Simulation of a Hybrid Vehicle Powertrain using a Fully Electrical System

by

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Submitted to the Department of Electrical Engineering, Electronics, Computers and Systems
in partial fulfillment of the requirements for the degree of
Master of Science in Electrical Energy Conversion and Power Systems
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Abstract

The Department of Electrical Engineering, Electronics, Computers and Systems of the University of Oviedo wants to set up a test bench at their laboratory in which the powertrain of a HEV will be emulated. This HEV has some particular and interesting aspects. Since this system will be operating in an indoor room, instead of using an Internal Combustion Engine (ICE), an induction machine will be controlled in such a way that it will behave as if it was an ICE.
This powertrain has been modeled based on the powertain of the 2004 Toyota Prius. Matlab/simulink software has been used to simulate the powertrain of this vehicle.

This thesis has been divided into four big sections, which are the description of the vehicle itself, the control of the electrical machines and its implementation in Matlab/Simulink,the simulation of the 5 different modes of operation of a HEV and its transitions, and the implementation of the emulation of an ICE using an induction machine.

The first section covers all the information related to the Toyota Prius. The author has spent a very considerable amount of time just looking for information about the Toyota Prius and we believe that at least some of that information must be shared in this document.

The second section is the electrical machines section, specially focusing on the big electric motor, or also known as MG2 (by Toyota). It will cover its description, its simulation in Matlab/Simulink and its control.

Third, the five different modes of operation of a series-parallel HEV will be simulated in Matlab/Simulink. Also, the transitions between the different modes will be emulated.

Last, the emulation of an ICE using an induction machine will described and simulated in Matlab/Simulink. From the author's point of view, this has been by far the most challenging part of the master's thesis. This chapter will cover in detail the emulation of the ICE using an induction machine.

This project is not finished and there are several steps that must be covered ir order to finish it. Some ideas will be proposed at the end of this document in the "future work" section.

Thesis Supervisor: Pablo García Fernández
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Chapter 1

Introduction

Conventional vehicles with ICE have improved their efficiency due to the new technologies and the strong pollution standards that made the car manufacturers develope new techniques to reduce such pollution. On the other hand, the efficiency of the ICE would not be dramatically improved in thefuture due to their own characteristics and that is why several car manufacturers have invested millions of dollars in developing new and different vehicles such as Hybrid Electric vehicles (HEV) and Electric vehicles (EV).

Any Vehicle Powertrain is designed to develope sufficient power to meet vehicle performance demands, high efficiency, carry sufficient energy on-board to support vehicle driving in the given range and emite few environmental pollutants. A vehicle may have more than one energy source, such as a battery for instance. A vehicle that has more than one energy source is called a hybrid vehicle. A hybrid vehicle with an electrical energy source is called a Hybrid Electric vehicle (HEV).

A common powertrain of a hybrid vehicle will include no more than two powertrains. Hybrid drivetrains are bidirectional in order to allow the energy going back and forth. Which means that for instance, that the system is able to recover energy when the vehicle is braking that would usually wasted as heat.

The next figure shows the concept of a hybrid drive train as shown in [1]:

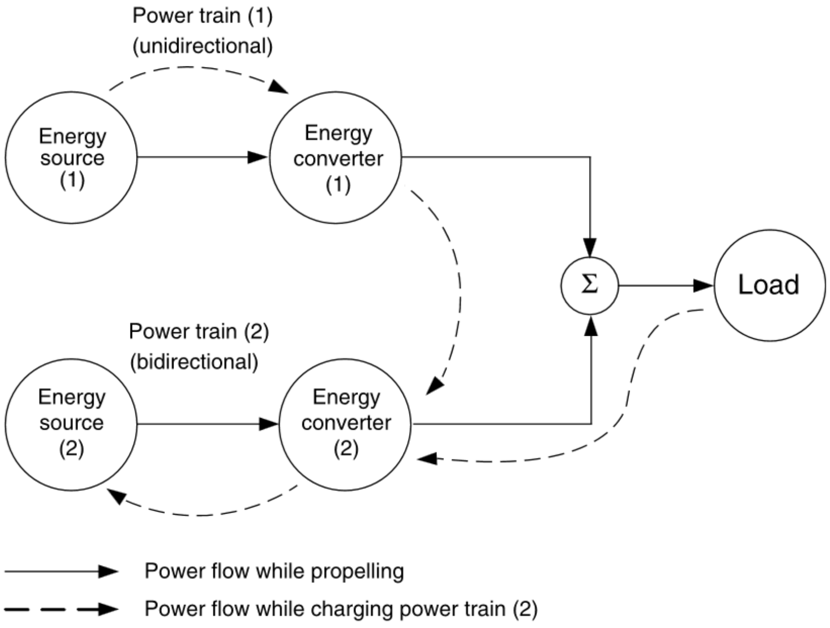

Figure 1-1: Hybrid drive train (As a concept)[1].

Chapter 2

Objectives of the Master Thesis

The Department of Electrical Engineering, Electronics, Computers and Systems is planning on developing a HEV test bed at their laboratory.The very first steps of this challenging project have been covered within this Master's Thesis.

The first sections of this document will cover the simulation of the HEV Powertrain. The 2004 Toyota Prius has been taken as a reference. As it was mentioned before in the abstract, this HEV has some unique characteristics. There is not ICE. In fact, an induction machine will be controlled in such a way that it will behave as if it was an ICE. This particular section will be covered at the end of this document.

Last, this is a very large project and it is not finished. My personal goal was to learn as much as possible about Hybrid powertrains and to develope the first simulations, the first steps, of this challenging project.

Chapter 3

HEV drive trains: architectures

This is defined as the connection between the components that define the energy flow routes and control ports[1]. Nowadays there are several HEV configurations but traditionally, they were divided into two big families: Series and Parallel HEV. However, there are some other configurations that are like a mix between these two different configurations. That is the case of the Toyota Prius (that has been taken as a reference to our simulations), which is also known as series-parallel HEV.The next figure shows the most common solutions that can be found in the market.

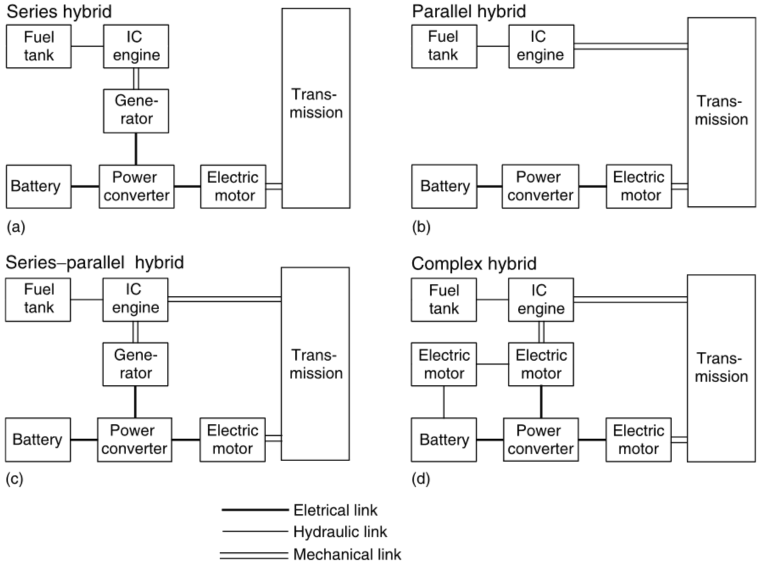

Figure 3-1: HEV drive trains; Different configurations[1].

3.1 HEV drive trains: Series Hybrid

In this configuration, two different power sources feed the same plant, which is an electric motor. This electric motor will be the only machine in charge of propelling the vehicle down the road. The next figure shows the most common series configuration that can be found nowadays in the market:

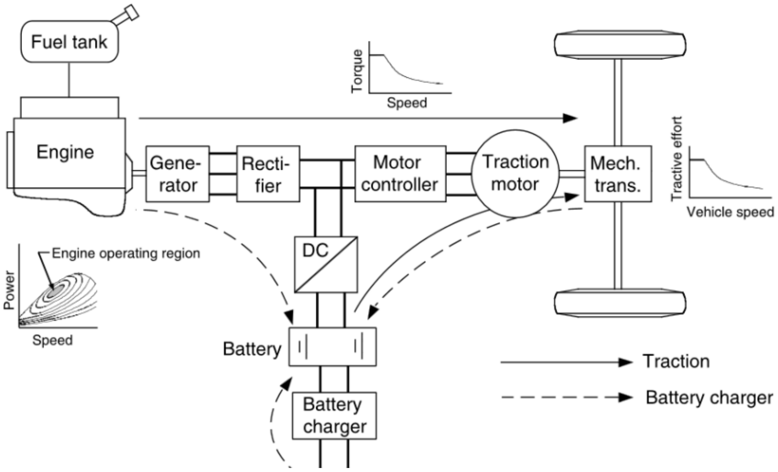

Figure 3-2: HEV drive trains;Series Hybrid[1].

The unidirectional energy source is a fuel tank and the unidirectional energy converter is an engine coupled to an electric generator[1]. The output shaft of this electric generator is connected to the DC bus via a rectifier. The bidirectional energy source is an elechtromechanical batery pack that will be connected to the DC via a DC/DC converter. Series HEV have several modes of operation, which are[1]:

- Pure electric mode: The engine is turned off and the vehicle is propelled just by the battery.

- Pure engine mode: The battery will not draw any power from the drive train nor propel the vehicle. The car is only running on the ICE. The electric machines will operate as an electric transmission from the ICE to the wheels.

- Hybrid Mode: The traction power is drawn from both the ICE and the battery.

- Engine traction and battery charging mode: The ICE supplies power to charge the batteries and propel the vehicle.
- Regenerative braking mode: The ICE is turned off and the traction motor is operated asa generator.
- Battery charging mode: The traction motor receives no power and the ICE charges the battery
- Hybrid battery charging mode: Both the ICE and the traction motor operate as generators to cherge the battery.

Series Hybrids offer some major advantages, which are:

- Since the ICE is not connected to the wheels, it can be operated at its maximum efficiency region.
- The electric motors do not need multigear transmissions because they have nearly udeal torque-speed characteristics.

-On the other hand, they have some important disadvantages:

- The energy coming the ICE is c onverted twice, which means that the efficiency is significantly affected by this.
- The generator adds additional weight and cost
- The traction motor must be considerably large because it is the only machine in charge of propelling the vehicle down the road.

3.2 HEV drive trains: Parallel Hybrid

The main difference between a series hybrid and a parallel hybrid is that in the case of the parallel, the ICE is allowed to drive the wheels whereas in the case of the series, this will never happen. This ICE is assisted by a small (in terms of power and size) generator. The electric motor and the ICE are coupled together by the mechanical coupling. This mechanical coupling could be either torque-coupling or speed-coupling. It is out of the scope of this thesis to explain how these two couplings work but for more information, please check reference number 1. The following figure shows the typical configuration for a parallel series vehicle:

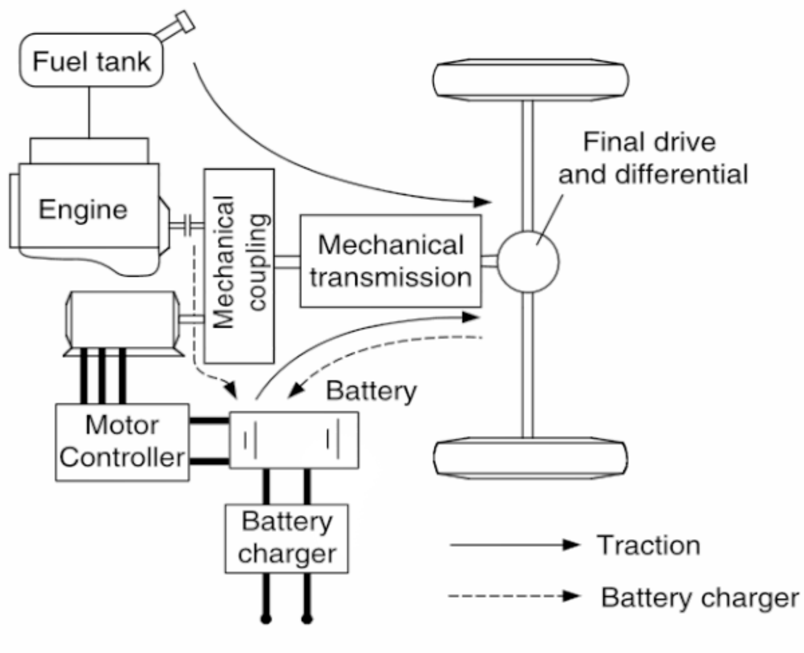

Figure 3-3: HEV drive trains;Parallel Hybrid[1].

3.3 HEV drive trains: Series-Parallel; Toyota Hybrid Synergy Drive(HSD)

As it was said before, the 2004 Toyota prius has been taken as a reference to our simulations. That is why we would like to briefly describe the Toyota Hybrid System, also known as Toyota HSD. This system (in particular the one that we have used to simulate our powertrain) will be described in detail later on. This is only to give a very brief idea in this introduction section of what has been used.

This configuration offers some of the benefits from both the series and the parallel configuration. This means that the car is able to run on the electric motor. There is not mechanical connection between the electric motor and the ICE. A planetary gearset is used to link the two electric motors and the ICE. Only the electric motor (traction motor or MG2) is connected to the wheels. This means that the ICE will never be directly connected to the wheels. The next figure shows a simple figure of this configuration layout[2]:

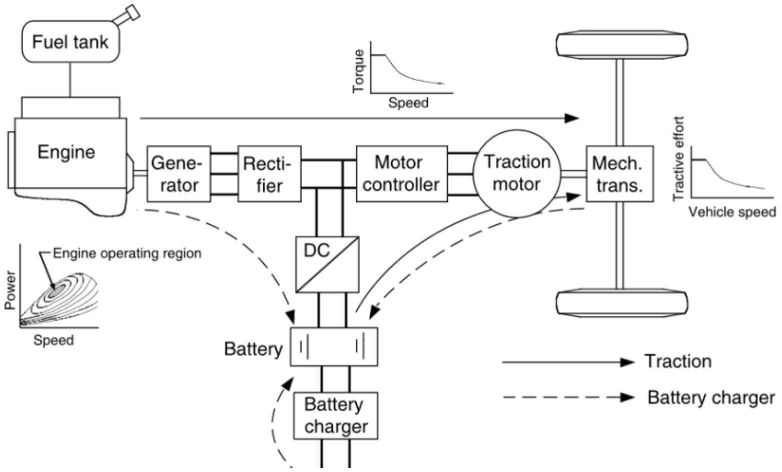

Figure 3-4: HEV drive trains;Series-parallel (Toyota Hybrid Synergy Drive)[2].

Chapter 4

2004 Toyota Prius

Since we have taken the 2004 Toyota prius as a reference to our simulations, we believe that this chapter should be dedicated to give some information about the 2004 Prius so that the readers will have enough information about this vehicle before moving on to the next chapters.

We will just give information about the vehicle body and the vehicle powertrain and the differences between the different generations of this vehicle. We are not trying to sell a car in this chapter. The aim is just to give enough information so that the reader will not be lost in the following chapters/sections. The following table collects some information regarding the vehicle body, which is the same data that we have been using in our simulations in Matlab/Simulink[3]:

2004 Toyota Prius body parameters	
Gross vehicle weight	1720 kg
Exterior Length	4.45 m
Exterior Width	1.72 m
Exterior Height	1.48 m
Drag coefficient	0.26

Table 4.1: 2004 Toyota Prius body parameters[3]

So far there are three different geenrations of the Prius. Within the next two years Toyota Will relase the fourth generation of the Prius but so far, there is no much information about it. We have picked the 2004 Prius (2nd generation) as a reference to our project because there is a lot of information available on books and on the internet.

The first generation was released in 1997 in Japan, and it was exported to the UK, Australia and also New Zealand. The second generation was launched in 2003 (2004 US model year). This model brought important differences in the hybrid system when compared to the previous generation. In order to give a quick view of the main differences between the two hybrid systems, please have a look at the following tables. This first table collects information regarding the engines that are used in the two generations[4]:

Item	THS II	THS
Type	1.5 L (High expansion ratio cycle	1.5 L (High expension ratio cycle)
Maximum output in kW	57	53
Maximum torque in Nm	115	115

Table 4.2: THS (1997 Prius) and THS II(used in 2004 Prius) MG2 comparison[4].

There are also several differences regarding the big electric motor (also known as MG2). For this second generation, this electrical machine is larger and more powerful than in the first Prius generation. The next table shows how different the maximum power and the maximum torque produced by this machine are in the two generations:

Item	THS II	THS
Type	Synchronous AC motor	Synchronous AC motor
Maximum output in kW	50	33
Maximum torque in Nm	400	350

Table 4.3: THS (1997 Prius) and THS II(used in 2004 Prius) motor (MG2) comparison[4].

There is a big difference between THSD and THSD II when it comes to the magnets position. The V-shaped configuration of the magnets in the 2004 Prius (THSD-II) provides about 50 per cent more power than in previous models. The next figure shows both configurations (THSD and THSD-II):

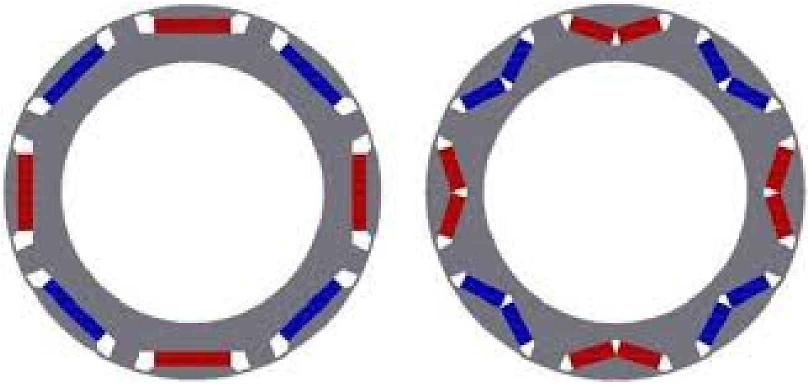

Figure 4-1: 1997 and 2004 Toyota Prius MG2 magnets disposition [5].

In the last table of this chapter, some information regarding the maximum output power of the whole system (MG1,MG2 and ICE). Some other information that can be observed in the follwing table is the maximum output torque provided by the system and the torque given when the vehicle speed is 22 km/h, which is an average speed for an urban cycle:

Item	THS II	THS
Maximum output in kW	82	74
Maximum torque in Nm	478	421
Maximum torque in Nm (22km/h)	478	378

Table 4.4: THS (1997 Prius) and THS II(used in 2004 Prius) system (MG2) comparison [4].

A cross-sectional view of the ICE, MG1 (generator), MG2 (motor) and the power split device is shown in the following lines. Please remember that the ICE will not be included in our project because it will be replaced by an induction machine that will behave exactly as if it was an ICE:

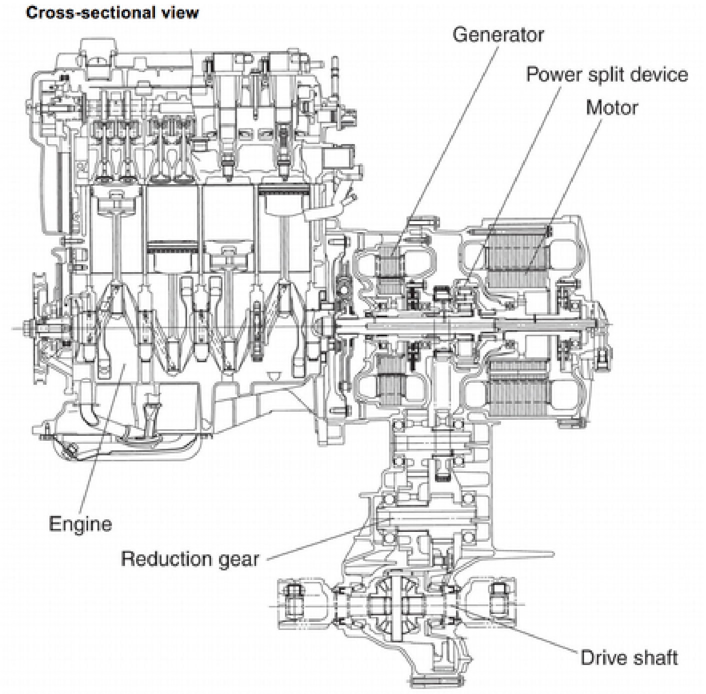

Figure 4-2: Cross-sectional view THSD[3]

There is one important limitation of this series-parallel configuration. Only a fixed amount of torque will be transmitted from the engine to the wheels. Also, the maximum speed will always be limited (physical limits) by the maximum speed of the small electric motor (MG1).

The efficiency of the whole system depends (heavily) on the amount of power that is transmitted over the electrical path. This become essential especially when cruising at medium-high speeds.

There are ways to increase the maximum speed. First, an obvious approach would be incresing the size of MG1. There is an smarter solution, which is incuding a second planetary gear so that MG1 will operate at a lower speed range. This is one of the main differences between the 2004 Toyota Prius and the 2009 Toyota Prius (the one that is still available in the market)

4.1 System Control

The aim of this section is to provide a wide idea of how the THSD-II works. This system is composed by many different elements such as the Boos converter, the A/C inverter, the two electrical machines (MG1 and MG2) and the ICE, and some others like for instance the ECU (stands for Electronic Control Unit) that even though they are nor part of our simulations, they must be described in order to give a good idea of what this system is and how it works. let's first have a look at the following figure which shows how the main alements are located in the vehicle before we start describing them and their main functions:

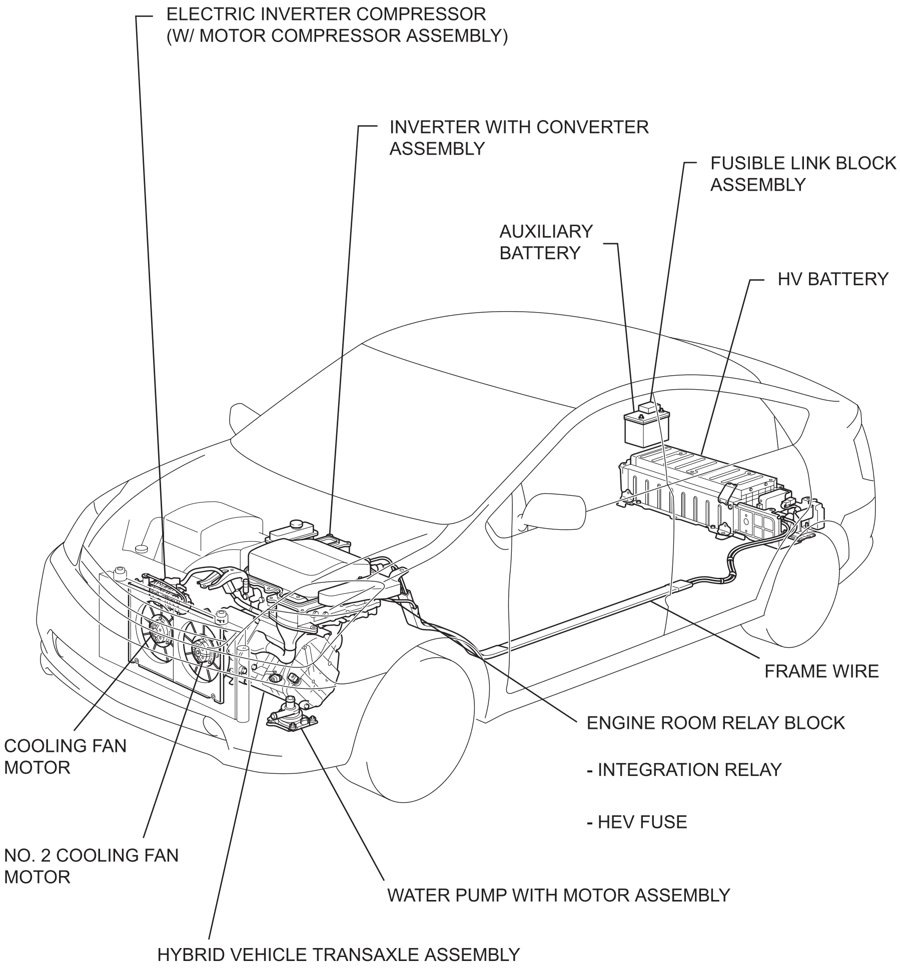

Figure 4-3: Main Elements layout[4]

4.1.1 MG1 and MG2 control

MG1 will generate a maximum voltage of 500 AC V. This voltage will be used to operate MG2 and the battery. MG1 will be forced to rotate by the ICE and it works as iif it was an starter to the ICE too. This will be simulated in one of the following sections in which the five different modes of operation are simulated, but please remember that in our particular this will not be needed because we will have an induction machine instead of an ICE.

Under normal driving conditions, MG2 will provide power to drive the vehicle. When the vehicle is braking (coasting) it will operate as a generator in order to take advantage of the energy that would usually wasted as heat. In the real vehicle, there are temperature sensors that send this information to the HV control ECU as well as position and speed sensors that actuate on both MG1 and MG2.

4.1.2 A/C Inverter control

The AC inverter converts the battery voltage, which is 201,6 DC to 201,6 AC. It also provides power to operate the compressor of the A/C system.

4.1.3 Converter control

Apart from the 201,6 V Li-ion battery, there is another 12V battery that will be used to supply energy to body electrical components. This DC/DC converter reduces the nominal DC voltage (201,6V) to 12 V in order to supply energy to some other body electrical components and to recharge the 12V battery as well.

4.1.4 Boost Converter control

This boos converter boosts the nominal voltage (201,6 V) up to 500V. The maximum voltage of 500V generated by MG1 or MG2 is converted into DC by the inverter

4.1.5 Inverter Control

This inverter converts a direct current (t he HV coming from the battery) into AC (MG1 and MG2) or vice versa. Also, this inverter supplies the MG1 AC power to MG2. On the other hand, when the power goes from MG1 to MG2, the eelctricity is converted into DC inside the inverter.

The HV control ECU sends the signal to the power transistor in the inverter for switching the U, V and W phase of the MG1 and MG2 in order to drive both MG1 and MG2.

4.1.6 HV Control ECU control

This HV ECU controls both MG1 and MG2, the engine (induction machine), regenerative brake and the battery state of charge (SOC).All these factors are determined by the shift position, the accelerator pedal position and the vehicle speed. For instance, when the shift position is in ”N”, the ECU shuts down control to electrically stop MG1 and MG2.If there is no traction given to the driven wheels, then the HV control ECU will perform a control traction control that will restrain the rotation of MG2, so that the planetary gear will be protected and prevent MG1 from generating excessive electricity.

Please have a look at *Appendix A*. There is a ECU System Diagram from the 2004 Toyota Prius that might be of interest. We have not included such file in this section because it’s not part of the master’s thesis scope.

4.1.7 Skid control ECU

This ECU acts when the vehicle is braking. This ECU will calculate the total braking force and it will transmit a regenerative braking force request to the HV control ECU. Upon recieving this signal, the HV control ECU calculates the magnitude of regenerative brake force required and it will send it to the ECU skid control. Last, based on this the skid control ECU calculates the required hydraulic pressure brake force needed.

4.1.8 Battery ECU control

This ECU will monitor the battery SOC and it controls it will set the cooling fan at the required speed in order to keep the battery at a given temperature.

Before moving on to the following section, this figure shows a diagram of how the different systems described above are connected:

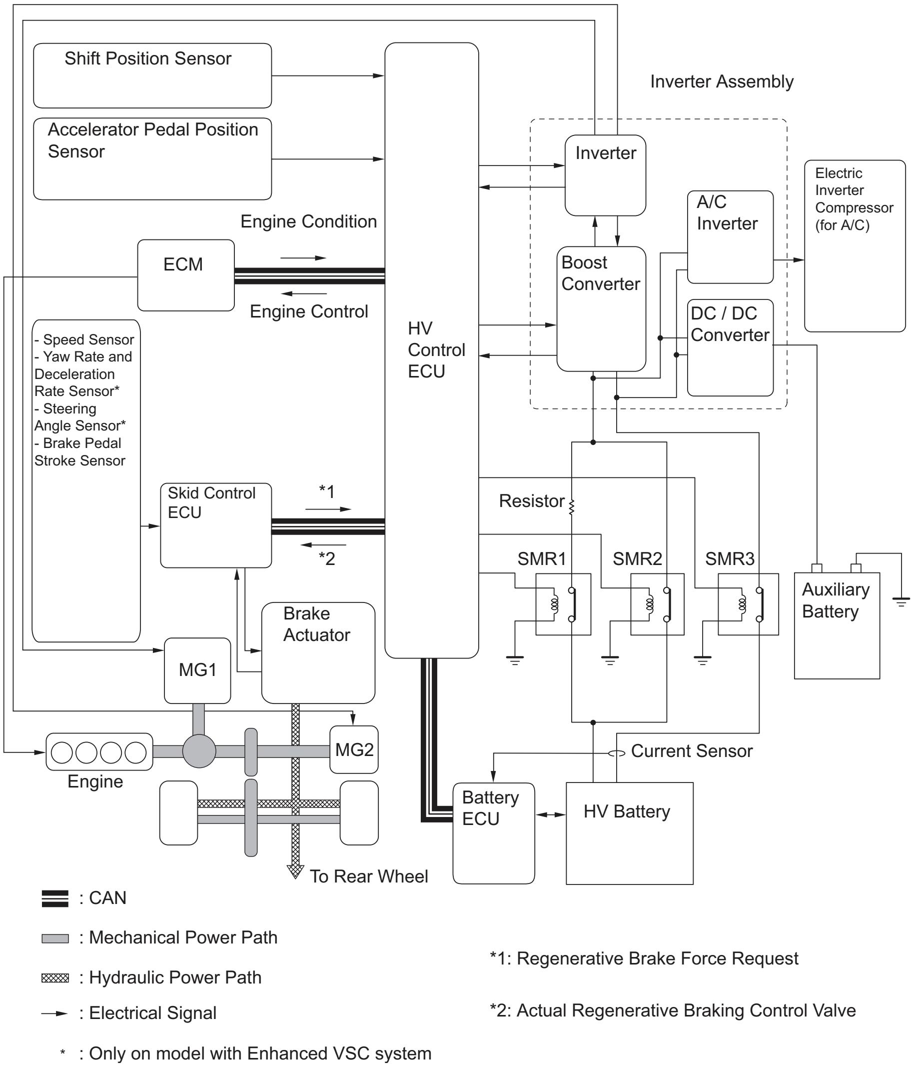

Figure 4-4: Main Elements layout[4]

Chapter 5

Simulation of the HEV Powertrain: First steps

This section will cover the simulation of the large electric motor (MG2). The machine specifications are shown in the following table:

MG2 is a Interior Permanent Magnet Machine (IPM).The magnets are placed inside the rotor of the machine and when compared to Superior Permanent Magnet (SPM) Machines, which are probably the most common PM machines together with IPM machines,are more resistant at high speeds. That is one of the reasons why these machines are more attractive than SPM machines. The following table collects the most relevant parameters of this MG2:

MG2 parameters	
Number of poles	8
Flux linkage	0.201
Ld	0.004635
Lq	0.006612
J	0.00179
Lambda	0.18667

Table 5.1: MG2 Parameters[6]

The DC link voltage has been set to 650V.

The D and Q-axis inductantes of an IPM machine are different whereas in the case of a SPM machine, they have the same value. This makes the control structure of an IPM machine more complex than in the case of an SPM machine. IPM machines have two different types of torque: synchronous and reluctance torque. This reluctance torque is due to the magnets. D-axis current must be negative in order to the have a positive reluctance torque. SPM machines do not have reluctance torque due to the fact that the D and Q-axis inductances have the same value.

The next figure shows the Matlab/Simulink Model that has been created inorder to simulate the vector control implementation on MG2:

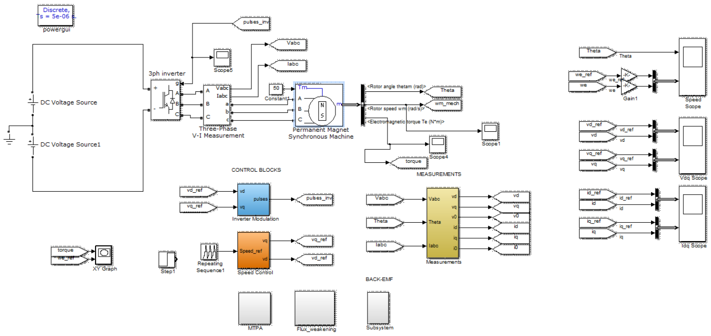

Figure 5-1: Matlab/Simulink Model used to simulate MG2.

This Matlab/Simulink model has been modified from a file that we have used in SIMUHEV (Pablo García). The control scheme used to control this machine will be shown next. We will not spend time explaining how this control scheme because it is not the scope of this master's thesis:

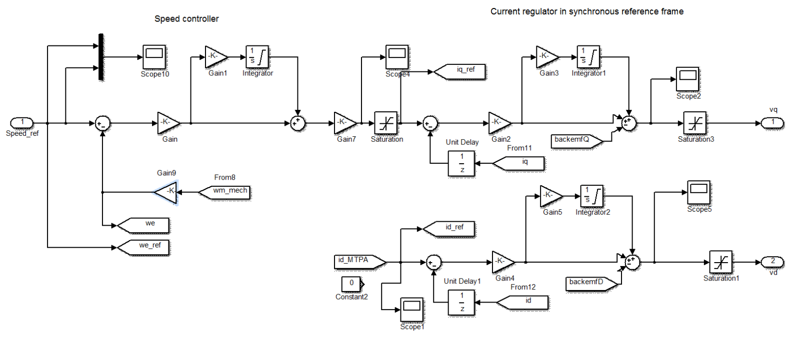

Figure 5-2: Matlab/Simulink Model used to implement vector control on MG2.

The PI controllers have been tunned using zero-pole cancellation. The gains for each controller can be shown in the following table:

PI tunning gains (Current controllers):	
Kp (Q-axis)	41,54
Ti (Q-axis)	0.0144
Kp (D-axis)	14.5613
Ti (D-axis)	0.0101

Table 5.2: Current Controllers gains

Next thing will be showing some of the results. The next figure shows the speed profile and the rotor speed together. As it can be observed, ir tracks the reference perfectly:

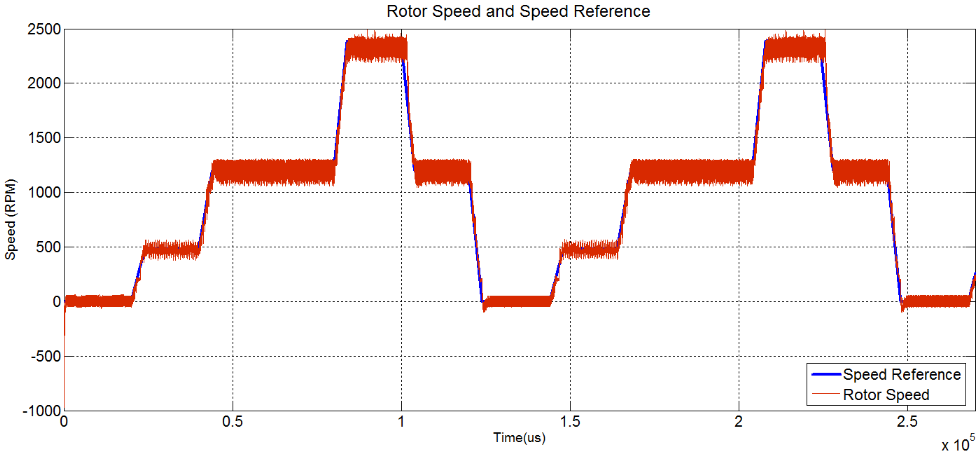

Figure 5-3: rotor speed and its reference (MG2).

The next figure will show both the Q-Axis reference and its reference. No much should be said anbout this. The reference is very well tracked too as it can be observed:

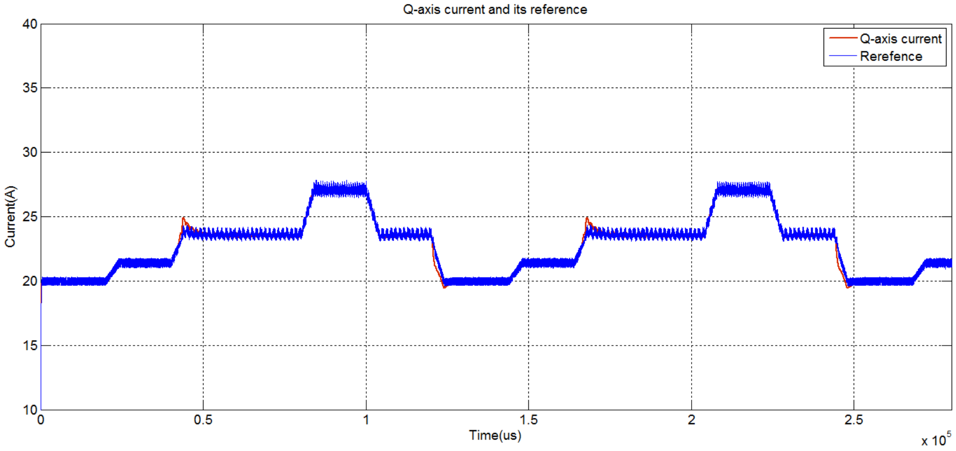

Figure 5-4: Q-axis current its reference (MG2).

Thesame procedure will be carried out for the D-axis:

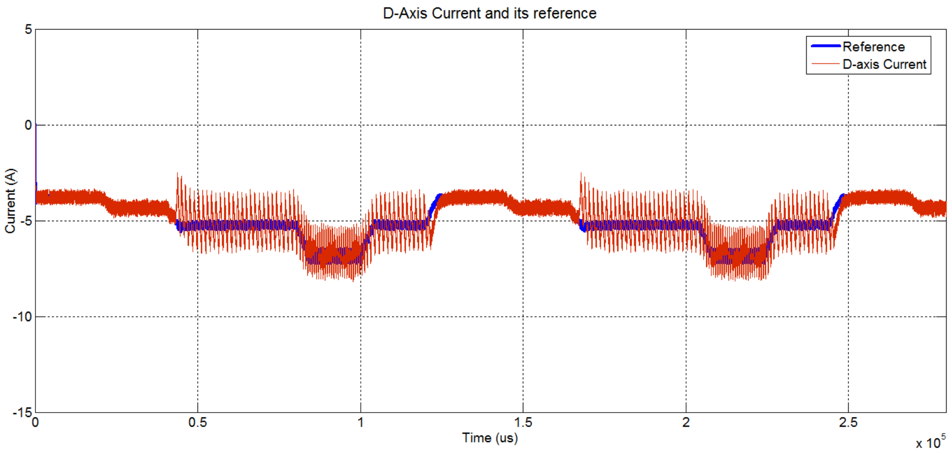

Figure 5-5: D-axis current its reference (MG2).

5.1 HEV: Modes of operation

In a parallel-series hybrid, there is a key element. This key element is the planetary gearset. This mechanical device allows the mechanical connection of the two electrical machines and the ICE (from now on, we will refer to the induction machine that will behave as if it was an ICE as "ICE"). There is no gearbox, starter or alternator in this kind of vehicles.

A planetary gearset has three different elements: the ring gear, the planetary gearset(also planet carrier) and the sun gear. MG2 is connected to the ring gear and MG1 is conencted to the sun gear. On the other hand, the ICE is connected to the planet carrier.

Only the ring gear is connected to the wheels. This means that MG2 is the only machine in charge of propelling the vehicle. The speed and torque of the three different elements of the planetary gearset are related to each other via the following equations:

$$\omega_{carrier} = \frac{N_r}{N_s + N_r} \cdot \omega_{MG2} + \frac{N_s}{N_s + N_r} \cdot \omega_{MG1} \tag{5.1}$$

$$T_{MG2} = -\frac{N_r}{N_s + N_r} \cdot T_{ICE} \tag{5.2}$$

$$T_{MG1} = -\frac{N_s}{N_s + N_r} \cdot T_{ICE} \tag{5.3}$$

$$T_{MG2} + T_{MG1} + T_{ICE} = 0 \tag{5.4}$$

The number of teeth that each element has is shown in the following table:

Planetary gearset speeds:	
Element	number of teeth
Ring gear	78
Sun gear	30
Planetary carrier	23

Table 5.3: Planetary gear set speeds

Series-Parallel HEV have 5 different modes of operation. These modes of operation will be described(and simulated in Matlab/Simulink) throughout the following subsections. Prior to that, the Simulink model that has been used to simulate these 5 modes is shown in the following figure:

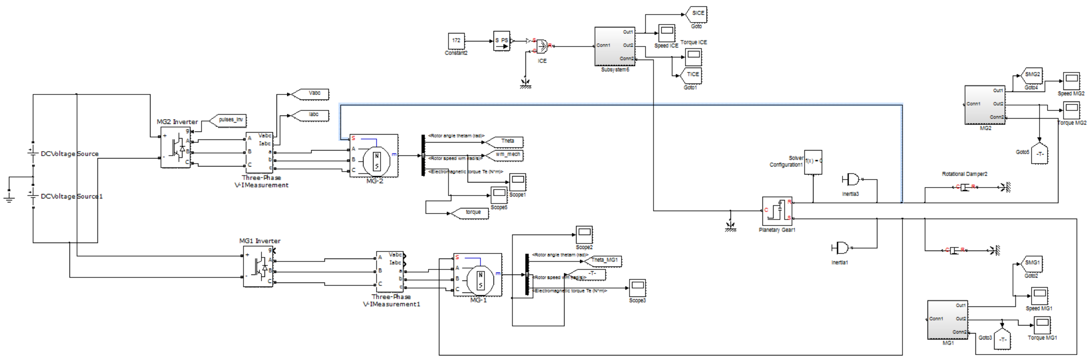

Figure 5-6: Matlab/Simulink Model used to simulate the 5 different moded of operation

5.1.1 Mode 1: Starting off

The torque for initial accelerations is given by MG2. As it was said before, MG2 is connected to the ring gear, that is also connected to the reduction gear that drives the wheels. THE ICE is not moving due to the fact that it is not efficient at this speed. MG1 is spinning backwards. The next figure shows the speeds of the three elements when the vehicle is starting off:

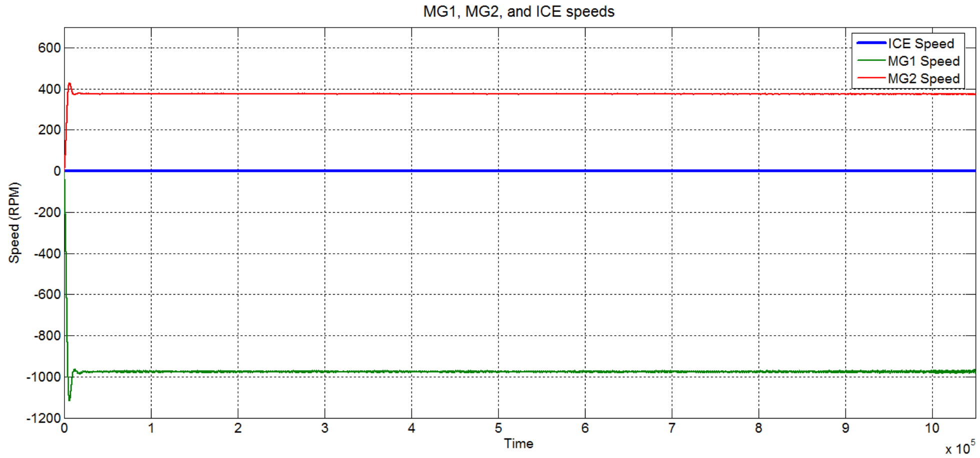

Figure 5-7: MG1, MG2, and ICE Speeds (Mode 1).

The speed and torque equations shown at the beginning of this chapter will be used in order to show that the system is working properly. The next table shows the speeds of the three elements (MG2,MG1 and ICE) at t=1 second:

Planetary gearset speeds:

Element	Speed(RPM)
Ring gear	39.3
Sun gear	-102
Planetary carrier	0

Table 5.4: Planetary gear set speeds

Plugging in the previous values on equation 5.2, we will get to:

$$0 = \frac{N_r}{N_r + N_s} \cdot 39.3 rad/s - \frac{N_s}{N_r + N_s} \cdot 102 rad/s \tag{5.5}$$

In the case of the output torque values, the ICE is producing no torque so that means that MG1 and MG2 torques are opposite to each other (equation 5.4).

5.1.2 Mode 2: Driving under normal conditions: Cruising

Under normal conditions, the power supplied by the engine must be kept to the minimum. As always, MG2 is in chage of propelling the vehicle and the power that comes from ICE will depend on the SOC of the battery and the speed of the vehicle. If the speed of the vehicle is above 42mph, then the ICE will be running in order to provide the desired power. The following figure shows the speeds of MG1,MG2, and ICE:

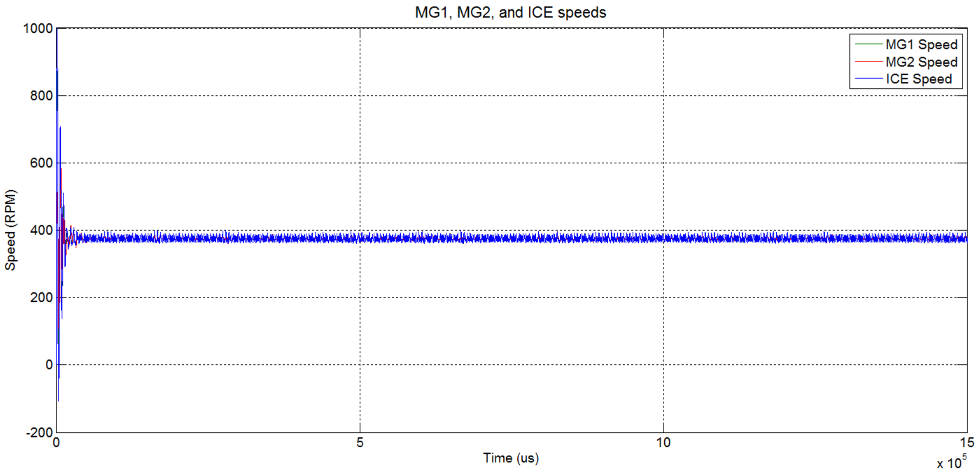

Figure 5-8: MG1, MG2 and ICE speeds (Mode 2).

As it can be observed in the figure from above, the speed of the three elements is exactly the same (393,2 RPM). Plugging in these values in equation 5.2 we will obtain:

$$393.2 = \frac{N_r}{N_r + N_s} \cdot 393.2rad/s - \frac{N_s}{N_r + N_s} \cdot 393.2rad/s \tag{5.6}$$

we will also use equation 5.4 in order to show that the system also satifies this torque equation. First, please have a look at the torque values that will be plugged in in equation 5.4:

Plugging in the previous values un equation 5.4 we will verify that the equation is

Planetary gearset output torque values:	
Element	Speed(RPM)
Ring gear	-124
Sun gear	-48
Planetary carrier	172

Table 5.5: Planetary gear set output torques (mode 2)

satisfied.

$$172 - 124 - 48 = 0 \tag{5.7}$$

Last, this figure shows the three different torques:

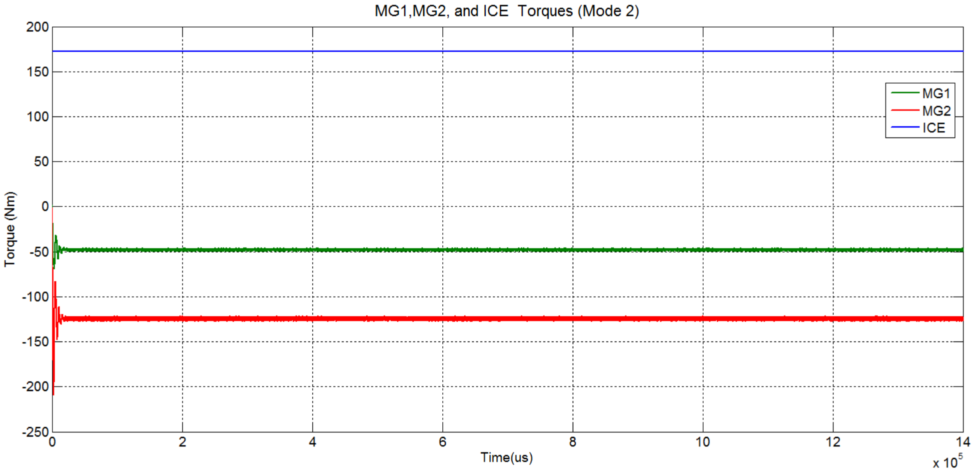

Figure 5-9: MG1,MG2, and ICE torques (mode 2).

5.1.3 Mode 3: Sudden acceleration

The power demand in this mode is very high. The MG2 is not able to propel the vehicle by itself and that is why the ICE is also running. Figure 14 shows the speeds of the three elements in a normal sudden acceleration. In the case the vehicle is in the middle of passing another vehicle (when for instance the power demand is as high as it could be), the situation here is a bit different; The ICE will be providing as much torque as it can and MG1 would also be spinning around its limits so that MG2 can also provide its maximum power.

In the previous case, it was mentioned that ICE will always be running if the speed vehicle is above 42 mph. Please notice that in this third case, the ICE is running because the torque demand is too high in order for the MG2 to generate such torque. That is why the ICE is forced to run then.

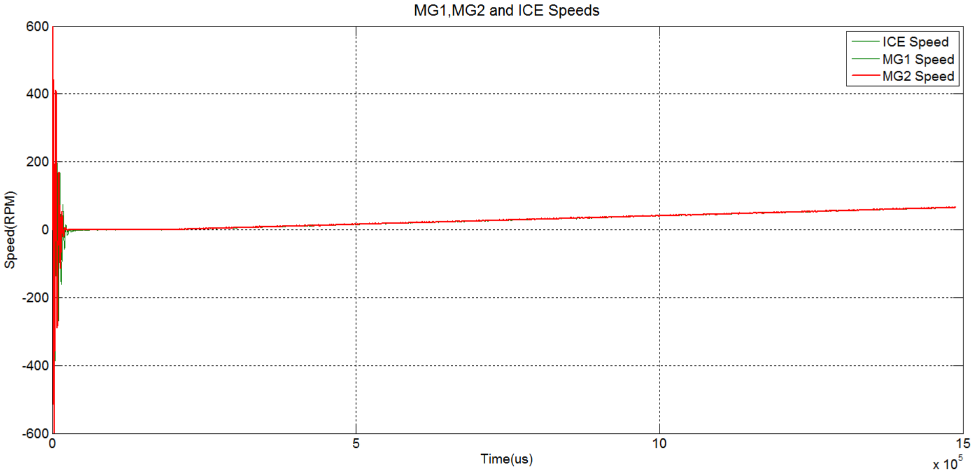

Figure 5-10: MG1,MG2, and ICE speeds (mode 3).

The same procedurewill be carried out in order to show that equation 5.4 will be satisfied. This table shows the values of the ouput torque for each of the three elements:

Planetary gearset output torque values:	
Element	Speed(RPM)
Ring gear	-124
Sun gear	-48
Planetary carrier	172

Table 5.6: Planetary gear set output torques (mode 3)

The next figure shows the results obtained from our Matlab/Simulink simulation:

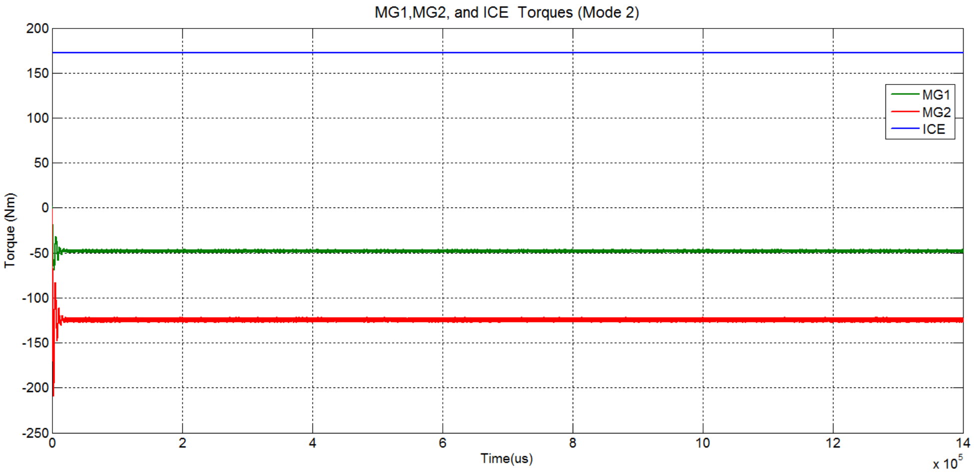

Figure 5-11: MG1,MG2, and ICE torques (mode 3).

5.1.4 Mode 4: Decelerating - Braking

The vehicle will be operating under these conditions when driver takes the foot off the accelerator. The car reduces its speed due to aerodynamic drag and rolling resistance. The ICE will never operate under these conditions. Only MG2 (generator mode) in order to take advantage of the energy that would be wasted as heat. When you coast, the car slows faster than would be the case if only rolling resistance and aerodynamic drag were acting on it. To produce this additional slowing force, MG2 is configured as a generator and charges the battery. Its generator drag simulates engine braking. On the other hand, powr will not be generated nor used by MG1. it just spins free. This energy (depending on the efficiency of the electric machines and mecanical couplings) will be sent back to the batteries so that it will be ready to use in the future. The next figure shows the speeds of MG1,MG2 and ICE when the driver steps on the pedal brake at 0.5 seconds:

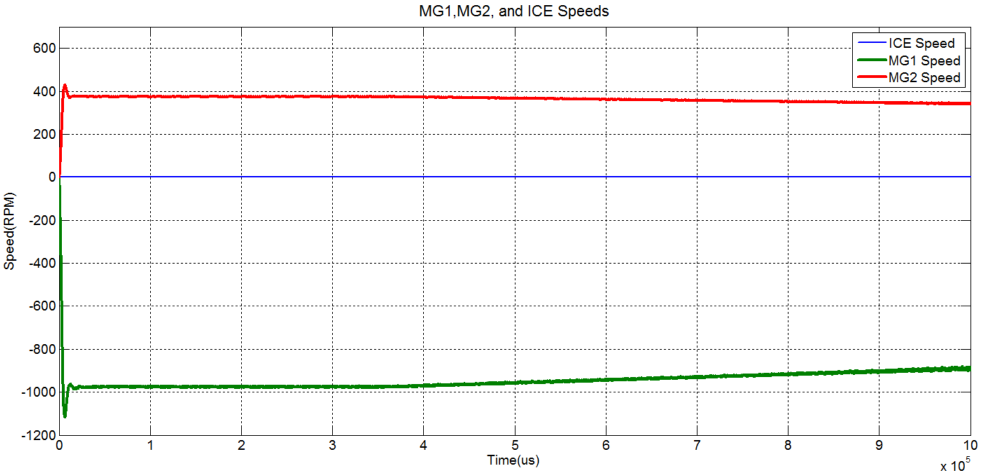

Figure 5-12: MG1,MG2, and ICE speeds (mode 4).

These are the speed values for the three different elements of the planetarty gearset:

Planetary gearset speeds:	
Element	Speed(RPM)
Ring gear	348.6
Sun gear	–906.36
Planetary carrier	0

Table 5.7: Planetary gear set speeds

Plugging in the previous values in equation 4.2, we will get to:

$$0 = \frac{N_r}{N_r + N_s} \cdot 348.6 rad/s - \frac{N_s}{N_r + N_s} \cdot -906.36 rad/s \tag{5.8}$$

In the case of the output torque values, since the ICE is not operating under this conditions, MG1 and MG2 output torques will be opposite and equal to each other. (equation 5.4)

5.1.5 Mode 5: Battery Charging

In this particular mode, the vehicle is not moving. MG2 will not be runing and the ICE will be running. It will be used to charge the battery for later use. MG1 will also be turning and it will be working as a generator.Keep it mind that the ICE will be operating at its highest efficiency so that the efficiency of this process will be kept at its highest.There is no much more to say about this particular mode. The next figure shows the speeds of MG1,MG2 and the ICE:

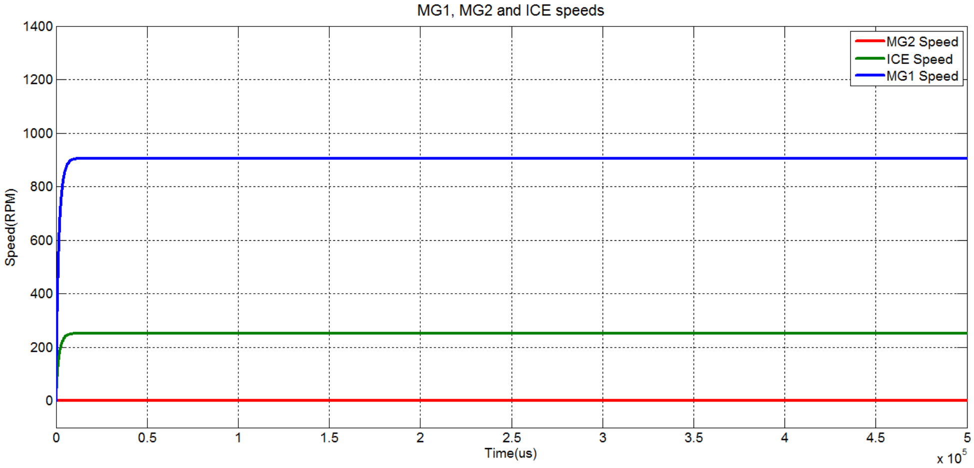

Figure 5-13: MG1,MG2, and ICE speeds (mode 3).

5.2 Transitions

This section covers the transitions between the five modes that have been described in the section from above. There are three major different transitions. The three of them have been simulated in Matlab/Simulink. The first one would be when the speed of the vehicle is initially below 42 mph and the vehicle starts speeding up. Once the vehicle speeds reaches 42mph, the ICE will start running.

The second simulation (or transition) will cover the transition between cruising mode and coasting mode. In other words, when the vehicle starts slowing down and MG2 is operating as a generator. The third and last simulation is just to show how the three machines behave when the car is not moving and the ICE is running to charge the battery.

The three simulations have been carried out using ideal torque sources due to their simplicity. This way the simulations are much faster. The next figure shows the simulink model that has been used for the three simulations. This three files can also be found in the folder that has been attached to this PDF file.

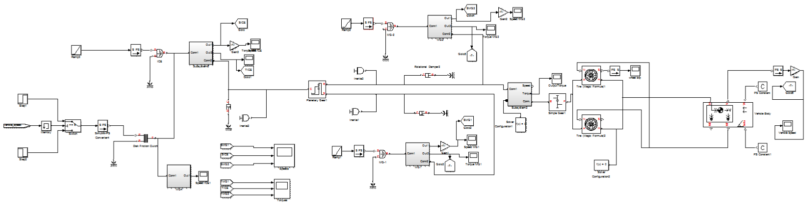

Figure 5-14: Matlab/Simulink Model used to simulate the different transitions between the modes.

5.2.1 Speeding up: ICE OFF - ICE ON

As it was mentioned above, this simulation will emulate the behaviour of the three machines when the vehicle is speeding up (the speed will initially be below 42mph) and it goes over 42 mph. Those 42 mph are the "threshold value" in which the ICE kicks in. The next two figures show the vehicle speed and the speeds of the three machines. Please notice that the ICE kicks in when the vehicle speed reaches 42 mph:

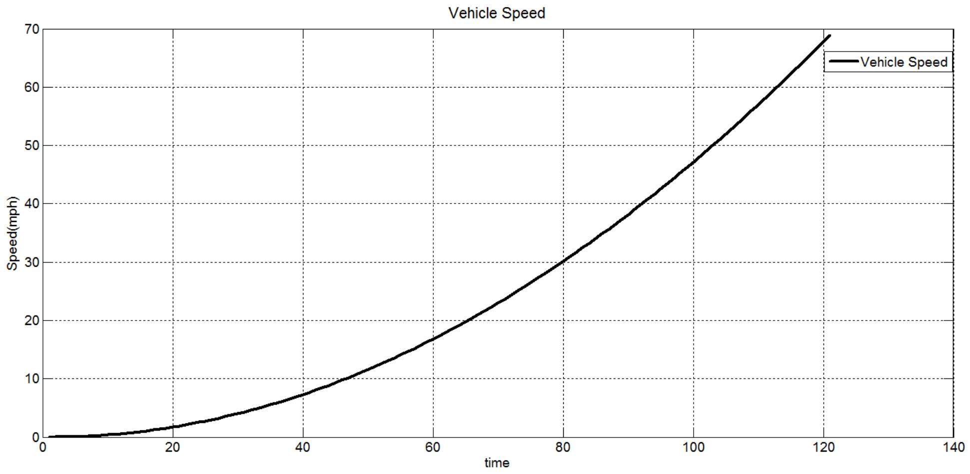

Figure 5-15: Vehicle Speed; ICE OFF-ON Transition).

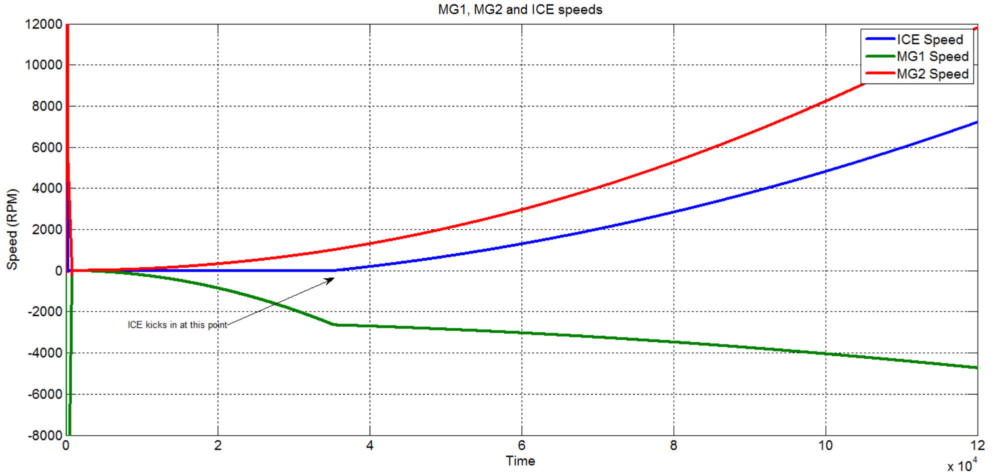

Figure 5-16: MG1,MG2, and ICE speeds (ICE ON-OFF transitions).

Once the ICE has kicked in, the speed of MG1 does not increase as fast as it used to do before. The reason why the limit has been set to 42 mph is because MG1 would reach extremely high speeds in a very short time and that will make it go over its manufacturing limits.

One of the major differences between the second and third generation of the Toyota Prius is that this third generation has a second planetary gearset that increases the time that it takes to MG1 to reach its limits which it also implies that the efficiency has been improved. This is due to the fact that the ICE will not be running until the vehicle reaches 68 mph. Next, we will follow the same procedure that has been used in the previous chapter. We will collect the speeds o the three elements in a table and then we will use equation 4.2 in order to show that such equation is always accomplished:

Planetary gearset speeds befoe ICE kicks in (t=2.5s):	
Element	Speed(RPM)
Ring gear	1705.56
Sun gear	-4434.45
Planetary carrier	0

Table 5.8: Planetary gear set speeds

Plugging in the previous values in equation 4.2:

$$393.2 = \frac{N_r}{N_r + N_s} \cdot 1705.56 rad/s - \frac{N_s}{N_r + N_s} \cdot -4434.45 rad/s \tag{5.9}$$

In order to show that this equation is still accomplished once the ICE has kicked in, we will follow the same procedure as before:

Planetary gearset speeds befoe ICE kicks in (t=6s):	
Element	Speed(RPM)
Ring gear	3125
Sun gear	-3007.12
Planetary carrier	1421.63

Table 5.9: Planetary gear set speeds

5.2.2 Coasting- regenerative braking

In order to simulate this transition between these two modes (coasting and braking), it will be assumed that the vehicle is cruising at a constant speed. The three machines will be running and at a given time, the vehicle will start slowing down. At this point, the ICE will stop and MG2 will act as a generator. The next figure shows the speeds of the three elemements:

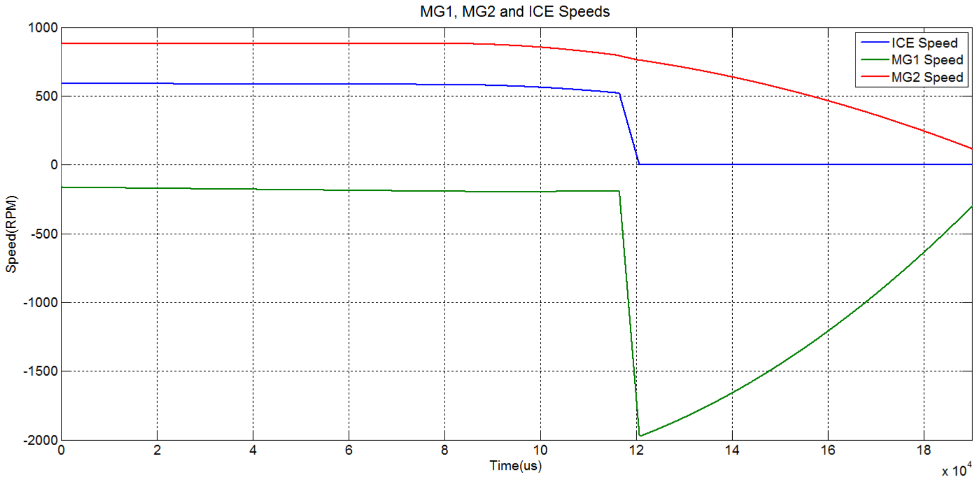

Figure 5-17: MG1,MG2, and ICE speeds (regenerative braking transition).

As you will see in the Simulink file,this simulation has been carried out the follwing way; a ramp with negative slope has been set as the speed command so that when the speed starts decreasing, the planet carrier is locked so that the ICE stops running. The nex table shows the speed of the three different elements of the planetarty gear set before the vehicle stars slowing down:

Planetary gearset speeds before the vehicle starts slowing down (t=5s):	
Element	Speed(RPM)
Ring gear	820.56
Sun gear	-220.45
Planetary carrier	531.39

Table 5.10: Planetary gear set speeds

As usual, we will plug in the previous values in equation 4.2:

$$531.39 = \frac{N_r}{N_r + N_s} \cdot 820.56 rad/s - \frac{N_s}{N_r + N_s} \cdot -220.45 rad/s \tag{5.10}$$

And the same procedure will be carried out once the vehicle starts slowing down:

Planetary gearset speeds once the vehicle starts slowing down (t=14s):	
Element	Speed(RPM)
Ring gear	589.23
Sun gear	-1531.41
Planetary carrier	0

Table 5.11: Planetary gear set speeds

As usual, we will plug in the previous values in equation 4.2:

$$0 = \frac{N_r}{N_r + N_s} \cdot 589.23 rad/s - \frac{N_s}{N_r + N_s} \cdot -1531.41 rad/s \tag{5.11}$$

5.2.3 Battery Charging (while idling)

This last simulation tries to emulate the behaviour of the three machines when the vehicle is not moving and the SOC is low. In that case, the ICE will start running to charge the battery. MG2 is not running and only the ICE and MG1 are running. The speeds of the three machines are shown in the following figure:

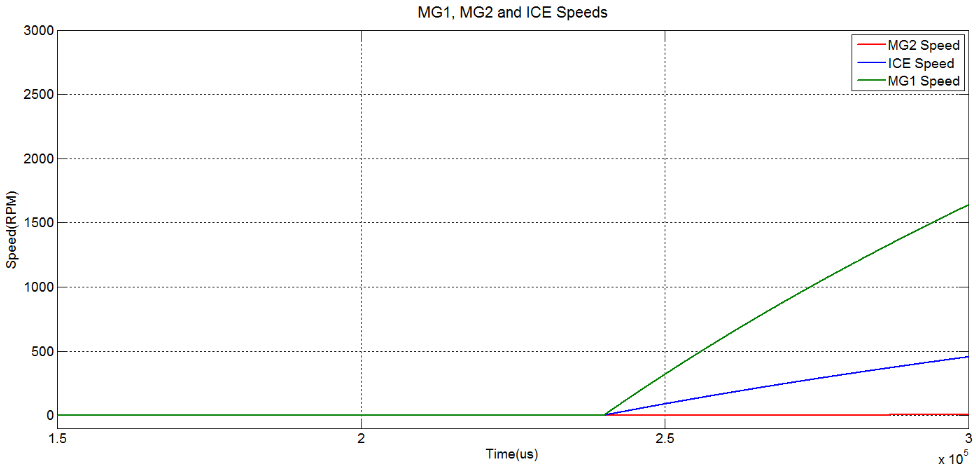

Figure 5-18: MG1,MG2, and ICE speeds (battery charging while idling).

Chapter 6

ICE Emulation using an Induction Machine

This chapter collects all the information regarding the emulation of an ICE using an induction machine. As it was said at the beginning, this is the innovative part of the project and from the author's point of view, the most challenging part too.This emulation process can be divided into 4 big sections. It is assumed that the reader has a basic knowledge of how an ICE works. We would like to point out that this model is based on the *sld engine* model. We have modified this model and we have implemented a control scheme that will satisfy our project demands. The objective is to make the dynamycs of the induction machine identical to the dynamics of an ICE. Some of the reasons that explain why this has been done are the following:

1. Different engine parameters can be evaluated just by modifying the parameters file.
2. The induction machine is much quieter than an ICE. And since it will be an indoor test bed, this can make a big difference.
3. There is no exhaust.

The ICE model that has been used is a non-linear transfer function made of 4 sybsystems, which are:

1. Throttle Body
2. Intake Manifold
3. Fuel Injection
4. Torque Production

Before describing in detail each of those subsystems, please have a look at the following figure that will make the explanation and comprehension a little bit easier:

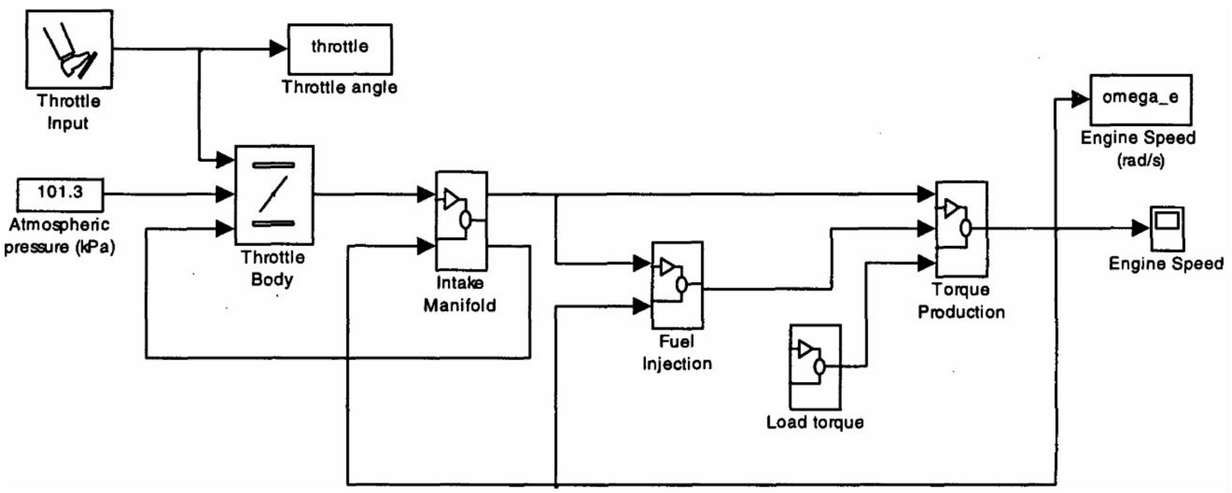

Figure 6-1: ICE emulation schematic as seen on [8].

The system control has been designed to simulate an ICE able to determine the proper speed comand at each time. But prior to the control stage, first we will explain how the ICE emulation blocks (or subsystems9 have been built in Matlab/Simulink.

6.1 Throttle Body

This is the first element or subsystem of the ICE emulation. There is only one control input which is the throttle angle. basically, the idea of this subsystem is to determine the amount of air (and gas) that will go into the intake manifold. This could be expressed as a result of two independent functions; the atmospheric pressure (it will be assumed to 1 atm) and the pressure created due to the throttle angle. There is an exception; If the intake manifold is too low (or in other words, great vacuum) the flow rate throw the throttle body is sonic and is only a function of the throttle angle[3]. The following equation is key in the design of this first subsystem[3]:

$$m_{ai} = f(\theta)g(Pm) \tag{6.1}$$

That is the mass flow rate into manifold in (g/s), where:

$$f(\theta) = 2.821 - 0.052231\theta + 0.10299\theta^2 - 0.00063\theta^3; \tag{6.2}$$

where:

$$\theta = throttle\, angle\, (deg) \tag{6.3}$$

g(Pm) can be expressed as a function of the value of Pm (Manifold Pressure). The next three equations determine the value of g(Pm) depending on the value of Pm:

$$g(Pm) = 1 \quad if Pm \leq \frac{P_{amb}}{2} \tag{6.4}$$

$$g(Pm) = \frac{2}{P_{amb}} \cdot \sqrt{P_m \cdot P_{amb} - P_m^2} \quad if \frac{P_{amb}}{2} \leq P_m \leq P_{amb} \tag{6.5}$$

$$g(Pm) = -\frac{2}{P_{amb}} \cdot \sqrt{P_m \cdot P_{amb} - P_m^2} \quad if P_{amb} \leq P_m \leq 2 \cdot P_{amb} \tag{6.6}$$

where:

$$P_m = manifold\ \ Pressure(bar)\ \ and\ \ P_{amb} = atmospheric\ \ Pressure(bar)) \tag{6.7}$$

The next figure shows the throttle body subsystem that has been implemented in Matlab/Simulink:

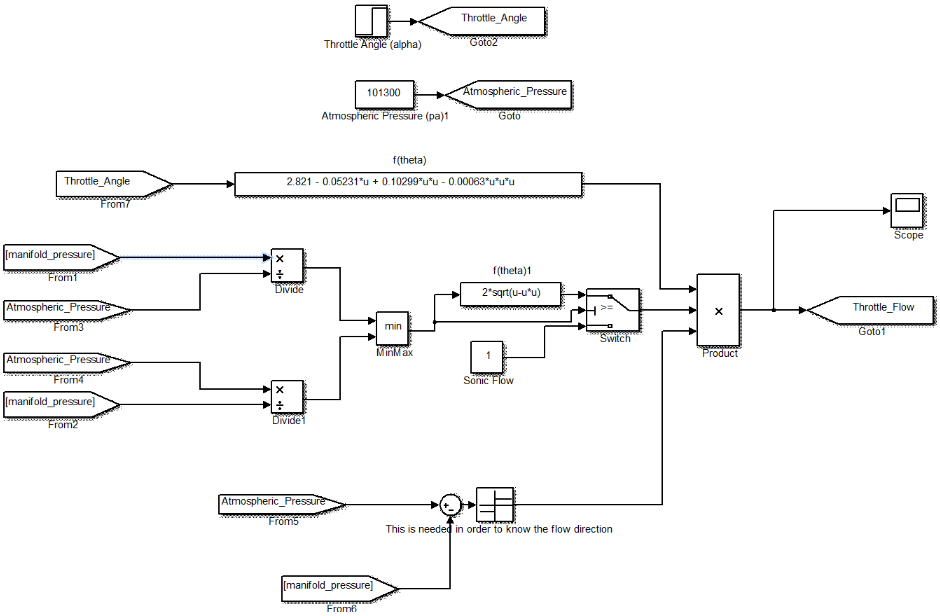

Figure 6-2: throttle body subsystem created in Matlab/Simulink.

The behaviour of the valves is not linear. As it can be observed in the figure from above, the system has three inputs. There is a switch that determines if the flow is sonic or not and the MIN block ensures that the direction of the flow goes from the highest to the lowest.As it was mentioned before, the output of this throttle body subsystem is the input to the intake manifold subsystem.

6.2 Intake Manifold

This second subsystem models the intale manifold as a differential equation for the manifold pressure. The difference between the outgoing and incoming mass flow represents the rate of change of air with respect to time. Accordingly to the equation of ideal gas (that is shown below), this rate change of air with respect to time is proportional to the time derivative of the manifold pressure. Exhaust Gas Recirculation (EGR) has not been implemented. EGR is a NOx reduction technique that recirculates a portion of the exhaust gases back to the cylinders at low RPMs. If order to implement this technique, please check reference[5]. This is the ideal gas equation:

$$P_m = \frac{RT}{V_m} \cdot (m_{ai} - m_{ao}) \tag{6.8}$$

where:

R = Specific gas constant

T = Temperature (K)

Vm = manifold volume (m3)

mao = mass flow rete of air out of the manifold (g/s)

Pm = rate of change of manifold pressure (bar/s)

6.2.1 Intake mass flow rate

The intake mass flow rate is a function of the manifold pressure and the engine speed. That is why the engine speed is feedback from the next subsystem to this second one. The mass flow that our subsystem pumps into the cylinders is given by the following equation:

$$m_{ao} = -0.366 + 0.08979NP_m - 0.0337NPm^2 + 0.0001N^2P_m \tag{6.9}$$

where N is the engine speed in rad/s and Pm is the manifold pressure (bar). To determine the total air charge pumped into the cylinders, the simulation integrates the mass flow rate from the intake manifold and samples it at the end of each intake stroke event. This determines the total air mass that is present in each cylinder after the intake stroke and before compression[5]. The next figure shows the Matlab/Simulink model that has been created to emulate this subsystem:

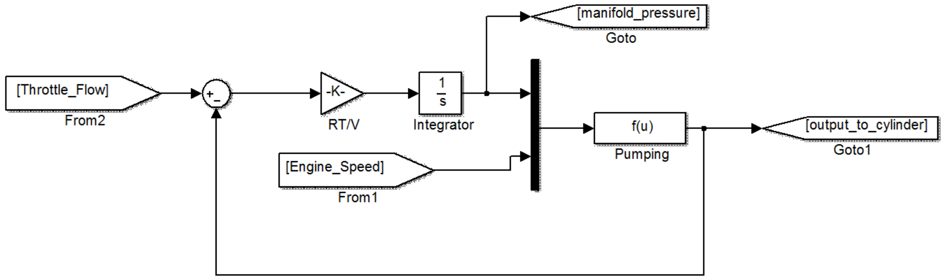

Figure 6-3: Matlab/Simulink subsystem corresponding to the second ICE emulation subsystem.

6.2.2 Intake, Compression and Combustion Strokes

Conventinal gasoline engines work under the Otto cycle conditions. However, this vehicle (inspired in the Toyota Prius) and many other HEV have an ICE that works under the Atkinson cycle conditions. The main difference between these two cycles is that in the compression stroke, the intake valves are still open at the very beginning for the Atkinson cycle whereas for the case of the Otto cycle, they are closed. This makes the Atkinson cycle slightly more efficient when compared to the Otto cycle.In an inline four-cylinder four-stroke engine (like the one that has been used for this project) of crankshaft revolution separate the ignition of each successive cylinder. This results in each cylinder firing on every other crank revolution.

In this model,the intake, compression, combustion, and exhaust strokes occur simultaneously (at any given time, one cylinder is in each phase). To account for compression, the combustion of each intake charge is delayed by 180° of crank rotation from the end of the intake stroke[5]. There is an integrator that will accumulate the cylinder mass air flow in the intake block. In order to manage both compression and intake timings, a valve timing block has been built. And this is the block where the main difference between an Otto cycle engine and an Atkinson cycle engine appears. When it comes to the valves, they change (open-close) every 180 degrees of crankshaft rotation. On the other hand, the compression subsytem creates a 180 degrees delay between the combustion and intake of each charge of air.

6.2.3 Torque Production

This last subsystem will emulate th torque produced by the ICE. It is no more than a equation that relates the mass of the air charge, the air/fuel mixture ratio, the engine speed and the spark advance to each other. The equation is the following:

$$\begin{aligned} T_{eng} = -181.3 + 379.36 m_a + 21.91(A/F) - 0.85(A/F)^2 + 0.26\sigma - 0.0028\sigma^2 + 0.027N - \\ - 0.000107N^2 + 0.00048N\sigma + 2.55\sigma m_a - 0.05\sigma^2 m_a \end{aligned} \tag{6.10}$$

Where:

ma = mass of air in cylinder for combustion(g)
A/O = air to fuel ratio
Teng = Torque produced by the engine

A torque load can also be included but it has been decided to not include it in our model due to the fact that such load torque will emulate the aerodynamic drag and rolling resistance. SInce this whole system would be operatin in an indoor test bed, such load torque has been rejected.

This is the first part of this ICE emulation chapter. In the next section, the control will be discussed.

6.3 ICE Emulation: Control

The induction machine must produce torque in such a way as if it was an ICE. On the other hand, the ICE of a HEV always tends to work on ”top gear”, or in other words, it always operates around its highest efficiency region.

At the beggining, when we first run the first simulations of this ”ICE emulation” section, we were not sure of the dynamics of the induction machine and its control would affect the emulation of the ICE. After running the first simulation, we realized that they do not affect the results by any means, which is obviously a good thing and it makes things easier for us.

The motor parameters are similar to the one that has been used in one of the references that has been follow to develope this last part of the master’s thesis:

Induction Machine Param.	
Number of poles (P)	4
Rated Frequency	50Hz
Rated Slip	2.2
J rotor	0.2318Nm2
D	0.096Nm/rad/s

Table 6.1: Induction Machine parameters[8]

The next figure shows the control scheme that has been built in Matlab /Simulink:

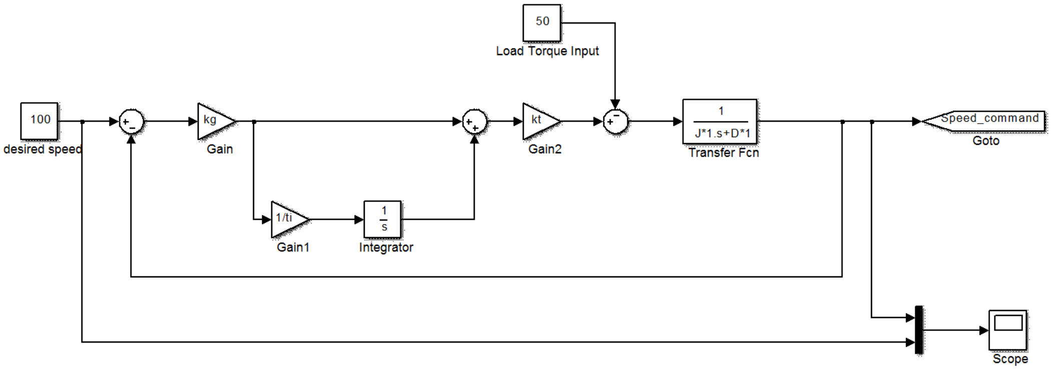

Figure 6-4: MG1,MG2, and ICE speeds (mode 3).

As it can be observed in the figure from above, a PI controller has been used in order to control the speed of the induction machine. The prameters of the plant of the system (J and D) have been described in table 5.1 The PI parameters can vary depending on how fast we want the repsonde to be. They are shown in the following table:

PI Speed Controller Parameters.	
Proportional gain (Kt)	from 0.025 to 2.5
Integral gain (Ki)	1/5

Table 6.2: PI Speed Controller Parameters

The next figure shows the induction machine (ICE) speed and its reference. As it can be observed, it tracks the reference perfectly:

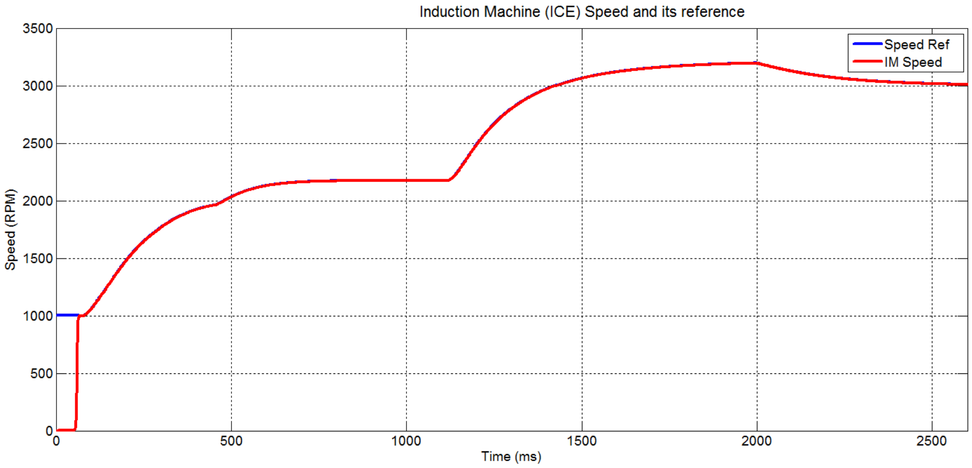

Figure 6-5: MG1,MG2, and ICE speeds (mode 3).

Chapter 7

Conclusions

This master's thesis has covered the simulation of a HEV powertrain. The 2004 Toyota Prius has been used a a model to our own system. The main section of this master's thesis are:

- Simulation and control of MG2
- Simulation of the five different modes of operation of a series-parallel HEV in Matlab/Simulink
- Simulation of the different transitions between the five different modes in Matlab/SImulink —item Emulation of an ICE using an Induction Machine in Matlab/Simulink

The most challenging part of this master's thesis were the transitions between the five different modes of operation of a series-parallel HEV and especially, the emulation of an ICE as if it was an induction machine. Approximately 25 percent of the total time that I have spent working on this master's thesis was just doing research about this technique.

There are many papers that cover this ICE emulation using an electrical machine and I would like to point out again that I have found this *sld engine* after all that research and that file was short of the key of success of this ICE emulation section. Thanks to that file I was able to implement the Prius parameters and modify it according to my own system characteristics.

This has been a very challenging project in terms of complexity and time management. There is a lot of information that must be reviewed before moving on to Matlab/Simulink to perform the first simulations. I believe that it is fair to mention that behind every simulation, there is an intense research work.

The next (and last) section would cover the ”future work” section.

Chapter 8

Future Work

As it was mentioned at the very beginning of this document, the aim of this master's thesis was to do a first approach to a very challenging and complex project like this. So far we have covered the simulation of the main electrical machine (the so called MG2), the simulation of the 5 different modes of operation of a HEV, the transitions between the different modes and last, the emulation of the ICE using an induction machine.

The following steps would include the implementation of this ICE emulation and after that, the next step would be to build the whole system. Of course this last step requires economical support.

Appendix A

System Diagram

The next figure has been extracted from the *Hybrid Control System Toyota Prius Manuals*. This is not part of any of this master's thesis sections but since we had a class in Vehicle Communications (also based on the Prius), we belive that it might be of your interest.

This first figure shows the Communication Diagram:

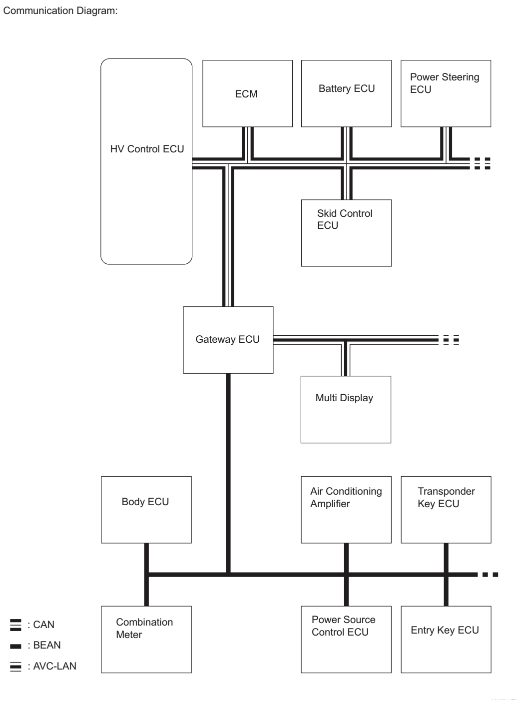

Figure A-1: 2004 Toyota Prius Communication Diagram[4].

The next figures will show the complete system diagram of the HEV ECU:

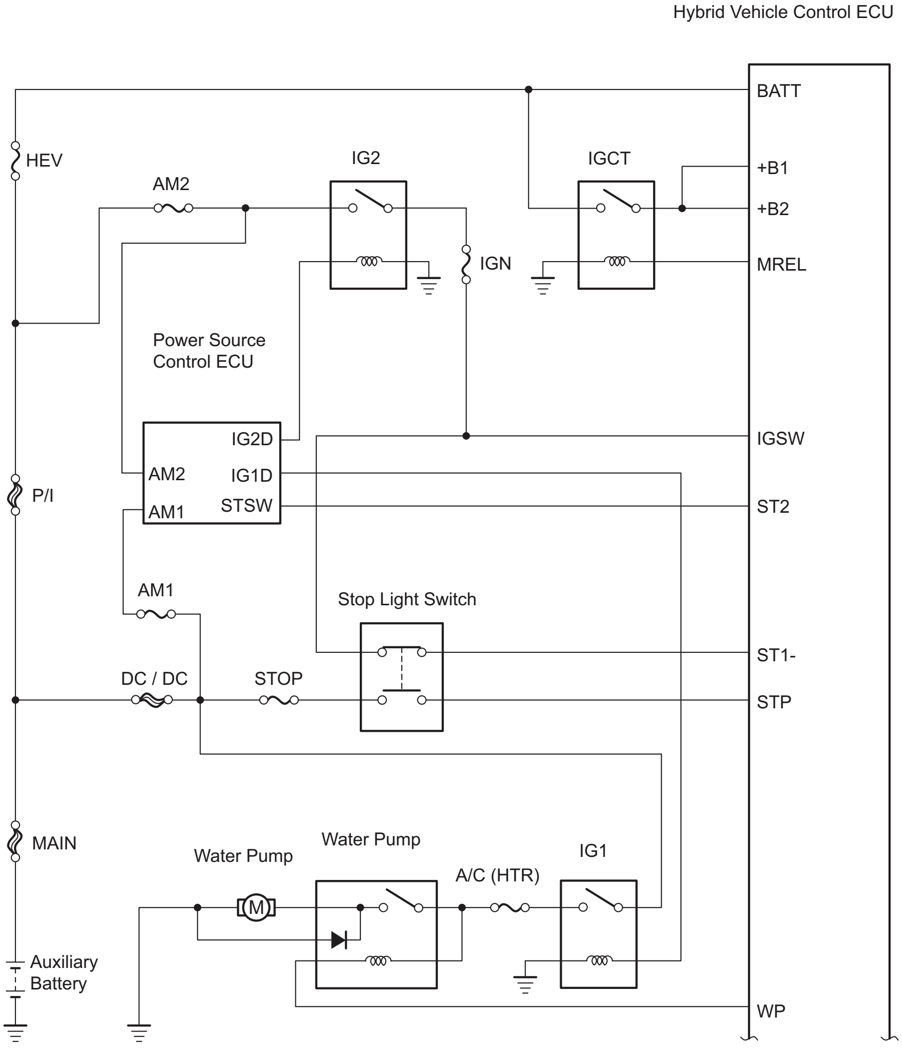

Figure A-2: HEV ECU system diagram (page one)[4]

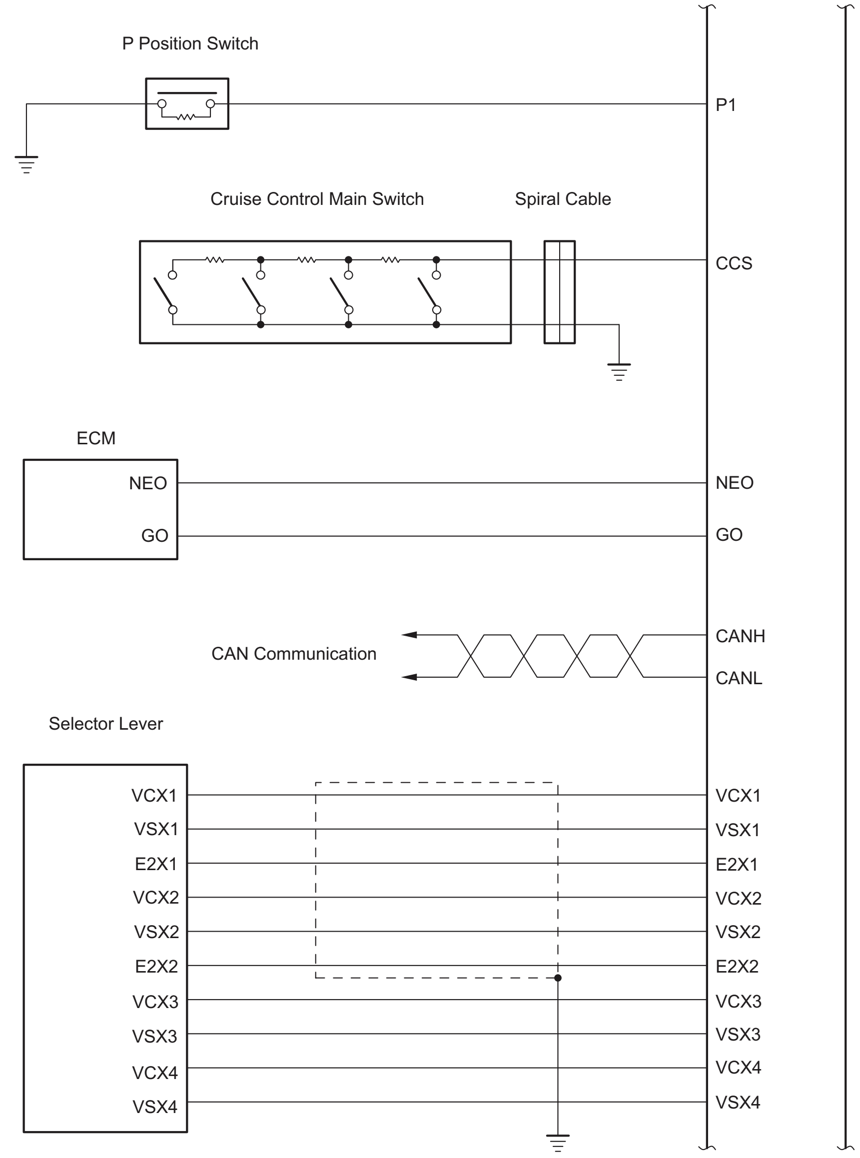

Figure A-3: HEV ECU system diagram (page two)[4]

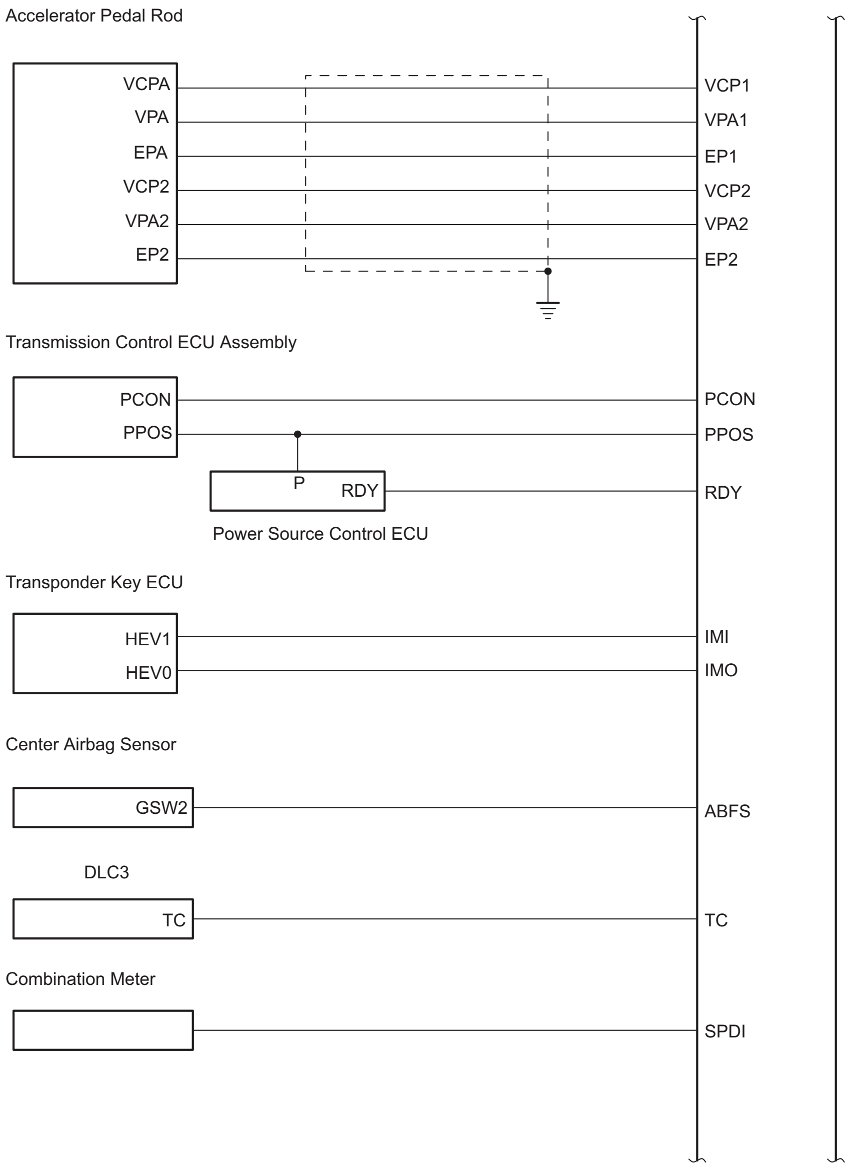

Figure A-4: HEV ECU system diagram (page three)[4]

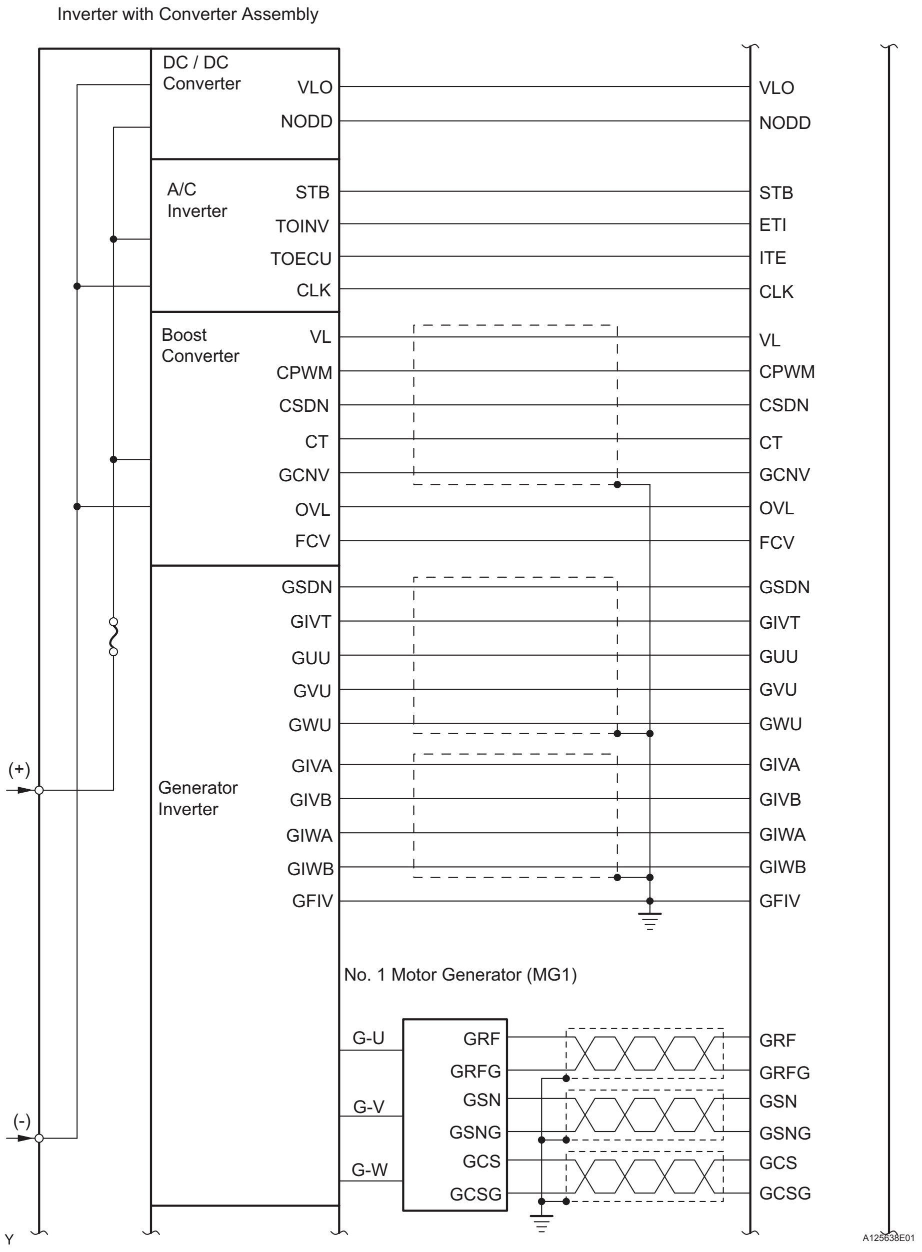

Figure A-5: HEV ECU system diagram (page four)[4]

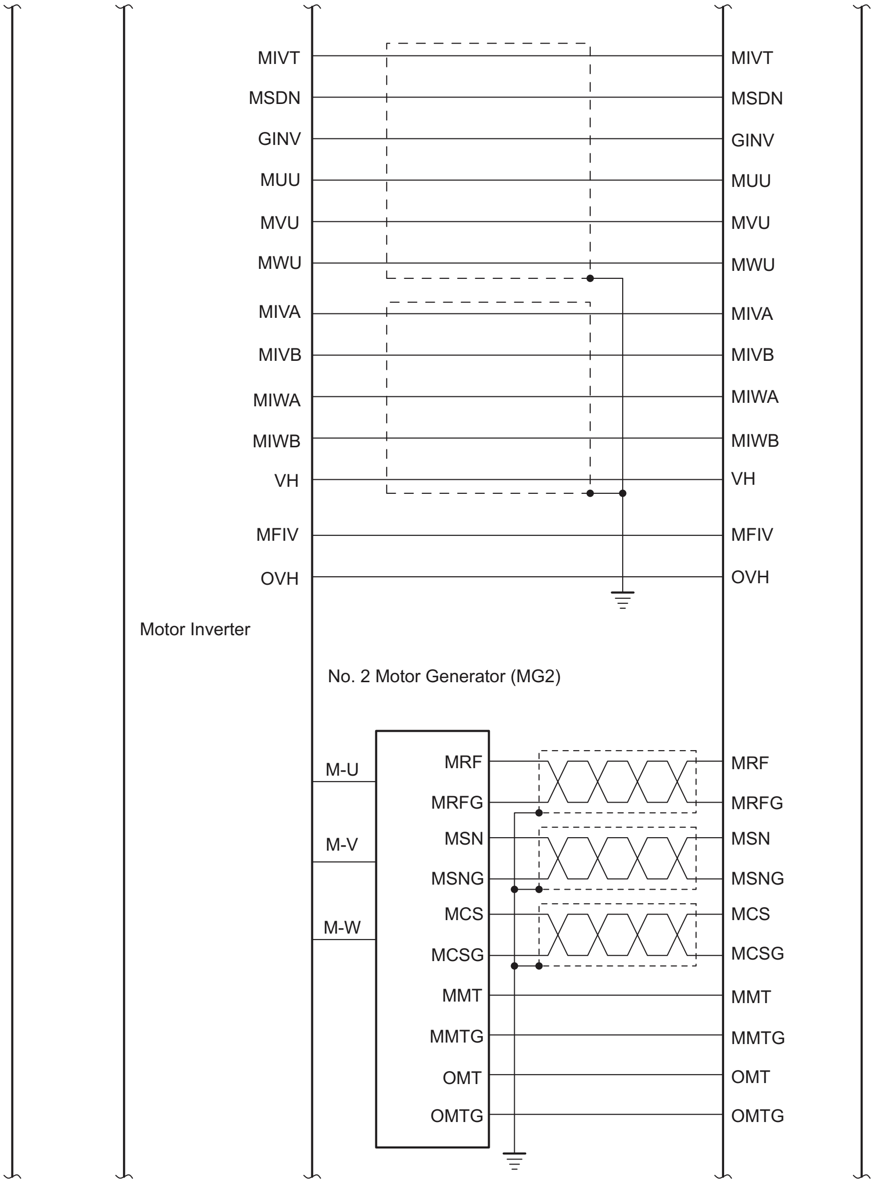

Figure A-6: HEV ECU system diagram (page five)[4]

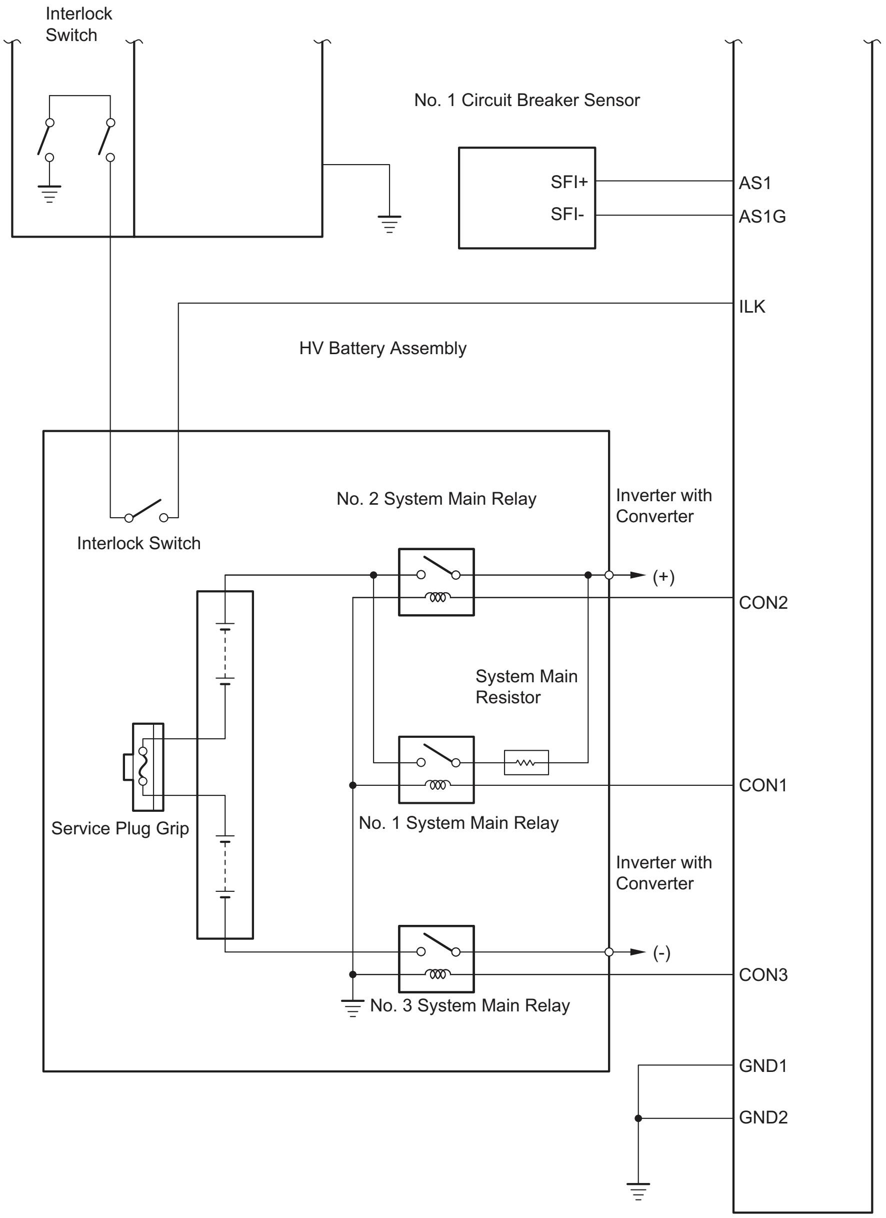

Figure A-7: HEV ECU system diagram (page six)[4]

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