MODELING, SIMULATION & IMPLEMENTATION OF LI-ION BATTERY POWERED ELECTRIC AND PLUG-IN HYBRID VEHICLES

A Thesis

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Master of Science

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ABSTRACT

The modeling, simulation and hardware implementation of a Li-ion battery powered electric vehicle are presented in this thesis. The results obtained from simulation and experiments were analyzed to develop the control algorithm for the vehicle. An existing electric vehicle was reengineered with a new Li-ion battery pack and an advanced control strategy. The implementation platform is a Solectria E-10 electric vehicle which was originally powered with a Lead acid battery pack.

A simulation model of the Solectria E-10 electric vehicle was first developed for vehicle simulation using various standard drive cycles. The supervisory control strategy was first developed and tested in simulation before it was implemented on actual hardware. A Power Save feature was developed to limit the vehicle power demand upon the driver request to increase the zero emissions vehicle range of the electric vehicle. Simulations were used to demonstrate the effectiveness of Power Save feature and it was shown that the range of the electric vehicle can be extended.

The feasibility for plug-in hybrid vehicle conversion of the developed electric vehicle to extend the range of the electric vehicle beyond its zero emissions driving range was studied through simulation. A control algorithm for plug-in hybrid vehicle was developed and simulated.
DEDICATION

Dedicated to my family and teachers
ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

1.1 Introduction

In recent decades, the oil consumption in the transportation sector has grown at a higher rate than any other sector. Statistical analysis has shown that, with the current rate of discovery of new oil reserves and the current consumption rate, the world oil reserve will be depleted by 2049 [1]. The increase in oil consumption has mainly come from new demands of vehicles powered by conventional internal combustion engines. The massive utilization of Internal Combustion Engine (ICE) vehicles has contributed dramatically to the pollution of the medium and large cities [2]. Since the environmental problems of the greenhouse effect and global warming are directly related to vehicle emissions, government agencies and organizations have developed stringent standards for fuel consumption and emissions [3].

In this scenario, battery powered Electric Vehicles (EVs) seem like an ideal solution to deal with the energy crisis and global warming since they have zero oil consumption and zero emissions on the road. The zero local emissions and the silent driving of the electric vehicles are few attributes that can help to restore the quality of life in cities [2]. Given the short range trips and frequent stop and go driving characteristics
of city driving, electric vehicles can deliver performance similar to an ICE vehicle at reduced costs compared to conventional gasoline engine vehicles under city driving [2,4].

1.2 History of Electric Vehicles

Electric vehicles have been in existence longer than conventional gasoline vehicles. The first lead-acid battery, which is the most commonly used battery chemistry in automobiles, was assembled in 1859 by Gaston Planté [6]. This discovery led to the first practical electric vehicle, which was an electrified tricycle built by Gustave Trouvé in 1881 [5]. It had a top speed and range comparable to a horse-drawn carriage. The first gasoline powered vehicle was not tested until 1885 [7].

The first commercial electric vehicle was Morris and Salom’s Electroboat [5]. This vehicle was operated as a taxi in New York City by a company created by its inventors. It was powered by two 1.5 hp motors that allowed a maximum speed of 32 km/h and a 40-km range. The most significant technical advancement in the field of electric vehicles was the invention of regenerative braking in 1897 by M.A Darracq, a French scientist. Regenerative braking allowed recuperating the vehicle’s kinetic energy while braking and recharging the batteries. It is one of the most significant contributions to electric and hybrid vehicle technology, as it contributes to energy efficiency more than anything else in urban driving [5].

In 1904, about one third of all horseless vehicles in New York, Chicago and Boston had electric powertrains because of the difficulty in starting gasoline powered vehicles. No single automotive technology was sufficiently mature along in the
development cycle to be seen as superior by the public [8]. In 1904 the Ford Motor Company went into full assembly production of cheap gasoline-powered cars [7,8]. The Model T went into production in 1908. Within a few years many electric car companies started to fold. After the electric starter became available in gasoline vehicles in 1913, the electric car industry died [7,8]. Only around 6,000 electric cars were sold in 1913, as compared to 182,809 Model Ts. For nearly 60 years, the only electric vehicles sold were common golf carts and delivery vehicles used in airports [9].

During the 1960s and 1970s, concerns about the environment triggered the research on electric vehicles. Despite the advancements in battery technology and power electronics, the range and performance of electric vehicles were still obstacles. However, the modern electric vehicle era culminated during the 1980s and early 1990s with the release of a few vehicles such as the EV1 by General Motors [5].

Tesla Roadster and Nissan Leaf are some of the modern electric vehicles that have generated back a lot of interest in electric vehicles in recent years. The Tesla Roadster is a battery powered electric sports car produced by the Tesla Motors in California. The Roadster is powered by a 3-phase, 4-pole electric motor, producing a maximum net power of 185 kW and a maximum torque 270 N-m. According to an independent analysis from the U.S. EPA, the Roadster can travel 244 miles on a single charge of its lithium-ion battery pack, and can accelerate from 0 to 60 mph in 3.7 seconds [10]. Tesla has announced its plans to release Model S, an electric vehicle in the four door luxury sedan class. The Leaf is a compact 5-door hatchback electric car produced by the Japanese automaker Nissan. The Leaf uses a front-mounted electric motor driving the
wheels, powered by a 24 kWh lithium ion battery pack and the expected range is 100 miles per charge [11].

1.3 Motivation for Research

According to the estimation available in [12], 70% of the population will live in urban areas, making daily trips of less than 100 km. The vehicle emissions occurring within these trips can be considered as an environmental pollution problem. Considering the majority of daily trips within 100 km or 62 miles, the short range of electric vehicles would not be a concern for daily driving. The frequent start and stop driving characteristics of city driving are also helpful in extending the range of electric vehicles. Electric vehicles also provide the means of a clean transportation with zero emissions. The concern of indirect emissions with the increase in electric vehicles can be addressed by increasing the electric power generation using renewable energy resources like solar power, wind power etc., instead of thermal power.

Electric vehicles can deliver a similar performance with lower costs compared to conventional ICE vehicles under urban driving conditions. The study in [4] shows that electric vehicles are the least expensive in terms of annual cost for fuel compared to any other available vehicle architecture. Figure 1.1 shows a comparison of annual operational costs among different vehicle architectures [4].
Figure 1.1: Annual operational cost comparison for different vehicle architectures [4].

A model of the electric vehicle will be essential to develop a supervisory control strategy and to study the performance of the vehicle under different driving conditions. Also, simulation of the vehicle control strategy is needed prior to testing the controller in actual vehicle, for both economic and safety issues. A model of the Solectric E10 electric vehicle will be developed for simulation purpose.

In order to overcome the limited range problem of the electric vehicles, different architectures can be considered for converting the existing electric vehicle into a Plug-in hybrid electric vehicle (PHEV). A PHEV is similar to a hybrid electric vehicle except that the on board energy storage unit can be recharged from the electricity available from the grid similar to that of electric vehicles [13]. Even though PHEVs are powered by both an engine and an electric motor, PHEVs can run on electricity for the entire range before the battery pack needs to be recharged. A conversion of the existing electric vehicle into a
PHEV is studied to take advantage of the fact that engine will be used only when battery pack needs to be recharged while driving.

The electric vehicle used in this thesis was a Solectria E-10 electric vehicle, which is a 1995 Chevrolet S-10 converted into an electric vehicle by the Solectria Corporation [14]. The original electric vehicle had a lead-acid battery pack and the drivetrain was controlled using analog signals without any vehicle communications. The primary objective of the research is to reengineer the existing electric vehicle with a Li-ion battery pack and an advanced control strategy such that the vehicle can deliver adequate range and performance. The vehicle used in this research is shown in figure 1.2.

![Figure 1.2: Solectria E10 Electric Vehicle.](image)

1.4 Thesis Overview

Chapter II of the thesis provides the necessary background information of an electric vehicle drivetrain and briefly explains the electric vehicle developed in this research. An overview of the different vehicle architectures considered for converting the
existing electric vehicle into a plug-in hybrid electric vehicle are discussed. The approach considered for modeling the electric vehicle in Matlab – Simulink software is discussed. The different stages in the process of developing the electric vehicle drivetrain are explained.

Chapter III explains the development of a Matlab-Simulink model for the EV under research. An equivalent electrical circuit model for the Li-ion batteries used in the vehicle is developed based on experimental data. Control strategies for the developed electric vehicle and series PHEV models are discussed. Development of models for different drivetrain sub-systems is also presented.

Chapter IV presents the simulation results of the electric vehicle model developed in Matlab-Simulink environment. The analysis based on the simulation results is presented. The feasibility of converting the existing electric vehicle into a series PHEV is discussed along with simulation results.

Chapter V describes various hardware components used in the vehicle with their layouts. The control algorithm developed for the vehicle is discussed. It also presents the real time error diagnostics implemented in the vehicle.

The results and analysis based on the real time data logged during the tests on vehicle lift and on road operation are discussed in Chapter VI. The vehicle communications and the display of real world driving statistics to driver are explained.

Chapter VII provides summary and suggestions for the future works.
CHAPTER II

BACKGROUND WORK

2.1 Introduction

This chapter briefly describes the electric vehicle drivetrain and the subsystems used to improve the performance of the 1996 Solectria E-10 electric vehicle. Different vehicle architectures for converting the existing electric vehicle into a plug-in hybrid electric vehicle are discussed. The advantages of modeling and simulation for the development of electric and hybrid electric vehicle drivetrains are presented along with the approach considered for vehicle modeling in this thesis. The development process of the electric vehicle drivetrain and the control algorithm are explained.

2.2 Electric Vehicle Drivetrain

The electric vehicle drivetrain generally consists of an energy storage system and a motor drive. The energy available from the energy storage system is transformed into mechanical energy by the motor drive, for vehicle propulsion. A motor drive comprises of a traction motor and a power electronic converter. If a DC motor is used, a DC/DC converter is used to regulate the power flow according to the driver pedal input. Similarly, DC/AC converters are used to regulate the power flow if AC motors are used. If regenerative braking is employed, bi-directional converters are needed to process the

8
power flow in reverse direction from the wheels to the battery pack. Figure 2.1 shows a general configuration of an electric vehicle drivetrain.

![Figure 2.1: Electric vehicle architecture.](image)

Popular choices for AC motors for electric vehicle applications include induction machines and permanent magnet machines. Induction machines offer low cost and maintenance free operation, but the size and weight imposes a constraint on their high speed operation. The permanent magnet machines offer high power density but, the increasing cost of permanent magnets can become a constraint in future. Recently, switched reluctance machines (SRM) are also being studied for electric vehicle applications because of their high power density and low production costs. However, acoustic noise and torque ripple are the disadvantages of the SRMs [15].

The electric vehicle designed in this thesis has been developed with a Li-ion battery pack as an energy storage system. The motor drivers convert the DC power from the Li-ion battery pack into 3-phase AC power for the induction machines, according to the pedal input from the driver. The induction machines are connected to the rear differential, which propels the wheels. A battery charger was used to recharge the battery
pack, from a standard 110 VAC power outlet. The configuration of the electric vehicle developed in this thesis is shown in figure 2.2.

![Architecture of electric vehicle developed in this thesis.](image)

**Figure 2.2: Architecture of electric vehicle developed in this thesis.**

2.3 Vehicle Architectures for Plug-in Hybrid Conversion

In order to extend the range of the vehicle beyond its zero emissions vehicle (ZEV) range, the electric vehicle can be converted into a plug-in hybrid electric vehicle (PHEV). A PHEV can function as an electric or a hybrid electric vehicle, and has the capability to recharge its battery pack using the electricity available from the grid. The plug-in capability enables the vehicle to operate as a purely electric vehicle, resulting in zero emissions and zero fuel consumption [13]. The vehicle can operate as a hybrid electric vehicle using the internal combustion engine if the energy available from the battery is exhausted.

Different PHEV architectures were studied to select the most appropriate design for conversion, with minimum changes to the existing drive train. The different architectures considered for PHEV conversion are discussed in the following sections.
2.3.1 Series Architecture

In a series hybrid, the engine is not connected to the drivetrain and the propulsion required by the vehicle is derived only from the electric motor. The mechanical output from the engine is directly converted into electricity using a generator. The electricity either charges the battery or propels the vehicle using electric motor. The advantages of the series architecture are the simplicity of its drivetrain and the capability to run the vehicle in purely electric mode for short trips. However, the drivetrain components such as the engine, generator and motor must be sized to deliver the desired performance under heavy load conditions. Figure 2.3 shows the series hybrid architecture.

![Series Architecture Diagram](image)

Figure 2.3: Series Architecture.

2.3.2 Parallel Architecture

In parallel architecture, both the engine and the motor can operate in parallel and deliver propulsion power simultaneously to the wheels. The vehicle can derive its propulsion power from the electric motor and/or the gasoline engine. The advantage of parallel architecture is that a smaller engine and a smaller motor can be used to get a similar performance as that of the series architecture. However, the disadvantages of the parallel architecture are increased complexity and the necessity of a complex mechanical
device for power blending between the engine and the motor [15]. Figure 2.4 shows the parallel hybrid architecture.

![Parallel Architecture Diagram]

**Figure 2.4: Parallel Architecture.**

### 2.3.3 Series – Parallel Architecture

In the series – parallel architecture, the benefits of both series and parallel architectures are combined with additional mechanical links. The engine can be used to recharge the battery pack as in a series hybrid and it can also drive the wheels like a parallel hybrid [9]. Although, it possesses the advantages of both series and parallel hybrids, it is very complicated and costly compared to the other architectures. Figure 2.5 shows the series – parallel 2x2 architecture of ChallengeX vehicle developed at the University of Akron [9]. With a higher capacity energy storage system and a power converter to recharge the energy storage system, this configuration can be converted into a series – parallel 2x2 PHEV.
Figure 2.5: The University of Akron Series - Parallel 2x2 Architecture [9].

2.3.4 Selection of Vehicle Architecture for PHEV conversion

The drivetrain of the electric vehicle developed in this thesis is connected to the rear wheels through a differential. Both parallel and series-parallel architectures are complicated and involve heavy mechanical changes to the drivetrain, since the engine is used to drive the wheels in both the configurations. Considering the least number of mechanical changes to the existing drivetrain and a less complicated architecture, the series architecture was chosen to be the most appropriate for conversion. The feasibility of conversion will be studied through simulations in this thesis.

2.4 Modeling Approach

Compared to conventional vehicles, there are more electrical components used in electric and hybrid electric vehicles such as electric machines, power electronics, and
embedded powertrain controllers. In addition to these electrical subsystems, conventional internal combustion engines and mechanical/hydraulic systems may still be present. Prototyping and testing each design combination is difficult, costly, and a time consuming process. This results in increased difficulty in predicting the interactions among various vehicle components and systems [16].

Therefore, modeling and simulation are essential for concept evaluation, prototyping and analysis of electric and hybrid electric vehicles. Also, a modeling environment that can model not only the powertrain components, but also the embedded software used to control the components is needed. Depending on the level of details needed for evaluation, different modeling and simulation tools such as the Powertrain System Analysis Toolkit (PSAT), Advanced Vehicle Simulator (ADVISOR), Power Electronics Simulator (PSIM) etc. are commercially available.

Most of the modeling and simulation tools use a Graphical User Interface (GUI) to interact with the user and use MATLAB – Simulink for performing calculations internally. Figure 2.6 shows the GUI for simulation of a selected HEV configuration in PSAT software.

![Figure 2.6: PSAT simulation of a HEV configuration. [16].](image)
In order to develop vehicle models, two types of modeling techniques based on the direction of calculation were considered this thesis: forward facing models and backward facing models. Backward facing models start with the tractive effort required at the wheels and work backward towards the engine. Whereas, forward facing models start from the engine and work forward in terms of the transmitted torque available at the wheels. Backward facing models are typically much faster than forward-facing models in terms of simulation time. But, forward facing models better represent the real system setup and are preferred whenever the controls development and hardware-in-the-loop testing is necessary [16].

Since the vehicle models were also intended for controls development, a forward facing model was developed in MATLAB – Simulink environment. Individual blocks for the driver, supervisory controller and powertrain components were developed using both experimental data and principles of physics. The individual blocks were connected together to form the vehicle model.

2.5 Development of Electric Vehicle Drivetrain

Several factors were taken into account in the process of developing the new electric vehicle drivetrain and its control algorithm. The drivetrain components and control algorithm were designed to be technologically on par with the recent industry norms. The following sections explain the selection of different components and technologies used in the electric vehicle.
2.5.1 Battery Selection

The basic requirement of purely electric vehicles is a portable supply of electrical energy, which is converted into mechanical energy in the electric motor for vehicle propulsion. Among the available choices for portable energy storage devices, batteries have been the most popular choice. Of the variety of battery chemistries available, the major types of rechargeable batteries used or being considered for electric and hybrid vehicle applications are:

- Lead-acid

- Nickel-metal-hydride (NiMH)

- Sodium Sulfur (NaS)

- Lithium-ion (Li-ion)

Based on the desirable features of batteries for electric vehicle applications such as high specific power, high specific energy and, long calendar and cycle life; Li-ion battery technology is the most promising among the four battery chemistries mentioned above [15]. Table 2.1 gives a brief overview of the different properties of the above mentioned batteries.
Table 2.1: Properties of electric and hybrid electric vehicle batteries [15].

<table>
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<tr>
<th>Battery Type</th>
<th>Specific Energy (Wh/Kg)</th>
<th>Specific Power (W/Kg)</th>
<th>Energy Efficiency (%)</th>
<th>Cycle Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid</td>
<td>35 – 50</td>
<td>150 – 400</td>
<td>80</td>
<td>500 – 1000</td>
</tr>
<tr>
<td>NiMH</td>
<td>60 – 80</td>
<td>200 – 400</td>
<td>70</td>
<td>1000 – 2000</td>
</tr>
<tr>
<td>Sodium-sulfur</td>
<td>150 – 240</td>
<td>230</td>
<td>85</td>
<td>1000</td>
</tr>
<tr>
<td>Li-ion</td>
<td>90 – 160</td>
<td>200 – 350</td>
<td>&gt;90</td>
<td>&gt;1000</td>
</tr>
</tbody>
</table>

Li-ion batteries also have good high-temperature performance, low-self discharge and components of Li-ion batteries are recyclable [15]. All these characteristics make Li-ion batteries highly suitable for electric and hybrid vehicles, so the new drivetrain of the Solectria E10 electric vehicle was developed on Li-ion battery technology. With a good cycle life of more than 5000 cycles for 70% depth-of-discharge (DOD) and more than 3000 cycles for 80% DOD, ThunderSky LiFePO4 batteries were chosen for the battery pack of the vehicle [22]. A generic term ‘Li-ion batteries’ will be used for ‘LiFePO4 batteries’ further in this thesis.

2.5.2 Controls Development

The controls for the electric vehicle were developed using Rapid Control Prototyping (RCP) process. The RCP is a process which lets the engineer quickly test and iterate control strategies on a real-time computer with real input/output devices [17]. In rapid control prototyping, the control algorithms are developed as symbolic models using
a popular math modeling package such as Matlab-Simulink. The advantage of using RCP
is that the controls engineer can work on developing the control strategy in a familiar
modeling environment and does not have to worry about translating the model to C-code.
The typical development procedure for RCP is given below:

1. Control strategy is developed using a model based environment such as Matlab -
   Simulink.
2. Symbolic input/output blocks are added to the model and wired to the appropriate
   points to add input/output capability to the control strategy.
3. The model is built into a target specific executable code, following a build process
   as given below:
   - The model is built and an automatic code generator delivers a C-code
     ready to compile.
   - The C-code is compiled and linked to obtain an executable code for the
     real-time target.
4. Using a Graphical User Interface (GUI), the executable code is programmed to
   the target.

A MotoTron Electronic Control Unit (ECU) was used as a Supervisory Control
Module (SCM) in the electric vehicle. Based on a 56MHz Freescale MPC565
microprocessor internally, the MotoTron ECU is capable of delivering complex control
strategies [18]. The onboard floating-point unit and high clock frequency of the
MotoTron ECU allow user software to be executed in shorter times. The CAN 2.0B
datalink ensures interoperability with other vehicle systems.
The control strategy for the electric vehicle was developed using MotoHawk toolbox in Matlab-Simulink environment [18]. The developed control strategy was translated into MotoTron controller executable code, following a rapid control prototyping process. Upon a successful build, the executable file can be programmed into the MotoTron controller using MotoTune, a GUI tool for development activities related to the MotoTron family of controllers. Figure 2.7 shows a typical rapid control prototyping process.

Fig 2.7: Rapid control prototyping process.

2.5.3 Vehicle Communications

Exponential growth of electronic devices and circuits used in automobiles in the recent years, has led to an increasing complexity of wiring the systems for in-vehicle communications [19]. Controller Area Network (CAN) is a communication protocol
widely used in the automotive industry for in-vehicle communications among different systems. CAN was initially created at German automotive company Bosch in the mid-1980s, for automotive applications as a method for enabling robust serial communication. The automotive industry quickly adopted CAN for its flexibility and advantages such as immunity to noise, robust message transfer with fault confinement and reduction in wiring [20].

Each CAN message has an unique 11 bit or 29 bit message identifier, which is transmitted in the header of each message. An 11 bit message identifier is called a ‘Standard Identifier’ and a 29 bit message identifier is called an ‘Extended Identifier’. Figure 2.8 shows the structure of a standard CAN message. CAN protocol uses non-destructive bitwise arbitration, with a dominant bit represented by a logical 0 and a recessive bit represented by a logical 1 [21]. Message priority is decided based on the contents of the identifier field. If two or more nodes start transmitting CAN messages simultaneously, the node sending the message with the lowest identifier has the highest priority and wins the bus arbitration to transmit the data. The other nodes have to wait until all higher priority transmissions are accomplished and the bus is idle, before attempting to transmit the data again.

![Figure 2.8: CAN message format [21.]](image_url)
All nodes in the system receive every message transmitted on the bus and it is up to each node in the system to decide whether the received message should be processed or discarded. A single message can be transmitted for one particular node, or multiple nodes based on the way the network and system are designed. CAN protocol was used in this project to implement vehicle communications between the SCM and the local microcontrollers because of the robust message transfer and reduction in wiring feature.

2.6 Conclusion

The architecture of the electric vehicle drivetrain, which is the research platform for this thesis project, was introduced in this chapter. Different architectures for converting the existing electric vehicle into a PHEV were discussed and series architecture was chosen for further analysis of a PHEV conversion. The necessary background for the importance of modeling and simulation was presented along with the approach considered for modeling in this thesis. The following chapters provide the details of the modeling and simulation of the electric vehicle and the series PHEV.

The various components and technologies used in the development process of an electric vehicle drivetrain and the criteria for their selection will be discussed in the next chapter. The detailed development and the experimental results from the electric drivetrain developed will also be discussed in the following chapters.
CHAPTER III

MODELING & SIMULATION

3.1 Simulation Overview

In order to design and test the supervisory control algorithm, the electric vehicle was modeled in MATLAB/Simulink environment. Additionally, the feasibility for converting the existing electric vehicle into a series PHEV was studied using simulations with Matlab/Simulink. Simulating the control strategy in Simulink facilitates the final hardware implementation, since the hardware for the Supervisory Control Module (SCM) used in the electric vehicle can be programmed directly from a Simulink model.

The models were developed using both physical principles and experimental data. Emphasis was given to keep the component models simple so that, the system level simulations can be completed effectively and efficiently. It was thus possible to run a large number of simulations in order to tune the control strategy to perform well under a wide range of driving conditions.

For vehicle simulation, a forward looking model was developed where the model responds to the driver input commands to develop and deliver torque to the wheels [3]. The SCM uses the driver input commands to control the different sub-system components and collects feedback data from the sub-system components. The vehicle model uses the
command torque information from sub-system components to calculate the traction force for the vehicle, and it models the effect of different forces acting on the vehicle. The vehicle velocity calculated from the vehicle model was given as a feedback signal to the driver model. The simulation block diagram of the Simulink model showing the interactions among the driver, the SCM, the subsystems, and the vehicle model is shown in the figure 3.1. The different models used in the simulation are discussed in the following sections of this chapter.

![Simulation layout](image)

Figure 3.1: Simulation layout.

### 3.2 Driver Model

The driver was modeled using a drive cycle and a speed controller to evaluate the vehicle’s performance. The speed profile of the drive cycle was assumed to be the vehicle speed desired by the driver. The driver was assumed to provide accelerator and brake pedal inputs according to a PI control law. The PI controller creates a pedal position based on the error between the desired and the actual vehicle speed. The pedal positions were read into the Supervisory Control Algorithm and a subsequent action was taken depending on whether propulsion or braking was required. It was assumed that both the pedals cannot be depressed simultaneously.
3.2.1 Drive Cycles

Drive cycles are standardized speed and road grade profiles used to evaluate the performance of a vehicle. The standard drive cycles are used by the federal agencies and automotive industry for performance evaluation of a vehicle, which includes certification of fuel economy [15]. Although a drive cycle may have both speed and road grade components, typically one is held constant while the other is varied.

Two commonly used standard driving cycles are the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET) for simulating the urban and highway driving, respectively. The UDDS and HWFET drive cycles are shown in figures 3.3 and 3.4 respectively. Another standard driving cycle is the US06 drive cycle, which is used to test the vehicle control strategy in extreme driving conditions. The US06 drive cycle, shown in figure 3.5 is the most aggressive drive cycle among the above three drive cycles mentioned. Table 3.1 summarizes few characteristics of different driving cycles considered for simulation purposes.
Table 3.1 Drive cycle data.

<table>
<thead>
<tr>
<th>Drive Cycle</th>
<th>Maximum Speed (mph)</th>
<th>Average Speed (mph)</th>
<th>Total Distance (miles)</th>
<th>Duration (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDDS</td>
<td>56.67</td>
<td>19.59</td>
<td>7.45</td>
<td>1372</td>
</tr>
<tr>
<td>HWFET</td>
<td>59.9</td>
<td>48.3</td>
<td>10.26</td>
<td>764</td>
</tr>
<tr>
<td>US 06</td>
<td>80.29</td>
<td>48.37</td>
<td>8.01</td>
<td>600</td>
</tr>
</tbody>
</table>

Figure 3.3: UDDS drive cycle.
Figure 3.4: HWFET Drive cycle.

Figure 3.5: US 06 Drive cycle.
3.3 Motor Model

In electric and series hybrid vehicles, the electric machine is the sole propulsion unit and it must also be designed to process the power flow in reverse direction during regenerative braking. In the process of developing the motor model, the electrical dynamics of the motor and the power converter were neglected as the switching frequencies are in the order of tens of kHz. Also, a model including the phase windings of the motor and power converter is impractical for the simulation time step considered for system level diagnosis [9].

The torque command ($\tau$) and machine speed ($\omega$) were used to calculate the power developed by the machine. The efficiency for any given torque and speed of the electrical machine was assumed to be constant. The speed of the machine ($\omega$) is considered to be a linear function of vehicle velocity ($V_{vehicle}$), since there is no gear arrangement between the motors and the differential in the actual vehicle.

Figure 3.6 shows the block diagram of the motor and the battery models used in the simulation. The operation of the motor was modeled using the following relationships:

\[
I_{calc} = \frac{\omega \tau}{\eta_{mot} V_t} \quad \text{for motoring and} \quad (3.1)
\]

\[
I_{calc} = \frac{\eta_{mot} \omega \tau}{V_t} \quad \text{for regenerating} \quad (3.2)
\]
where, $I_{calc} = \text{Current drawn from the battery (A)}$

$\omega = \text{Motor Speed (rad/s)}$

$\tau = \text{Motor Torque (N-m)}$

$\eta_{mot} = \text{Motor Efficiency (\%)}$

$V_t = \text{Terminal Voltage of the battery (V)}$

![Motor and battery models](image)

**Figure 3.6 Motor and battery models.**

### 3.4 Battery Pack Sizing & Modeling

Batteries have been the most popular choice of portable energy source for electric vehicles since the early stages of research and development in electric vehicles. Among the available battery technologies, Li-ion battery technology was chosen for its desirable features such as high specific power, high specific energy, and long calendar and cycle life [15]. The size of the battery pack was determined to achieve the desired mileage from
the electric vehicle. A simulation model was developed for the batteries used in the electric vehicle to obtain fairly accurate simulation results.

The Li-ion batteries used for the electric vehicle were manufactured by Thunder Sky Batteries. The Thunder Sky LiFePO4 batteries have a good cycle life with more than 5000 cycles for 70% depth-of-discharge (DOD) and more than 3000 cycles for 80% DOD [22].

3.4.1 Battery Sizing Calculations

The Zero Emissions Vehicle (ZEV) range of an electric vehicle can be described as the distance travelled by the vehicle on a single charge. The desired ZEV range of the electric vehicle was considered to be 60 miles, when operated at 45 mph on a level road. For battery sizing, the two parameters that were to be determined are the battery pack voltage and the battery pack Ah rating. The Solectria E10 electric vehicle drive system operates at a nominal DC voltage of 150 volts, which required a total of 50 cells connected together in series to form the battery pack. And, the Ah rating of the battery was determined using the following relationships:

\[ P_{Tr} = F_{Tr} \times V_{vehicle} \]  \hspace{1cm} (3.3)

\[ E = \frac{P_{Tr}}{\eta_{D}} \times \left( \frac{ZEV \ Range}{3600 \times V_{vehicle}} \right) \]  \hspace{1cm} (3.4)

\[ Battery \ Ah \ rating = \frac{E}{V \ (Nominal)} \]  \hspace{1cm} (3.5)

where, \( F_{Tr} \) = Traction force (N)
\[ P_{Tr} = \text{Traction Power (W)} \]

\[ V_{\text{vehicle}} = \text{Vehicle velocity (m/s)} \]

\[ ZEV \text{ Range} = \text{Zero Emissions Vehicle Range (m)} \]

\[ \eta_{DT} = \text{Drivetrain efficiency} \]

\[ E = \text{Energy required (Whr)} \]

\[ V \text{ (Nominal)} = \text{Battery Nominal Voltage (volts)} \]

From the voltage specifications of Solectria E10 electric vehicle and calculations as shown above, the Li-ion battery pack capacity was determined to be 100 Ah. Refer to Appendix A for Matlab code used for the battery sizing calculations given above.

### 3.4.2 Modeling of Li-ion Batteries Used

In order to integrate the new Li-ion batteries into the simulation model, an equivalent electrical circuit-based model was developed. Circuit-based models use a combination of circuit elements like resistors, capacitors and dependant sources to give a circuit representation of the behavior and the functionality of the electrochemical cell. These parameters are generally determined by performing discharge and charge tests under controlled conditions, and monitoring voltage, current and temperature.

For modeling, discharge and charge tests were conducted on an individual cell at a constant current level. It is common practice to refer to the value of the battery current as a fraction of the battery capacity in Ah; for example, for a 100 Ah battery a current of
1C corresponds to 100 A, 0.5C to 50 A, and 0.1C to 10 A. A constant current rate of 0.125C i.e. 12.5 A, is used for both charge and discharge tests for the model used in the simulations. During the discharge test, the battery was allowed to rest before it was switched for discharge again in order to extract the other parameters of the battery model. [15]

![Equivalent circuit model for Li-ion battery.](image)

Dissertation [23] proposes using charge and discharge curves to extract the parameters for a circuit based model as shown in figure 3.7. The open circuit voltage (OCV) of the battery is represented by $V_o$. Ohmic resistance drop is represented by a series resistor $R_o$ and the storage capacitance is represented by the series capacitor $C_S$. The parallel RC branch accounts for the diffusion charge, where $R_d$ represents diffusive resistance and $C_d$ represents diffusive capacitance. $V_t$ is the terminal voltage of the battery as measured across its terminals.
Figure 3.8: Discharge test on Li-ion battery.

Figure 3.9: Charge test on Li-ion battery.
3.4.3 Extraction of Parameters for Circuit Based Model

Battery voltage in the charge and the discharge tests was re-plotted as a function of the SOC of the battery to determine the open circuit voltage ($V_o$) of the battery. The open circuit voltage was approximated as the average of voltages from the charge and the discharge curves at 20% SOC. The open circuit voltage of the cell was determined to be approximately 3.26 volts. The plot for open circuit voltage approximation is shown in figure 3.11.

![Figure 3.11: Open circuit voltage approximation.](image)

The storage capacitance ($C_s$) of the cell was approximated by calculating the slope of the average of the charge and discharge voltage curves between 20% to 100% SOC as shown in figure 3.10. The storage capacitance was calculated to be 1,760,000 F.
The ohmic resistance of the cell can determined either by calculating the immediate voltage rise when the test circuit is opened or by calculating the immediate voltage drop when the test circuit is closed. The immediate voltage drop/rise is divided by the constant current rate considered for the discharge test to obtain the ohmic resistance ($R_o$) of the cell. In either of the cases the ohmic resistance was determined to be 0.00241 ohms. Figure 3.11 shows the immediate voltage rise and the immediate voltage drop in battery voltage when the test circuit was switched off and on respectively, at a discharge current of 12.5 A.

![Effect of Ohmic Resistance on Battery Voltage](image)

Figure 3.11: Calculation of Ohmic resistance from discharge test.

Diffusivity Resistance ($R_d$) of the cell is determined from the voltage rise between the instant after the immediate rise in battery voltage and the instant when the battery voltage reaches a steady value during the rest period. The voltage difference is divided by...
the constant current used for the discharge test to calculate the diffusivity resistance. Figure 3.12 shows the plot for voltage levels for calculating the diffusivity resistance of the cell. The diffusivity resistance was calculated to be 0.00271 ohms using a discharge current 12.5 A.

The diffusivity capacitance is determined from the time constant for the battery voltage to reach a steady value after the test circuit was closed. The time constant was divided by the diffusivity resistance to obtain value of the diffusivity capacitance as 96000 F. The plot used for calculating the diffusivity capacitance is shown in figure 3.13.
The equivalent circuit model for a single Li-ion cell is shown if figure 3.14. The battery pack used in the vehicle has a total of 50 cells Li-ion cells connected in series. The open circuit voltage, ohmic resistance are multiplied by the total number of cells and the storage capacitance was divided by the total number of cells as the cells were connected in series. The diffusivity capacitance was divided by the total number of cells and the diffusivity resistance was multiplied by the total number of cells, resulting in the same time constant as that of a single cell. Figure 3.15 shows the circuit based model for the battery pack.
3.4.4 State of Charge Estimation

The State of Charge (SOC) represents the present capacity of the battery. It is the amount of capacity of the battery that remains after discharge from a top-of-charge condition [15]. Estimation of SOC of Battery is important, since it is used to predict the zero emissions range of the vehicle and developing the overall control strategy of the
vehicle. The SOC of the battery pack is calculated from the initial state of charge \( (SOC_{initial}) \) and the battery current \( (i_{calc}) \) using the integral equation,

\[
SOC(t) = SOC_{initial} - \frac{1}{3600} \int_{t_0}^{t} i_{calc}(t) dt
\]  

(3.6)

where, \( SOC(t) \) = Instantaneous battery SOC (%)

\( SOC_{initial} \) = Initial battery SOC (%), at time = \( t_0 \)

\( (t - t_0) \) = time interval under consideration (sec)

3.5 Vehicle Dynamics Model

The vehicle dynamics model represents the traction part of the powertrain. It models the different forces acting on the vehicle at any instant of time and calculates the actual velocity of the vehicle. The calculated actual velocity is given as a feedback signal to the driver model, for issuing pedal inputs based on the error between the desired and the actual velocities.

Depending on the net value of the traction force \( (F_{tr}) \), three operating modes can be identified for the vehicle:

1. Traction, if \( F_{tr} > 0 \)

2. Braking, if \( F_{tr} < 0 \)

3. Coasting, if \( F_{tr} = 0 \)

The tractive force at the wheels was calculated using the relation,
\[ \tau_{wh} = F_{tr} \ast r_{wh} \quad (3.7) \]

where, \( F_{tr} \) = tractive force (N),

\[ r_{wh} = \text{radius of wheels (m)} \] and,

\[ \tau_{wh} = \text{torque at wheels (N-m)} \]

The vehicle kinetics were defined using the relation,

\[ m \frac{dV_{vehicle}}{dt} = F_{tr} - F_{RL} \quad (3.8) \]

where, \( m \) = mass of the vehicle (kg),

\( V_{vehicle} = \text{Vehicle velocity (m/s)} \),

\( F_{RL} = \text{Road load forces on the vehicle (N)} \)

The road load forces acting on a vehicle were defined using the relations,

\[ F_{RL} = F_{AD} + F_{roll} + F_{gxt} \quad (3.9) \]

\[ F_{AD} = \text{sign}(V_{vehicle}) \ast \left( \frac{1}{2} \rho C_D A_F (V_{vehicle} + v_0) ^2 \right) \quad (3.10) \]

\[ F_{roll} = \text{sign}(V_{vehicle}) \ast mg \cos \beta \ast (C_0 + C_1 V_{vehicle} ^2) \quad (3.11) \]

\[ F_{gxt} = mg \sin \beta \quad (3.12) \]

where, \( F_{AD} = \text{Aerodynamic Drag on the vehicle (N)} \)

\( F_{roll} = \text{Rolling Resistance (N)} \)

\( F_{gxt} = \text{Gravitational Force (N)} \)
\( v_0 \) = Head Wind Vehicle velocity (m/s)

\( g \) = Gravitational acceleration (m/s\(^2\))

\( \beta \) = Road Grade angle (radians)

\( C_0 \) = First co-efficient of rolling resistance (dimensionless)

\( C_1 \) = Second co-efficient of rolling resistance (s\(^2\)/m\(^2\))

\( C_D \) = Aerodynamic drag coefficient (dimensionless)

\( \rho \) = Density of air (kg/m\(^3\))

\( A_f \) = Equivalent frontal area (m\(^2\))

From the equation 3.8, we can write

\[
\frac{dV_{\text{vehicle}}}{dt} = \frac{F_{\text{tr}} - F_{RL}}{m}
\]

(3.13)

For simulation, the equation 3.13 was transformed into discrete form using Euler’s forward rule, as shown in equation 3.14.

\[
\frac{V_{\text{vehicle}}_{n} - V_{\text{vehicle}}_{n-1}}{\Delta T} = \frac{F_{\text{tr}_{n-1}} - F_{RL_{n-1}}}{m}
\]

(3.14)

\( V_{\text{vehicle}}_{n}, V_{\text{vehicle}}_{n-1} \) = Vehicle velocities at time intervals n & n-1 (m/s)

\( \Delta T \) = Simulation time step (sec)

\( F_{\text{tr}_{n-1}} \) = Traction force at (n-1)\(^{th}\) time interval (N)

\( F_{RL_{n-1}} \) = Road load force at (n-1)\(^{th}\) time interval (N)

The actual velocity was calculated as shown below in equation 3.15,
\[ V_{\text{vehicle}}_n = V_{\text{vehicle}}_{n-1} + \Delta T \left( \frac{F_{tr_{n-1}} - F_{RL_{n-1}}}{m} \right) \] (3.15)

The distance travelled by the vehicle was obtained, integrating equation 3.15.

\[ s = \int_{t_0}^{t} V_{\text{vehicle}}(t) \, dt \] (3.16)

where, \( s \) = distance travelled (m)

\( (t - t_0) \) = time interval under consideration (sec)

3.6 Engine Model

In a series hybrid, the electric motor provides all the traction power demanded by the driver and the IC engine is independent of the active vehicle powertrain control. The energy storage system control is based on an on/off control method, which is also known as the thermostat control of the IC engine [15]. The engine on/off criterion is set by the SOC limits of the battery. Figure 3.16 shows the thermostat control of the engine in a Series hybrid electric vehicle. The maximum and minimum SOC limits are set such that the driver demand can always be met by the electric motor.

![Figure 3.16: Series PHEV control strategy based on battery SOC [24].](image-url)
The objective in the series mode is to maintain constant IC engine speed and torque at the most efficient operating point. Therefore, it has been assumed that torque, speed and BSFC parameters of the engine are constant, for a particular point of operation whenever the engine was turned on. The operational point of the engine may be chosen based on the requirements of fuel economy or tail pipe emissions.

The IC engine is modeled ignoring the combustion dynamics and engine non-linearities, for simpler engine model. The transients in engine torque and rpm whenever the engine is on/off is neglected. When in the off state, the ICE model is disconnected from the vehicle model and no losses are introduced. However, when the engine is on, a constant 5% loss is assumed into the driveline due to the transmission.

Figure 3.17: BSFC consumption map for a 1.9L Volkswagen Diesel Engine [25]
The engine was modeled based on the given Brake Specific Fuel Consumption (BSFC). Brake Specific Fuel Consumption (BSFC) is a measure of fuel efficiency within an engine. It is the rate of fuel consumption divided by the power produced. It may also be thought of as power-specific fuel consumption. BSFC for a particular point of operation of the engine is usually extracted from BSFC maps. Figure 3.17 shows a typical BSFC consumption map for a 1.9L Volkswagen diesel engine [25]. It has been assumed that the BSFC for a particular operating point of the engine is always constant for modeling purposes.

\[
Q_f = \frac{BSFC}{\rho_f} \left[ \frac{\omega_{eng} \cdot \tau_{eng}}{1000} \right]
\]  

(3.17)

\[
f = \left( \frac{1}{3.79} \right) \int_{t_0}^{t} \frac{Q_f}{3600} \cdot dt
\]

(3.18)

where, \(BSFC\) = Brake Specific Fuel Consumption (g/kW.h)

\(\omega_{eng}\) = Engine speed (rad/s)

\(\tau_{eng}\) = Engine torque (N-m)

\(\rho_f\) = Specific gravity of fuel used (kg/lit)

\(Q_f\) = Fuel flow rate (lit/h)

\((t - t_0)\) = time interval under consideration (sec)

\(f\) = total fuel used (gal)
3.7 Generator Model

In a series hybrid vehicle, the battery pack is charged on-board using a generator. Engine acts as the prime mover for the generator. Usually, the generator is operated at its maximum efficiency point. The generator was modeled on the same lines as the motor, ignoring the electrical dynamics.

The generator was modeled as a dependent current source. The current from the generator was calculated using the previous mechanical power input ($P_{mech}$), generator efficiency ($\eta_{gen}$) and the battery voltage, as shown in equation 3.19.

$$I_{gen} = \frac{\eta_{gen} P_{mech}}{V_{bus}}$$  
(3.19)

3.8 Supervisory Control Module

The Supervisory Control Module (SCM) operates the desired control strategy as programmed by the user, depending on the driver inputs and sub-system feedback signals. The SCM contains the Supervisory Control Algorithm, which was coded in Matlab-Simulink for easy portability from simulation to implementation in the Solectria E10 electric vehicle. Figure 3.18 shows the block diagrams of the SCM and its contents.

A 5-ms time delay was used in simulation to model the execution delay of the microcontroller used for implementation. The SCM used in simulation differs from the SCM used in implementation, in terms of the additional code necessary to interface with the sensors, actuators and communication networks used in the microcontroller.
3.8.1 Electric Vehicle Control Strategy

Electric vehicle control algorithm is mainly used to control the motor torque since propulsion for the vehicle is derived from the motor only. The supervisory control algorithm reads the pedal and direction inputs from the driver and calculates the motor torque command depending on the pedal input from the driver. The torque command signal is given as an output to the motor model. In regenerative braking, a negative torque command is given to the electric machine, to act as a generator. The following rules govern the ignition on/off strategy in electric vehicle simulation.

If $SOC > SOC_{min}$, turn ignition on.

If $SOC < SOC_{min}$, turn ignition off.

3.8.2 Series Plug-in Hybrid Electric Vehicle Control Strategy

A rule based energy management strategy was used by the supervisory control algorithm to control the different operational modes of the vehicle in series PHEV.
operation. The operating modes in a series PHEV are the electric and the series hybrid modes. During the electric mode, the engine was turned off and the vehicle derives its propulsion power from the stored energy in the battery. When the battery SOC falls beyond a minimum SOC limit, the engine was turned on to recharge the battery pack. The engine was turned off when the battery SOC reaches a maximum SOC limit. In series hybrid mode, the engine was also turned off whenever the power demanded by the vehicle was negative, in order to capture the energy from regenerative braking.

The following rules define the operating modes of the vehicle. The vehicle operating modes were based on the SOC of the battery pack and the power demanded by the vehicle ($P_{demand}$). The mode selection strategy also uses the fuel remaining ($Fuel$) and the minimum and maximum limits on the SOC of the battery pack ($SOC_{min}$, $SOC_{max}$) for selection between electric and series hybrid modes. The following rules govern the operation of the series PHEV simulation model:

If $SOC > SOC_{min}$ or $Fuel > 0$, turn ignition on.

If $SOC > SOC_{min}$, the default state to enter is electric mode.

If $SOC < SOC_{min}$ & $Fuel > 0$, engine is turned on, enter series PHEV mode.

While $P_{demand} < 0$, turn off the engine

If $SOC > SOC_{max}$ & engine is on, turn off the engine and enter electric mode.

If $SOC < SOC_{min}$ & $Fuel = 0$, turn ignition off.
Figure 3.19 gives the flow chart representation of the rule based energy management strategy used in series PHEV operation.

![Flow chart representation of series PHEV control algorithm.](image)

Figure 3.19: Flow chart representation of series PHEV control algorithm.

3.9 Conclusions

The modeling of an electric and a series plug-in hybrid vehicle has been presented. Matlab/Simulink based simulation models have been developed based on the algorithms presented in this chapter. The purpose of the simulation models are to test the effectiveness of the control algorithm for Solectria E10 electric vehicle and to study the
feasibility of converting the existing Solectria E10 electric vehicle into a series PHEV.
Control strategies have been developed for both the EV and series PHEV simulation models.

The next chapter presents the simulation results of the vehicles modeled in Matlab – Simulink. A Power Save feature in the Supervisory control algorithm that focuses on increasing the ZEV range is also discussed in the next chapter, along with results.
CHAPTER IV

SIMULATION RESULTS

4.1 Introduction

Several simulations of the modeled vehicles were performed in order to determine the effectiveness of the control strategy and the vehicle performance under different driving conditions. Four different drive cycles were used to simulate general day to day driving conditions such as highway, city, cruising etc. HWFET and UDDS drive cycles were used to simulate highway and urban driving respectively. US 06 drive cycle was used to evaluate the vehicle performance under aggressive driving conditions, involving higher speeds and accelerations. A steady 45 mph drive cycle was used to estimate the ZEV range of the electric vehicle, under a cruising velocity.

All the drive cycles were simulated with the same model using identical initial conditions. Regenerative braking was used in both electric vehicle and series plug-in hybrid electric vehicle simulations to capture the energy fed from the motor to the energy storage system. The power of the motor drive system was limited 24 kW by the control algorithm, to replicate the continuous power rating of the motor drive used in the Solectria E10 electric vehicle [14].
4.2 Electric Vehicle Simulation Results Overview

Several simulations of the Matlab-Simulink model for the Solectria E10 electric vehicle were performed to evaluate the performance of the vehicle under different driving conditions. Figure 4.1 shows the block diagram of the EV simulation model. The pedal commands issued by the driver model are read by the SCM block. Depending on the pedal inputs, the SCM controls the drivetrain subsystems.

![Block diagram of EV Simulation model.](image)

Figure 4.1: Block diagram of EV Simulation model.

An initial SOC of 60% was chosen to be the initial SOC of the battery pack in order to protect the battery pack from overcharging due to regenerative braking. No modifications were made to the electric vehicle model or the control strategy between simulations. The control strategy was not optimized to maximize performance in any one
of the drive cycles considered for simulation. Table 4.1 summarizes the different parameters of the Solectria E10 electric vehicle electric used for EV simulation model [24].

<table>
<thead>
<tr>
<th>EV Simulation Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curb Weight (m)</td>
<td>1360 kg</td>
</tr>
<tr>
<td>Rolling Resistance Coefficient ($C_0$)</td>
<td>0.0015</td>
</tr>
<tr>
<td>Rolling Resistance Coefficient ($C_1$)</td>
<td>0 $s^2/m^2$</td>
</tr>
<tr>
<td>Aerodynamic Drag Coefficient ($C_{AD}$)</td>
<td>0.44</td>
</tr>
<tr>
<td>Frontal Area ($m^2$)</td>
<td>2.88 $m^2$</td>
</tr>
<tr>
<td>Wheel Radius ($r_{wh}$)</td>
<td>0.38 m</td>
</tr>
<tr>
<td>Motor Drive</td>
<td>24 kW</td>
</tr>
<tr>
<td>Battery Pack</td>
<td>Li-ion, 100 Ah, 180 kg, 150 VDC Nominal</td>
</tr>
</tbody>
</table>

Table 4.1: Electric vehicle simulation parameters
4.2.1 UDDS Drive Cycle Simulation Results

The Urban Dynamometer Driving Schedule (UDDS) drive cycle was used to simulate the urban/city driving of a vehicle, providing frequent start and stops. The UDDS drive cycle runs a distance of 7.5 miles in 1369 seconds and has an average speed of 19.6 mph. During this cycle, the SOC of the battery pack fell approximately to 50% from a 60% initial SOC. The frequent start and stop characteristics of the city driving were more suitable to recapture energy using regenerative braking.

The simulation results show that the vehicle was able to meet the demands of the driver, as it can be seen that the desired and actual vehicle velocities were almost identical. Figure 4.2 shows the plots for desired and actual velocities of the vehicle simulated with UDDS drive cycle, along with the plots for motor torque, motor power and battery SOC.
4.2.2 HWFET Drive Cycle Simulation Results

The Highway Fuel Economy Test (HWFET) drive cycle was used to simulate the highway driving of a vehicle. The HWFET drive cycle runs a distance of 10.26 miles in 765 seconds and has an average speed of 48.3 mph. During this cycle, the SOC of the battery pack fell approximately to 43% from a 60% SOC.
The simulation results show that the vehicle was able to meet the higher continuous power demand of the HWFET drive cycle, resulting in a faster discharge of the battery pack. Figure 4.3 shows the plots for desired and actual velocities of the vehicle simulated with HWFET drive cycle, along with the plots for motor torque, motor power and battery SOC.

Figure 4.3: Results for Electric vehicle simulation with HWFET drive cycle.
4.2.3 US06 Drive Cycle Simulation Results

The US06 drive cycle was used to evaluate the vehicle performance under aggressive driving conditions. The US 06 drive cycle runs a distance of 8.01 miles in 600 seconds and has an average speed of 48.37 mph. During this cycle, the SOC of the battery pack fell approximately to 44% from a 60% SOC. The simulation results show that the vehicle was unable to meet the peak power demands resulting from high accelerations and high speeds.

The power available for traction was limited at 24 kW by the control algorithm, to emulate the continuous power limit in the motor drive in Solectria E10 electric vehicle. A motor drive with a higher continuous power limit would help the vehicle to meet high accelerations. Figure 4.4 shows the plots for desired and actual velocities of the vehicle simulated with US06 drive cycle, along with the plots for motor torque, motor power and battery SOC.
4.2.4 Steady 45 Drive Cycle Simulation Results

In order to approximate the ZEV range of the vehicle with the selected powertrain components, a steady 45 mph drive cycle was used. The drive cycle was designed in such a way that the vehicle has to accelerate from 0 to 45 mph in 10 s and the speed stays constant after 10 s at 45 mph. The constant 45 mph drive cycle was simulated for a distance of 5 miles. During this cycle, the SOC of the battery pack fell approximately to
52.7% from a 60% SOC. And driving at the same constant 45 mph speed, the projected ZEV range of the vehicle was 68.5 miles with the selected battery pack size. Figure 4.5 shows the plots for desired and actual velocities of the vehicle simulated with a constant 45 mph drive cycle, along with the plots for motor torque, motor power and battery SOC for the first 100 seconds of the simulation.

Figure 4.5: Results for Electric vehicle simulation with Steady 45 drive cycle.
4.3 Power Save

In order to extend the ZEV range of the electric vehicle, a Power Save feature was developed. In the Power Save mode, the power demanded by the vehicle is limited by the controller following a request from the driver. During Power Save mode, the vehicle follows the drive cycle as long as the power demanded by the vehicle is within the set limit. The power available is held constant at the set limit, as long as the power demanded by the vehicle is more than the set limit. Three different power limits 15 kW, 12.5 kW and 10 kW were considered to study the effect of power save on vehicle performance under highway and urban driving conditions. Figures 4.6 shows HWFET drive cycle with a 12.5 kW power limit and figure 4.8 shows UDDS drive cycle with a 10 kW power limit.

An initial SOC of 60% was chosen to be the initial SOC of the battery pack, in order to protect the battery pack from overcharging due to regenerative braking. Repetitive cycles of HWFET and UDDS drive cycles were considered to increase the distance travelled by the vehicle beyond the normal distance covered by the vehicle, in a single drive cycle. No changes were made to the control algorithm or the simulation model in between the simulations. Figures 4.7 and 4.9 show the plots for SOC of the battery pack against the distance travelled in miles for the different power save limits considered with HWFET and UDDS drive cycles, respectively.
Figure 4.6: HWFET drive cycle without and with 12.5 kW power limit.

Figure 4.7: Battery SOC as a function of distance travelled for HWFET drive cycle.
Figure 4.8: UDDS drive cycle without and with 10 kW power limit.

Figure 4.9: Battery SOC as a function of distance travelled for UDDS drive cycle.
In order to calculate the projected ZEV range of the electric vehicle, an 80% SOC of the battery pack was considered usable for driving. A 20% minimum SOC of the battery pack was considered to be left unused in order to protect the battery pack from being overly discharged. Table 4.2 gives the projected ZEV range of the simulated electric vehicle model with an 80% usable SOC of the battery pack.

<table>
<thead>
<tr>
<th>Power Save Limit (kW)</th>
<th>HWFET drive cycle Projected ZEV range (miles)</th>
<th>UDDS drive cycle Projected ZEV range (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>48.05</td>
<td>59.20</td>
</tr>
<tr>
<td>15</td>
<td>50.06</td>
<td>60.90</td>
</tr>
<tr>
<td>12.5</td>
<td>52.70</td>
<td>62.25</td>
</tr>
<tr>
<td>10</td>
<td>57.30</td>
<td>64.06</td>
</tr>
</tbody>
</table>

Table 4.2: Projected ZEV range for HWFET and UDDS drive cycles

Results for UDDS drive cycle from table 4.2 show an 8% or 4.86 miles increase in the total ZEV range, with the 10 kW power save limit compared to the no power save limit. Similarly, a 9.25 miles increase in ZEV range was observed in HWFET drive cycle with 10 kW limit when compared to the ZEV range with the no power save limit. But, it was observed from figure 4.6 that the maximum velocity of the vehicle was limited by the control algorithm in the power save mode. This may be undesirable while operating the vehicle on highways, where the speeds are normally above 55 mph. Therefore, a lower limit on power save is not recommended for highway driving.
For the UDDS drive cycle with the lowest power save limit of 10kW, it can be observed from figure 4.8 that the vehicle was able to meet the driver demand throughout the drive cycle except under conditions when high acceleration was needed. The results show that the power save feature is most effective for city driving conditions with speeds under 45 mph.

4.4 Series Plug-in Hybrid Electric Vehicle Simulation

In order to study the feasibility for converting the existing EV into a series plug-in hybrid vehicle, a Matlab/Simulink model of the desired series plug-in hybrid was developed. Figure 4.10 shows the block diagram of the simulation model of the Series PHEV. An engine model was developed to work in conjunction with a generator model, to work as a range extender for recharging the battery if its SOC is low. The engine model was developed based on the Brake Specific Fuel Consumption (BSFC) which was held constant for all the simulations.

A control strategy was developed to effectively manage the different energy sources available for recharging the on board battery pack. The turn on point for the engine was assumed to be at a minimum SOC of 60% and the turn off point was chosen to be 70% to quickly evaluate the performance of the control algorithm.
4.5 Series PHEV Simulation Results

The operation of the designed control strategy was tested using the same drive cycles used for the electric vehicle simulation. The control strategy was not optimized to maximize performance in any one of the drive cycles considered for simulation. Table 4.3 summarizes the different parameters of the series plug-in hybrid electric vehicle used for simulation [14].
<table>
<thead>
<tr>
<th>Series PHEV Simulation Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curb Weight (m)</td>
<td>1360 kg</td>
</tr>
<tr>
<td>Rolling Resistance Coefficient ($C_0$)</td>
<td>0.0015</td>
</tr>
<tr>
<td>Rolling Resistance Coefficient ($C_1$)</td>
<td>$0 \text{ s}^2/\text{m}^2$</td>
</tr>
<tr>
<td>Aerodynamic Drag Coefficient ($C_{AD}$)</td>
<td>0.44</td>
</tr>
<tr>
<td>Frontal Area (m$^2$)</td>
<td>2.88 m$^2$</td>
</tr>
<tr>
<td>Wheel Radius ($r_{wh}$)</td>
<td>0.38 m</td>
</tr>
<tr>
<td>Motor Drive</td>
<td>24 kW</td>
</tr>
<tr>
<td>Battery Pack</td>
<td>Li-ion, 100 Ah, 180 kg 150 VDC Nominal</td>
</tr>
<tr>
<td>Engine + Generator</td>
<td>30 kW, 200 kg</td>
</tr>
</tbody>
</table>

Table 4.3: Series PHEV simulation parameters

4.5.1 UDDS Drive Cycle Simulation Results

For the UDDS drive cycle, the initial SOC of the battery pack was assumed to be 40% and it can seen that the engine was turned on, as soon as the power demanded by the vehicle was greater than zero. The engine was turned on/off, as dictated by the control strategy whenever regenerative braking was applied. The turn on and turn off of the engine can be seen from the switching characteristics of the engine torque and generator torque. Figure 4.11 gives the results for series PHEV simulation with UDDS drive cycle.
The results include the desired and actual velocities, motor torque, motor power, battery SOC, engine torque and generator torque.

4.5.2 HWFET Drive Cycle Simulation Results

For the simulation with HWFET drive cycle, an initial SOC of the battery pack was assumed to be 65%. It can be seen that the engine was not turned on, until the SOC of the battery pack fell below the minimum SOC limit 60%. The battery was recharged using the engine and generator set, according to the control algorithm. Because of its highway driving characteristics where fewer instances of braking were required, the engine was turned on/off few times compared to the UDDS drive cycle. Figure 4.12 gives the results for series PHEV simulation with HWFET drive cycle.

4.5.3 US06 Drive Cycle Simulation Results

An initial SOC of 60% was assumed for the US06 drive cycle and the engine was turned on, with a positive power demand from the vehicle. The vehicle performance was similar to the electric vehicle simulation, indicating the use of a motor drive with an increased power rating to meet the power demand. Figure 4.13 gives the results for series PHEV simulation with US06 drive cycle.

4.5.4 Steady 45 Drive Cycle Simulation Results

In order to test the control strategy under a cruising velocity, a steady 45 mph velocity drive cycle was used. An initial SOC of the battery pack was assumed to be 65% and the vehicle was operated in the default electric mode. The engine was turned on when
the SOC of the battery pack fell below 60% and it was turned off after the SOC of the battery pack reached 70%. The results demonstrate that the energy storage system control was achieved, with the desired thermostat control of engine under a series PHEV operation [15]. Figure 4.14 gives the results for series PHEV simulation with Steady 45 mph drive cycle.
Figure 4.11: Results for Series PHEV simulation with UDDS drive cycle.
Figure 4.12: Results for Series PHEV simulation with HWFET drive cycle.
Figure 4.13: Results for Series PHEV simulation with US06 drive cycle.
Figure 4.14: Results for Series PHEV simulation with Steady 45 drive cycle.
4.5 Conclusions

A simulation model of the existing Solectria E10 electric vehicle was studied for its performance under different driving conditions. The simulation results show that the vehicle was able to meet most power demands of the driver, except under the conditions involving aggressive accelerations and speeds.

A Power Save feature was developed to extend the ZEV range of the electric vehicle, limiting the maximum power demanded by the vehicle upon driver request. The results demonstrate that the Power Save was effective in saving battery-pack energy for the same distance covered and a significant increase in projected ZEV range was observed. It was observed from the results that, the power save feature was more appropriate for urban driving conditions compared to the highway driving conditions.

A simulation model of a series PHEV was developed and the simulations show that the conversion of the existing electric vehicle into a series PHEV was feasible. A rule based control strategy was developed and the operation of the developed control strategy under different driving conditions was verified. The next chapter discusses the hardware components and the design of the supervisory control algorithm for the developed electric vehicle powertrain.
CHAPTER V

DRIVETRAIN COMPONENTS & CONTROL ALGORITHM DEVELOPMENT

5.1 Introduction

This chapter describes the development of the supervisory control algorithm and the integration of new hardware components into the Solectria E10 electric vehicle. A new supervisory control module was introduced to control the different operations of the electric vehicle. Significant changes were made to upgrade the control strategy of the vehicle with the inclusion of new embedded controllers and vehicle communication protocols. No modifications were made to the drivetrain except the integration of a new Li-ion battery pack. The vehicle was developed to have isolated low and high voltage systems, for control and traction parts respectively. The different components of the low and high voltage systems and the development of control algorithm are discussed in the following sections of this chapter.

5.2 Low Voltage System

The low voltage or the 12 VDC system layout is shown in figure 5.1. The DC/DC converter provides the main power supply for the low voltage system. A 12VDC lead-acid battery was connected in parallel in the circuit to provide backup power, accommodating any failure from the DC/DC converter. The 12 VDC battery acts as the
primary power supply for the controllers required to control the operation of the high
voltage relay that connects the battery pack to the powertrain. Once the high voltage relay
is closed, the battery pack powers the DC/DC converter to supply the low voltage system.
The high voltage relay remains closed unless the vehicle was turned off or one of the
emergency stop switches are activated.

The other components connected in the low voltage layout were the Supervisory
Control Module (SCM), motor controller gateway, sensor data interface and the 12 VDC
factory accessories.

![Low voltage power circuit layout](image)

Figure 5.1: Low voltage power circuit layout.

5.2.1 Supervisory Control Module

The Supervisory Control Module (SCM) is the main controller that operates the
supervisory control algorithm in the vehicle. The SCM reads the inputs from the driver
and the battery pack and controls the motor controllers as directed by the supervisory
control algorithm. A MotoTron automotive grade controller from Woodward Control
Solutions was used as the SCM in the vehicle [18]. The SCM was programmed using
MotoHawk and Stateflow toolboxes for MATLAB - Simulink. It has two CAN channels, communicating at a bus speed of 250 kbaud. The SCM used in the vehicle is shown in figure 5.2.

![Figure 5.2: MotoTron controller.](image)

The SCM reads the key switch, forward/reverse direction switch, accelerator pedal, regenerative braking switch and power save switch as inputs from the driver. It receives the battery voltage, battery current and motor speed as a CAN message from the sensor data interface. The SCM controls the high voltage relay using an analog output to connect/disconnect the battery pack from the powertrain. The SCM commands the motor controllers via CAN messages using the motor controller gateway according to the control algorithm. The SCM uses CAN messages to display the driving information to the driver in real time, on the display gauges. Figure 5.3 shows the different input/output signals associated with the SCM.
5.2.2 Motor Controller Gateway

As the vehicle’s existing motor controllers use analog signals, a CAN interface is needed between the SCM and the motor controllers for CAN communication. Therefore, a gateway was developed using PIC18F458 microcontroller to interface the motor controllers to the CAN Bus. The microcontroller receives CAN messages from the SCM, over the CAN Bus to produce appropriate digital outputs.

The digital outputs from the microcontroller were used to provide the analog inputs to the motor controllers. A Printed Circuit Board (PCB) was designed to translate the digital data from the microcontroller into analog signals for the motor controllers. The PIC18F458 microcontroller and the PCB together comprise the motor controller gateway. The motor controllers connect to the motor controller gateway through a DB-25 cable.
Figure 5.4 shows the block diagram of the different components and signals associated with the motor controller gateway.

5.2.3 PCB Design

A Printed Circuit Board (PCB) was designed to convert the digital data from the microcontroller to analog signals for the motor controllers. The analog control inputs to the motor controllers were the main switch, forward/reverse directional switch, regenerative braking switch and the accelerator pedal command from the driver.

The digital data from the PIC microcontroller was given to the PCB using a ribbon cable connection. On the PCB, MOSFETs were used to produce the switch inputs needed by the motor controllers. A digital to analog (D/A) converter was used to obtain the 0-5 VDC analog equivalent of the 8 bit accelerator command from the PIC microcontroller. The motor controllers receive the analog signals from the PCB on a DB-
25 cable. Also, the motor controllers give battery voltage, battery current and speed of the motors, on the DB-25 Cable. The PCB was also designed to access to the feedback data from the motor controllers, on the corresponding pins of the DB-25 Cable. A photo of the designed PCB is shown in figure 5.5. Refer to Appendix D for the schematic of the PCB designed.

![PCB Diagram](image)

Figure 5.5: PCB used in motor controller gateway.

5.2.4 Sensors

In order to calculate the SOC of the battery pack, current from the battery pack was measured using current sensors. Two sensors were used to ensure that a failure from one of the sensors can be tolerated. Open loop Hall Effect current sensors from Tamura Corporation were used as the current sensors in the vehicle [35]. Figure 5.6 shows the current sensors connected in the vehicle. The sensors can be used over a current sensing range of -200 A to 200 A with a linear output of 0 – 4 VDC.
The motor controllers use internal voltage sensors to give the voltage of the battery pack as a feedback signal on a designated pin of the DB-25 cable connectors. A 0 – 5 VDC signal is the sensor output for the battery voltage from 100 to 200 VDC.

The outputs from the current sensors and the voltage sensors are connected to the analog to digital converter channels of the sensor data interface board. The sensor data interface board contains a PIC microcontroller to convert the analog information from the sensors into digital data. The digital data is then sent to the SCM as a CAN message.

5.2.5 CAN Bus Layout

The SCM communicates with the local controllers using the CAN protocol and it has two CAN channels. The CAN bus was programmed to communicate at a bus speed of 250 kbaud. The motor controller gateway, sensor data interface and display gauge 1 were connected to CAN bus 1 and display gauge was connected on CAN bus 2. Each CAN bus, was terminated with two 120 ohm resistances to ensure proper transmission of CAN messages. Figure 5.7 shows the layout of CAN bus in the vehicle.
5.3 High Voltage System

The high voltage system consists of the Li-ion battery pack, battery charger, the motor controllers and the DC/DC converter. The nominal voltage of the high voltage system was 150 VDC. The high voltage system layout can be seen in figure 5.8.
All high voltage connections were fused before each component. The DC/DC converter was fused at ten amps and the motor controllers were fused with one 180 amp fuse. The fuses were placed to prevent no damage of the components from any surge in the current drawn.

The Li-ion battery pack was installed in the original battery compartment in the vehicle. The battery pack consists of 50 individual Li-ion batteries connected in series to form the battery pack to store the energy for vehicle propulsion. The high voltage relay connects the battery pack to the drivetrain, as controlled by the SCM. Figure 5.9 shows the battery pack placed inside the battery compartment used in the vehicle.

![Figure 5.9: Li-ion battery pack.](image)

The Solectria E10 motor controllers control and coordinate all functions of the electric motors during vehicle operation. The motor controllers were mounted on top of the battery compartment. The motor controllers were equipped with thermally-switched cooling fans to maintain stable operating temperatures when used under heavy load. In
reverse direction, the speed of the vehicle was limited approximately to 12.4 mph by the motor controllers internally [26]. Figure 5.10 shows the motor controllers used in the vehicle.

![Motor controllers](image1.jpg)

**Figure 5.10: Motor controllers.**

Two Induction motors mounted at the rear of the vehicle propel the vehicle by converting the energy stored in batteries into vehicle motion as regulated by the motor controllers. Each motor was connected by a wiring harness to one of the controllers. The motors operate in parallel and drive the rear wheels via drive belts, connected by the drive shaft to the differential. The induction motor drive has a 24 kW continuous power rating [14]. Figure 5.11 shows the induction motors used in the vehicle.

![Induction motors](image2.jpg)

**Figure 5.11: Induction motors.**

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To supply 12 volts to all of the 12-volt accessories and controllers, an isolated DC/DC converter was used. An isolated converter is necessary to provide electrical isolation between the high and low voltage systems. The converter steps down the high voltage to supply the 12 VDC needed for the low voltage system. Figure 5.11 shows the layout of the low voltage volt system. This converter also acts as a charger to keep the backup lead acid battery charged. Figure 5.12 shows the isolated DC/DC converter used in the vehicle.

![Isolated DC/DC converter](image)

Figure 5.12: Isolated DC/DC converter.

In order to recharge the battery pack, an on-board charger was used to operate from a standard 110VAC outlet. An automotive grade charger was used to survive the ruggedness of the road conditions and automotive environment [27]. The on-board charger can be connected to the power grid with an extension cord plugged into the charge port on the vehicle. The charge port is located in the traditional gas tank fill area. Figure 5.13 shows the charge port and the on-board charger used in the vehicle.
5.4 Driver Controls and Display Gauges

The driver controls are located on the center of the dash. The driver control cluster includes a direction switch, regenerative braking switches and a power save switch. Also, two programmable display gauges from MotoTron were used to display the driving information and vehicle status to the driver in real time. Figure 5.14 shows the driver controls and display gauges in the vehicle.

Figure 5.14: Driver controls and display gauges.
A center-position type switch was used as the direction switch. When the switch is in the centre position, it is not possible to drive the vehicle but the motor control unit remains ready for operation. The other two switch positions permit the vehicle to be driven in forward/reverse directions respectively [14].

The other switches on the control cluster were the regenerative braking switch and power save switch. The regenerative braking switch turns regenerative braking on/off depending on the input from the driver. The power save switch was used to limit the acceleration demand to obtain more range from the battery pack upon request from the driver.

Two gauges from MotoTron were used for displaying vehicle status and driving information to the driver in real time. The gauge 1 was connected to CAN bus #1 and the gauge two was connected to CAN bus #2 of the SCM, as each gauge required a dedicated CAN bus. The battery SOC, battery voltage, battery current and motor speed were displayed to the driver on gauge 1. The position of the shifter and error diagnostics were displayed on gauge 2.

5.5 Supervisory Control Algorithm

The Supervisory Control Algorithm contains the logic behind the operation of the vehicle. The supervisory control algorithm was developed in Matlab-Simulink using MotoHawk, a dedicated tool box for control algorithm development for MotoTron family controllers. The algorithm was programmed into the SCM using MotoTune, a software
for programming, calibration and data logging activities related to MotoTron family of controllers [18].

The SCM receives command inputs from the driver, and controls the operations of the battery-pack and the motor controllers as dictated by the supervisory control algorithm. The supervisory control algorithm was mainly divided into 5 categories:

- Ignition management
- Shifter management
- Pedal management
- SOC calculation
- Error diagnostics

5.5.1 Ignition Management

The vehicle’s readiness for driving was denoted by the control variable, Ignition. Ignition was made on only if the key was turned on and SOC of the battery pack was greater than the set minimum SOC level ($\text{minSOC}$). This allows the control algorithm to protect the batteries from being overly discharged and to protect the vehicle from accidentally turning on, when being charged. Figure 5.15 denotes the flow chart for ignition sequence.
Figure 5.15: Flow chart for ignition management.

5.5.2 Shifter Management

The driver inputs the intended direction of the vehicle, using the direction switch from the control cluster on the dashboard. The SCM checks the status of ignition before issuing a direction command to the motor controllers, for a particular direction input from the driver. This was used to prevent the vehicle from accidentally making a decision on direction, if the battery pack SOC was low or if the vehicle was being charged. If a valid direction input was received from the driver, the algorithm next verifies for the pedal to be greater than at least 5% of the total pedal input. This was done in order to verify a valid acceleration command from the driver. Figure 5.16 denotes the flow chart for shifter management.
5.5.3 Pedal Management

The Pedal Management block manages the accelerator pedal command from the driver. Pedal input was read into the SCM, only when the ignition was turned on. Also, the algorithm verifies for the pedal to be greater than at least 5% of the total pedal input. This was done in order to verify a valid acceleration command from the driver.

The accelerator pedal was read into the SCM as a 10-bit unsigned integer value, ranging from 0-1023 for a 0-100% acceleration command. This 10-bit value was then
converted into an 8-bit unsigned integer value, to be given out as a CAN message to the motor controller gateway. The motor controller gateway uses this 8-bit acceleration command and converts it into a 0-5V analog voltage, which corresponds to 0-100 % accelerator command for the motor controllers.

![Flow chart for pedal management.](image)

Figure 5.17: Flow chart for pedal management.

If power save was turned off, the actual pedal value was considered to be the final pedal value. Similarly when power save was turned on and the power demand is within the power save limit, the actual pedal value was considered to be the final pedal value. If power save was turned on and the power demanded by the vehicle is above the power
save limit, the final 8-bit pedal value was reduced by multiplying the actual 8-bit pedal value with a power save factor ranging from 0.5 to 1.0. Figure 5.18 shows the map for power save factor calculation.

![Power Save Factor Map](image)

Figure 5.18: Power save factor map.
5.5.4 SOC Calculations

A SOC calculation algorithm was used to provide the driver with the information regarding the energy capacity remaining in the battery. The SOC remaining and the energy used were calculated using the relations (5.1) and (5.2), respectively.

\[
SOC(n) = \left( \frac{SOC(n-1) - \frac{1}{3600} \int i(t) \, dt}{Q_T} \right) \cdot 100\% \quad (5.1)
\]

Energy Used (kWh) = \int \frac{v(t) \cdot i(t)}{3600+1000} \, dt \quad (5.2)

where, \( SOC(n) \) = SOC at the \( n^{th} \) instant of time (%)

\( SOC(n-1) \) = SOC at the \( (n-1)^{th} \) instant of time (%)

\( i(t) \) = instantaneous current drawn from the battery (A)

\( Q_T \) = Ah capacity of the battery pack (Ah)

\( v(t) \) = instantaneous voltage of the battery (V)

5.5.5 Error Diagnostics

In order to report any errors that can be detected by software, the SCM was programmed for error detection and diagnosis. When an error was detected by the SCM, it was displayed on display gauge 2 with a proper code. Upon the display of an error code, the user was required to perform the designated actions to check the status of the sub-systems related to the error code displayed.
The SCM was programmed to detect errors related to the battery current, battery voltage, motor speed and the direction switch of the vehicle. Table 5.1 gives the list of different errors and their error codes, along with the suggested actions to diagnose the error. Unless an error was detected, a default code ‘00’ was displayed in the error field of the display gauge 2, indicating no error in the operation of the vehicle.

<table>
<thead>
<tr>
<th>Type of Fault</th>
<th>Error Code(s)</th>
<th>Action(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>10</td>
<td>a) Check 180A fuse</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Check current sensor</td>
</tr>
<tr>
<td>Motor</td>
<td>21</td>
<td>a) Check motor 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Check speed sensor 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c) Check PCB 1</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>a) Check motor 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Check speed sensor 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c) Check PCB 2</td>
</tr>
<tr>
<td>Voltage</td>
<td>31</td>
<td>a) Check motor controller 1</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>b) Check PCB 1</td>
</tr>
<tr>
<td>Direction</td>
<td>40</td>
<td>Check direction switch on dash board</td>
</tr>
</tbody>
</table>

Table 5.1: List of Errors and diagnostics
5.6 Hardware Theory of Operation

The operation of the vehicle can be classified into driving and charging modes. During driving, the vehicle uses the energy stored in the Li-ion battery pack for propulsion. While charging, the vehicle used the off board electricity from the grid to recharge its battery pack.

5.6.1 Driving

An acceleration command from the driver was converted to an electronic signal by the Supervisory Control Module (SCM). The SCM uses the supervisory control algorithm to verify if the vehicle was ready to be driven. Upon a successful verification, the SCM sends an acceleration and direction commands to the motor controller gateway via CAN message protocol. The motor controller gateway uses the information in the CAN messages to give analog control signals to the motor controllers. The motor controllers then convert DC power from the battery to AC power for the induction motors. The induction motors drive the rear wheels directly, using a differential arrangement.

The induction motors and controllers were rated to produce sufficient torque at low speed and spin fast enough so that, a single gear ratio is adequate for all normal driving conditions [14]. The speed of the motors, battery voltage, battery current were given as a feedback to the SCM, as a CAN message from the sensor data interface. Based on the feedback data and the driver inputs, the SCM controls the operation of the vehicle.
5.6.2 Charging

An on-board charger was used to recharge the Li-ion battery pack from a standard 110 VAC outlet, with an extension cord plugged into the charge port on the vehicle. Before charging the battery pack, the key switch must be turned off and the charge switch must be turned on. The charge switch by-passes the key switch and allows the SCM and gauges to be powered up so that, the battery pack voltage, the current and the SOC can be monitored during charging. By using the charge switch instead of the key switch, the motor controllers were not powered up because the key switch input is still in the off position. The charge switch serves the purpose of preventing the vehicle from accidentally getting turned on during recharging. The battery charger was programmed internally by the manufacturer, to shut down upon a 100% SOC of the battery pack automatically [29].

5.7 Conclusions

An electric vehicle powertrain based on Li-ion battery technology and CAN bus communication protocol was developed. A supervisory control algorithm has been successfully developed to control the operations of the vehicle. The supervisory control algorithm was programmed into the Mototron controller serving as the SCM. The experimental results from the powertrain developed are presented in the next chapter.
CHAPTER VI

EXPERIMENTAL RESULTS

6.1 Introduction

This chapter presents the experimental results obtained on the developed electric vehicle powertrain. The supervisory control algorithm was programmed into the SCM and the algorithm was tuned for better performance. Analysis of the vehicle performance was done using the experimental data collected from the vehicle using real time data acquisition. The experimental analysis of CAN bus messages to ensure the desired operation of the vehicle is presented. The real time display of driving statistics to the driver is also discussed in this chapter.

6.2 CAN Bus Analysis

The communication between different controllers in the vehicle was developed using CAN protocol. The SCM, the motor controller gateway and the sensor data interface were the different controllers operating over the CAN bus with receive and transmit capabilities. The identifiers for the intended CAN messages between the controllers were defined by the user. The MotoTron display gauges, however use factory set identifiers for CAN communication with the SCM.
A total of 4 different CAN messages were developed for the use of controllers and their operation. All the controllers connected to the CAN bus in the vehicle were designed to operate at a bus speed of 250 kbaud. Table 6.1 summarizes the different CAN messages used in the vehicle with the functionalities of each message. The identifiers of each message in table 6.1 were displayed in hexadecimal format.

<table>
<thead>
<tr>
<th>Message ID</th>
<th>Time Interval (ms)</th>
<th>Sending Module</th>
<th>Receiving Module</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x100</td>
<td>10</td>
<td>SCM</td>
<td>Motor Controller Gateway</td>
<td>Key Switch, Vehicle Direction, Regenerative Braking Control and Accelerator Pedal Control</td>
</tr>
<tr>
<td>0x200</td>
<td>200</td>
<td>Sensor Data Interface</td>
<td>SCM</td>
<td>Battery Voltage, Battery Current and Motor Speed Sensor Data</td>
</tr>
<tr>
<td>0x300</td>
<td>200</td>
<td>Sensor Data Interface</td>
<td>SCM</td>
<td>Battery Voltage, Battery Current and Motor Speed Sensor Data</td>
</tr>
<tr>
<td>0x400</td>
<td>100</td>
<td>SCM</td>
<td>Sensor Data Interface</td>
<td>Non-Volatile Memory Storage of Battery SOC %</td>
</tr>
</tbody>
</table>

Table 6.1: CAN message list

6.2.1 CAN Message Verification

With multiple controllers connected to the CAN bus, it was needed to verify the correct transmission and reception of CAN messages over the CAN bus in the vehicle. In order to observe and analyze the bus traffic over the CAN bus in the vehicle, CANKing
software was used. CANKing allows the numerical online display of the data transmitted in the CAN messages used in different forms such as hexadecimal, decimal or octal [30].

A computer with CANKing software was connected to the CAN bus using MotoTron USB to CAN module [31]. The different messages on the CAN bus were displayed in an order, sorted according to the message identifier in hexadecimal data form. The data fields of the received messages were also displayed to monitor the contents of each message. Figure 6.1 shows a screenshot of CANKing software used, highlighting the user defined CAN messages in a box shown by the arrow.

Figure 6.1: Online display of CAN messages using CANKing software.
6.3 Calibration & Data Acquisition

After the supervisory control algorithm was programmed into the SCM, the supervisory control algorithm was tuned for better performance. Also, the data from the SCM was collected for the purpose of analysis using data acquisition. Parameter tuning and data acquisition were done using MotoTune, a PC-based software for calibrating and data-logging activities related to MotoTron family of controllers [18].

6.3.1 Calibration

Online calibration was used to compensate any offset values from sensors to obtain precise measurements from the sensors. Calibration was also used to vary other user defined parameters in real time without having to re-program the SCM such as the minimum SOC, power save level.

The different parameters of the control algorithm intended for calibration were defined as calibration variable type in the control algorithm. A calibration type data definition in the control algorithm allows the parameter to be varied online in the MotoTune window. The MotoTune software communicates with SCM using MotoTron USB to CAN interface. Figure 6.2 shows a screenshot of calibration using MotoTune software with the calibration of power save and minimum SOC variables identified using an arrow.
6.3.2 Data Acquisition

In order to perform post-test analysis on the vehicle operation, the data related to vehicle operation was collected using data acquisition. Any variable or parameter within the control algorithm of the SCM can be logged in real time, with a request from the user in the MotoTune window. The MotoTune software communicates with SCM using MotoTron USB to CAN interface and stores the values of all the data logged, at a user selected destination on the computer in a text file. The user can also specify the number of samples that can be collected per second in the settings panel of the data logging tab. Figure 6.3 shows a screenshot of data acquisition of the 8 bit accelerator pedal value using MotoTune software.
6.4 Experimental Results

After the integration of the new Li-ion battery pack into the powertrain, the vehicle was tested for the validation of the control algorithm. Experimental tests were conducted on the vehicle and data from the tests was collected using the real time data acquisition window in MotoTune software. Driving statistics were displayed to the driver in real time using the MotoTron display gauges on the dash board.

The battery voltage, battery current and motor speed were collected from each test. The results show plots for the data collected in real time along with data generated from calculations like the battery power, energy used from the battery and battery SOC. The control algorithm performance was successfully verified with tests on the test bed and on the road.
6.4.1 Test-bed Results

Initial experiments for validation of the control algorithm were conducted on a test bed, prior to driving the vehicle on road. It was done in order to ensure the safety of personnel and property in case of an unexpected operation from the vehicle or its control algorithm.

The vehicle was tested with a pedal input gradually increased from 0 to 100% and held constant at 100% for a brief period of time. An immediate drop in the battery voltage accompanied with an increase in current drawn was observed with a pedal input. It was also observed that the motors hit their maximum speed, for a 100% pedal input. Figure 6.4 shows the experimental data collected from the truck operated on a test bed.

The battery pack was fully recharged before the test. So, the initial SOC of the battery pack was considered to be 100% before the test. The test was conducted for a total duration of 350 seconds on a test bed. At the end of the test, the SOC of the battery pack was 98.8%. The peak power drawn from the battery was approximately 10 kW and the total energy used during the test was calculated to be approximately 0.18 kWh.
Figure 6.4: Results from test bed operation.
6.4.2 On-road Test Results

Upon the verification of the control algorithm on the test bed, the truck was taken on road for further tests and tuning of the control algorithm. The battery pack was charged to 100% SOC before the vehicle was tested on road and the battery pack was not recharged in between the tests. No modifications were made to the control algorithm in between the tests. On the road, the vehicle has to overcome the friction and inertia before getting into motion. It was evident from the road test results, that the current drawn from the battery was increased when compared to the test bed results.

Figure 6.5 shows the results for the first on road test conducted on the vehicle. The initial SOC of the battery pack was considered to be 100%, as the battery pack was fully recharged before the test. The test was conducted for a total duration of 450 seconds. At the end of the test, the SOC of the battery pack was 94%. The peak power drawn from the battery was approximately 17.5 kW and the total energy used during the test was calculated to be approximately 1 kWh.

Figure 6.6 shows the results for the second on road test conducted on the vehicle. The SOC of the battery pack was 94% from the first test on the vehicle. This SOC was used as the initial SOC of the vehicle for the second test. The test was conducted for a total duration of 600 seconds. At the end of the test, the SOC of the battery pack was 92%. The peak power drawn from the battery was approximately 18.5 kW and the total energy used during the test was calculated to be approximately 0.3 kWh.
Figure 6.5: Results from on-road test #1.
Figure 6.6: Results from on-road test # 2.
6.4.3 Driving Statistics Display

The driving statistics were displayed to the driver in real time using the two MotoTron display gauges on the dash board. The SCM was programmed to display data on the MotoTron display gauges using MiniView, a Simulink based toolbox for MotoTron display gauges [28]. The display gauges accept CAN messages from the SCM and display data to the driver.

Battery voltage, battery current, battery SOC and motor speed were the variables displayed on gauge 1. The battery SOC was the default variable displayed to the driver. The driver can toggle between other variables using the up and down buttons on the display gauge. Display gauge 2 was used to display the vehicle shifter position and error diagnostics to the driver. Figure 6.7 shows the two display gauges in operation.

![Image of the two display gauges in operation](image)

Figure 6.7: Driving statistics displayed to the driver.
6.5 Conclusions

The electric vehicle powertrain was successfully designed and implemented using Li-ion battery technology and CAN bus communication protocol. The operation of the supervisory control algorithm was verified and the experimental results show that the battery pack was able to meet the demands of the vehicle. The driving statistics and data were successfully displayed to the driver in real time using the two display gauges on the dash board.
CHAPTER VII

CONCLUSIONS & FUTURE WORK

7.1 Conclusions

In this thesis, an overview of modeling an electric vehicle and the feasibility of converting the existing electric vehicle into a Series PHEV using simulation are discussed. The various stages in the algorithm development and hardware implementation of a control strategy are also discussed. The operation of the vehicle according to the developed control algorithm was validated by test bed and on road tests.

7.2 Modeling & Simulation

A simulation model of an electric vehicle was developed to study the vehicle performance under different driving conditions. The model was developed in Matlab-Simulink environment, using both physical principles and experimental data. An electric circuit based model was developed to integrate the new Li-ion battery pack into the vehicle model. The simulation results show that the vehicle was able to meet most power demands of the driver, except under the conditions involving aggressive accelerations and speeds.

A simulation model of a series PHEV was developed to study the feasibility of converting the existing electric vehicle into a series PHEV. A rule based control strategy
was developed and the operation of the developed control strategy under different driving conditions was verified. The simulation results showed that the conversion of the existing electric vehicle into a series PHEV was feasible.

7.2.1 Power Save

In order to extend the ZEV range of the electric vehicle, a Power Save feature was developed. In Power Save mode, the power demanded by the vehicle is limited by the controller following a request from the driver. Simulation results for UDDS drive cycle showed an 8% or 4.86 miles increase in the total ZEV range, with a 10 kW power save limit when compared to the ZEV range with no power save limit. Similarly, a 9.25 miles increase in ZEV range was observed in HWFET drive cycle with 10 kW limit when compared to the ZEV range with no power save limit. However, a limit on maximum velocity of the vehicle may be undesirable while operating the vehicle on highways where the speeds are normally above 55 mph. The results show that, power save feature is most effective for city driving conditions with speeds under 45 mph.

7.3 Electric Vehicle Control Algorithm Design & Implementation

A supervisory control algorithm has been successfully developed to control the operations of the vehicle. The supervisory control algorithm was programmed into the SCM. The electric vehicle power train was successfully designed and implemented, using the recent industry technologies such as Li-ion battery technology and CAN bus communication protocol. The operation of the supervisory control algorithm was verified and the experimental results show that the battery pack was able to meet the demands of
the vehicle. The driving statistics and data were successfully displayed to the driver in real time using the two display gauges on the dash board.

7.4 Suggested Future Work

A simulation model of the electric vehicle was developed in Matlab-Simulink software. An emphasis was placed on making models that were simple enough to be quickly simulated. However, a simulation with detail modeling of the sub-systems would yield much more accurate results.

A Li-ion battery powered electric vehicle drivetrain was successfully developed as a major contribution of this thesis. The power save feature presented in the simulation can be tested for a real time driving range results on a dynamometer. The vehicle also provides a platform for wide range of possibilities for future research. Few topics for suggested future research are discussed in the following sections.

7.4.1 Conversion of EV to Series PHEV

In order to extend the limited range of the electric vehicle, it can be converted into a PHEV. Given the powertrain configuration of the existing electric vehicle, series architecture is the most suitable design for range extension in terms of minimal electrical and mechanical changes to the existing electric powertrain. The block diagram for a series PHEV architecture is shown in figure 7.1. A downsized engine operated in conjunction with a generator may be used to recharge the battery pack whenever the State of Charge (SOC) falls below a certain minimum limit. The engine maybe turned off, after
the SOC of the battery pack reaches a certain maximum limit. This on/off method based on SOC of the battery pack is known as thermostat control of engine [15].

The SCM can be used to monitor the SOC of the battery pack and actuate the engine on/off commands based on the battery pack SOC. The engine-generator set can be placed either under the hood or in the bed of the truck. The battery pack may be recharged from electricity available from the grid, whenever the vehicle is not in use.

Figure 7.1: Series PHEV block diagram.

7.4.2 Li-ion Battery Pack Management System

Due to the manufacturing variations, temperature differences, and aging, the individual cells perform differently. When a complete battery pack is charged and discharged as a single two-terminal circuit element, some cells are overcharged, undercharged, or overdischarged, all of which tend to reduce cell life [32]. Literature suggests that during series string operation of batteries, voltage and temperature
differences in the cells can lead to electrical imbalances and decrease pack performance by as much as 25% [33].

The new Li-ion battery pack has a total 50 Li-ion cells connected in series. During the course of research presented in this thesis, no battery management system was developed as the emphasis of the research was on controls development for the electric vehicle drivetrain. However, a battery pack of the given size needs a battery management system (BMS) to monitor the individual cells for better performance and durability. New techniques such as active charge equalization can be used to achieve efficient cell balancing [32].

7.4.3 Vehicle to Grid Power Supply

Generally EV’s and PHEV’s have larger battery packs compared to HEV’s, which provides an opportunity to implement vehicle-to-grid (V2G) technology. The primary idea behind V2G technology involves connecting the vehicles to the grid while they are not in operation, and using their on-board battery packs to supply energy to the utility. And, the utility will pay the user for the amount of energy given out by the vehicle.

Additionally the vehicle can also be designed to provide power for standby power applications, such as back-up power to a home through its V2G capability. However, the amount of energy that can be provided is limited by the size of the on-board battery pack of the vehicle. Bi-directional power converters that can process the power flow between the utility and the vehicle and accurate metering system to calculate the energy given out by the vehicle would be required to implement V2G functionalities [34].
REFERENCES


APPENDIX A: BATTERY SIZING CALCULATIONS

% Battery Sizing Calculations using MATLAB

% Vehicle Parameters
m = 1220+180+150;
Cd = 0.44;
Af = 2.8;
C0 = 0.015;
C1 = 0;
g = 9.81;
row = 1.16;

% Velocity (45 mph) in m/s
v = 20.1168;

% Aerodynamic Drag (N)
Fad = 0.5*row*Cd*Af*(v^2);

% Rolling Resistance (N)
Froll = m*g*C0;

% Tractive Force (N)
Ftr = Fad + Froll;

% Tractive Power (kW)
Ptr = (Ftr*v)/1000;

% Power Losses (kW)
Ploss = 0.5;

% Total Power (kW)
P = Ptr + Ploss;

% Battery Nominal Voltage
BV = 150;

% EV Range in Miles
ZEV = 60;

% Battery Size
AH = (P*(60/45))/BV;
AH*1000
APPENDIX B: SIMULINK MODELS

The MATLAB-Simulink models of EV and Series PHEV are described in the following sections. All Simulink signals are routed between the models using tags, for visual clarity.

Electric Vehicle Model:
Series PHEV Model:
Model: Driver

Description: This block models the driver behavior. The inputs are the ignition signal from the SCM and the actual vehicle velocity. Drive cycle selection, Minimum SOC level, Power Save and Regenerative braking can be given as an input using the dialog box of the driver model.
**Function Block Parameters: Driver**

**Subsystem (mask)**

Driving Cycle: Select a Driving Cycle from different Cycles

Min SOC%: Set a minimum limit on SOC% of the Battery Pack

Initial Fuel Level: Enter the fuel in the tank initially, in Gallons

Power Save: Check Power Save to turn ON the Power Save Feature

Turning on Power Save reduces the acceleration of the vehicle, but helps to extend the Zero Emissions Range, when running on Battery

Regenerative Braking: Check to turn ON Regenerative Braking.

Regen allows energy to be given back to the Battery from Motor instead of wasting it.

**Parameters**

Driving Cycle

2

Min SOC%

20

- Power Save
- Regenerative Braking

[Images of diagrams and flowcharts related to the Function Block Parameters]
Model: Motor

Description: Torque command, vehicle velocity and power save are the inputs to the motor model. Motor speed, motor power, traction torque are the outputs from the motor model. The motor model is connected to the battery model using SimPower Systems toolbox of Simulink.
Model: Battery

Description: This block models the battery pack for EV and Series PHEV simulations. The battery pack model is electrically connected to motor model using SimPower Systems toolbox. The different battery parameters like open circuit voltage, storage capacitance, ohmic resistance, and diffusivity capacitance and diffusivity resistance can be given using the dialog box. Battery SOC, battery voltage, battery current, power drawn from the battery pack, energy used etc are calculated and displayed to the user.
Model: Vehicle Dynamics

Description: This block models the effect of different forces acting on the vehicle. The inputs to the vehicle dynamics block are the propulsion torque \((T_p)\), braking torque \((T_b)\) and the road grade. The actual velocity of the vehicle is calculated and given as a feedback to the driver model. The distance travelled and the propulsion power are displayed to the user.
Function Block Parameters: Vehicle Dynamics

Subsystem (mask)
This block models the vehicle dynamics of the Solectria E-10 Electric Vehicle.

Parameters

Vehicle Mass (kg)  
1180+180+74

Tyre Radius (m)  
0.38

Acceleration Due to Gravity (kg/m^2)  
9.81

Coefficient of Drag (Cd)  
0.36

Vehicle Frontal Area (m^2)  
2.8

Density of Air (kg/m^3)  
1.16

Rolling Resistance (C0)  
0.015

Rolling Resistance (C1)  
3

OK  Cancel  Help  Apply
Model: Engine

Description: The inputs to the engine model are the engine on/off control signal and the BSFC value chosen for a given operation point of the engine. The parameters calculated from the engine model are the engine torque, engine speed, engine power and the fuel used.
**Model:** Generator

**Description:** This block models the generator for Series PHEV operation. Engine model is connected to the generator model using a standard gear ratio. The inputs to the model are the torque and speed calculated from engine speed and engine torque after applying the gear ratio.
APPENDIX C: MOTOTRON SCM CODE DOCUMENTATION

The Simulink code for the MotoTron SCM is described in the following sections. The code is mainly arranged into three components:

- Inputs
- Outputs
- Control Algorithm
Block: Inputs

Description: The input block contains the information that is received from the different sensors and CAN messages. This information is further processed and given to the Control Algorithm block for decision making.
Block: Control Algorithm

Description: Control Algorithm block contains the main logic behind the operation of the vehicle. The control algorithm receives the information from the inputs block. The different components of the Control Algorithm block are:

- Ignition management
- Pedal management
- Shifter management
- SOC calculation
Block: Ignition Management

Description: The ignition management block determines the readiness for the operation of the vehicle. The inputs to the ignition management block are the key switch, battery SOC and the battery voltage. The outputs from the ignition management block are the ignition value and the estop relay control.
Block: Pedal Management

Description: The pedal management block is used to determine the acceleration command issued to the motor controllers. The inputs to the pedal management block include the acceleration command from the driver, power save status and the ignition value. The output from the pedal management block is the final pedal command issued to the motor controllers.
**Block:** Shifter management

**Description:** The shifter management block is used to make a decision on the direction command issued for the motor controllers. The inputs are the direction inputs from the driver, ignition value and the acceleration input. The output are the forward and reverse direction commands.
**Block:** SOC Calculation

**Description:** The SOC calculation block is used to calculate the SOC of the battery pack using the battery pack current. The SOC calculation block also contains the logic to calculate the battery power and battery energy using battery voltage and battery current.
**Block:** Outputs

**Description:** The outputs block is used to issue the control signals to other sub-systems within the vehicle.
APPENDIX D: PCB SCHEMATIC DESIGN LAYOUT

A printed circuit board (PCB) was designed in order to interface the analog motor controllers with the Supervisory Control Module (SCM) using a Controller Area Network (CAN) interface. A PIC micro controller acts as the CAN interface and the PCB converts digital inputs from the PIC microcontroller into analog inputs for the motor controllers. The PCB was designed using PCB123 software. The schematic design layout of the PCB is shown in the figures below.

Top view: