energy methods are based on the concept of combining the energies from the internal combustion engine and electrical machines on the same scale, by defining equivalent fuel consumption. In this way, a single cost function can be formulated in order to apply conventional optimization techniques.

3. Dynamic programming is based on energy management. The performance index is linked to minimizing the fuel consumption and emissions outputs. The controller specifies the commands and settings, e.g. power split between IC engine and electric motor, which achieves this goal, within certain constraints, e.g. battery state of charge.

Another control technique that could be implemented in the long term is called Genetic algorithm. This technique is based on natural biological evolution and has been applied to the HEV driveline management problem.

2.3.3 Engines and Motors

Responsible for the propulsion of the vehicle and responsible for the greatest amount of lost energy, engines and motors are subject to considerable research. Not only must new components provide a high level of efficiency and minimal emissions, they must also provide the power required to produce a driving experience permissible as a personal transportation solution. New developments and current technologies in electrical motors and engines are contained in the following sections.

2.3.3.1 Electrical Engines

Propelling a car with an electric motor has efficiency greater than propulsion by an internal combustion engine. In terms of efficiency, electric motors reach a minimum of 75% efficiency in the conversion of chemical energy into mechanical energy. Conventional internal combustion engines (ICE) reach a maximum of 20% yield, with losses resulting as heat, noise, and vibration. While electric motors do not emit any emissions, they do increase electricity generation needed to recharge the batteries of the car. Electric motors produce very little noise in comparison with conventional ICEs and can operate in various environmental conditions without problems. Additionally they can produce more powerful acceleration. Electric motors do not require special care as conventional internal combustion engines.

An important aspect for electric motors used in electric cars is that they must have the capability of functioning as a generator. Figure 13 shows four types of induction motors which are currently produced for application in various electric cars for America or Europe. Car companies typically design an electric motor that is unique to each vehicle.

Figure 13: AC induction motors

Nowadays, thanks to strong research performed in the automatic control of electrical drives and due to advancing technology in power electronics, a new type of electric motor, Permanent Magnet Synchronous Motor, is preferred in EV/PHEVs.

a) Permanent Magnet Synchronous Motor (PMSM)

The Permanent Magnet Synchronous Motor (PMSM) technology is a viable and new alternative to classical induction motors and has a good performance in driven applications. This technology is also known as “Brushless DC” or “AC Servo”. The dynamic performance, efficiency, and power density of PMSM technology are strong reasons to use in vehicles applications.

The PMSM is a rotating electric machine that consists of a classical 3-phase stator and surface-mounted permanent magnets on the rotor. A cross section is presented in Figure 14.

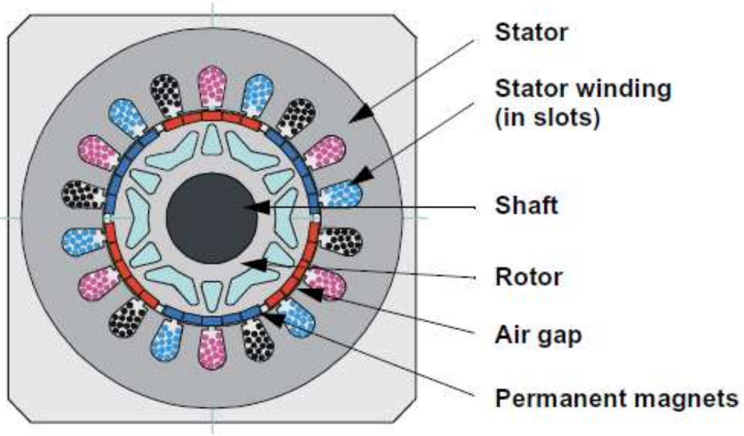


Figure 14: Cross section of a PMSM

b) Permanent Magnet Synchronous Motor Control Theory

Due to sophisticated control methods such as vector control, it is easy to command a PMSM based system. Vector control theory is newest method for PMSM control. This method controls the magnetic flux and torque separately. To do this, it is necessary to set up the rotary coordinate system called "d, q-coordinate system" connected to the rotor magnetic field. To compute the mathematical equations, a high-performance CPU is incorporated. In Figure 15, the block diagram of the CPU function in a vector control system is shown.

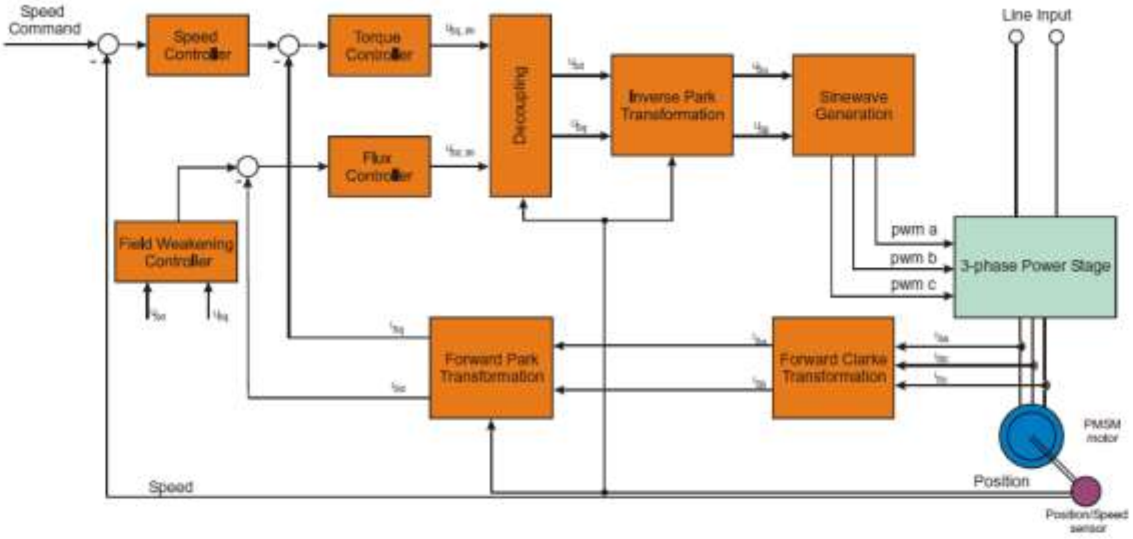


Figure 15: PMSM vector control block diagram

The following are necessary requirements for vector control functioning:

- Measure the motor quantities (phase voltages and currents)
- Transform them into the two-phase system (α , β) using Clarke transformation
- Calculate the rotor flux space-vector magnitude and position angle
- Transform stator currents into the d, q-coordinate system using Park transformation
- The stator current torque (isq) and flux (isd) producing components are controlled separately by the controllers
- The output stator voltage space-vector is calculated using the decoupling block
- The stator voltage space-vector is transformed back from the d,q-coordinate system into the two-phase system fixed with the stator by inverse Park transformation
- Using the sine wave modulation, the output three phase voltage is generated

2.3.3.2 Engines

Although focus is shifting away from the use of conventional fossil fuel based engines to power automobiles, technology necessary to eliminate them from the automotive industry does not yet exist. Moreover, a recent study in the US shows that consumers prefer lower-cost, high efficiency gasoline engines over higher-priced alternative fuel or electric vehicles. Regardless, a new outlook on the role of engines, such as the previously mentioned range extenders, has led to a number of new developments. A few of the most innovate technologies, illustrating the overall picture of new engine developments, are presented in the following.

The first technology is on advances in diesel injection and control systems. Delphi Corp. has developed new fuel injection equipment and control systems to help substantially reduce diesel engine emissions. Enhancements to Delphi's "balanced-valve servo-solenoid system and advanced direct-acting piezo system" increases operating pressure to 2400 bar with improved high-pressure atomization. Along with improvements in their control system for "direct combustion parameter control, based on real-time in-cylinder pressure measurement" and hydraulic efficiency, this technology exceeds the demanding emissions standards in Europe. One of the two systems from Delphi that employees this technology is featured on the new 1.2L Volkswagen Polo BlueMotion. The result is 3.3L/100km and CO_2 of only 87g/km.

Second, a new combustion cycle developed by LiquidPiston, called High Efficiency Hybrid Cycle (HEHC), was recently presented to the 2010 SAE World Congress. Borrowing elements of Diesel, Otto and Atkinson cycles, a 20% to 50% improvement in thermodynamic efficiency is attainable (4). Furthermore, the cycle allows for ultra-compact engine design with one horsepower per pound and quiet operation even without a muffler. It is surmised that the HEHC could provide passenger vehicles with efficiency of over 100mpg within the decade.

> *Combining the high peak pressures produced during constant volume combustion with Atkinson expansion, which continuously extracts energy as exhaust gases expand to atmospheric pressure, delivers unprecedented fuel efficiency. Also, using a ported design rather than conventional poppet valves makes for extraordinarily quiet operation.*
>
> —LiquidPiston co-founder and Chief Technology Officer Nikolay Shkolnik

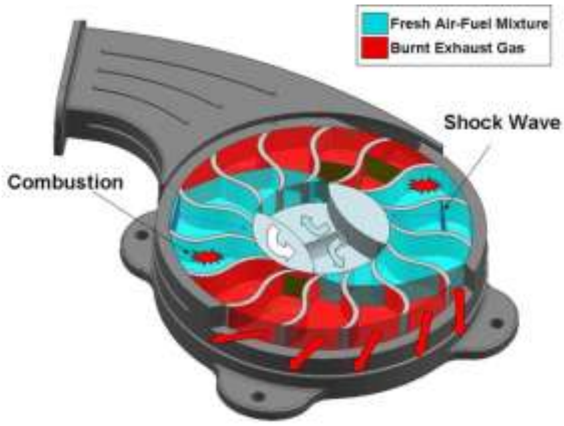


Figure 16: Wave disc engine/generator (3)

The final and most theoretical concept to illustrate new concepts in engine developments is that of creating a wave disc engine/generator for series hybrid applications. The US Dept of Energy has funded Michigan State University to complete its prototype development of a gasoline-fueled wave disc engine and electricity generator. This hyper-efficient engine aims to replace traditional engine/generator technologies in plug-in hybrid vehicles by promising "to be five times more efficient than traditional auto engines in electricity production, 20% lighter and 30% cheaper to manufacture."

2.4 Software Benchmark

2.4.1 Software Overview

1. **acslX:** acslX is a simulation software which is developed by acslsim. It uses ready-to-use code blocks. Also its textual language is named ACSL(Advanced Continuous Simulation Language).
2. **Advisor 2.0:** Advisor is the simulation software of The National Renewable Energy Laboratory (NREL) which developed it first in 1994. It is basically an advanced vehicle simulator. It is rather useful to design PHEVs and EVs. It has easy-to-use graphical user interface. It also has HTML(web-browser based) documentation detailed block diagram model descriptions and equations, algorithms behind the control strategies, complete listing of input and output variables, and a user's guide. It is possible to run simulation under different condition such as highway, or city. It is suitable with Matlab-Simulink.
3. **Automation Studio™:** Automation Studio™ is an innovative system design, simulation and project documentation software solution for the design and support of automation and fluid power systems. General-talking, it is a software that using to designing and simulating of different automation technologies such as pneumatic, hydraulic, and electronics. Including libraries are: hydraulic, proportional hydraulic, pneumatic, electrical control, digital electronic, plc stairs diagrams, electrotechnic, and sfc/grafcet.
4. **Labview:** LabVIEW is a graphical programming environment used by millions of engineers and scientists to develop sophisticated measurement, test, and control systems using intuitive graphical icons and wires that resemble a flowchart. It is developed by National Instruments. It uses a graphical approach. User should put different boxes to

define any operation, function, or variable, and these boxes gets dependent to write a program. It is mostly used in the topics such as instrumentation or instrument control. It has a quite big sub vi library. With only basic coding information, you can write many programs (That's why, their motto is "Software is the instrument"). Like Matlab-Simulink, your labview code can be transferred to a real-time hardware and make it work independent. After 8.6 version, it is possible to make simulation diagrams/blocks tidy by one click. Basically it is easy to use but, when you begin to work on bigger and more complicated systems, it is not as useful as Matlab-Simulink.

5. **MathModelica:** MathModelica is modeling and simulation software of Mathcore Engineering AB. It includes libraries on different development areas such as modeling, simulation, analysis, and documentation. It is used in the areas such as robotics, complex machinery, life science, and autonomy. It includes graphical/textual user interface, a-casual/causal modeling, and based on the non-proprietary, object-oriented, equation based, Modelica language.
6. **Matlab-Simulink:** Matlab is software of Mathworks. Simulink is a program which works under Matlab. Matlab-Simulink is the most common simulation software. While designing dynamic systems and performance testing it is quite useful. It is possible to simulate complicated systems not only simple systems. It has toolboxes those make lots of possibilities. Also there are huge help files if you are stuck. Matlab-Simulink has a few disadvantages about big calculations because it is slow. But comparing to other simulation programs it is not such a big problem. Matlab-Simulink updates its version in every six months and in every new version, it is possible to find new libraries. Besides in Matlab, it is possible to convert codes in other programming languages and it is possible to transfer Matlab codes to a real-time hardware and make it work independent. So instead of writing codes in different programming languages, users can focus on working principles of algorithms.
7. **Simplorer:** Simplorer is the simulation software of Ansoft. It is a multi-domain simulation program. It is used in designing, modeling, analyzing, optimization of high performance systems including electrical, thermal, electro mechanic, electromagnetic and hydraulic designs. These complex systems are commonly found in the automotive, aerospace/defense, and industrial automation industries. Since it presents many and different ways to modeling techniques analysis skills, it provides system functionality and design confirmation. Therefore, while time and cost for development go down, system reliability and system optimization go up. It also has a student version which can be downloaded in the official site of the producer. It is possible to get more realistic results instead of ideal ones in this software.

8. **VisSim:** VisSim is a block diagram language for creating complex nonlinear dynamic systems. Its working principle is dragging blocks in the workspace and connecting them with wires like almost all the other simulation software. It includes 120+ built-in linear and nonlinear blocks. It is fit for MATLAB, Mathcad, and Maple integration.

Table 1: Model and simulation softwares

Name	**Website link**
acslX	http://www.acslsim.com/products/
ADVISOR 2.0	http://www.nrel.gov/vehiclesandfuels/vsa/pubs_simulation.html
Automation Studio™	http://www.automationstudio.com/PRO/index.htm
dSPACE	http://www.dspace.com/ww/en/pub/home.cfm?nv=n1
INTEGRATED software	http://www.integratedsoft.com/
Labview	http://www.ni.com/labview/
MathModelica	http://www.mathcore.com/products/mathmodelica/
MATLAB-SIMULINK	http://www.mathworks.com/
Simplorer	http://www.ansoft.com/
VisSim	http://www.vissim.com/products/vissim.html

2.4.2 Decision matrix

A basic decision matrix was constructed for use when choosing what software should be utilized for the modeling and simulation of electric and plug-in hybrid electric vehicles and their components. Seven criteria were defined as significant factors in determining which software to utilize and are listed below. The number of asterisks inside the parenthesis corresponds to the suggested weight of the criteria. It is suggested that a scale of 1 to 5 be utilized during the evaluation of each criteria per each software. The decision matrix can be found in Appendix B.

1. **Component Libraries (***):** This is one of the most important criteria in determining which software to utilize. Although models and simulations can be created through the development of proprietary code, it is extremely beneficial to have prefabricated templates of the commonly used models in order to ensure efficient and effective use.

2. **Modeling Capabilities (***):** Equally as important as Component Libraries, Modeling Capabilities includes the overall capacity to produce models/simulations along with sub-criteria such as ease of learning, user friendliness, formal logic, representativeness of models, simulation modeling approach, documentation notes, on-line help, and model and data separation.

3. **Graphic User Interface (GUI)(**):** The GUI of a program significantly impacts the process conducted in model development as well as making the overall process easier. It should be clear and logical, including easy prompt menus for template use.

4. **Hardware and Software Considerations (**):** Software compatibility is an important consideration. This should be addressed in both the subject of compatibility with other versions of the software/other programs that may be necessary for extended testing and also in the subject of ensuring that the computer hardware is capable of running the software effectively.

5. **Price (*):** In some situations, such as small or independent projects, price is a significant factor. However, it is assumed that because the main focus of the software is for EV development, a major focus of the next generation of personal transportation, the cost will be mitigated by the economic gain produced from a viable EV design.

6. **Simulation Capabilities (***):** This criterion is very important too because of includes lots of sub criterions. These sub criterions are visual aspects (such as animation, graphic library…), efficiency (such as robustness, level of detail, model reliability, queuing policies…), testability (such as logic checks, error messages, trace files, display of the workflow path…), experimentation facilities (such as warm-up period, breakpoints, speed adjustment…), and statistical facilities (such as theoretical statistical distributions, user-defined distributions, output data analysis, confidence intervals…).

7. **Input/output Issues (***):** This criterion is about input/output values and analyze, so it is directly about the results. Sub criterions of that criterion are input data reading from files, quality and understandability of output reports, user defined output, periodic output of simulation results, what-if analysis, conclusion-making support, and optimization.

3. Project Development

3.1 Project Approach

The project was conducted in five phases in order to efficiently achieve the greatest amount of results in during the time period available. A brief description of the phases is included below:

1. Phase One – Project Identification
    - Receive purpose and expected outcomes from SEAT
    - Identify project goals
    - Determine expected works to be conducted
    - Assign responsibilities
    - Develop a timeline
2. Phase Two – Investigation and Research
    - Investigate software capable of EV modeling and simulation
    - Research state of the art technologies
    - Familiarization with EV systems
3. Phase Three – Initial Model Development
    - Define necessary input and output parameters
    - Model individual components and subsystems
    - Assemble EV system

4. Phase Four –Testing and Revision
    - Validate components and systems
    - Implement revisions as necessary
5. Phase Five – Graphic User Interface:
    - Develop a graphic user interface for the final model

Although the project is partitioned into five unique phases, it is important to note that several aspects overlapped one another as they were either ongoing or critical to another's full completion.

Also included in the project approach is the schedule of meetings conducted throughout the semester. Group members met twice a week to discuss the project and work on necessary aspects. Meetings with academic advisors took place on a weekly basis for progress review and SEAT representatives met with the team every two to three weeks as schedule permitted.

3.2 Initial Goals

Initial goals for the project were established after meeting with SEAT on 12 March 2010. Requests from the company detoured from the first impressions related to developing models and simulations for electric and hybrid vehicles. Because of this, new goals were immediately set and research and knowledge development was immediately shifted to the appropriate subject matter. Focus was switched from designing new architectures based upon researching and implementing state of the art systems to modeling two architectures provided by SEAT for their future vehicles. This required a more in-depth understanding of how to model and simulate in MatLab and Simulink and also of what individual components must be employed to properly model the proposed architectures.

Initial Goals

1. Create simple basic models both the Electric and Plug-in Hybrid Electric Vehicle to simulate
    a. Driving Cycles
    b. Energy consumption
    c. Range
    d. Charging and discharging battery cycles
2. Design input system to allow modification of component variables
3. Benchmark characteristics of alternative modeling and simulation software

3.3 Revised Goals

Throughout the course of the project, it was necessary to reevaluate the expected outcomes based upon the time and resources available, taking into account manpower available and state of knowledge with respect to the task at hand. The following goals were defined as the reasonable compromise and can be considered as the final targets for the project.

Revised Goals

1. Create a comprehensive model of the Electric Vehicle to simulate
    a. Driving Cycles
    b. Energy consumption
    c. Range
    d. Charging and discharging battery cycles
2. Design input system to allow modification of component variables, including battery and driving cycle selection capabilities
3. Benchmark characteristics of alternative modeling and simulation software

3.4 Responsibilities

In order to achieve the goals set forth, it was necessary to assign specific responsibilities to individuals. These were carried forth through the entire term, with additional specific responsibilities being assigned on an as needed basis.

The Team Lead oversaw the project management and development with the expectation of aiding in all project works when available. The division of the modeling and simulation task resulted in three categories: battery, charging, and traction. Each of these sub-systems was assigned a System Lead, and, in some cases, extra assistance. Further needs of modeling that spanned across systems were assigned on an individual basis congruent with the competencies and workloads of team members. Model revision tasks were led by the Team Leader but relied significantly on the contributions and technical knowledge of the System Leads. Additionally, all project deliverables were managed by the Team Leader with an appropriate amount of contribution from each individual team member, congruent with their assigned responsibilities. These general responsibilities are indexed below and a work breakdown spreadsheet for further detail can be referenced in Appendix A: Work Breakdown Structure.

Team Lead:	Patrick Satchell
Battery System:	Ioan Tudosa, Vedat Kilickaya
Charging System:	Josep M. Fabrega
Traction System:	Xavier Laxague

4. Electric Vehicle Model Development

4.1 Systems Design

4.1.1 EV Global System Architecture

A standardized electric vehicle architecture was provided by SEAT Automotive for the purpose of creating a computer-based model and simulation as shown in the figure below. The architecture is divided into three main systems: battery, charging, and traction. A lithium-ion battery acts as the power source for the vehicle, which is propelled by a permanent magnet synchronous motor through the means of a single gear transmission. A three mode plug-in charger is incorporated to simulate charging cycles of the battery. While each of these systems serves and independent purpose, they are interdependent on one another to achieve a fully functioning EV model. The model developments for the system design are presented in the following sections.

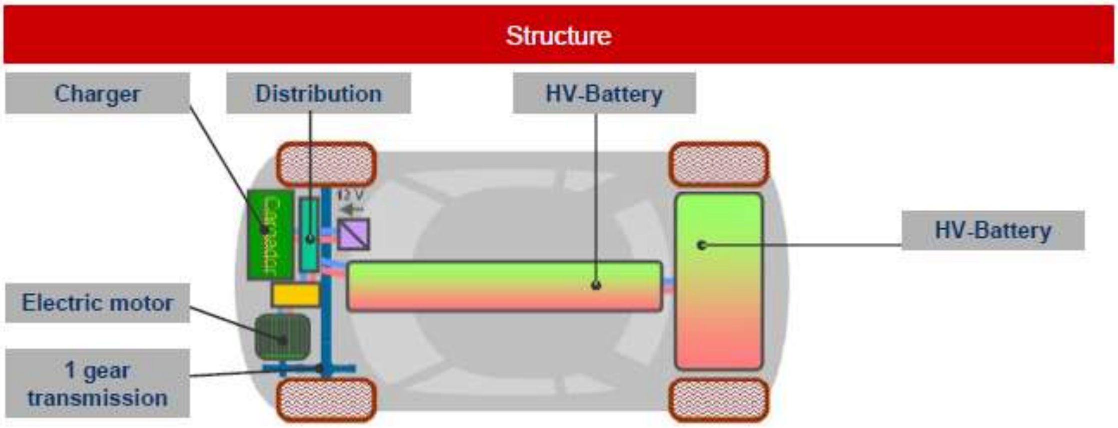


Figure 17: EV architecture

4.1.2 Battery and Battery Management

4.1.2.1 Battery model

The battery model that is used in this project is from Matlab/Simulink library. This model is a dynamic model of a generic battery model, which is parameterized to represent a Lithium-Ion battery. This model is delivered in a library from SimPowerSystems->Electrical Sources. The graphical representation of the model is presented in Figure 18.

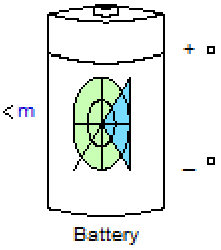


Figure 18: Simulink battery

The battery outputs are two wires that are connect to a consumer block in a simulation model. These connections are noted with + and –. The outputs signal from battery model used create a management system are multiplexed in a single wire noted with *m*. In Table 3 the details of this output signal are given.

Table 2: Output signals delivered by *m*

1	State-of-Charge	%
2	Battery current	A
3	Battery voltage	V

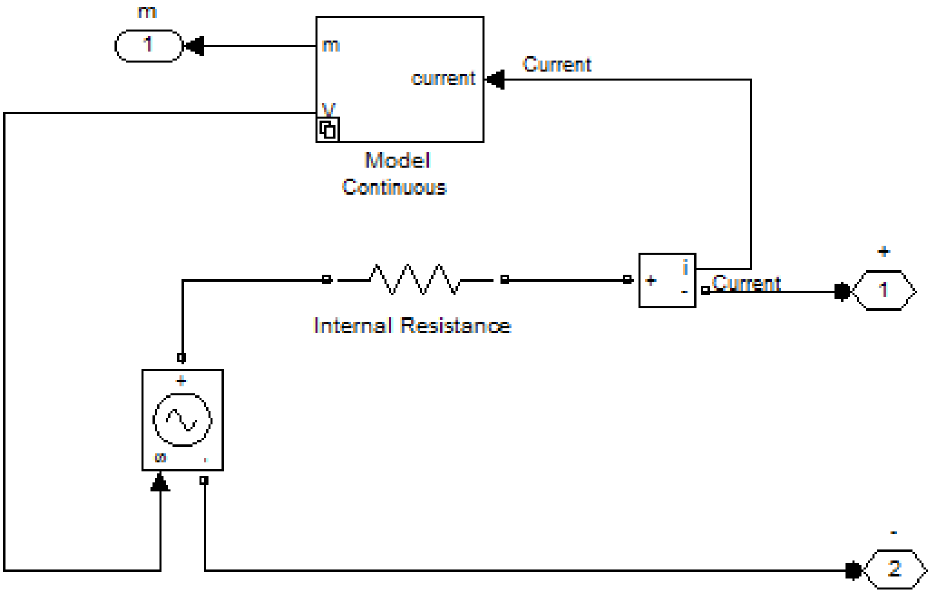


Figure 19: Internal structure of battery model

The architecture of the internal battery structure is presented in Figure 19. The detailed internal structure is presented in Figure 20.

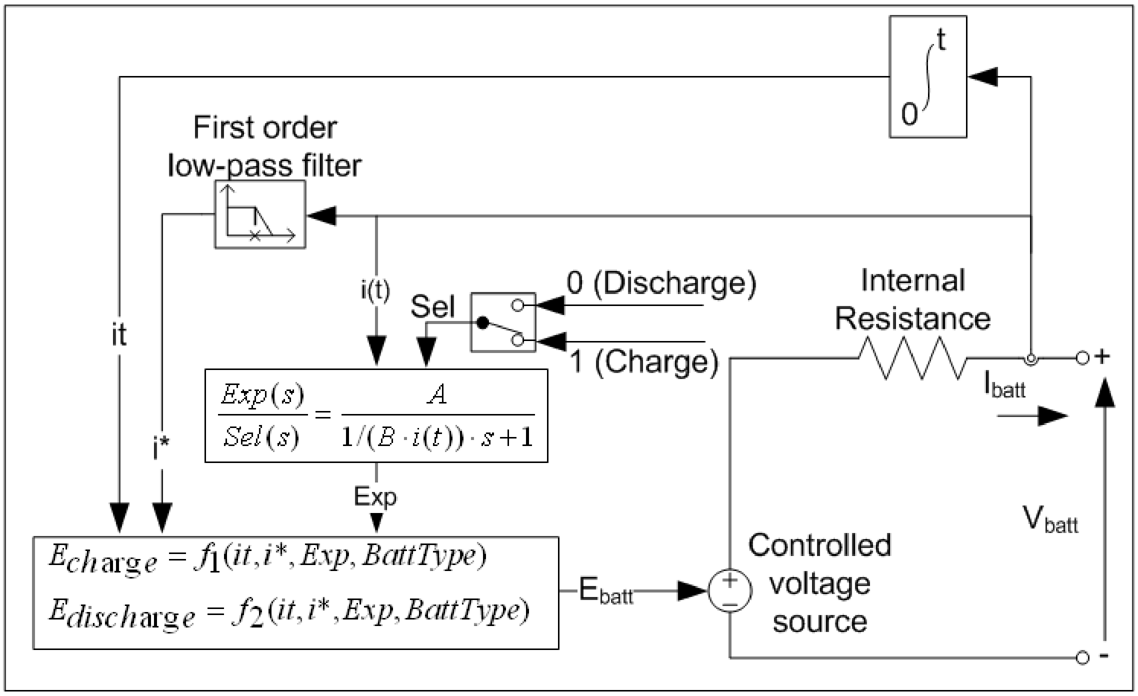


Figure 20: Equivalent circuit of the battery

The schematic from Figure 20 uses different mathematical calculations for battery charge and discharge. These calculations also depend on what kind of battery is in use. The mathematical equations that are computed in the battery model for Li-Ion are showed below:

Discharge Model (i* > 0)

$$f_1(it, i^*, i) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot exp(-B \cdot it)$$

Charge Model (i* < 0)

$$f_2(it, i^*, i) = E_0 - K \cdot \frac{Q}{it + 0.1 \cdot Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot exp(-B \cdot it)$$

Here is a typical discharge curve composed of three sections:

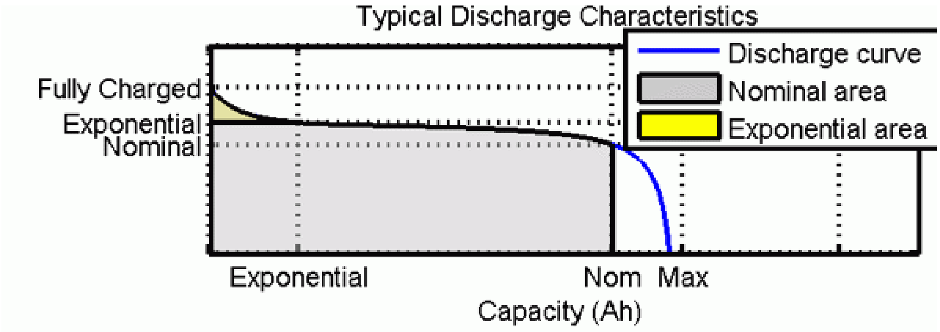


Figure 21: Typical discharge characteristics

a) **First Section:** The Exponential voltage drop when the battery is charged. Wideness depends on battery type.
b) **Second Section:** The charge that can be extracted from the battery until the voltage drops below the battery nominal voltage.
c) **Third Section:** The total discharge of the battery when the voltage drops rapidly.

4.1.2.1.1 Cells in Series and/or in Parallel

Modeling a set of cells in series and/or parallel depends on the parameters of a single cell. To describe series and/or parallel cells the number of series cells is referred to as "Nb_ser" and parallel cells as "Nb_par". To calculate other values manually as well, the following should be taken into consideration: Nb_ser at *Fully Charged Voltage,* Nb_par at *Maximum Capacity, Nominal Discharge Voltage, Capacity @ Nominal Voltage,* and both Nb_par and Nb_ser at *Internal Resistance* and *Exponential zone.*

4.1.2.1.2 Battery Pack

Table 1.2 Parameters to set-up the battery pack where Nb_ser = 83 cells and Nb_par=7 cells.

Table 3: Battery pack setup parameters

Battery type	**Li-Ion**
Nominal Voltage (V)	3*Nb_ser
Rated Capacity (Ah)	10*Nb_par
Initial State-of-Charge (SoC %)	100
Use parameters based on Battery type and Nominal Voltage	
Maximum Capacity (Ah)	10.5*Nb_par
Full Charged Voltage (V)	3.65*Nb_ser
Nominal Discharge Current (A)	10*Nb_par
Internal Resistance (Ohms)	0.002*Nb_ser/Nb_par
Capacity (Ah) @ Nominal Voltage	9.5*Nb_par
Exponential zone Voltage (V)	2.05*Nb_ser
Exponential zone Capacity (Ah)	3.65*Nb_par

The computed data from the battery model is:

Table 4: Parameters obtained from simulation

Use parameters based on Battery type and Nominal Voltage	
Maximum Capacity (Ah)	**70**
Full Charged Voltage (V)	**289.8328**
Nominal Discharge Current (A)	**30.4348**
Internal Resistance (Ohms)	**0.035571**
Capacity (Ah) @ Nominal Voltage	**63.3043**
Exponential zone Voltage (V)	**269.0161**
Exponential zone Capacity (Ah)	**3.43913**

The battery model created has the option to plot the battery discharge characteristics curves. The resulting discharge characteristics graphs are shown in Figure 22. The first graph represents the nominal discharge curve (at the Nominal Discharge Current) and the second graph represents the discharge curves at the specified discharge currents. When the checkbox is active, the graph remains on and updates itself when a parameter changes in the dialog box. The curves represented are obtained for discharge current [1.5 3 5 10 15 30 35].

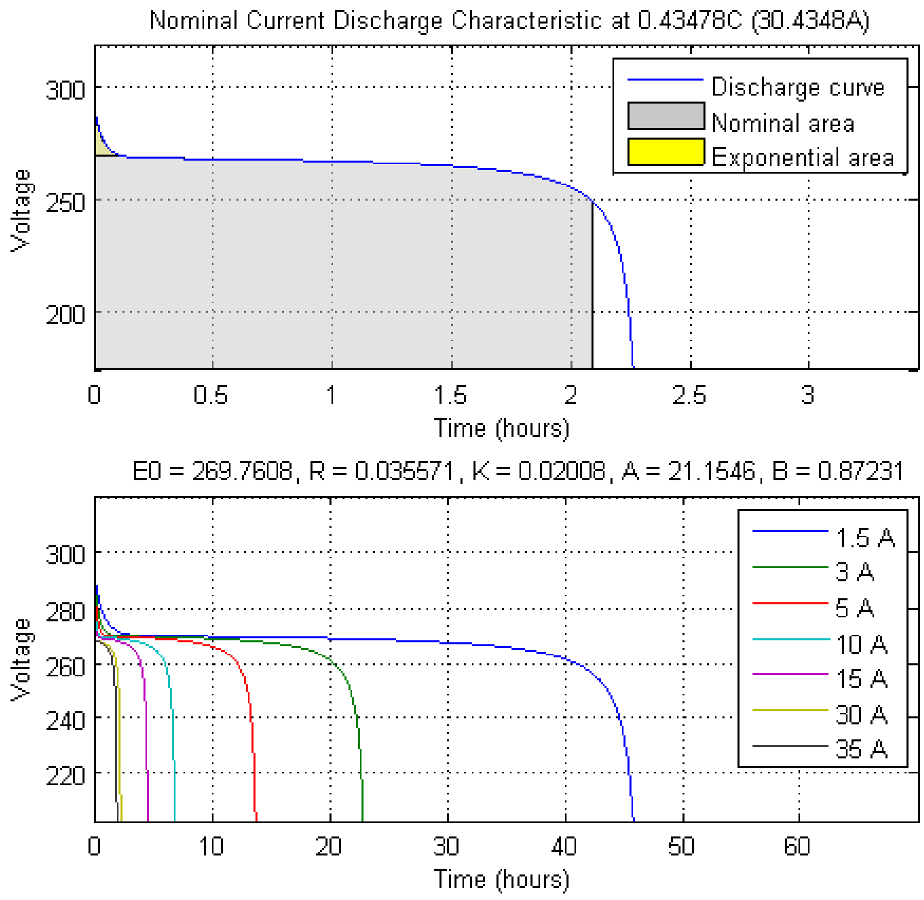


Figure 22: Discharge characteristics

4.1.2.2 Battery management system

Automotive battery management systems (BMS) interface with a number of different on-board systems to work in real time with rapidly changing conditions as the electric vehicle accelerates and brakes. In practice, these BMSs can incorporate more vehicle functions than simply those for managing the battery. They can determine the vehicle's desired operating mode, whether it is accelerating, braking, idling or stopped, and implement the associated electrical power management actions.

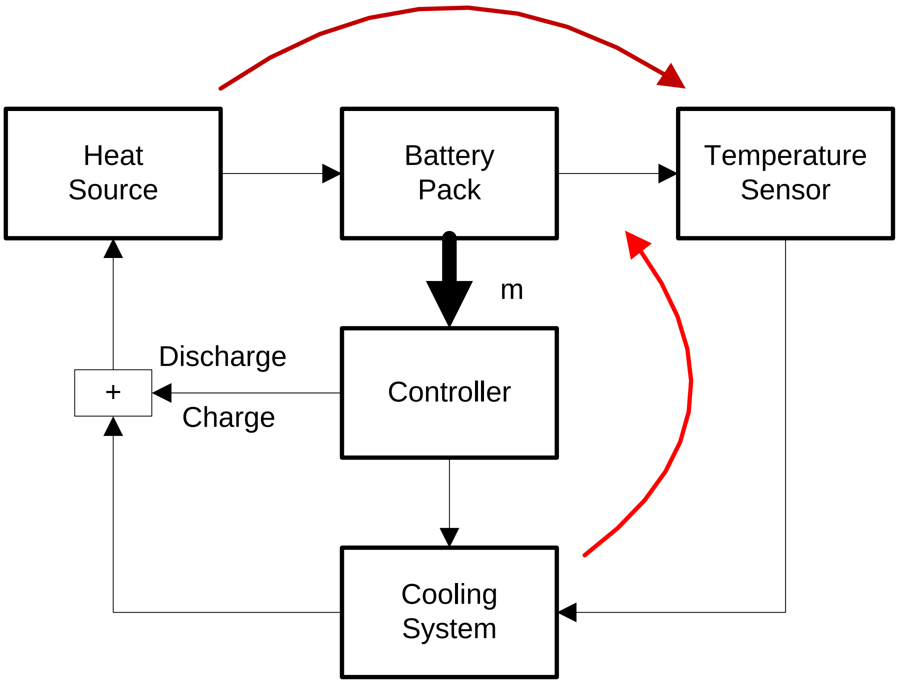


Figure 23: Controller for cooling system

One of the first functions of the BMS is to provide the necessary monitoring and control to protect the cells of the battery. As well as individual cell protection, the automotive BMS system must be designed to respond to external fault conditions by isolating the battery as well as addressing the cause of the fault. If the battery overheats, cooling systems can be activated, and if the overheating becomes excessive then the battery can be disconnected. Figure 23 represents a cooling system control.

The state of charge (SOC) of the battery is the second major function of the BMS. The SOC is necessary for providing the Fuel Gauge indication. The BMS monitors can calculate the SOC of each individual battery cell to check for uniform charge, verifying that individual cells do not become overstressed. Overstressed cells can produce serious damage in the battery pack by exploding. Another important parameter that we can monitor with the SOC indication is the end of the charging and discharging cycles. Over-charging and over-discharging are two very important states that can cause battery failure. The BMS must also maintain all of the cells within the desired depth of discharge operating limits to ensure proper battery life.

EV batteries require both high-power charge capabilities for regenerative braking and high-power discharge capabilities for launch assist or boost. Because of this, the battery pack must be maintained at a SOC that can discharge the required power but still have enough headroom to accept the necessary regenerative power without risking overcharging the cells. Figure 24 represents the SOC logic employed in the developed model.

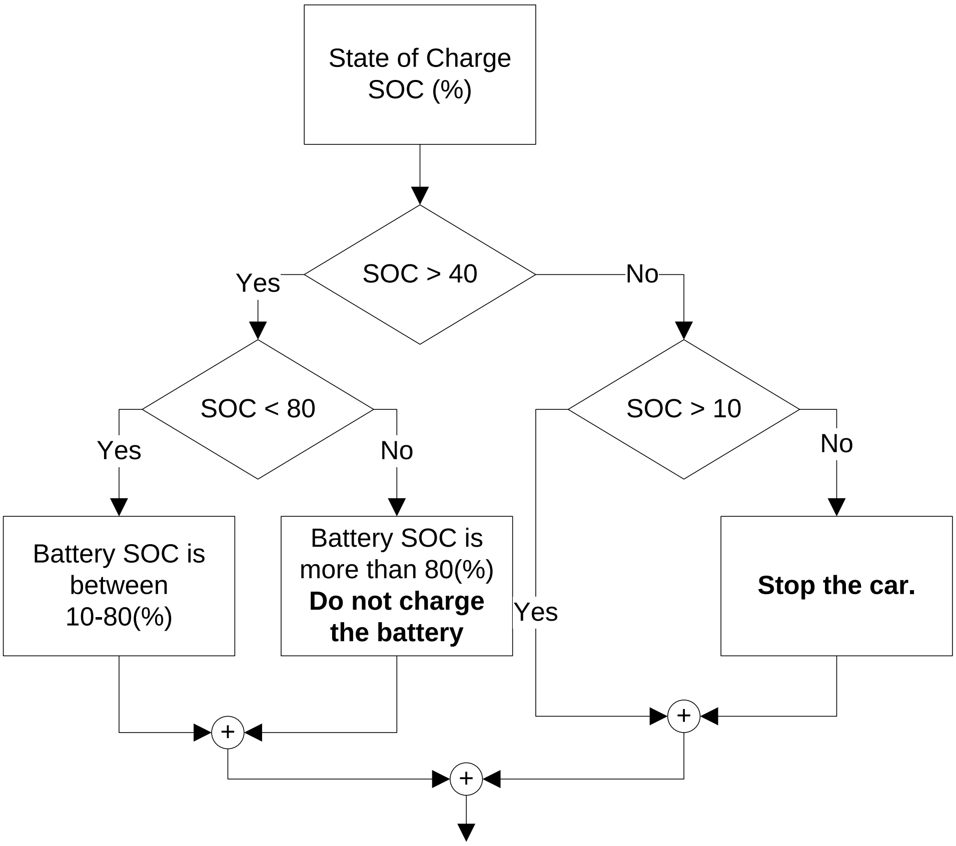


Figure 24: State of charge logic diagram

This algorithm is used to model the SOC maintenance and is developed in the block management. The lower limit of this logic is 10% to prevent over-discharging and the upper limit is 80% to prevent over-charging. Accuracy of the SOC information is therefore necessary for EVs to keep the battery pack operating within the required and safe limits.

4.1.3 Charging

The charging system of an EV functions as two independent components: plug-in charging and regenerative braking. They both serve to charge the battery but in two different methods.

The plug-in charger converts the current provided by an external electric source, when necessary, to a direct current in order to charge the battery. There are three different charging models available; each depending on the voltage and current that the external source supplies.

Regenerative braking is used to recover energy from the car during braking or deceleration. The electric motor(s) used for propulsion operates as a generator to convert the kinetic or potential energy into electric energy that can be stored in the battery. The main goal of this system is to recover as much braking energy as possible, extending the car's autonomy. The regenerative system consists of the following parts: PM synchronous motor, inverter; and battery.

4.1.3.1 Plug-in charger

The plug-in charger allows the battery to be charged while the car is stopped. When the external source is alternating current, it is necessary to convert the current and match the voltage supplied by this source with the battery voltage using a rectifier and DC converter.

The rectifier converts the alternating current to direct current and the DC converter adapts the voltage supplied by the external sources to match that of the battery voltage.

The following table represents the different charging modes:

Table 5: Charging modes

Charging modes	**Standard**	**Semi-rapid**	**Rapid**
Voltage (V) / Current (A)	230 Vac / 16 A	400 Vac / 29 A	250 Vdc / 133 A
Power (KW)	3.5	20	33
Time to charge (minim) (h)	3.4	0.6	0.3
Time to charge (optimum)	8	1.5	0.3

When the model was designed, it was necessary to take into account that the voltage follows the proportion $V_p = \sqrt{3} \cdot V_{ac}$. In the model, represented by the figure below, the three constants on the left hand side allow selection of which source will charge the battery.

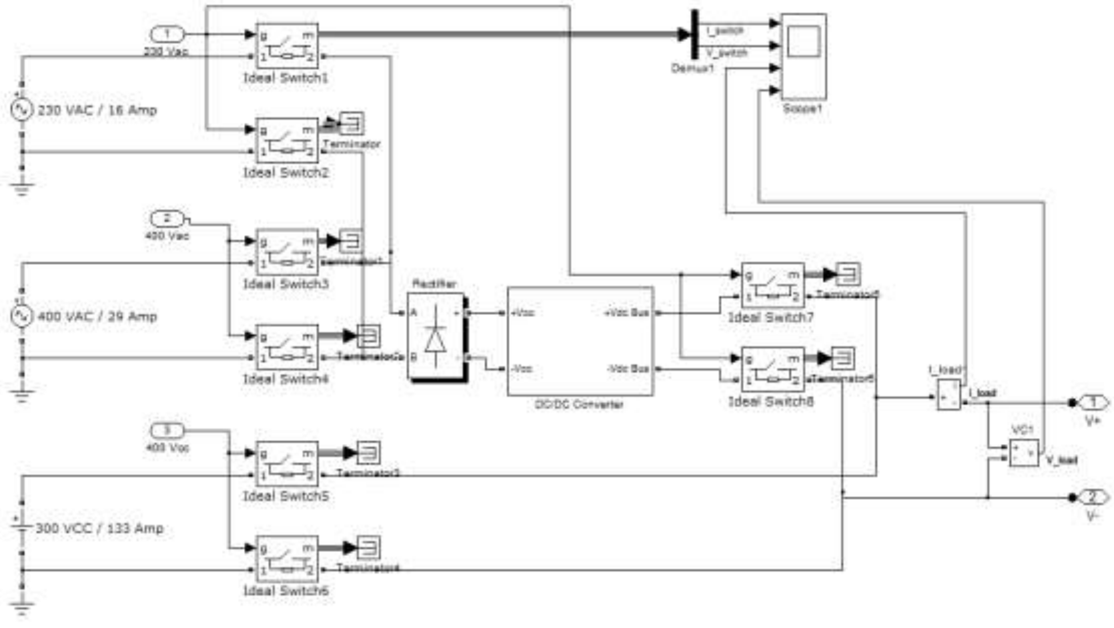


Figure 25 : On-board charger model

4.1.3.2 DC converter

A buck-boost DC converter was implemented in order to match the voltage supplied by the generator with the voltage of the battery. It is necessary to use this converter when the nominal voltage of the battery is larger than the voltage produced by the generator. The DC converter is also utilized when it is necessary to decrease the voltage supplied by some external source. The buck-boost converter allows both the increase and decrease of the voltage.

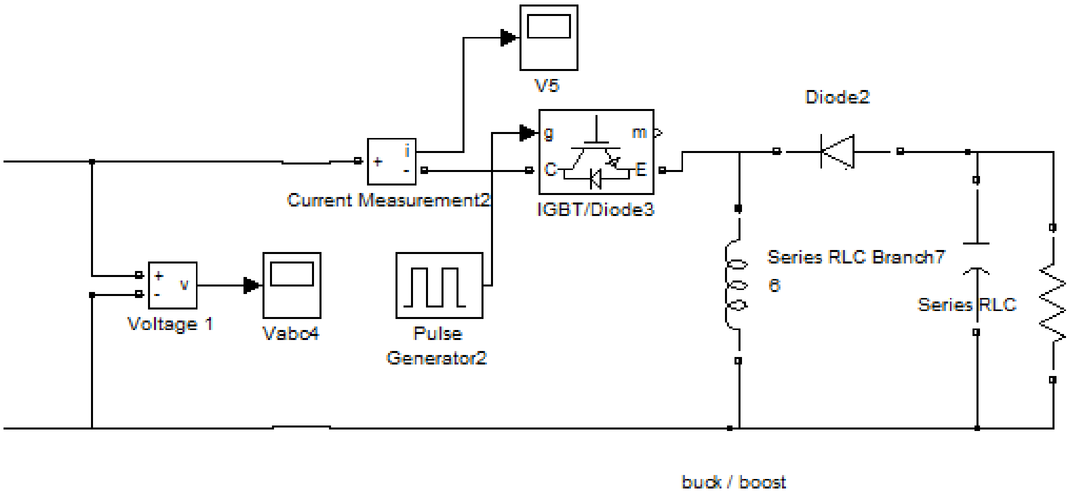


Figure 26. Buck-boost DC converter model

The DC converter consists of an inductor, capacitor, IGBT, diode, and pulse generator. The basic principle of the buck–boost converter is the following:

- On-state: the input voltage is directly connected to the inductor (L). This results in accumulating energy in L. Also, the capacitor(C) supplies energy to the battery.
- Off-state: the inductor is connected to the output and capacitor, energy is transferred from L to C and the battery.

By changing the duty cycle of the pulse generator, the IGBT allows modification of the voltage. If the duty cycle is under 50%, the output voltage is smaller than the input voltage. On the other hand, when the duty cycle is over 50%, the output voltage is larger than the input voltage.

The capacitors are used to level the voltage waveform. It is also important to take into account that the polarity of the output voltage is opposite to the input.

4.1.3.3 PM synchronous motor

The PM synchronous machine used in the EV model can work either as a generator or as a motor. Its corresponding behavior depends on two commands: speed and torque. Both commands must be negative when the electrical machine is to work like a generator.

As the next picture shows, the generator management block was implemented in order to change the motor speed sign.

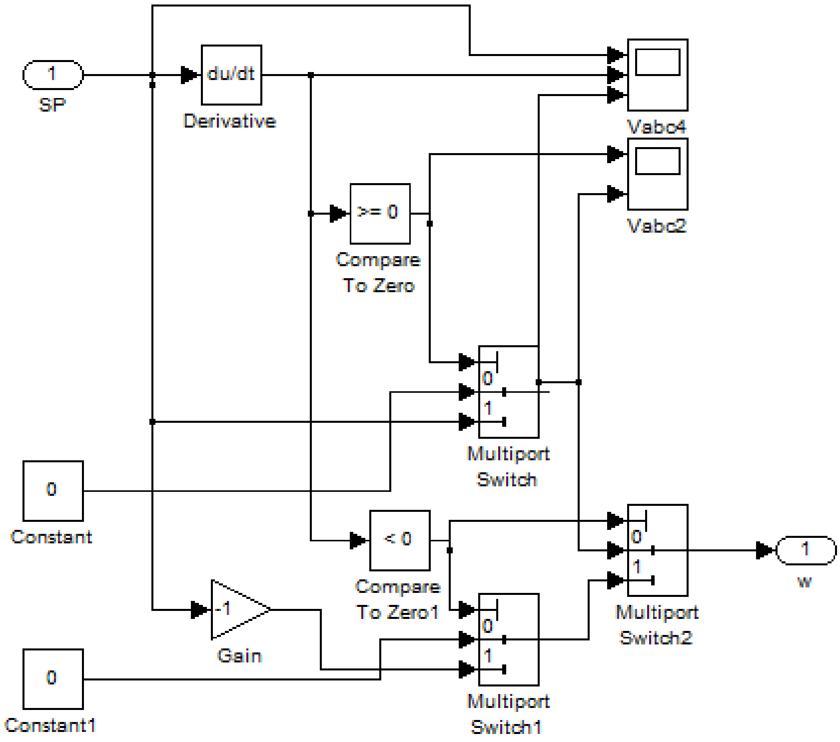


Figure 27: Generator management block

In the generator management, the derivative block calculates the acceleration from the speed trend. When the acceleration is negative, the logic operators make the speed negative also. When the acceleration is positive, the motor speed is not changed.

4.1.3.4 Inverter

The main purpose of the inverter is to convert the direct current to alternative current. However, this model utilizes a bidirectional inverter allowing current produced by the generator to be converted from alternating current to direct current. Therefore, the current flows through the diodes which are in parallel to the IGBT's.

The three-phase inverter is composed of 6 IGBT and 6 diodes and is divided into 3 parallel branches. Each branch consists of 2 IGBT's and 2 diodes in parallel.

4.1.4 Traction

The traction system converts the stored energy from the battery into mechanical energy in order to propel the vehicle. Therefore, the traction system is one of the most important components of the model. In developing the traction system, research findings, specifications from SEAT, and an academic lecture have been used to create the model. This section will present the developed model following this structure:

4.1.4.1 Overview of the traction system
4.1.4.2 Traction modeling

4.1.4.2.1 PM synchronous motor drive model
4.1.4.2.2 Vehicle dynamics model

4.1.4.1 Overview of the traction system

The first step in modeling was to understand the overall function of the traction system and to analyze how each component interacts together. Although the team members had basic knowledge about vehicle components, it was necessary to study the function of all vehicle components more precisely and the means to simulate them in Matlab. Each meeting with SEAT was used to clarify the vehicle functioning and different components specifications. A basic explanation of how the traction system works is provided below.

The role of the traction is to move the vehicle at the requested speed. The traction system is a set of mechanical and electrical components which allows propels the vehicle using the battery as the source of power. In the electrical part, there is the electrical motor, power converter and the speed controller. In the mechanical part, there are transmission systems and the vehicle information.

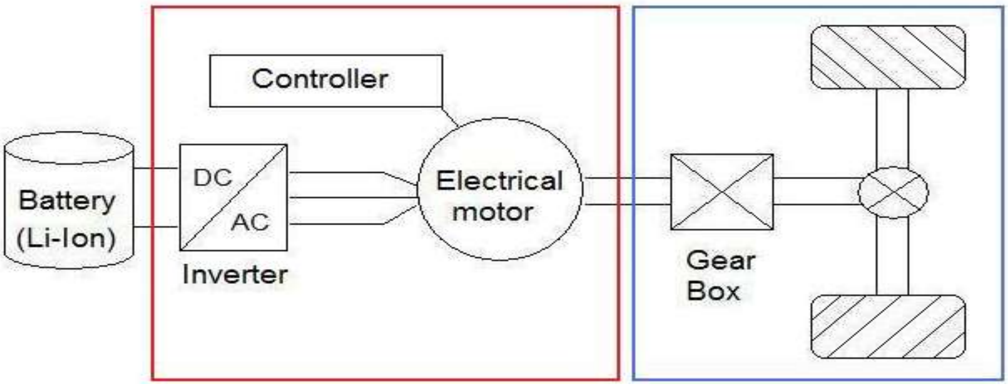


Figure 28: Traction system overview

Before supplying the electrical motor, the current from the battery has to be modified. Therefore, it is necessary to use a power converter which converts the direct current from the battery to a three phase alternative current for the electrical motor. Then, the electrical motor is controlled by the speed controller in order to ensure the driver speed request. The torque from the output of the vehicle is sent to the mechanical system. The torque is also called moment force and it is the rotation force around an axes. The torque from the electrical motor goes to the gear box and then creates the rotation of the wheels.

4.1.4.2 Traction Modeling

In the following text, the development of the traction system in Matlab-Simulink will be explained.

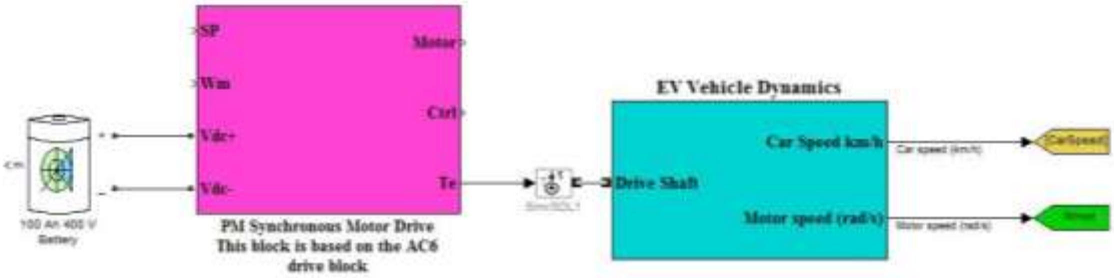


Figure 29 Traction system overview in Matlab

The traction system in Matlab is composed of two boxes: the PM Synchronous Motor Drive which is the electrical part and the Vehicle Dynamics box which is the mechanical part. In the PM Synchronous Motor Drive there are two inputs for the electrical source and there is an individual input for the speed and the torque command. There are three outputs in this box which are "Motor", "Ctrl" and "Te". The most important output is "Motor" because it gives all information about the electrical motor such as:

Table 6: PM synchronous motor outputs

Output information	Specific name
Stator current	is_a /b/c/q/d
Stator voltage	Vs_q/d
Phase back EMF	e_a/b/c
Hall effect signal	h_a*/b*/c*
Rotor speed	wm
Rotor angle	thetam
Electromagnetic torque	Te

The electromagnetic torque also has its own output called "Te". The "Ctrl" output gives all information about the speed controller such as:

- The torque reference
- The torque Error
- The speed reference

In the output of the motor, the motor creates an electromechanical torque signal to be analyzed with an oscilloscope. A "torque actuator" is then used to transform the electromechanical signal from the electric motor to a mechanical torque.

The vehicle dynamics box in Matlab contains all the mechanical power transmission components and all information about the vehicle. There is the gear box system, differential, tire information and vehicle information. This box is very important because all forces applied to the vehicle are calculated and the dynamics of the vehicle are created. In the output of this box, the real speed of the car can be collected.

4.1.4.2.1 PM Synchronous Motor Drive Subsystem

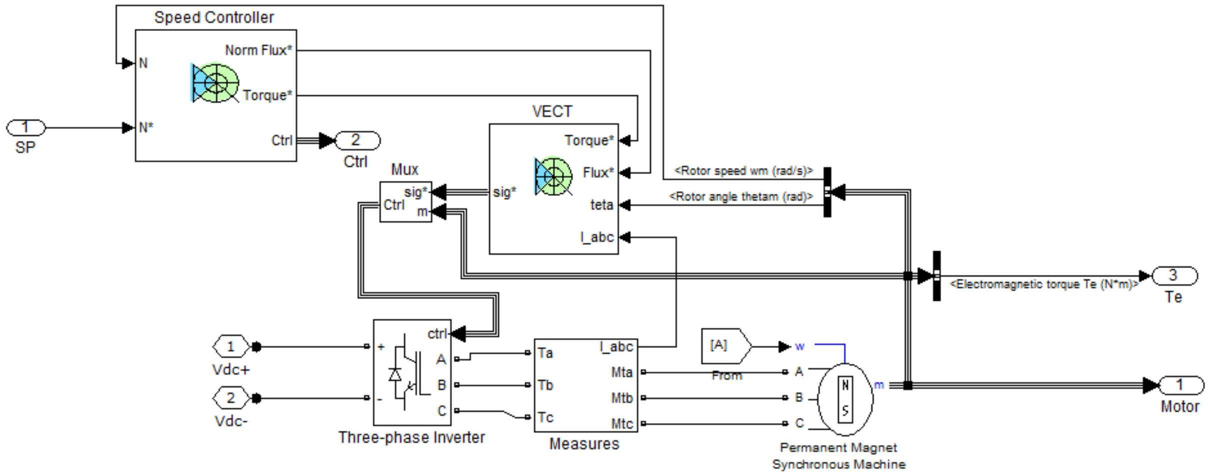


Figure 30: PM synchronous motor drive subsystem

The diagram above represents the subsystem of the PM synchronous motor drive. It is made of the permanent magnetic synchronous motor, speed controller, vector controller, and three-phase inverter. The electrical source goes to Vdc+ and Vdc- and is modified with the three-phase inverter before supplying the electrical motor. The speed controller compares the real speed of the car with the driver's requested speed and if there is a difference, the vector controller sends a signal to the three-phase inverter in order to correct the error. The following points describe in more detail each block:

a) Speed controller

The speed controller compares the torque in the output of the motor with the torque reference asked by the driver. Therefore, in this case it will be better to call this box "Torque controller". In the N input, the torque from the electrical motor is sent and in the N* input, the requested torque. Then, in the output of this box, in "Norm Flux" the flux weakening constant is sent; in "torque*" output the torque correction for the electrical motor is sent; and in the Ctrl output the torque reference, speed reference and torque error is sent. All this information goes to the vector controller in order to generate a signal which is going to correct the torque error.

This box also limits the torque power. The maximal torque is 611Nm, the minimal -611Nm and the sampling time used for the simulation is 120e-6 seconds.

b) Vector controller

The vector controller receives information from the speed controller and electrical motor in order to generate a signal to the inverter. From the speed controller, the torque that the electrical motor has to produce in order to correct the error is sent and the flux weakening is sent. From the electrical motor, the rotor angle thetam and the supplying current value are sent to the vector controller. Then, with all this information, the box generates a signal to the three-phase inverter.

In this simulation, the electrical motor has 16 pairs of poles and the inductances values are 0.134e-3 H. It is not possible that inductances had the same value therefore; the Lq inductance has 0.13e-3 H. Other values are Matlab's initial values such as:

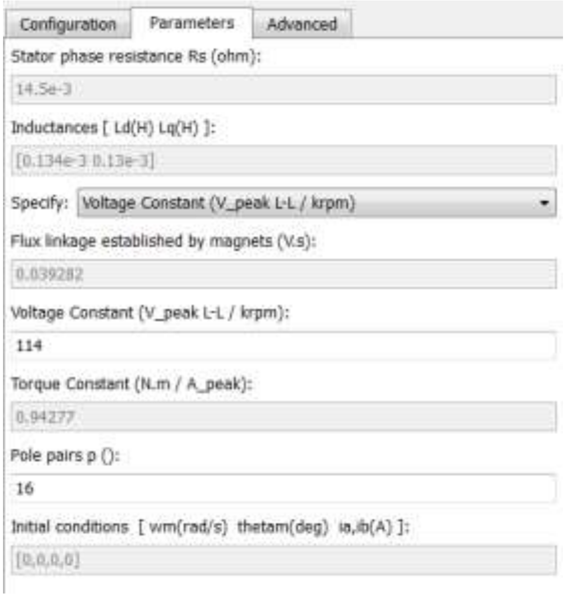
Table 7: Vector controller values

Name	Matlab's value
Flux induced by magnets	40.07111510954334 Wb
Maximum switching frequency	20e-3 Hz
Sampling time	60e-6 s
Current Hysteresis bandwidth	0.1 A

c) PM synchronous electrical motor

The motor can be controlled by the speed or the torque. In this case, the speed command is used to control the motor. As previously explained in section 4.1.3.3, when the speed is negative, the motor works like a generator. The electrical source is a three phase alternative current and the voltage is around 300V.

The electrical motor has a 14.5e-3 ohm Stator phase resistance and 0.134e-3 H Ld inductance and 0.13e-3 H Lq inductance. It is necessary to inform either the Flux linkage established by Magnets or theVoltage Constant or the Torque Constant. When one of these values is saved, Matlab calculates automatically other values. In this case, the Voltage Constant is used and its value is 114 V/krpm. The motor pairs of pole are 16 and there are not initial conditions.



Stator phase resistance Rs (ohm):
14.5e-3
Inductances [Ld(H) Lq(H)]:
[0.134e-3 0.13e-3]
Specify: Voltage Constant (V_peak L-L / krpm)
Flux linkage established by magnets (V.s):
0.039282
Voltage Constant (V_peak L-L / krpm):
114
Torque Constant (N.m / A_peak):
0.94277
Pole pairs p ():
16
Initial conditions [wm(rad/s) thetam(deg) ia,ib(A)]:
[0,0,0,0]

Figure 31 : Electrical motor parameters

4.1.4.2.2 Vehicle dynamics

The role of the vehicle dynamic box is to transmit the rotational force of the electrical motor to the wheel rotation.

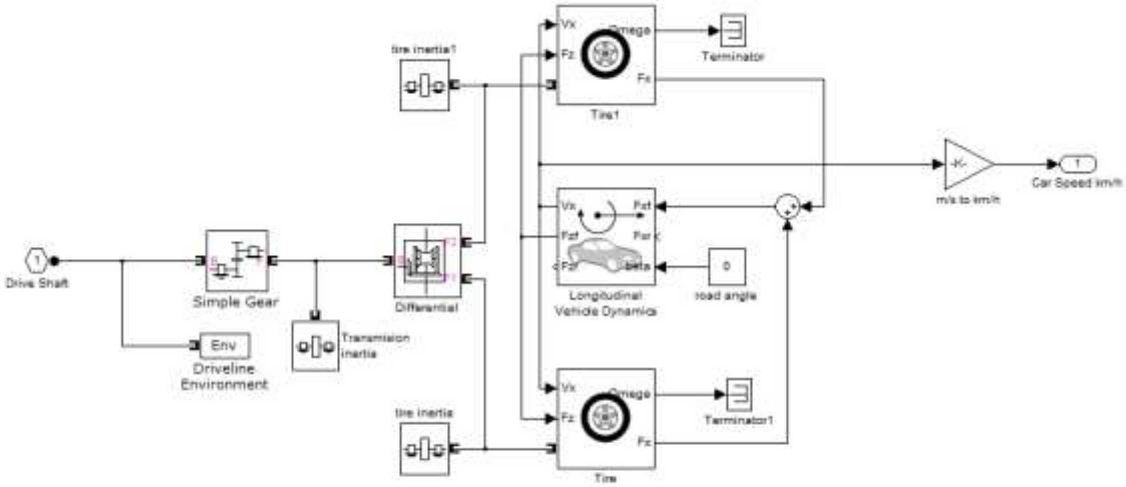


Figure 32: **Vehicle dynamics subsystem**

The torque from the electrical motor moves the Drive Shaft and after, this power is modified by the simple gear. In this case, the simple gear ratio is 4. The power is then sent to the differential and split between the front wheels. Wheels are represented with the tire box model. In this box, there is all the information about the tires. Another box called longitudinal vehicle dynamics which contains all information about the vehicle characteristics. In this box, all forces applied to the vehicle are calculated and thus, it is possible to collect the real speed of the vehicle. For each component, the inertia is included which is 1.5e-3 kg*m^2. The following paragraphs explain the boxes used in the vehicle dynamics model in more detail.

a) Simple gear

At the request of SEAT, the EV model only uses a simple gear. For a simple gear, the driveline environment box must be included in the model and the "default clutch velocity tolerance" value set to 1e-3 rad/s. In the simple gear box, there is a single value which is the gear ratio between the follower and base. In this simulation, the ratio is 4.

b) Differential

The differential is used to distribute the power from the electrical motor to the wheels. In this box also, there is only one value to write which is the drive gear ratio. In this case, the Drive gear ratio is 1 which means that 50% of the power is sent to the left wheel and 50% of the power is sent to the right wheels.

c) Tire box

The box contains all information about the tire. In the input of this box, the mechanical power is sent in order rotate the wheel. There are also two values sent from the "longitudinal vehicle dynamics" to the input of the tire box which are the vertical load applied to the tire (Fz) and the vehicle speed (Vx). With all these information, the box calculates the wheel angular velocity (Ω) and the longitudinal force exerted by the tire on the wheel (Fx).

All parameters used for the tire characteristics are standard values.

Table 8: Tire characteristics

Characteristic's name	Standard Value
effective rolling radius	0.25m
rated vertical load	3000N
peak longitudinal force at rated load	3500 N
slip at peak force at rated load	10 N
relaxation length at rated load	0.2 m

d) Longitudinal vehicle dynamics

This box contains all information about the vehicle dynamic and calculates all forces applied to the vehicle. In the input of this box, the front longitudinal force on the vehicle is sent and the incline of the road is given to the box. Then, inside the box, the vehicle's information is written with most of them being standard values:

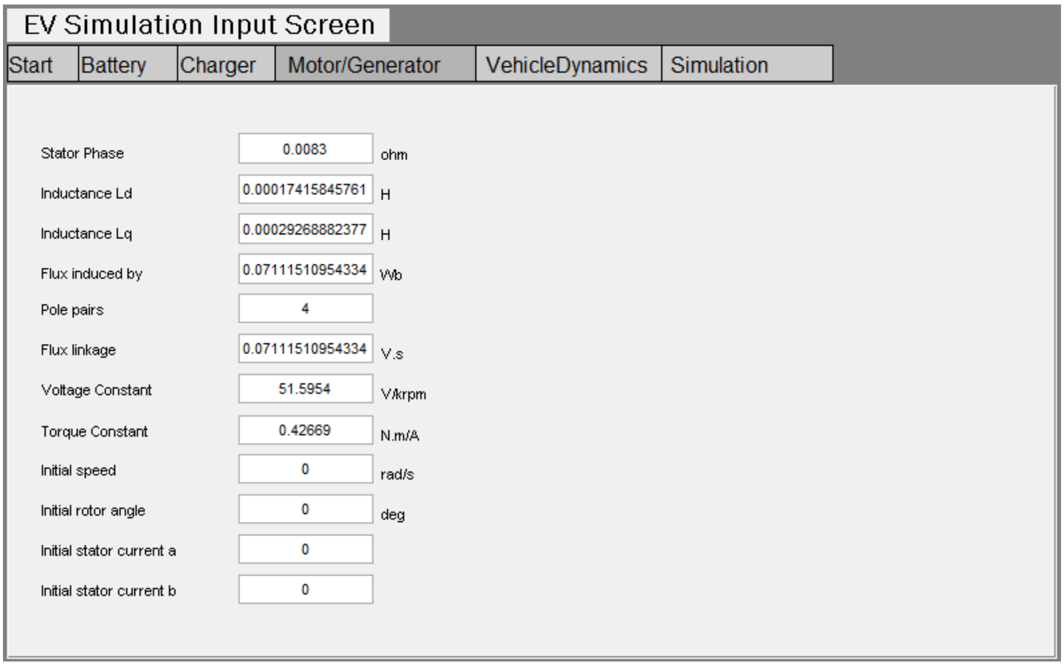
Table 9: Longitudinal vehicle dynamics values

Characteristic's name	Standard Value
mass of the vehicle	1625 kg
horizontal distance from the centre of gravity to the front axle	1.4m
horizontal distance from the centre of gravity to the rear axle	1.4m
centre of gravity from the ground	0.5m
frontal area of the vehicle	2.7m^2
drag coefficient	0.26
Initial longitudinal velocity	0m/s

In the output of this box it is possible to collect the real speed of the vehicle. Because of the speed in the output the box is in m/s, there is a gain box which converts the speed from m/s to km/h.

4.1.5 Graphic User Interface

The graphic interface allows the user to modify model parameters easily. The user can adjust the initial values which are then sent to the model automatically. The graphic interface is divided into 6 tabs. Four of them represent vehicle systems and contain values to be modified in order to configure the model. The following graphic is a screen shot of the Motor/Generator input screen.



Stator Phase 0.0083 ohm
Inductance Ld 0.00017415845761 H
Inductance Lq 0.00029268882377 H
Flux induced by 0.07111510954334 Wb
Pole pairs 4
Flux linkage 0.07111510954334 V.s
Voltage Constant 51.5954 V/krpm
Torque Constant 0.42669 N.m/A
Initial speed 0 rad/s
Initial rotor angle 0 deg
Initial stator current a 0
Initial stator current b 0

Figure 33: Graphic user interface screenshot

The next picture shows the simulation tab of the graphic interface. On the top, there are several buttons that allow selecting the state of the simulation such as start, stop, pause and continue. On the top left, there is a pop-up menu that allows selecting which chart is going to be showed such as vehicle speed, motor torque, motor speed, state of charge, etc.

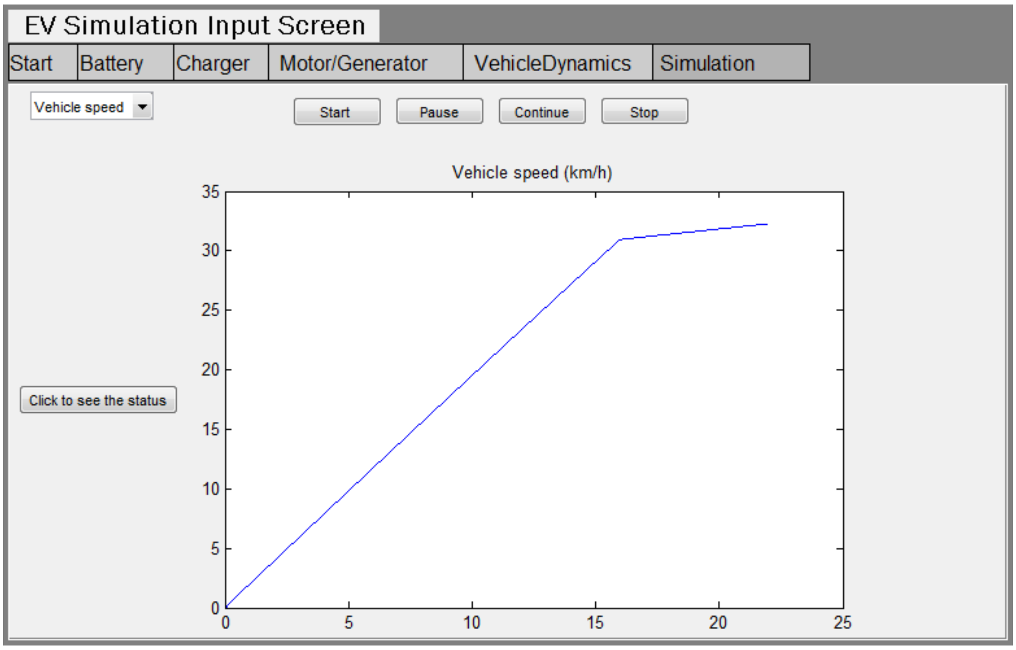


Figure 34: Simulation tab of the graphic interface

4.1.5.1 Graphic interface programming

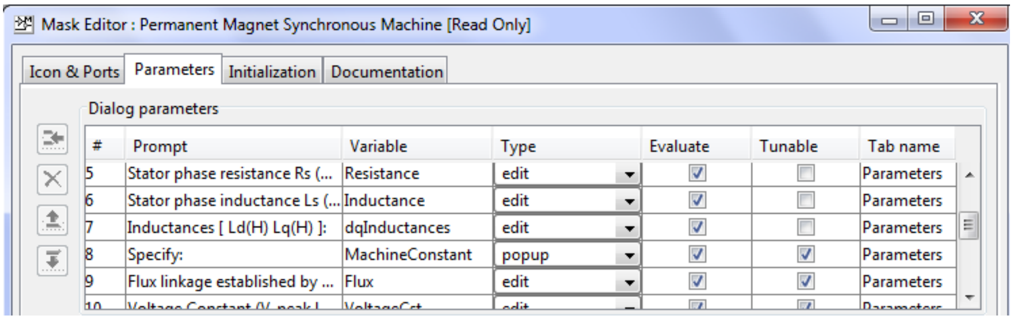
To program a graphic interface using Matlab/Simulink, it is necessary to use two different files: m-file and GUI-file. The code used to program is quite similar to any type of structural codes such as

C++, Java, etc. The m-file consists of some lines of code that allows linking the graphic interface and the model. Moreover, it is very important to take in account that all the variables that are sent to the model are strings. The GUI-file is only the graphic part that the user can manipulate. A brief overview of three common programming functions present in the developed GUI follow.

The following functions allows the GUI to find and open the model file. The GUI, m-file, and model must all be in the same folder to be found.

```
find_system('Name','EV_Vehicle_80kmh');
open_system('EV_Vehicle_80kmh');
```

To identify which parameters can be modified in a model, right click on any block, for example the PMSM, and then select "View mask", "Parameters." The next picture shows which values can be modified such as stator resistance, stator inductance, flux, etc, and also their name to be addressed such as Resistance, Inductance, dq Inductances, etc.



Mask Editor : Permanent Magnet Synchronous Machine [Read Only]

Dialog parameters

#	Prompt	Variable	Type	Evaluate	Tunable	Tab name
5	Stator phase resistance Rs (...	Resistance	edit	☑	☐	Parameters
6	Stator phase inductance Ls (...	Inductance	edit	☑	☐	Parameters
7	Inductances [Ld(H) Lq(H)]:	dqInductances	edit	☑	☐	Parameters
8	Specify:	MachineConstant	popup	☑	☑	Parameters
9	Flux linkage established by ...	Flux	edit	☑	☑	Parameters

Figure 35: PMSM block mask

The following function allows configuring any block of the model. The part of the code that is necessary to include is the name of the model file, then, the name of the box that contains the block, then, the name of the block. The second part of the code is the name of the parameter that the user wants to modify, in our case, 'VoltageCst'. Finally, last part of the code should include the name of the variable or value that is associated to the parameter of the block.

```
set_param('EV_Vehicle_80kmh/PM Synchronous Motor Drive This block
is based on the AC6 drive block/Permanent Magnet Synchronous
Machine','VoltageCst',VoltageCst);
```

The following part of code is an example of a callback. When the user click on a button, the callback associated to this button is executed. The first line of the code is the header of the function. Ini_velocity is the variable that contains the value written by the user. The last part of the code allows sending the value to the model.

```
function edit54_Callback(hObject, eventdata, handles)
ini_velocity=get(hObject,'String');
set_param('EV_Vehicle_80kmh/EV   Vehicle   Dynamics/Longitudinal
Vehicle Dynamics','v0',ini_velocity);
```

4.2 Model Assembly

The last step of model development is to assemble all different components in order to realize the vehicle simulation. At this moment, the global assembly is not entirely finished due to some problems occurring during the simulation. Therefore, this section will address the current functionality of the final assembly, with suggested improvement given in section 6.1 Further Model Revisions.

4.2.1 Functionality of the final assembly

The final assembly is composed of all models realized separately and each individual model is included in a subsystem box. Therefore, the final model includes these models:

- Battery model
- Battery temperature model (grey)
- PM Synchronous Motor Drive model (magenta)
- Vehicle Dynamics model (blue)
- Driving cycle management model (green)

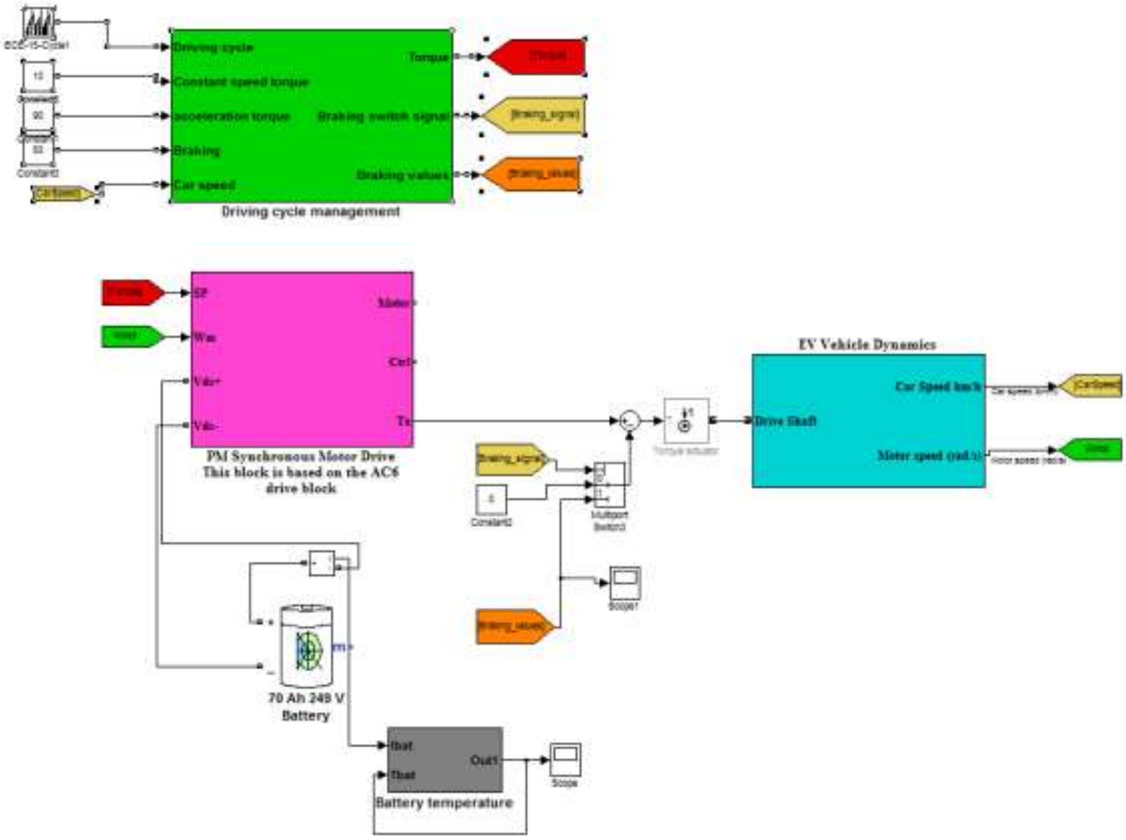


Figure 36: Simplified model assembly

4.2.1.1 Battery/PM synchronous motor drive assembly/Battery temperature

The first step of the assembly is to link the battery to the PM Synchronous Motor Drive in order to supply the electrical motor. Between these two boxes, the battery management takes the electrical current value and calculates by itself the evolution of the battery temperature.

4.2.1.2 PM synchronous motor drive /Command assembly

Once electrical motor is supplied, it is necessary to create a speed command and a torque command in order to command the electrical motor. Therefore a new box is used which is called "driving cycle management" box. This box generates the torque that the electrical motor has to produce in order to follow the driver's speed request. This box contains 5 inputs:

- Driving cycle: In this input, the driving cycle that the model must simulate is sent
- Constant speed torque: This input receives the value of the torque that the motor has to produce while it is staying in a constant speed
- Acceleration Torque: This input receives the value of the torque that the electrical motor has to produce when the vehicle is accelerating
- Braking: This input receives the braking force which is going to slow down the vehicle
- Car speed: This input receives the current speed of the vehicle

The box also contains 3 outputs:

- Torque: This is the torque value which is sent to command the torque of the electrical motor
- Braking switch signal: This is the signal which commands the switch situated just before the vehicle dynamics box
- Braking value: This is the value of the braking force

The driving management box works like a speed controller. The current speed of the car is compared with the driving cycle speed and then this box decides if the car has to accelerate or brake. They are three possibilities:

1. If the speed of the car is less than the driving cycle speed AND if the driving cycle is accelerating, the "acceleration torque" value is sent to the "Torque" output
2. If the speed of the car is more than the driving cycle speed AND if the driving cycle is decelerating, the "Braking" value is sent just before the vehicle dynamic in order to slow down the car until the required speed
3. If the speed has to be constant AND if the car is not at 0km/h, a low torque value is sent to the motor in order to maintain the speed and overcome forces applied to the vehicle

This method of simulating the driving cycle has some limits. The problems related to this box will be explained in the next chapter.

4.2.1.3 PM synchronous motor drive/Vehicle dynamics assembly

As previously explained, the torque obtained from the electrical motor is converted in the torque actuator and then, this mechanical torque is sent to the vehicle dynamic. This box contains the transmission system of the car and all information about the vehicle. Finally, in the output of this box, the actual speed of the vehicle is collected.

4.3 Model Validation

Validation of individual components and system assemblies is essential to producing a viable EV model capable of simulating real-world driving cycles. Standard processes used for these validation processes will be given in the following sections.

4.3.1 Component Testing

4.3.1.1 Battery

The battery is a simple component which is producing electrical voltage and electrical current according to the electrical motor requirements. Therefore, in order to see if the battery is working properly, it is necessary to use scopes to analyze the battery voltage and current. These following points have to be respected:

- The battery voltage should stay between 249V and 300V
- The voltage should not vary a lot
- During the acceleration, the current should increase
- The current should stay under 560A which is the maximal current from the battery
- During the acceleration, the electrical motor is consuming power so; the state of the charge of the battery should decrease (only if the SOC is less than 80% and more than 10%)

4.3.1.2 On-board charger

The buck boost converter was implemented using a capacitor of 0.01 F and an inductor of 0.02 H. At the beginning, the voltage waveform supplied by the converter was too varied. In order to solve this problem, a bigger capacitor was included to the model. As said before, the voltage supplied by charger should be constant and close to 250 volts in order to charge the battery.

4.3.1.3 Generator

The main purpose of this test is to check the behavior of the motor/generator. It is necessary to make sure that when the speed of the car is decreasing, the behavior of the motor changes. Therefore, the behavior switches motor to generator. It is also important to take in account the other results of the simulation in order to check the values and parameters of the PMSM and the battery. In order to simplify the test the driving cycles are not included in the model.

4.3.1.4 Traction system validation

In order to validate or see if the model is working properly, the PM Synchronous Motor Drive and the Vehicle dynamics boxes have to be analysed separately.

4.3.1.4.1 PM synchronous motor drive

The system validation of this box is realized with the configuration presented in the traction system part: the torque command is sent to the speed controller and the speed command to the electrical motor input. In order to see if the model is working properly it is necessary to run the simulation and then analyse motor characteristics with scopes. First, it is necessary to make sure that all values given in the traction system part are applied correctly in the model and then to analyse simulation's values such as the motor torque and the rotor speed:

- The torque sent to the input of the speed controller has to be produced in the output of the motor. This value appears in "the Electromagnetic Torque Te" of the electrical motor output
- In the output of the electrical motor, the torque value has to be less than 611Nm

- If the torque value is more than 611Nm, make sure that the speed controller limits are [-611;611]
- The speed sent to the input of the electrical motor has to be produced in the output of the electrical motor. This value appears in the "Rotor speed Wm" of the electrical motor output
- In the output of the electrical motor, the rotor speed has to be less than 6000rpm
- The power of the electrical motor has to be less than 85kw
- The value of the number of pole has to be the same in the electrical motor, in the vector controller and in the three-phase inverter
- The maximal current of the electrical motor has to be 500A
- Make sure that all values given in the traction system part are applied correctly in the model

4.3.1.4.2 Vehicle dynamics

This subsystem is doing a lot of calculations so; there is not specific procedure to follow in order to see if this model works properly. It is necessary to check if all values are written and if components don't produce problems:

- The Driveline Environment box often has problems with the simulation time so, make sure that this box doesn't stop the simulation
- If this box stops the simulation, it is necessary to try another time step or to modify initial values of the torque
- Make sure that the simple gear ratio is 4 and that the differential ratio is 1
- Make sure that the vehicle has all information
- Make sure that the speed of the car starts at the same initial speed written in the "longitudinal vehicle dynamics" box

4.3.2 Assembly Testing

In order to see if the global assembly is working properly, first all components have to be tested using individual components testing methods. Afterwards, the final assembly testing has to be realised and the following points will explain how to see if the model is working correctly:

- Before starting the simulation, constant torque values have to be written in the input of the driving cycle management box. For example these values can be used:
    - Acceleration torque: 90Nm
    - Constant speed torque: 10Nm
    - Braking value: 50
- Use a driving cycle which is accelerating, maintaining in a constant speed and decelerating in order to analyse all possibilities of the car.
- The driving cycle has to be introduced in the input of the "Driving cycle management" box and this speed has to be realised exactly in the output of the "Vehicle dynamics" box
- When the car is slowing down, check if the generator starts to produce electricity for the battery (only if the state of the charge of the battery is less than 80%). In this case, the state of the charge of the battery has to increase
- When the car is accelerating or is maintaining a constant speed, make sure that the real torque result is the same as the requested torque
- When the car is decelerating, using a scope, check if the vehicle is braking.
- Analyse the electrical motor's rotor speed and check if the rotor speed is evolving in the same way as the vehicle speed.

5. Results

5.1 Charging System

5.1.1 Battery

The figure below represents the battery response when a constant speed request of 80km/hr at maximum acceleration is requested from the model. All three measures follow the expected behaviors with the voltage decreasing, current increasing, and SOC depleting by 0.4% over the 12 second acceleration.

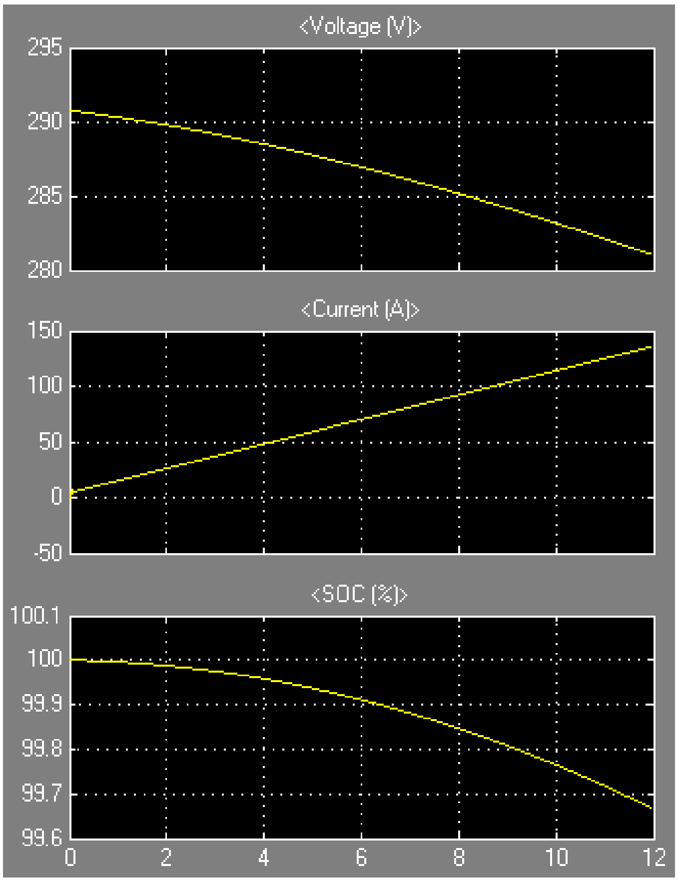


Figure 37: Output values of battery

5.1.2 On-board Charger

The next pictures show the voltage output of the different charging modes. The first picture shows the voltage when the external source supplies 230 V_{ac} / 16 A , the second one shows the voltage when the external source supplies 400 V_{ac} / 29 A and the third one shows the voltage when the external source supplies 250 V_{dc} / 133 A. Moreover, in the first case, the pulse generator produces a pulse with a duty cycle of 38% and, in the second case, the pulse generator produces a pulse with a duty cycle of 26%.

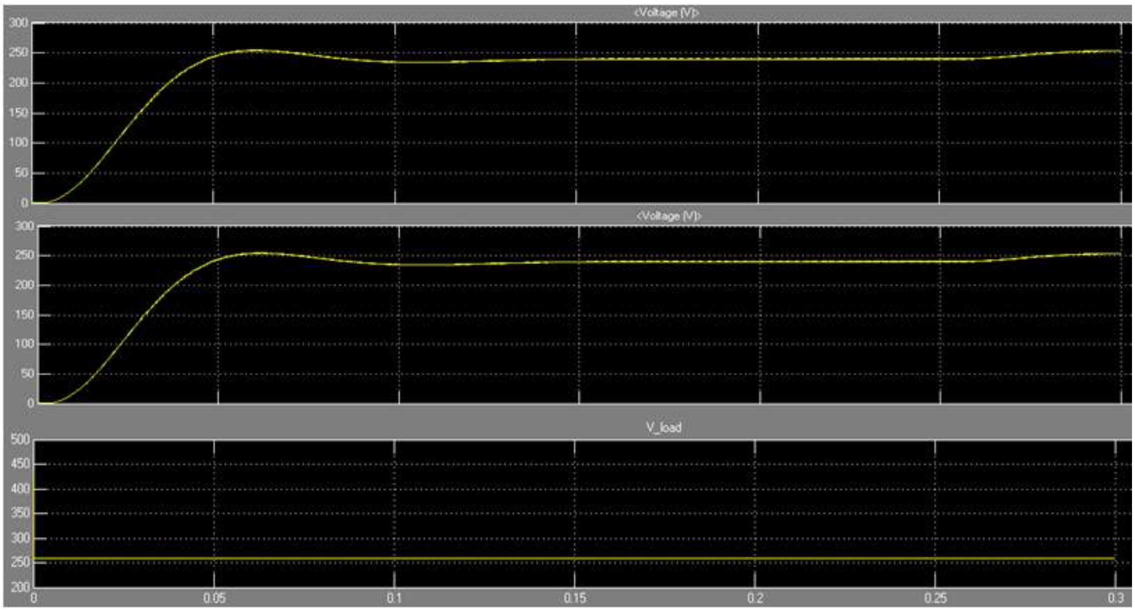


Figure 38: Output voltage of the charger

5.1.3 Generator

As the fist chart of the next picture shows, the electromagnetic torque is around 250 Nm. The torque is maximal when the car speed is maximal. The nominal torque of the motor is 332 Nm. The second chart shows the rotor speed (rpm). When time is 12 seconds, the rotor speed is maximal. Then, the speed is decreasing. Therefore, the acceleration is negative and the generator might start to produce electrical power. The third chart shows the mechanical power. While the speed is positive and is increasing, the power is also increasing. The nominal power is around 45 kW. The fourth chart shows the stator current that the motor consumes. The higher trace corresponds with the line current and the lower trace corresponds with the phase current. The last chart shows the voltages supplied by the battery.

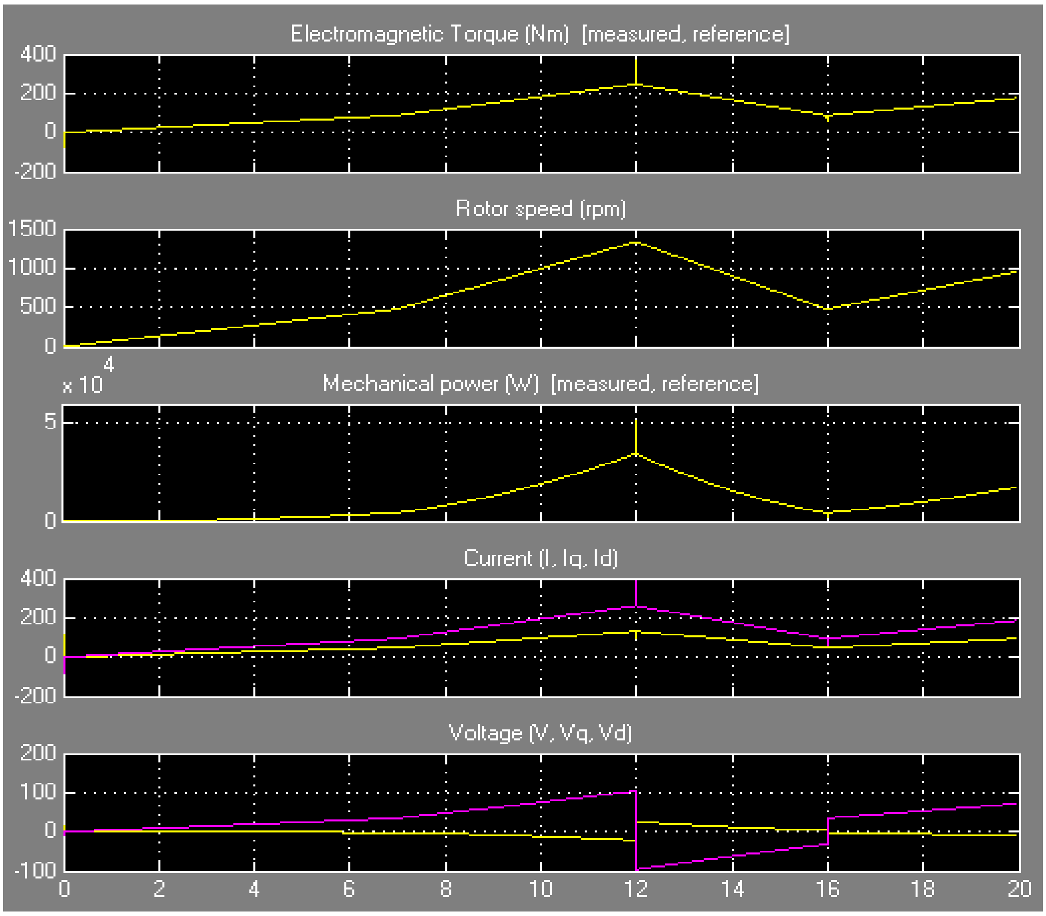


Figure 39 : Motor/Generator results of the generator validation

The following picture shows the behavior of the battery. The first chart shows the battery voltage. Its value is between 470 and 463. Therefore, the value is quite constant. The battery current on the second chart is positive when the battery supplies electrical current. On the other hand, the current is negative when the battery is being charged. The third chart shows the battery state of charge. At the beginning, the curve is decreasing because the motor consumes electrical power. Then, the curve is increasing slowly because the generator is producing energy. The last chart shows the power of the battery. Obviously, the power depends on the current and the voltage that the battery supplies.

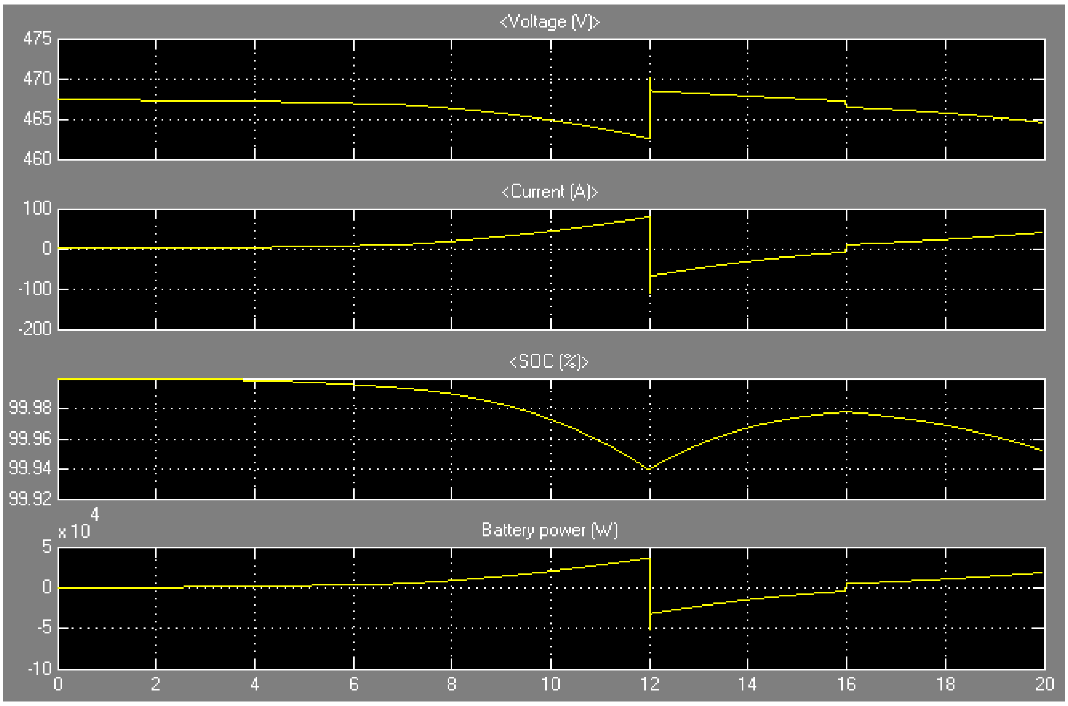


Figure 40: Battery results of the generator validation

5.3 Traction system results

This part is going to explain some results about the traction system and the coherences of the results. In order to see if the model is working properly, it is necessary to use a simulation model as a basic result and then, simulate again making some modifications in the vehicle dynamic. Thus, it will be possible to see if the traction system answers properly to vehicle dynamic modifications.

In the first case, the vehicle has these characteristics:

- The vehicle mass 1500kg
- The frontal area 2.7m^2
- The drag coefficient of the car 0.26.

When the simulation is finished, the vehicle speed diagram has to be analysed. In this case, the vehicle speed scope's shows that the vehicle needs 1.1 second to achieve 5km/h.

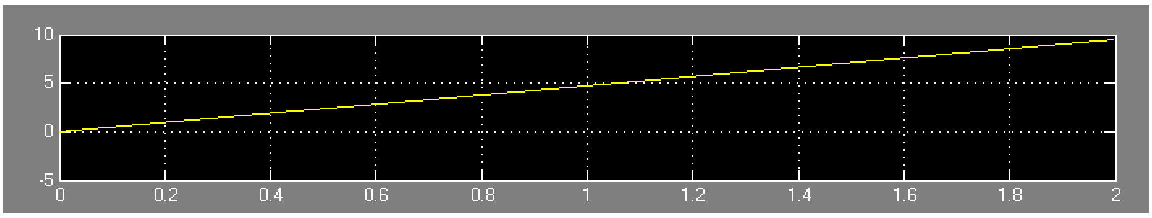


Figure 41 First simulation result

In the second case, the vehicle characteristics are bigger:

- The vehicle mass is raised to 2000kg
- The front area and the drag coefficient values are multiplied by 2, namely 5.4m^2 and 0.52.

If the simulation is working correctly, the vehicle should put more time to achieve 5km/h. The figure below shows the result:

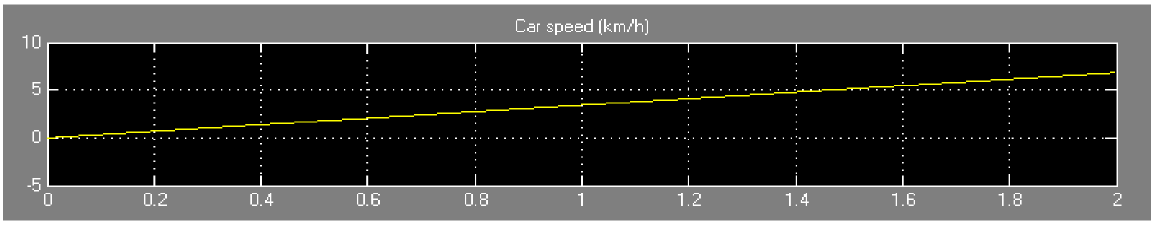


Figure 42 Second simulation result

After analysing this curve, it is possible to see that the traction system is working properly. Comparing to the first case, the vehicle runs slowly and in this second simulation, the vehicle needs 1.5 seconds to reach until 5km/h. Therefore, the traction system takes into account all modifications done in the model and affects these modifications to the vehicle speed.

5.4 Model assembly results

This section is going to present the model assembly results. Because of the problems explained in the model validation part, the simulation gives bad results when the vehicle is going to high speed and we haven't been able to have good results for different driving cycles. Therefore, in order to see some results of the simulation, a simple simulation will be done in low speed and obtained results will be analysed.

First, it necessary to put the speed request that the model must simulate in the input of the "driving cycle management" box. The simulation will be acceleration until 30km/h in 16 seconds, then constant speed during until 25seconds and deceleration until 40second. Moreover, as explain in the validation chapter, constant torque values have to be decided so, these values will be used for this simulation:

- Acceleration torque: 90Nm
- Constant speed torque: 10Nm
- Braking value: 50

The figure below shows the requested speed curve:

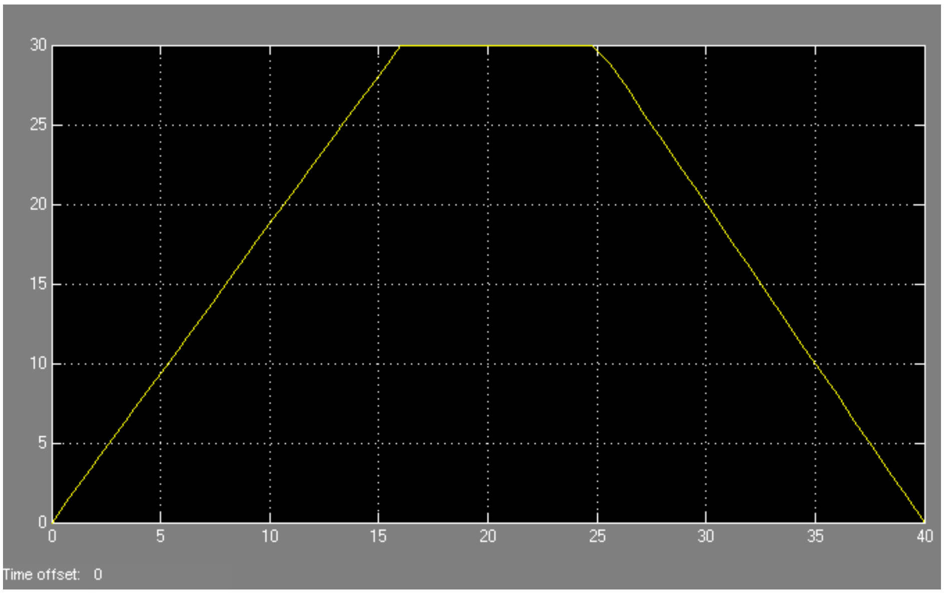


Figure 43: Requested driving cycle

Then simulation has to be run and the vehicle has to produce exactly the same speed. In the output of the Vehicle Dynamics box, it is possible to see the vehicle speed evolution and in this case, this is the result:

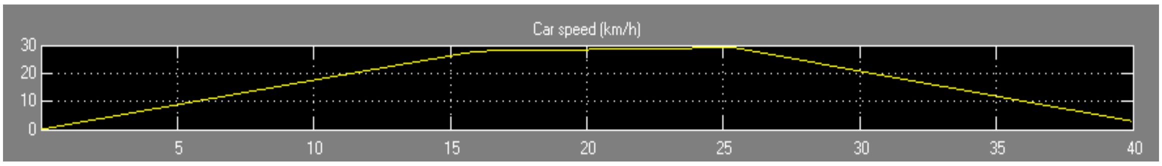


Figure 44: Real speed of the car

The figure above shows that the model simulation almost reproduces the driving cycle speed request. There are two small problems in this result:

- The speed is not exactly constant at 30km/h. This problems means that the constant speed torque should be a little bit lower.
- After 40 seconds simulation, the speed of the car doesn't achieve 0km/h. The brake of the car should be stronger.

It is also very interesting to analyse the electrical motor torque and power. The figure below shows the evolution of these characteristics during the simulation.

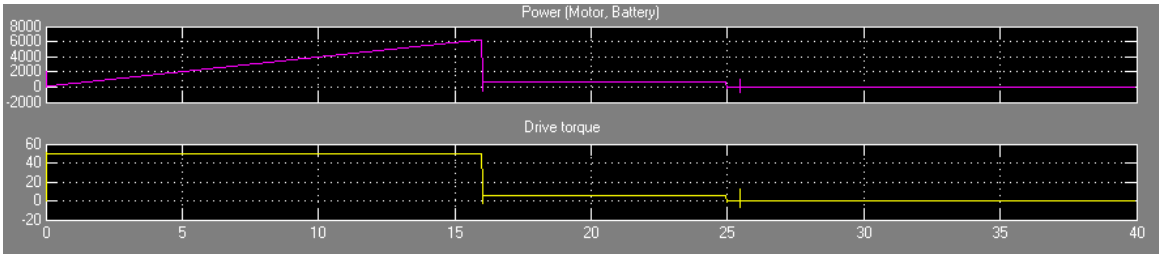


Figure 45: Electrical motor Power and Torque

First the torque from the electrical motor has to be analysed. The electrical motor doesn't produce exactly the requested torque because for example, during the acceleration, the torque should be 90Nm but in reality the drive torque is 50Nm. Concerning the power of the battery, the power increases when the car accelerates until 6kw, stays constant in the constant speed and the power is zero when the vehicle brakes. Because of the simplicity of the simulation, all these values are under maximal values which are 611Nm for the motor torque and 85KW for the motor power. In the analyze of the electrical motor, the motor rotor speed has to be analysed as well. This is the result of the rotor speed during the simulation:

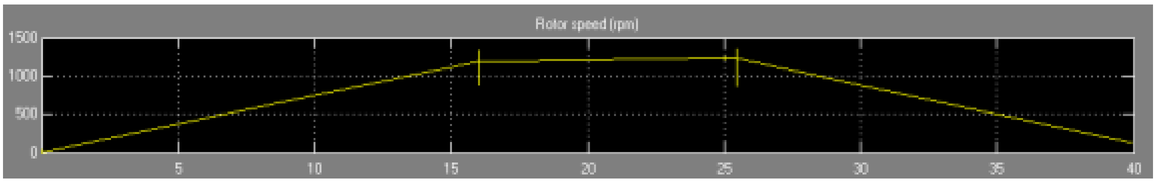


Figure 46: Electrical motor's rotor speed

The rotor speed is evolving like the real speed of the car. In this case the maximal rotor speed is around 1200rpm. This result is less than the nominal speed which is 2400rpm and of course less than the maximal speed which is 6000rpm.

The last interesting diagrams to analyse are the electrical source characteristics. The following figure shows the evolution if these values:

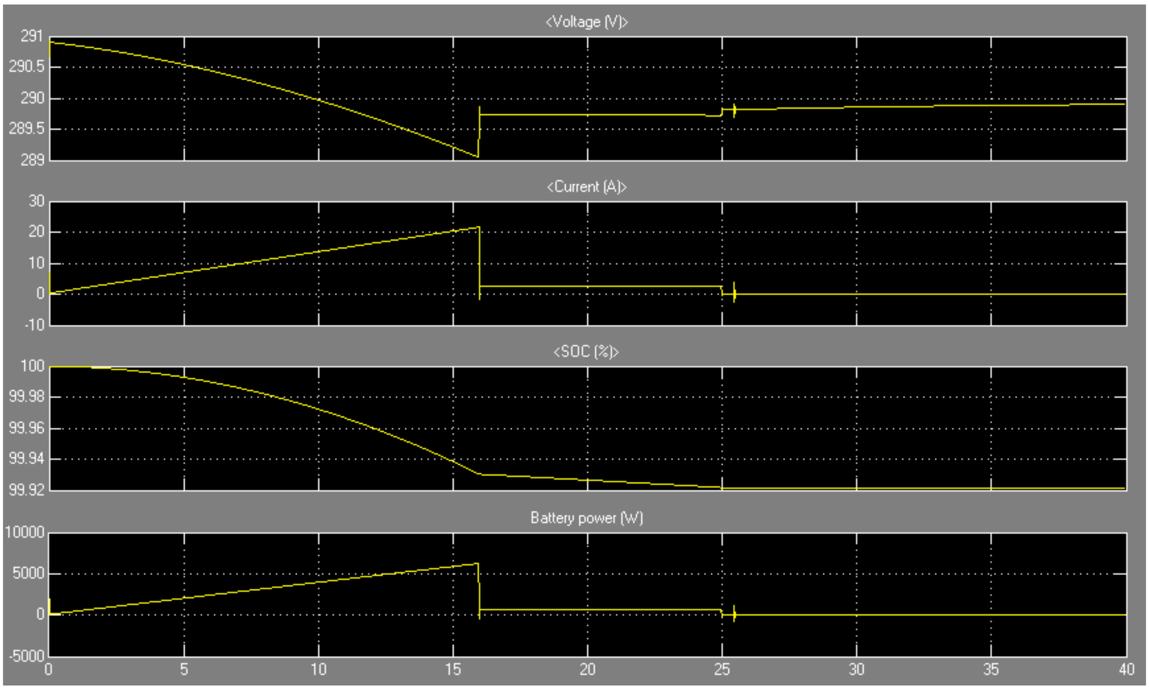


Figure 47: Battery characteristics

The battery voltage is correct because it stays between 249V and 300V. During the acceleration part, the voltage is decreasing but during constant speed, the voltage stays constant. In the contrary, the current of the battery is increasing during the acceleration but stays constant in the constant speed as well. The maximal current of the battery is 22A and because of the type of the simulation, this value is very small comparing to the theoretical nominal current value which is 210A. Related to the current and the voltage, there is also the battery power graph in the bottom of the figure. In this simulation, the power increases during the acceleration until 6Kw. Finally, the last curve in this figure is the evolution of the state of the charge of the battery. As the result shows, the battery is discharging rapidly during the acceleration, then in constant speed, the battery discharges slowly and when the vehicle brakes the battery is not used. In this case, the generator doesn't recharge the battery during the braking because the state of the charge of the battery is more than 80%.

In conclusion, as said before, this simulation is very simple and doesn't represent real conditions of the vehicle. Unfortunately, vehicle high speed simulations and driving cycle simulation have not been simulated because some problems have still to be fixed. Anyway, this results show that all components answer to the evolution of the speed and confirm that different part of the model assembly works together.

6. Project Extensions

6.1 Further Model Revisions

6.1.1 Assembly improvements

Because of the lack of time and the lack of knowledge, the final assembly doesn't work properly. Therefore, this chapter is going to explain different problems found in the actual model and some assumptions in order to improve the model. Globally, there are 6 main problems that we have encountered and they will be explained in this order:

- Battery charging model incompatibility
- The torque command according to the driving cycle
- The braking system
- Battery temperature curve
- Battery charging conditions
- Generator current

6.1.1.1 Battery charging model incompatibility

At the beginning, the charging system of the battery has been realised in a separate file and then it was assembled in the final model. When the charger is assembled in the final, an error appears and prevents to simulate the model. Apparently, there is a problem between switches used in the charger and the "Driveline Environment" box included in the Vehicle dynamics block.

6.1.1.2 Torque command according to the driving cycle

In the actual simulation, it is necessary to write the torque value for specifics conditions such as the torque used during the acceleration. Therefore, the electrical motor torque doesn't evolve automatically according to the driving cycle and this specific value is not always appropriate for the driving cycle. For example, if the acceleration torque value is too strong for the driving cycle, every seconds or less, the car is going to accelerate and brake, then again accelerate and brake... By this way, the electrical motor is working by fits and starts which generates very bad results. A box which calculates appropriate torque should be created.

6.1.1.3 Braking system

The braking problem is the same as the torque problem. The braking system reduces the torque before the Vehicle Dynamics box but the braking value is not calculated from the real speed of the vehicle. Therefore, sometime the car is not braking enough or is braking too much and obtained results can be very bad. A box which calculates appropriate braking force should be created.

6.1.1.4 Battery temperature curve

In the final assembly, there is a box which calculates the evolution of the battery temperature because the battery has to be maintained in a specific temperature. Unfortunately, all necessary values haven't been found for thermal equations so, the model in the box may be correct but not the results.

6.1.1.5 Battery charging conditions

For security reason, the battery doesn't have to be charged all the time. Moreover, in order to protect the life of the battery, the battery doesn't have to be charged if the state of the charge is more than 80% and the car has to stop when the state of the charge is less than 10%. The theoretical logic has been realised but these conditions do not work in the model assembly.

6.1.1.6 Generator current

The generator is included in the PM Synchronous Motor Drive and recharges the battery when the vehicle is slowing down. The problem in the generator is that the produced current is very high and has a lot of noises. In spite of spending a lot of time to resolve this problem, the problem hasn't been corrected yet.

6.2 Project Expansion

With a significant basis for the development of a computer based model and simulation of an electric vehicle architecture established, several expansions are possible for either SEAT Automotive or future editions of the EPS at the Escola Politecnica Superior d'Enginyeria de Vilanova I la Geltru. The following list provides a summary of the most logical expansions possible.

- Conduct further validation testing and revisions on the developed model to correct the errors present
- Development of vehicle control logic algorithm to analyze driving cycle requests and provide the appropriate signals to follow the request according to component capabilities
- Create a battery model for implementation that allows unique characteristics, such as thermal properties, to be incorporated into the model
- Use basic design for development of a plug-in hybrid electric vehicle model

7. Conclusion

7.1 Summary

Throughout this document, the process and development for the creation of a computer-based model of an electric vehicle was presented. Furthermore, the current state of the art technologies in electric and plug-in hybrid electric vehicles were overviewed and possible expansions of the project identified. The framework of EV modeling and simulation begun by this project and detailed in the report serves to aid in the progression of EV as mainstream modes of transport for the general public. To convey the work and process conducted in producing an electric vehicle model in Matlab-Simulink the following points were assessed.

I. State of the Art. This section presented an overview of the current state of the art technologies in electric and plug-in hybrid electric vehicles.
II. Project Development. Contained in this section was a description of the process, goals, and responsibilities associated with the final project outcomes.
III. Electric Vehicle Model Developments. In this section, the final model developed was presented along with sections for the assembly, graphic user interface, and model validation.
IV. Results. Relating to model validation and overall design, the results for the model development were presented in this section.
V. Project Extensions. As the final subject, future works for the project were identified.

7.2 Closing Comments

While electric vehicles are far from a new concept in the automotive industry, they have not been subject to the intense amount of research and development placed on traditional internal combustion engine vehicles throughout the past century. In light of potential increases of up to 30% in green house gas emissions in the transportation sector by 2030, it is imperative that focus shifts to producing mainstream vehicle solutions capable of reducing and/or eliminating emissions. The rapid turnover in electric vehicle technologies dictates a necessary method of assessing the viability and potential implementation of these technologies in future architectures.

It has been proven that utilization of computer-based modeling and simulation in the automotive design process can effectively reduce the design time by over 50% of that of traditional methods. Incorporation of these principles into the development of EVs will allow for a fast response to new technologies, resulting in effective mainstream market alternatives for personal transport. The Matlab-Simulink model and simulation created for the collaborative project of *Design and creation of different simulation architectures for hybrid and electric vehicles* between the Escola Politecnica Superior d'Enginyeria de Vilanova I la Geltru and SEAT Automotive serves to meet the demands of creating an efficient and effective method of electric vehicle architecture research and development.

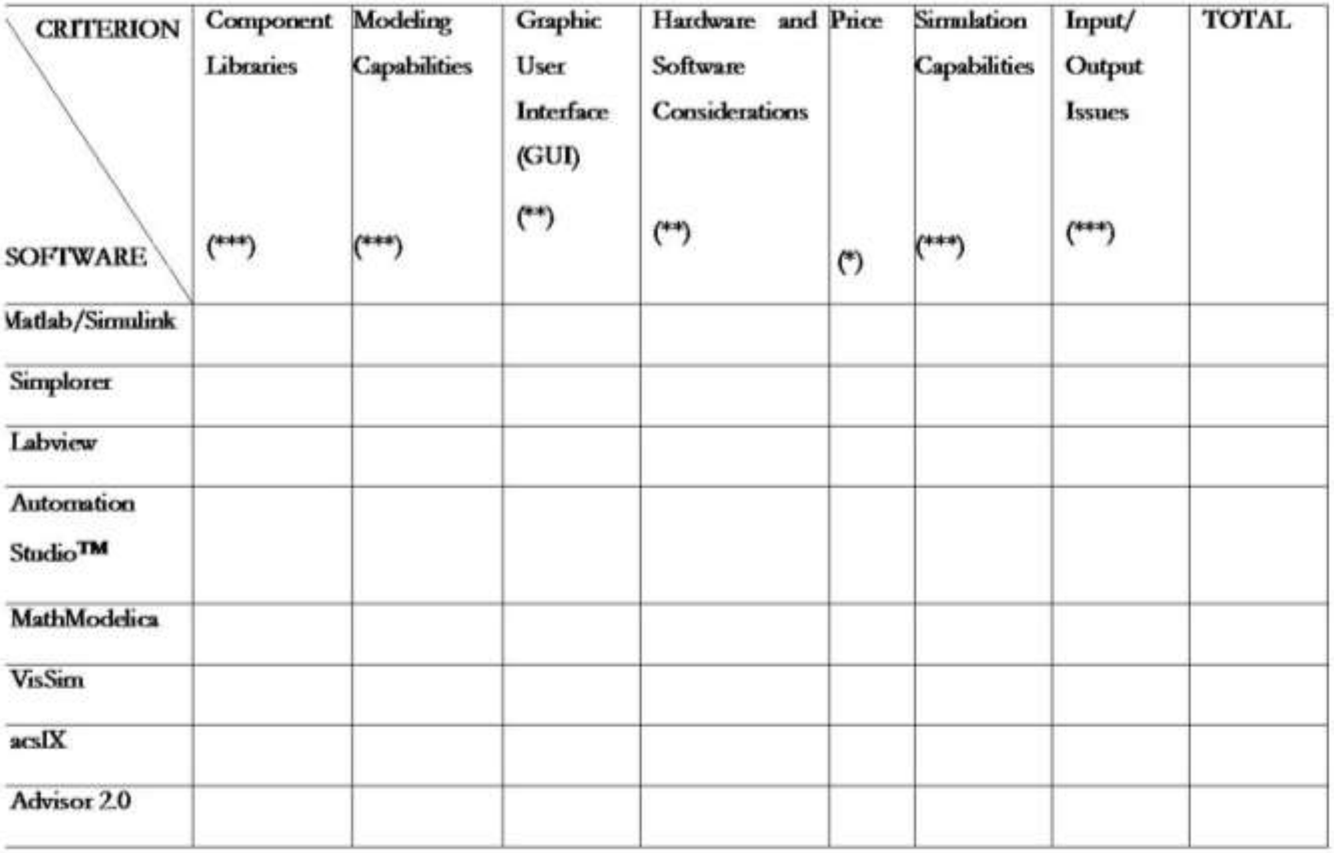
Appendix A: Work Breakdown Structure

Work Breakdown Structure and Responsibility Matrix

	Patrick	Ioan	Josep	Vedat	Xabi
Investigate and analyze current availability and market trends of hybrid and electric vehicle technologies.	R	S	S	S	S
Assess the state of the art technology and its applicability to the project.	R	S	S	S	S
Identify resources needed to understand the various components to be included in the project and assign specific roles to group members.	R	S	S	S	S
Research and understand components contained in the individual roles on a technical basis.	R	R	R	R	R
Identify battery system input variables for models and design the components.		R		S	
Identify charging/generating input variables for models and design components.		S	R		
Identify mechanical input variables for models and design components.	S				R
Create master database of variables and components with input values/ranges.	R	R	R		R
Determine output variables and assessments needed for models.	R	S			S
Assemble subcomponents and simulate preliminary design for electrical vehicle model.	S	R	R	S	R
Evaluate results.	R	R	R		R
Impose design revisions based upon prior testing	R	R	R	S	R
Develop a graphic user interface.	R		S		S
Complete a simulation/design software benchmark for SEAT.	S			R	
Create Midterm report and presentation	R	S	S	S	S
Create final document detailing project work, process, outcomes, and recommendations.	R	S	S	S	S

R - Responsible   S - Supporting

Appendix B: Software Decision Matrix Template



CRITERION / SOFTWARE	Component Libraries (***)	Modeling Capabilities (***)	Graphic User Interface (GUI) (**)	Hardware and Software Considerations (**)	Price (*)	Simulation Capabilities (***)	Input/ Output Issues (***)	TOTAL
Matlab/Simulink								
Simplorer								
Labview								
Automation Studio™								
MathModelica								
VisSim								
acslX								
Advisor 2.0								

Appendix C: Graphic User Interface Variables

Battery	
Variables	**Units**
Nominal voltage	V
Rated capacity	Ah
Maximum capacity	Ah
Fully charged voltage	V
Nominal discharge current	A
Internal resistance	Ω
Capacity (Ah) @ nominal	
Voltage exponential zone	V
Capacity exponential	Ah

Variables	Units
Motor / Generator	
Stator phase	Ω
Inductance Ld	H
Inductance Lq	H
Flux induced by magnets	Wb
Pole pairs	
Flux linkage	V.s
Voltage constant	V/krpm
Torque constant	N.m/A
Initial speed	rad/s
Initial rotor angle	deg
Initial stator current a	A
Initial stator current b	A
Vector controller	
Maximum switching frequency	Hz
Sampling time	s
Current hysteresis bandwidth	A
Speed controller	
Control output torque saturation	Nm
Controller sampling time	s
Three-phase inverter	
Ron	Ω
Source frequency	Hz

Charger
Without Charger
Standard 230 Vac/16 A
Semi fast 400 Vac / 29 A
Fast 250 Vdc / 133 A

Vehicle Dynamics	
Variable	**Units**
Simple gear ratio	
Differential drive	
Transmission inertia	Kg*m^2
Vehicle mass	Kg
Horizontal distance from CG to front axel	m
Horizontal distance from CG to rear axel	m
CG height from ground	m
Frontal area	m^2
Drag coefficient	
Initial longitudinal velocity	m/s
Road angle	rad
Tire characteristics	
Effective rolling radius	m
Rated vertical load	N
Peak longitudinal force at rated load	N
Slip at peak force at rated load	%
Relaxation length at rated load	m
Tire inertia	Kg*m^2

Works Cited

1. *Radial-flow wave rotor concepts, unconventional designs and applications.* Piechna, Janusz, et al. Anaheim : ASME, 2004.

2. Kahn Ribeiro, S., S. Kobayashi, M. Beuthe, J. Gasca, D. Greene, D. S. Lee, Y. Muromachi, P. J. Newton, S. Plotkin, D. Sperling, R. Wit, P. J. Zhou. *Transport and its infrastructure. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)].* Cambridge, United Kingdom and New York, NY, USA : Cambridge University Press, 2007.

3. *The state of the art of electric and hybrid vehicles.* Chan, C. C. 4, April 2007, Proc. IEEE, Vol. 95, pp. 705-718.

4. History of Electric Vehicles. *US Department of Energy.* [Online] 2005. [Cited: June 2, 2010.] http://www1.eere.energy.gov/vehiclesandfuels/avta/light_duty/fsev/fsev_history.html.

5. *Green Car Congress.* [Online] BioAge Group, LLC., 2010. [Cited: June 09, 2010.] http://www.greencarcongress.com.

6. Françoise Nemry, Guillaume Leduc, Almudena Muñoz, Plug-in Hybrid and Battery-Electric Vehicles: State of the research and development and comparative analysis of energy and cost efficiency, JRC 54699 Technical Note, 2009

7. M. Duvall, Advanced Batteries for Electric-Drive Vehicles A Technology and Cost-Effectiveness Assessment for Battery Electric Vehicles, Power Assist Hybrid Electric Vehicles, and Plug-In Hybrid Electric Vehicles, Final Report 1009299, May 2004

8. Andrew F. Burke, Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles, Proceedings of the IEEE, Vol. 95, No. 4, April 2007

9. Olivier Tremblay, Louis-A., Abdel-Illah Dekkiche, A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles, Vehicle Power and Propulsion Conference, 2007 VPPC 2007. IEEE