<u>İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY</u>

MODELLING AND SIMULATION OF A SERIES PARALLEL HYBRID ELECTRICAL VEHICLE

M.Sc. Thesis by
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Department : Electrical Engineering

Programme: Electrical Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

SERI PARALEL HIBRİT ELEKTRİKLİ ARACIN MODELLENMESİ VE SİMÜLASYONU

YÜKSEK LİSANS TEZİ

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ÖNSÖZ

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Mayıs 2005 Müh. Can GÖKÇE

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ABBREVATIONS

APU	: Auxiliary Power Unit
BEV	: Battery Electrical Vehicle
BLDC	: Brushless Direct Current (Motor)
CAD	: Computer Aided Design
DC	: Direct Current
DSP	: Digital Signal Processor (Processing)
ECU	: Electric Control Unit
EMS	: Energy Management System
EV	: Electric Vehicle
FC	: Fuel Cell
FCEV	: Fuel Cell Electric Vehicle
FEM	: Finite Element Method
HEV	: Hybrid Electrical Vehicle
ICE	: Internal Combustion Engine
IGBT	: Insulated-gate Bipolar Thyristor
IMA	: Integrated Motor Assist
ISA	: Integrated Starter Alternator
ISG	: Integrated Starter Generator
NdFeB	: Neodymium Iron Boron
PE	: Power Electronic
PM	: Permanent Magnet
PWM	: Pulse Width Modulation
SOC	: State of Charge
SPHEV	: Series-Parallel Hybrid Electrical Vehicle
SUV	: Sports Utility Vehicle

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SYMBOLS

$\mathbf{A_f}$	: Frontal area of the vehicle
$\mathbf{c_r}$	: Rolling resistance coefficient
$\mathbf{c_t}$	:Wheel resistance coefficient
$\mathbf{g}$	: Gravity
$\mathbf{m}$	: Total mass of the vehicle
$\mathbf{r_w}$	: Wheel Radius
$\mathbf{V}$	: Speed of the vehicle
$\boldsymbol{\alpha}$	: Slope angle
$\boldsymbol{\delta}$	: Air density
$\boldsymbol{\omega_w}$	: Wheel rotational speed

SERI PARALEL HIBRIT ELEKTRIKLI ARACIN MODELLENMESI VE BENZETIMI

ÖZET

Sayıları her gün artan kara taşıtlarının petrol ithal eden ülkelerin ekonomilerine olan etkileri, tükenmekte olan fosil yakıtları, büyük şehirlerde tehlikeli boyutlara ulaşan emisyon gazları ve ozon tabakasındaki delik ve benzeri tüm dünyayı etkileyen çevresel sorunlar nedeniyle kara taşıtlarında alternatif enerji kaynaklarının geliştirilmesi bir zorunluluk haline gelmektedir. Son kullanıcı noktasından bakıldığında, otomobil kullanıcıları yükselen petrol fiyatları ve çevre konusunda gelişen bilinçlenme soncunda artık çok büyük motorlu ve güçlü araçlar yerine ekonomik motorlu, ancak konforu yüksek ve kullanışlı araçlar aramaktadırlar. Otomotiv firmalarının bu eğilime günümüzde gelişen teknolojiler sayesinde cevap verebilmeye başlaması sonucunda 90'lı yılların sonundan bu yana, hibrit elektrikli araçların otomotiv piyasasında artarak ve gelişerek yer aldığını görmekteyiz.

Hidrojen, alkol ve benzeri alternatif yakıtlarla, yakıt pilleriyle yada aküyle çalışan araçların ticarileşmesinin önünde teknolojik yada altyapısal sorunlar bulunmaktadır. Örneğin şu anda benzin, motorin ve benzeri yakıtların altyapısının hidrojen, alkol yada diğer alternatif yakıtların altyapısından çok daha gelişmiş olması bu tipte araçların ticarileşmesini engellemektedir. Yakıt pili uygulamalarında hidrojenin saklanması ve pillerin ısı ve benzeri nedenlerle verim problemleri ile yüksek maliyetleri yine bu tipteki araçların önlerinde bir engel teşkil etmektedir.Yalnızca aküden beslenen elektrikli araçların kısa menzilleri, maliyetleri ve uzun şarj süreleri iyileştirmek için çalışmalar sürmekte ancak ticari ürünler henüz piyasada çok fazla yer alamamaktadır. Akü yada yakıt pili gibi teknolojilerde büyük atlamalar olmadıkça, hibrit araçlar, yakıt olarak petrol ürünü yakıtları kullanmalarına karşın, piyasada var olmaya devam edeceklermiş gibi gözükmektedir. Bu nedenle başta büyük otomobil firmaları olmak üzere, çok çeşitli ticari ve akademik kurumlarda hibrit teknolojisi üzerine prototip, tasarım, iyileştirme ve maliyet düşürme çalışmaları yapılmaktadır. Bu çalışmalarda gelişmiş bilgisayar ve modelleme teknikleri sayesinde düşük maliyetli, hızlı sonuç alınıp kolay iyileştirebilen sayısal benzetim yöntemlerine çokça başvurulmaktadır.

Tez kapsamında elektrikli ve hibrit elektrikli araç teknolojileri tanımlanmış, bu araçlarda kullanılan ana bileşenler teker teker ele alınmış ve bu bileşenlerin çalışma özellikleri ilgili bağıntılar yardımıyla açıklanmıştır. Daha sonra her bileşen bilgisayar ortamında modellenip bunların performans değerleri hesaplanmıştır. Özetle bu bileşenler aşağıdaki gibidir:

- İçten yanmalı motor: Hibrit elektrikli araçlar dışarıdan şarj olmadıkları için ana enerji kaynağı olarak pertrol yakıtlarını kullanırlar. Bu nedenle alışılagelmiş içten yanmalı motorlar hibrit araçlarda, hacimleri küçültülerek kullanılır. Modelleme sırasında üretici firmalardan alınan değerler doğrultusunda performans grafikleri oluşturulmuş ve simülasyonda bu grafiklerden faydalanılmıştır.
- Elektrik makinası: Tam hibrit araçlarda aracı belirli hızlara kadar çıkarabilen elektrik makinaları kullanılır. Modellenen aracı istenen değerlerde çalıştırabilecek elektrik makinasının performansı modellenmiş ve simülasyonda kullanılmıştır.
- Generatör: Seri-paralel hibrit araçta içten yanmalı motorun gücünü paylaştıran planet dişli sistemine bağlı bir elektrik generatörü bulunur. Aracın elektrik enerjisi üretimine ve vites ayarlamasına yardımcı olan bu generatörün de performans modeli kurulmuş ve simülasyonda kullanılmıştır.
- Planet dişli sistemi: Seri-paralel hibrit aracın güç dağıtımında faydalanılan bu mekanik sistemin modeli oluşturulmuş ve simülasyonda kullanılmıştır.
- Yük modeli: Aracın hız ve yol koşullarına göre değişen yüklerin matematiksel ifadeleri ve modeli kurulmuş, simülasyonda kullanılmıştır.
- Kontrol mantıksal modeli: Seri-Paralel hibrit elektrikli aracın çalışma evreleri tanımlanmış ve bu evreler göz önüne alınarak kontrol mantıksal modeli geliştirilmiştir. Bilgisayar ortamında geliştirlen model simülasyonda kullanılmıştır.

Tüm sistemin modellenmesi bu bileşenler yardımıyla gerçekleştirilmiş ve aşağıdaki çalışma konumlarının her birisi için enerjinin ne kadarının içten yanmalı motordan, ne kadarının generatör üzerinden alındığı, ne kadar enerjinin aküde depolandığı, elektrik makinasının motor olarak çalışıp tekerleklere ne kadar enerji aktardığı ve frenleme sırasında enerjinin ne kadarını tekerleklerden alıp, aküye gönderdiği gibi hususlar incelenmiştir. Bahsedilen bu çalışma konumları şunlardır:

- Aracın çalışmaya başlaması ve düşük hızlar: İçten yanmalı motorun veriminin düşük olması nedeniyle bu evrede elektrik makinası ile çalışma uygundur.

- Normal çalışma: İçten yanmalı motorun verimli çalışma konumlarında akünün çok fazla tüketilmemesi ve performans kaybı olmaması için elektrik makinasının yanısıra içten yanmalı motor da devreye girer.
- Ani hızlanma: Bu durumda aracın ani hızlanma durumu göz önüne alınmıştır. Elektrik makinası generatörden de aldığı enerji yardımıyla tam performansta çalışır.
- Geri kazanımlı frenleme: Araç yavaşlama sırasında elektrik makinasını generatör modunda çalıştırır ve kinetik enerjisini elektrik enerjisine çevirerek akülerde depo eder.
- Akü şarjı: Aracın akü seviyeleri düşmeye başladığında içten yanmalı motor verimli bölgelerinde çalıştırılarak generatörün yardımıyla aküler şarj edilebilir.

Kurulan modeller ve geliştirilen mantıksal kontrol sistemi soncunda çeşitli sürüş çevrimleri için simülasyon çalıştırılmış ve sonuçlar incelenmiştir. Bu sonuçlar özellikle enerji tasarrufu yönünden incelenmiştir. Şehir içi sürüş çevrimi ve şehir dışı sürüş çevrimi için ayrı ayrı aracın mekanik ve elektriksel dinamik davranışı hesaplanmış ve bu sürüşler çerçevesinde nasıl enerji tasarrufu sağlanabileceği irdelenmiştir.

MODELLING AND SIMULATION OF A SERIES-PARALLEL HYBRID ELECTRICAL VEHICLE

SUMMARY

Increasing number of land vehicles and their impacts on economies of oil importing countries and depleting fossil fuels, besides, dangerous levels of emission gases in large cities and global environmental problems like the ozone gap led an obligation for developing alternative energy sources for land vehicles. From the last users' point of view, with the increasing oil prices and the more sensitive approach to environmental problems, automobile users are looking for comfortable and useful vehicles with more economic engines, rather than powerful vehicles with big engines. As automotive companies are able to answer these requests with the help of new technologies, it is seen that from the end of nineties to today, hybrid electrical vehicles have an increasing and developing part in the automotive market.

There are technological and infrastructure problems present behind the commercialization of vehicles using alternative fuels like hydrogen, alcohol etc. or utilizing fuel cells and batteries. For example, the infrastructure of petroleum fuels are much more developed than alcohol, hydrogen or other alternative fuel infrastructures and this presents a problem on commercialization of this kind of vehicles. In the fuel cell applications there are problems on storing the hydrogen, also, fuel cells still have heat and efficiency problems and high cost. Research on battery electrical vehicles is continuing. Short ranges, long recharging times and cost of these vehicles are improving but they do not have many commercial applications yet. Although they use petroleum fuels, the hybrid electrical vehicles are seemed to maintain their popularity if a breakthrough in battery or fuel cell does not occur. For this reason, there are many intense research projects on designing, prototyping, optimizing and cost reducing of hybrid electrical vehicles are conducted in many academic and commercial institutes, especially in automotive manufacturer companies. In these projects, with the help of advanced computer technologies and

modeling techniques, low cost, fast response, easily optimized digital simulation techniques are widely used.

In this thesis, technologies of electric and hybrid electric vehicles have been defined, information on main components of this vehicles have been given. Later, their performances have been modeled in computer, and the performance values have been calculated. The components are:

- Internal combustion engines: As the hybrid electrical vehicles do not get recharged externally, they use petroleum fuels as the main source of energy. For this reason, conventional internal combustion engines are used downsized in hybrid electrical vehicles. With the data taken from the manufacturing companies, look-up tables have been built and used in the simulation.
- Electrical machine: In the full hybrid configurations, electrical machines are used to drive vehicles up to certain speed levels. The performance of an electrical machine, which is able to run the vehicle up to desired speed levels has been built and used in the simulation.
- Generator: In the series parallel hybrid electrical vehicles, a generator is connected to the power splitting planet gear. This generator, which helps the energy generation and gear adjustment, has been modeled and used in the simulation.
- Planet Gear System: This mechanical system is used in the power distribution of the series parallel hybrid electric vehicle. Its model has been developed and used in the simulation.
- Load Model: Vehicle's load model, which changes with the speed and road conditions, has been mathematically built and used in the simulation.
- Control Logic: The vehicle's working modes have been developed and these developed models are built in the computer. This model has been used in the simulation.

The modeling the overall system is realized by the help of these component models and how much energy is taken from the internal combustion engine, how energy is generated by the generator, how much energy is stored in the batteries, how much energy is conducted by the electrical machine to the wheels and how much energy is recovered from the regenerative braking are calculated for each of the working conditions seen below. These conditions are:

- Vehicle start up and low speeds: As the internal combustion engine is inefficient in this range, acceleration with electrical machine is suitable.

- Normal working: To avoid the battery flat-outs and excessive performance losses in this range, vehicle is driven by both internal combustion engine and electrical machine.
- Sudden acceleration: In this mode, full throttle acceleration of the vehicle is considered. With the help of the extra energy from the generator, electrical machine runs in its full performance. So internal combustion engine and electric motor together produce the maximum available power.
- Regenerative braking: During deceleration, vehicle generates energy from its kinetic energy by running the electric machine in generator mode.
- Battery recharge at rest: When the state of charge is below certain levels, it is possible to run the internal combustion engine in its efficient ranges and recharge the batteries with the help of the generator.

As a result, by using these models and developed control logic, the simulation has been run in different driving cycles and computational results are investigated. The main issue of these investigations is the energy save. Mechanical and electrical behavior of the vehicle in urban driving and highway driving is separately calculated and energy saving policy of the vehicle is discussed.

1. INTRODUCTION

The idea of electric propulsion was introduced in 1830s, by the inventor Robert Anderson. The primitive versions were using non-rechargeable batteries, but after the developments on battery technology in late 1800s, electric vehicles became very popular. In first years of the 20th century, 90% of the taxis in New York were electric.

Electric automobiles had various advantages in those years. Unlike their competitors with internal combustion gasoline engines, electrical automobiles did not have vibration, smell and noise. Internal combustion engines needed hand cranking and also, it was very difficult to change gears. Electrical automobiles did not need hand cranking, and did not have gears. Steamers, which were automobiles with external combustion engines, did not need cranking or did not have gears, either, but it took over 45 minutes to start them in cold mornings. Thus, electric cars were successful until 1920s, with a peak production in 1912.

Figure 1.1: Electric Automobile; Woods Electric 1912, Model 1316

Some major developments after 1920 brought the declination of electrical automobiles. Better system of roads developed in USA. Connection of cities needed longer range vehicles. Despite Thomas Edison's persisting researches and investments on battery technology, batteries could not manage to reach enough ranges for electric automobiles. In 1917, C. E. Woods Company had built the first hybrid car, utilizing electric motor and internal combustion engine together. It did not help the electric concept to get popular again because some breakthrough incidents have happened. For example, the discovery of crude oil in Texas took the gasoline prices more affordable. Hand crank had already become history with the invention of electric starter by Charles Kettering in 1912. As it is very well known, Henry Ford was the initiator of mass production of internal combustion cars, which made all the other types of cars obsolete by 1930s. [1]

Since 1990s, several legislative and regulatory actions have been made to decrease the effect of exhaust emissions and also to reduce the gasoline usage. With the developments on electronics, particularly power electronics and semiconductor switch technologies, more sophisticated electric vehicles have been developed and electric concept on both civil and military automotive industry became commercial.

In civil applications, electric vehicles seemed to be an important concept due to their low or no fossil fuel consumption, which also makes an environmentalist effect on exhaust emissions. Due to the recent trend researches made in the USA [2], increases in the oil prices in year 2004, made more people to consider buying hybrid electric vehicles. Other advantages of electric vehicles are; noiseless operation and lesser need on maintenance. Also, as the electric motors have the ability to produce high torque in low speeds, whereas internal combustion engines can produce high torque in high speeds, this leads an improvement on driving comfort.

In military applications, some strategic aspects of electric concept become interesting. Lower thermal action will help un-detection and may confuse the thermal missiles. Also silent operation is very crucial for un-detection.

The hybrid vehicle concept is very popular since the commercialization of the first hybrid vehicle in 1998. The hybrid models of automotive manufacturers and the research for high performance hybrids have been increasing since then. The reason of this popularity is hybridization of a vehicle needs some investment in the vehicle's topology, resulting high efficiency and low emission vehicles, remaining all other infrastructure as it was. Battery electric vehicles were not able to achieve this success because of the limitations of battery technology, which is resulted in low range vehicles with long recharging times. Also, it needed a big investment to develop a new infrastructure for recharging them. For a foreseeable future, it is seen that hybrid electrical vehicle will maintain its popularity.

Previous works about hybrid electrical vehicle included the modeling of parallel hybrid electrical vehicle [3, 4] and series hybrid electrical vehicle [5]. The aim of this master thesis is to explain electrical vehicle concept and built a mathematical model for a series parallel hybrid electrical vehicle with all its subsystems and develop the logic for an optimized energy management of this hybrid vehicle. In this manner, electric and hybrid electric vehicle configurations have been explained in Chapter 2. In Chapter 3, electrical propulsion and its realization are mentioned. Also, components and technologies of electric propulsion are mentioned. Lastly in Chapter 3, the main obstacle, which is the electrical energy storage, is mentioned. Functions and benefits of Hybrid Electrical Vehicles are mentioned in Chapter 4. Also energy management and amortization of hybrid investment is mentioned in this chapter. In the 6^{th} Chapter, a series parallel full hybrid electrical vehicle is defined and components of this vehicle are mathematically modeled. Also, these models have been integrated and the whole model is obtained. In the last chapter, the results of the simulation are discussed.

2. ELECTRIC VEHICLE CONCEPT

The modern Electric Vehicle (EV) is a road vehicle with electric propulsion, which consists of an electric motor, power circuits and an energy source. While describing the EV concept, it must be considered that EV is a new system for clean and efficient road transportation.

EV engineering is the integration of automotive engineering and electrical engineering. Thus, system integration and optimization are crucial to achieve a good performance from the EV at an affordable cost. The design of a modern EV includes technologies of automotive engineering, electrical and electronic engineering, computer hardware and software engineering and even chemical engineering to adopt this new concept with unique designs and develop special manufacturing techniques. Followings points can be the typical considerations for EV design.

- The niche market and the environment should be identified.
- Technical specifications should be determined, the drive cycle should be considered.
- Infrastructure, including the recycle of batteries, should be defined.
- System configuration should be determined. (EV configurations will be defined in this chapter)
- Chassis and body should be determined.
- Energy source should be determined.
- Propulsion system should be determined. This includes electric converters, transmission motor types and number of motors. If a hybrid configuration is decided, type of internal combustion engine should be considered, too.
- Specifications of electric propulsion (power, torque, speed) and energy source (capacity, voltage current) among the considered drive cycles should be determined.
- Intelligent energy management system (EMS) should be adopted.
- When the EV subsystems are decided, interaction among those should be analyzed to understand the degree of interaction that affects the cost,

performance and safety. For this analyze, an example of quality function matrix can be seen in Figure 2.1.

- The efficiency of the motor drive, according to the selected driving patterns and operation conditions should be optimized
- Overall system should be optimized using a computer simulation [7].

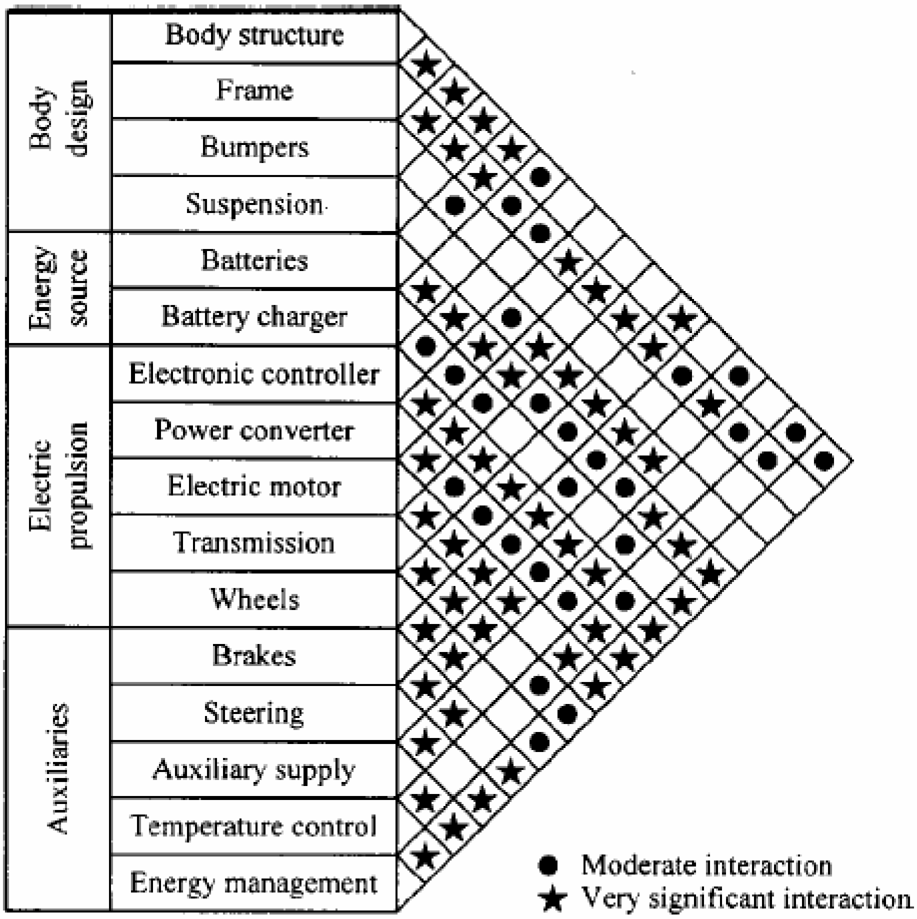

Figure 2.1: Interactions among EV subsystems [7]

As a result of above mentioned points, the key technologies of EVs include automotive technology, electrical technology, electronic technology, information technology and chemical technology. Energy source and the management of this energy are very important. Actually, system succeeds only if it realized in an effectively designed body, with convenient electrical machines and power electronic circuits, which are optimized for the pre-considered driving conditions and cycles, with the management of an optimized energy management system.

As the purpose of this work is to define an energy management system, it will be done in details in following chapters. But, to utilize the energy management system, some specifications of the vehicle should be given. In this respect, a series-parallel hybrid electric configuration in a mid-sized family sedan is considered. Detailed information will be given in the respective chapters.

2.1 Electric Vehicle Configurations

Electric concept is applied on vehicles in two main configurations:

- Electric Vehicles (EV)
- Hybrid Electric Vehicles (HEV)

2.1.1 Electric Vehicles (EV)

First main electric concept on vehicles is realized with only an electric machine driving the vehicle and electrical energy is obtained from batteries (Battery Electric Vehicles – BEVs). As mentioned in the first chapter, electric vehicles have been known for years. Today, BEVs are commercially applicable especially on indoor vehicles like forklifts, delivery cars that work early in the morning, golf carts etc. Some concept car, truck and SUV applications give very exciting clues for the future of the BEVs.

As seen in Figure 2.1, an electric vehicle generally has an electric machine fed from a battery pack, through a power electronic circuit. Today, two types of electric machines are generally used in EVs; asynchronous machines and brushless DC (BLDC) machines. Power electronic circuit is generally an inverter but controllers work totally different for these two types of motor. In example, asynchronous machines utilize vector controlling or direct moment control algorithms and BLDC controllers have a trend to utilize sensorless control techniques. [8]

Electric vehicles need to be recharged after a certain time of operation although they generally use the ability of recharging from the vehicles' own kinetic energy during operation by the process called regenerative braking. In this process, controller runs the electric machine as a generator and the vehicle generates electrical energy to be stored back to the battery back during braking. Also, some sophisticated energy management algorithms are made to save the energy as much as possible. For example, running in generator mode during driving downhill is a good way to generate electricity in a vehicle.

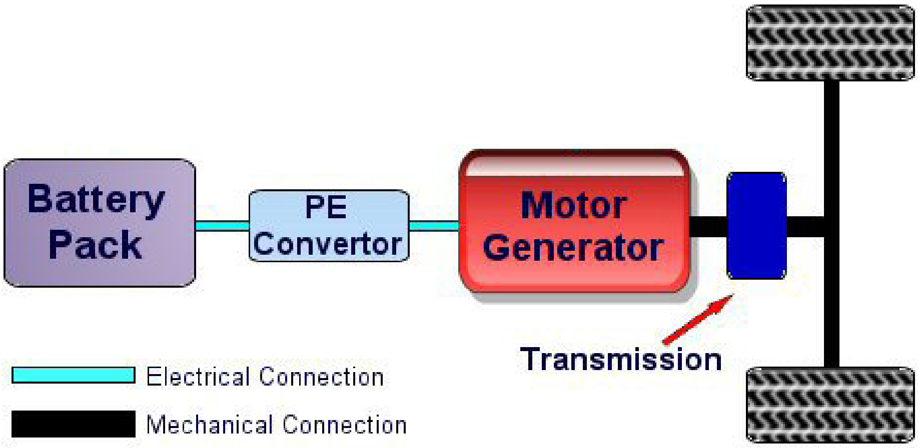

Figure 2.1: Battery Electric Vehicle Schematic View

Fuel cell concept lets another thrilling application to be developed based on electric vehicles, electric vehicles without external charging. In a fuel cell, hydrogen and oxygen are used to produce electrical energy through an electrochemical reaction. Some companies and academic institutes have build concept or experimental fuel cell electric vehicles and this technology seemed to be one of the most exciting concepts for vehicle future, as they use hydrogen as a fuel and there is no emission except water vapor. A schematic view of a FCEV can be seen in Figure 2.2.

Hydrogen production is a complicated process, with efficiency about 55% (from natural gas to H2). As hydrogen is very explosive, hydrogen gas tank in a vehicle is very dangerous. But, some recent developments are leading some safer techniques for storing hydrogen for mobile applications, like storing hydrogen in a compound material and extracting it when needed. [9] Another handicap for fuel cells is the operating temperatures. Even the most applicable FC type, which is Proton Exchange Membrane (PEM) type runs about 70-80^{o}C. [5] Price is another consideration for a FCEV because current systems are much more expensive than other competing systems.

When overall well-to-wheel (from hydrogen source, which is natural gas, to the energy to run the wheels) efficiency is considered, efficiency of a commercial FCEV is about 29%, which is about 15% higher than a conventional car of 2003. [10] Well to wheel efficiency of FCEV are targeted to be about 42% in near future. [11] After a certain research and optimization processes are done, fuel cells seemed to become a cutting edge power source for future electric vehicles.

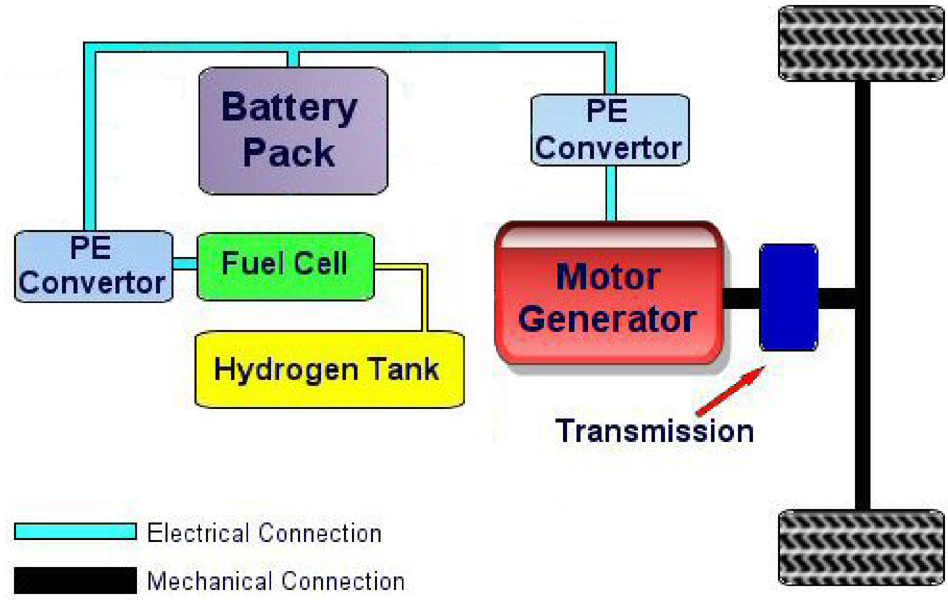

Figure 2.2 - Fuel Cell Electric Vehicle Schematic View

2.1.2 Hybrid Electrical Vehicles (HEV)

Range is always one of the biggest disadvantages of electric vehicles. Battery packs generally have great volume and weight. They have limited ability to supply peak powers and need long time to get recharged. Despite the advances of regenerative breaking, there is an effective zone for generator action and also efficiency is not perfect, so there is always a loss. Ultracapacitors could help batteries to supply peak powers, but, to achieve greater distances with an electric vehicle; electricity should be generated from another source inside the car.

If there are one or more motive sources beside the electric machine in a vehicle, that vehicle is called a hybrid electric vehicle (HEV). Simplest example is an electric bike. Electric bikes are powered with human power plus electric motor.

Hybridization is a crucial and effective way to eliminate dependency of external electric chargers. Until the development of fast charging, high capacity electric batteries, or optimization of fuel cells are done, technology and automobile producing companies tend to research on different electric – gasoline hybrid vehicle configurations.

Conventional cars are hybridized to benefit an electric machine. Depending of the degree of hybridization, electric machine can be used as an extra torque supply, a standalone driving source, a generator in regenerative braking, advanced starter motor for instant cranking, torque ripple compensator for internal combustion engine (ICE), etc. Also, different hybrid configurations are developed to optimize the efficiency of HEVs. Companies are in competition to develop and commercialize new and advanced hybrid configurations.

2.1.2.1 Hybrid Electric Vehicle Configurations

It is reasonable to classify HEVs into two basic types; Series HEVs and Parallel HEVs. Series/Parallel and Complex HEV configurations are basically combination of these two main configurations.

In a series HEV, energy source of the vehicle is hybridized. In the series hybrid, wheels are driven by one or more electric machines and the electricity is generated inside the vehicle. Series hybrid solutions are generally advisable in heavy duty vehicles, like city buses. It also seemed interesting, for example, as a range extender, in light duty vehicles and passenger cars. The electricity is generated by an internal combustion engine, which works as a generator set. This source is commonly called Auxiliary Power Unit (APU). The APU can be used to feed a power buffer, which could be batteries or ultracapacitors. Also, it can be used as a direct electrical energy source in the vehicle, if needed.

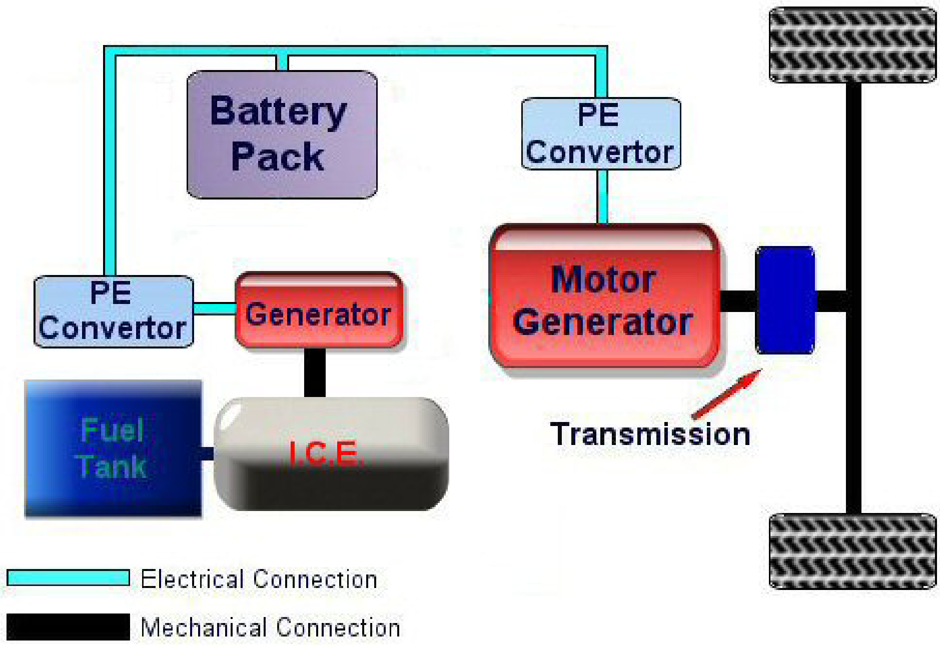

Figure 2.3 - SHEV-Series Hybrid Electric Vehicle Schematic View

In an SHEV (seen in Figure 2.3), the Fuel Cell is replaced by an ICE to drive a generator to charge the batteries and feed the electric traction motor when needed. Since the engine is not connected to the wheels, transmission is removed. This leads to 10% to 15% of energy save, which was lost in the transmission. In an ICE-HEV, operation of the ICE is optimized to the most efficient point, thus, emissions are minimized and a noteworthy fuel save is obtained. The ICE is shut down when not needed. As the vehicle uses the electric motor for motion, it does not consume fuel in idling.

Series Hybrid configurations have some disadvantages. There are energy losses in mechanical-electrical-mechanical transformation. The energy in the ICE's shaft is transformed into electrical energy in the generator and electrical and mechanical losses occur here. While the produced electrical energy is used in the traction motor, controller and motor losses occur. Also, the traction motor should be chosen to cover the peak loads of the vehicle. [5]

In parallel hybrid configuration, drive system is hybridized. Parallel hybrid vehicles can be driven by both electric motor and internal combustion engine. Complex hybrid vehicles have the ability to generate electricity from engine's surplus power and use it to drive another electric motor and also to charge the batteries. In Figure 2.4, a complex hybrid configuration can be seen. Most popular commercial hybrid electric vehicles are built as parallel or series-parallel hybrids. It is convenient to apply parallel or complex hybrid structures on passenger cars, sports utility vehicles and light pick-up trucks.

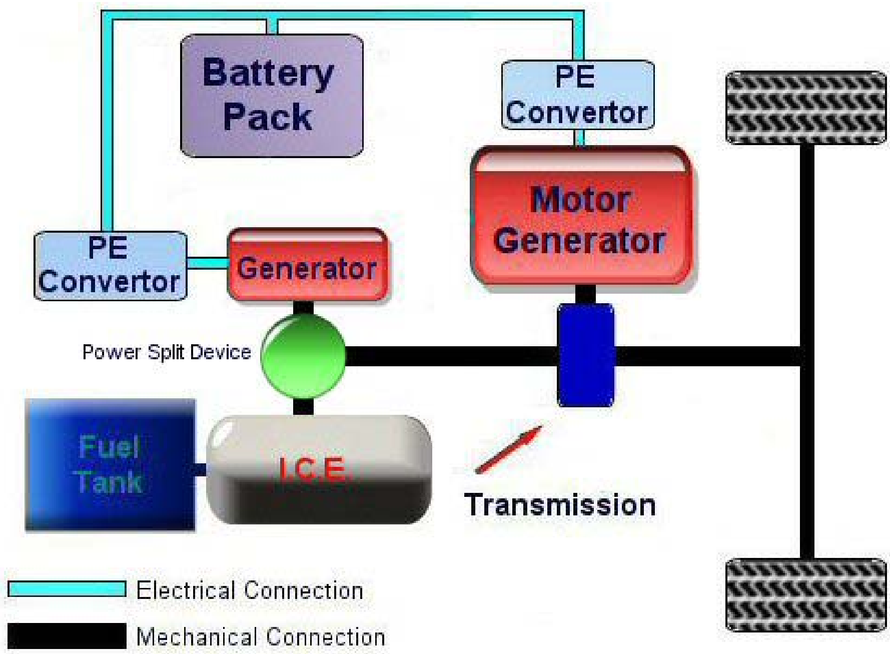

Figure 2.4 - SPHEV – Series Parallel Hybrid Electric Vehicle Schematic View

Honda adopted parallel hybrid technology and uses the electric motor an assist motor and also regenerator in braking (IMA™ - Integrated Motor Assist technology in Insight, Civic Hybrid and Accord Hybrid models). Toyota's most popular hybrid system, THS-II uses complex hybrid system uses a power split device, namely a planetary gear, where the output of the engine is divided into two; one output driving the wheels and other driving a generator to charge the batteries with the surplus power. This system also has an electric motor which drives the wheels. The newest system to mention is the Lexus' new hybrid SUV, which has the same system like THS-II but with an additional electric motor at the back, which helps to drive 4x4 and make regenerative braking more efficient by using rear wheels, too. There are many applications of Integrated Starter-Generator (ISG), like GM's some light pick up trucks; those should be considered as parallel hybrid. Detailed information can be found in relevant company websites.

3. KEY TECHNOLOGIES OF HYBRID ELECTRIC VEHICLES

3.1 Internal Combustion Engines as a Conventional Technology

Increase in the number of fossil fuel burning internal combustion engines brings big problems, too. In 2000, there are 700 million cars around the world, which is expected to be above 2.5 billion by 2050s. Today, 40% of the daily oil consumption, which is more than 10 billion liters per day, is used in transportation. The saddest fact about this consumption is that the ICEs used in vehicles are using only about 13% of this energy to run a car. [12] The rest is wasted as seen in Figure 3.1.

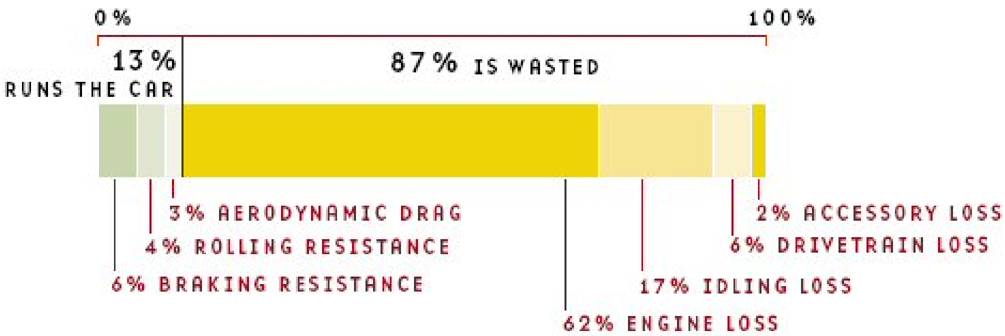

Figure 3.1 - Internal Combustion Engine Efficiency [12]

Most of the countries around the world should import oil from oil producing countries. Efficient oil reserves getting depleted. It is always getting more expensive to drill to new but deep reserves. Oil prices increase daily. Countries without adequate oil reserves pay more and more for oil each day. For a short term solution, countries are putting more taxes on cars with larger engines, thus, trying to lower their demand on oil. Also, automotive customers do not want to pay so much for gas and trying to have fuel efficient vehicles.

In the ecological point of view, traffic air pollution in large cities with long commutes between urban commercial centers and suburban residential centers, is getting worse day to day, reaching dangerous levels. Besides, it is claimed that global warming and reduction of ozone in atmosphere is mostly affected by exhaust gases.

Although ICE technology is still the most popular in all automotive industry, major companies are taking these disadvantages serious. Although there are many forms of clean and sustainable energy sources for vehicles, like bio-fuels or hydrogen; hybridization of current vehicles seems to be the most effective and fast way to adopt cleaner and more efficient vehicles, without changing the refueling and other infrastructure at the moment.

3.2 Electric Propulsion Systems

Combustion engines have been discussed above and it is realized that an alternative should be developed to avoid all the flaws that ICE technology has. As electricity is a very special form of energy that can be generated, stored and used in high efficiencies, electrical machines are presenting a good alternative for ICEs. Equipments for electromechanical energy management are appropriate in size and volume. Motors and generators, which are generally brushless DC machines, used in a hybrid electrical vehicle and power electronic circuit components had a great development. Nowadays, brushless DC machine technology offers 8kW/kg and 25kW/lt of power density, thanks to new high density NdFeB magnets and new topologies. Besides, new components let a power electronic circuit to have about 25kVA/kg and 40kVA/lt of power density. [7] As a family sedan is considered to have an internal combustion engine about 100HP, which is about 75kW, it may be replaced by a brushless DC motor, which is about 9.5kg in weight and 3lt in volume. A power electronic circuit for this application should not be heavier than 4 kilos and not be larger than 2 or 2.5 liters. When the efficiency of a brushless DC is considered, levels above 80% can be reached. Power electronic circuit in high voltage may be roughly 90% efficient thus the overall efficiency will never be as low as an ICE.

3.2.1 General Considerations

Electric propulsion for EVs consists of the electric drive system, transmission device, which is optional in some cases, and wheels. Motor drive system consists of electric motor/generator, power converter and electronic controller. A drive system is required to have:

- High instant power and high power density
- High torque at low speeds to start up and climbing
- High power at high speeds
- Constant torque and constant power regions in a wide speed range
- Fast torque response

- High efficiency over wide speed and torque ranges
- High efficiency in generator action (regenerative braking)
- High reliability and robustness
- Reasonable cost. [7]

To decide an electric propulsion system to be utilized in an HEV, functions of HEVs should be studied and level of hybridization should be decided first. More information on functions of HEVs can be seen in Chapter 2, Section 2.1.2.2. Choosing a level of hybridization is a somewhat complicated process. HEV producing companies generally prefer their conventional ICE models to build a hybridized model from them. Honda's hybrid Civic or Accord is two good examples for this. Generally those models have the same body and similar power-torque levels. There are also some manufacturers have models designed as a HEV. Toyota's Prius is the best example.

There are three important factors while choosing an electrical propulsion system for an EV or HEV vehicle. First, driver expectation should be decided. The driver expectation is defined by a driving profile, which should include the acceleration, maximum speed, climbing capability, braking and range. Then, vehicle restrictions should be defined. Vehicle restrictions depend on the vehicle type, vehicle weight and load. At last, energy source of the EV or HEV should be defined. Energy sources include batteries, fuel cells, flywheels and ultracapacitors. Especially, batteries and ultracapacitors as electrical energy source in hybrid electrical vehicles are important and these sources will be explained in Chapter 3, Section 3.3.

The electric propulsion system has been developed dramatically after the development of some technologies, including electric motors, power electronic components and topologies, microelectronic controllers and control strategies. Figure 3.2 shows an overview of electric propulsion system and technologies including electrical machines, design methodologies, power converters, control hardware, software and strategy. Key technologies in the propulsion system are as follows:

- Electronic Controller Software Technologies: VVVF (Variable Voltage Variable Frequency), FOC (Field Oriented Control or Vector Control), MARC (Model Reference Adaptive Control), STC (Self Tuning Control), VSC (Variable Structure Control), NNC (Neural Network Control) and Fuzzy Control.
- Electronic Controller Hardware Technologies: Microprocessors, Microcontrollers, DSP (Digital Signal Processors), Transputers.

- Power Controller Components: GTO (Gate Turn-Off Thyristor), BJT (Bipolar Junction Transistor), MOSFET (Metal Oxide Field Effect Transistor), IGBT (Insulated Gate Bipolar Thyristor) and MCT (MOS- Controlled Thyristor)
- Power Controller Topologies: DC/DC Converters, DC/AC Converters, AC/DC converters and DC/ AC Converters which utilize the one or few of the following techniques: chopping, pulse width modulation (PWM), resonance, zero voltage switching (ZVS), zero current switching (ZCS) techniques.
- Electric Machine CAD (Computer Aided Design) Technologies: FEM (Finite Element Method) on EM (Electromagnetic), Thermal and Force calculations. Graphical outputs.
- Electric Machine Types: DC Machines, IMs (Induction Machines), SRMs (Switched Reluctance Machines), PMSMs (Permanent Magnet Synchronous Machines), PMBMs (Permanent Magnet Brushless Machines) and PMHMs (Permanent Magnet Hybrid Machines)

Not all of the above mentioned technologies will be explained in this work. They have been all given to inform about the keywords.

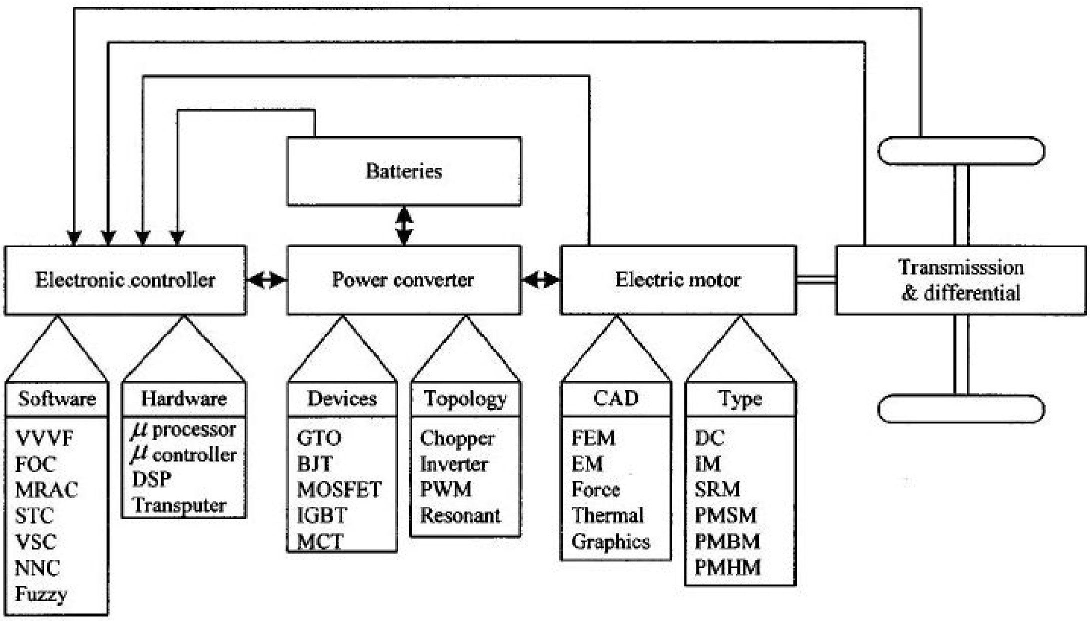

Figure 3.2: Electric Propulsion System [7]

Thanks to the achievements in the motor technology with the help of CAD methodologies, FEM analyzed induction machines and permanent magnet brushless machines are improved very well and they are the most promising machines for electric propulsion systems. When power electronic technology is considered, PWM

IGBT inverters are widely used. Microprocessor or DSP based vector controllers are the most common controllers in electric propulsion systems.

3.2.2 Electric Machines Used in Electric Propulsion Systems

As DC commutator motors may suit well to EV applications due to their good torque-speed characteristics and simple control systems, they are not usable in electric propulsion systems because of their need of regular maintenance. Instead, commutatorless machines, including PM brushless motors, vector controlled induction machines and promising switched reluctance motors are favorable. The Table 3.1 will be helpful to see the evaluation of electric machines in regard to power density, efficiency, controllability, reliability, maturity and cost. [7] Induction motors, PM motors and switched reluctance motors will be briefly explained in the following sub-abstracts.

Table 3.1: Electric Propulsion Drives

	DC Commutator	**Induction Machines**	**PM Brushless**	**Switched Reluctance**	**PM Hybrid***
Power Density	2.5	3.5	5	3.5	4
Efficiency	2.5	3.5	5	3.5	5
Controllability	5	4	4	3	4
Reliability	3	5	4	5	4
Maturity	5	5	4	4	3
Cost	4	5	3	4	3
Total	**22**	**26**	**25**	**23**	**23**

* PM Brushless with reluctance effect

3.2.2.1 Vector Controlled Induction Machines

Today, IM drives are the most mature drives among commutatorless motors. They are the most cost effective solution among others and also very reliable machines. In order to achieve good performance for electric propulsion, vector control is generally utilized. Although vector control is able to control torque current and field current to minimize the total losses in any loading conditions, efficiency at high speed range may be lower than expected. [13] In Figure 3.3, induction machine characteristics can be seen.

3.2.2.2 Permanent Magnet Brushless Machines

Permanent magnet brushless machines have high power density and efficiency because their magnetic field is excited by high energy permanent magnets. After the expiration of pending patents, permanent magnet prices started to drop and technology development on them is accelerated. This, of course, led the way of more and more efficient PM brushless motors everyday. PM brushless motors gained an advantage over induction machines because they have no rotor copper losses, which is the source of an efficiency drop in induction machines. Heat is only produces in stator and it can easily pass to surroundings easily. Also, because of the lower electromechanical time constant is lower on the rotor, it can be accelerated easily at a given input power.

The most common magnet used in PM brushless motors is Neodymium Iron Boron (NdFeB). Magnets can be surface mounted or buried to the rotor, depending on the application. Surface mounting is relatively easier and cheaper whereas buried applications are relatively more reliable in higher speed because they have no risk of come off because of the centrifugal force in high speeds. Some hybrid PM applications may include PM-rotor winding and PM-Switched Reluctance machines. The biggest disadvantage seemed to be their complex construction and control. As a result, advantage of PM brushless motors are more in most cases so that almost all of commercial electric and hybrid electric vehicles utilize PM Brushless motor in their applications.

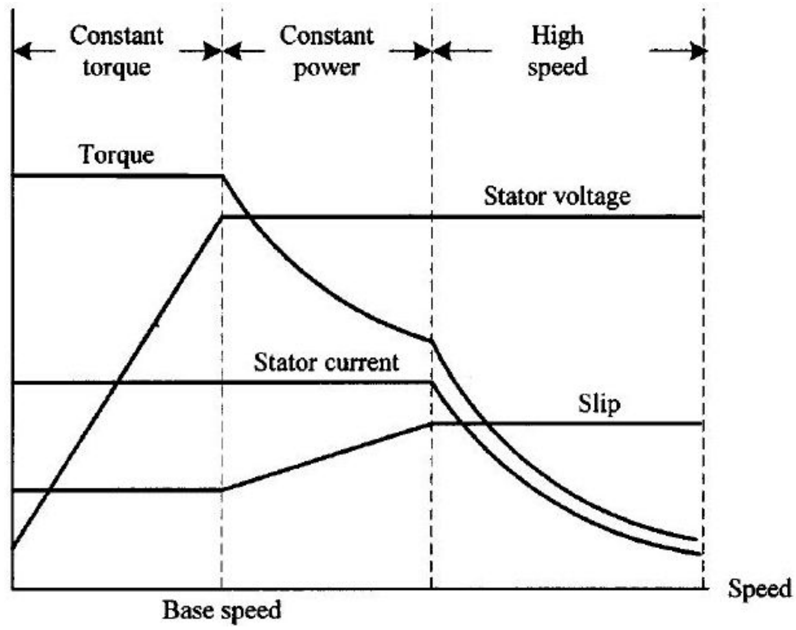

Figure 3.3: Induction Machine Characteristics

3.2.2.3 Switched Reluctance Machines

Switched reluctance motors are recognized to have great potential for EV applications since they have very good torque speed characteristics for electric propulsion. As they have simple construction, they have low manufacturing costs. Despite their construction is simple, they have a complex design and control.

Another problem is the acoustic noise. With the new control and design techniques, switched reluctance motors will be more widely used in electric propulsion systems.

3.3 Electrical Energy Sources

In EVs, it is possible and effective to use batteries, ultracapacitors and fuel cells as an energy source. In some applications, especially on big trucks or busses, flywheels, which are mechanical energy storage systems, are used, too. All this energy sources have some advantages and disadvantages and they are still in development. Energy source is still the major obstacle in EV commercialization. Because of this, at present and near future, development of energy sources for EVs is the most important issue for EV commercialization. For a good energy source for an EV, some criteria should be reached. Those are:

- High specific energy (kWh/kg) and energy density (kWh/L)
- High specific power (kW/kg) and power density (kW/L)
- Fast charge and deep discharge ability
- Long cycle and service lives
- Good self discharging rate and high charging efficiency
- Safe
- Economic
- Maintenance free
- Environmentally friendly and recyclable [7].

A concept of hybridization of energy sources is considered to use various energy sources to reach an optimum specific energy and specific power performance. For example, as ultracapacitors are able to supply peak powers (for a short time), they are used in ignition and start-up periods whereas the vehicle uses battery power, which lasts much longer and is stable while normal operation. Also, this configuration absorbs high regenerative braking power on the ultracapacitor, in case of a hard braking. In following abstracts, batteries and ultracapacitors will be briefly explained as they are widely used for electrical energy storage. Fuel cell applications are actually considered as a part of the EV applications (namely FCEV – Fuel Cell Electric Vehicles) and will not be considered as a HEV part.

3.3.1 Batteries

Batteries are the major energy sources of EVs. There is and organization in USA, which is called U.S. Advanced Battery Consortium (USABC), which has set mid-term and long-term performance goals for EV batteries. It can be seen in Table 3.2 and Table 3.3 that no existing technology is capable to reach the desired goals, which are aimed to make EVs to have a performance like ICE vehicles. Values in Table 3.3 are only for indicative purposes and may vary from different manufacturers. Also, as there is still a research activity on these types, parameters may vary due to technological advances.

As seen in the table, valve regulated lead acid (VRLA), nickel cadmium (Ni-Cd), nickel zinc (Ni-Zn), nickel metal hydride (Ni-MH), zinc-air (Zn-Air), aluminum air (Al-Air), sodium sulphur (Na-S), sodium nickel chloride ($Na\text{-}NiCl_2$), lithium polymer (Li-Polymer) and lithium ion (Li-Ion) type batteries are seemed viable at the moment. Among these, VRLA, Ni-Cd and Ni-MH are seemed to be the near term potential EV battery solutions whereas Li-Ion is told to be most promising midterm solution by battery manufacturers. Li-Ion has a major cost disadvantage. Battery manufacturers also accelerated their research on Li-Polymer batteries, as this type demonstrated good performance on EV applications.

Table 3.2 Performance Goals of USABC

Primary Goals	**Mid-Term**	**Long-Term**
Specific Energy (C/3 Discharge Rate, Wh/kg)	80 (100 Desired)	200
Energy Density (C/3 Discharge Rate, Wh/L)	135	300
Specific Power (80% DOD/30s, W/kg)	150 (200 Desired)	400
Power Density (W/L)	250	600
Life (Years)	5	10
Cycle Life (80% DOD, cycles)	600	1000
Price (US$/kWh)	150 max.	100 max.
Operating Temperature (C)	-30 to 65	-40 to 85
Recharge Time (h)	6 max.	3 to 6
Secondary Goals		
Efficiency (C/3 discharge, 6h charge)	75	80
Self Discharge (%)	15 max. (48h)	15 max. (1 month)
Maintenance	Free	Free
Thermal Loss	3.2 W/kWh	3.2 W/kWh

DOD : Depth of Discharge
SOC: State of Charge

Table 3.3 Key Parameters of EV Batteries

	Specific Energy at C/3 rate (Wh/kg)	**Energy Density at C/3 rate (Wh/l)**	**Specific Power at 80% DOD (W/kg)**	**Cycle Life at 80% DOD (Cycles)**	**Projected Cost as a reference (US$/kWh)**
VRLA	30-45	60-90	200-300	400-600	150
Ni-Cd	40-60	80-110	150-350	600-1200	300
Ni-Zn	60-65	120-130	150-300	300	100-300
Ni-MH	60-70	130-170	150-300	600-1200	200-350
Zn/Air	230	269	105	Not Available	90-120
Al/Air	190-250	190-20	7-16	Not Available	Not Available
Na/S	100	150	200	800	250-450
Na/NiCl2	86	149	150	100	230-350
Li-Polymer	155	220	315	600	Not Available
Li-Ion	90-120	140-200	250-450	800-1200	200 Min.
USABC	***200***	***300***	***400***	***1000***	***100 Max.***

3.3.2 Ultracapacitors

Because of the acceleration, braking and start-stop operations of EVs, charge-discharge characteristics are highly variable. A peak power in an EV can be 16 times higher than the average power. Ultracapacitors, just like ordinary ones, are able to absorb energy quickly and supply some for a short time. The only difference is the amount of power is very high in ultracapacitors.

Ultracapacitors are not considered to be a single energy source for EVs because of their low specific energy. To optimize the braking-acceleration and start-stop operations in respect to battery specific energy and specific power, the battery should be powered by an ultracapacitor set, which acts a bumper to absorb or supply peak levels. Due to the load leveling effect of the ultracapacitors, high current discharge is minimized, thus, available energy, endurance and life of the battery will increase. Moreover, ultracapacitors can provide much faster and more efficient energy recovery during regenerative braking. [14]

U.S. Dept. of Energy has set goals for ultracapacitor research. According to this, the near term specific energy and specific power should be better than 5Wh/kg and 500W/kg, respectively. They also indicated that advanced performance values should be 15Wh/kg and 1600W/kg. No ultracapacitor manufacturer is able to meet these specifications at the moment but research process is continuing.

4. FUNCTIONS AND BENEFITS OF HYBRID ELECTRIC VEHICLES

While considering a HEV, certain hybrid functions can be classified into different levels of hybridization. In Figure 4.1, this classification can be seen. Functions of HEVs will be studied due to this classification in this work.

Figure 4.1 - Hybrid Functions due to Level of Hybridization ([15], Updated)

In Micro (Mini) and Mild Hybrids, an Integrated Starter-Alternator (ISA or sometimes referred as integrated starter-generators, ISGs) is connected to ICE with a belt system or directly to the shaft. EM assists the ICE by supplying instant crank force. Thus, ISA installed vehicles are able to turn off their IC engines during red lights or traffic jams and start instantly when the clutch is engaged. By this cranking action, those vehicles do not consume fuel while idling. Also, they have some limited regenerative braking ability.

In a 42V system, ISA is able to assist the launch of the vehicle by supplying some torque to shaft. Also, this assistance occurs while the driver presses clutch pedal to shift gear. ISA supplies some torque to wheels, thus vehicle shifts without any traction loss. Some applications, like GM's and Continental Temic's ISA systems can supply a soft start assist to the ICE in start-stops and are able to cancel out the torque ripples of the ICE.

In medium and full hybridization levels, vehicles are especially designed and optimized for hybrid operation. More powerful electrical machines are used.

Electrical assist is much higher than micro and mild hybrids. Also, full regenerative braking is possible. In Figure 2.5, it can be seen that the level of voltage is increased above DC-144V, to realize a medium or full hybrid vehicle.

Different from medium hybrids, electrical machines are not only for assistance, but also they are able to run the vehicle alone in full hybrids. [11] [16] Honda's Insight is good and successful commercial example for medium hybrid applications. Toyota's new Prius, Lexus' and Ford's SUV models are the high end products, which can be good examples for full hybrid applications. Some of them are able to run in stealth (or silent) mode up to 60 km/h, with only electric motor running

4.1 Energy Management in Series-Parallel Hybrids

Automotive producing companies are aware that hybrid electrical vehicles will only succeed if they are able to meet key goals such as; maximum fuel economy with minimum emissions for a good price versus performance and all these without sacrificing the driving performance. Various energy management algorithms have been developed for various configurations of hybrid electrical vehicles.

Series parallel hybrid electric vehicle configurations are able to run in various modes, such as:

- Only electrical drive (Electrical Vehicle Mode)
- Only ICE drive (ICE Mode)
- ICE with Electrical Machine assisting by battery power (Parallel Mode)
- ICE driving the Generator and wheels (Generating Mode)
- ICE driving the Generator to supply Electrical Machine; ICE and Electrical Machine drive the wheels. (Series-Parallel Mode)
- Regenerative Braking

To optimize these modes in regard to the above mentioned key goals needs a good energy management system. In the following abstracts, energy management algorithms to achieve good driving performance and maximum fuel economy/minimum emissions will be studied. Also, energy management for safe and proper use of hybrid system will be defined.

4.1.1 Energy Management for Good Driving Performance

Torque is the most important component that affects the driving performance of a vehicle. Maximum torque levels are helpful to understand the maximum acceleration capability of a vehicle. Power component is useful to cover drag coefficients and other friction loads, thus, it becomes important in high speed. Maximum power is important in understanding the maximum speed levels.

When torque-speed and power-speed characteristics of ICEs and electrical machines, especially induction machines or permanent magnet machines are investigated, some important clues for energy management can be seen. ICEs are able to supply good torque levels in higher speeds whereas electrical machines have very good torque levels in low speeds. As power component is important in high speeds, we could say that both ICE and electrical machine can be used high speeds, as they are able to apply good power levels but it can be only ICE to drive in high speeds, as electrical machine could drain the battery power.

For a management clue, there are two aspects for a good driving performance. First, electric machine could be used in lower speeds to supply good traction. ICE should take more part in higher speeds to avoid battery consume. Second, as a planetary gear, with two degrees of freedom, can be used in mechanical transmission, ICE may always run in its high torque speed region whereas shaft speed is compensated by the generator connected to one of the two outputs of the planetary gear and vehicle may run in the desired speed. In both cases, it should not be forgotten that vehicle should not sacrifice fuel economy while building an energy management for a good driving performance.

4.1.2 Energy Management for Maximum Fuel Economy/Minimum Emissions

In a series-parallel hybrid electrical vehicle, ICE and electrical machine operations can be controlled in a very flexible range. Thus, as far as it is known what to do for a good driving performance, the ICE should be analyzed and some key considerations should be defined.

ICE’s optimal operating point in its torque speed plane can be a base to maximize the fuel economy and minimize the emissions. For this purpose, ICE fuel consumption is mapped as in Figure 4.2. For different power demands, different optimal points form the optional operating line as seen in Figure 4.2. With the help of optimal operating line, an optimal operating region can be defined. From the figure, it can be said that this engine may operate above 1500rpm up to 3500rpm. As the series parallel hybrid vehicle is able to start the engine instantly with a cranking power from its one of electrical machines, probably from the one which is not directly connected to the drive shaft, it is possible to stop the engine below this optimal operating region. Another important consideration is that the engine should not be exposed to high speed fluctuations, ICE dynamics should be minimized. Thus, when ICE is turned off, it also should not be turned on and off frequently. Such drawbacks will result in an extra fuel usage and more emissions.

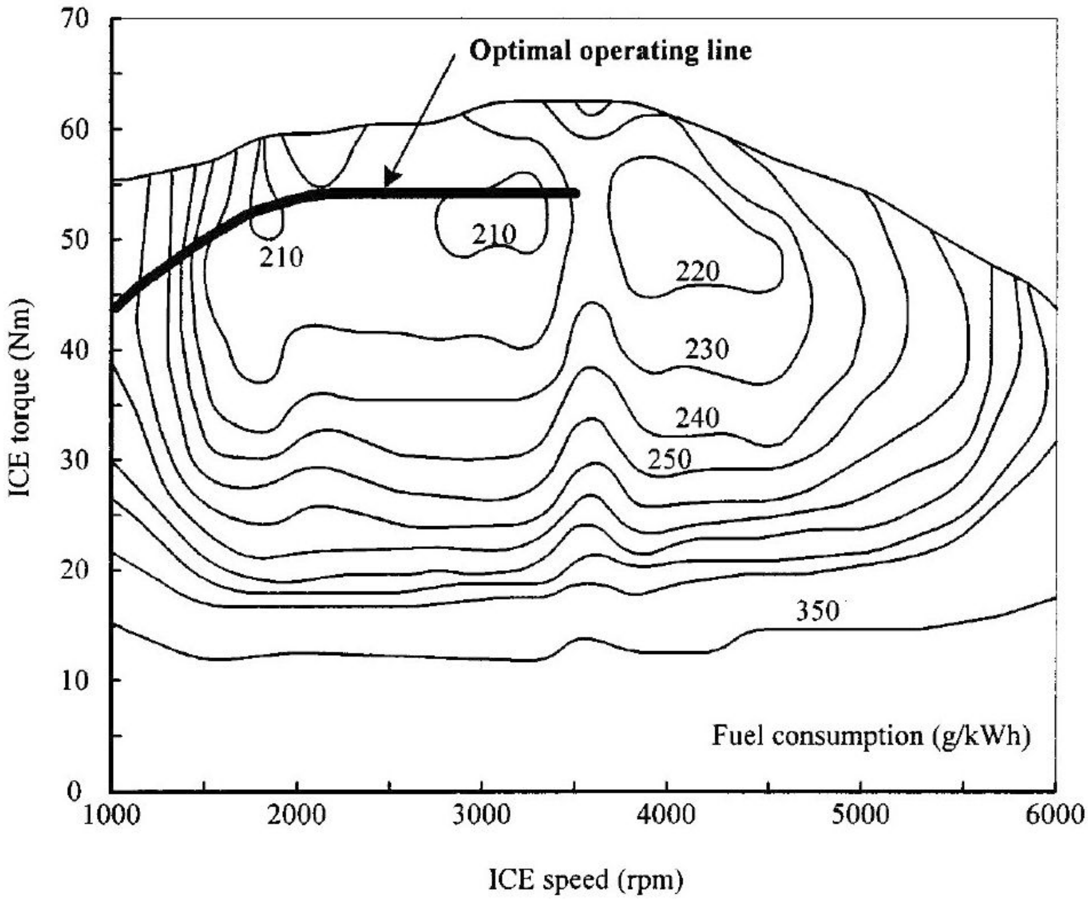

Figure 4.2: Fuel consumption and optimal operating line in an ICE [7]

4.1.3 Energy Management for Safe and Proper Use of Hybrid Vehicles

Another aim of the energy management is the safe and proper use of the hybrid system. For this, batteries should be managed.

Hybrid vehicles use electrical machines as an assist while accelerating. In full throttle acceleration, which may be needed in passing another vehicle, electrical machine and ICE runs in full power. To be able to run the electrical machine in full power, a certain level of battery power should be left in all cases. For this, ICE should increase its output to charge the batteries to proper levels by the help of the generator machine connected to one of the outputs of power split device. This may occur while driving in lower speeds or even while the vehicle is at rest. Engine could be set to its efficient points and the excess power is used to charge up the batteries. State of charge of the batteries should be investigated to be kept up in proper levels. If the proper levels are reached, by engine generation or regenerative braking, charging with engine power should be stopped to save fuel.

Undercharge of the batteries is also important in battery life. State of charge of the batteries should not be under some certain levels because batteries may not be able to be recharged after that level.

Another issue is the upper limit of the state of charge of the batteries. As the vehicle utilizes regenerative brake operation while braking, this generated power must be absorbed by the batteries. If upper limit is exceeded, this regenerative braking power overcharges the batteries, which may result in an excess heat that may harm the electrical circuits and also may damage the batteries. Energy management system should cut off the regenerative braking and power up the hydraulic brakes in case of an overcharge may occur.

4.2 Hybrid Investment Consideration

Commercial hybrid electrical vehicles use gasoline as the primary energy source. As the conventional gasoline vehicles are still very popular, using gasoline in a hybrid vehicle is also very important issue to succeed in commercialization because no new infrastructure is needed to be built to refuel the vehicles. Today, well to wheel efficiency of a series parallel hybrid electrical vehicle has reached about 29% and this level is very promising when compared with the other vehicle technologies. Competing technologies with well to wheel efficiencies can be seen in Figure 4.3. Please note that fuel cell vehicles also have 29% percent of efficiency but they need a new hydrogen infrastructure to operate.

	Well-To-Tank	Tank-To-Wheel
Average 2003 Car	79%	18%
1999 Prius	79%	27%
2003 Prius	79%	31%
2004 Prius with HSD	79%	37%
Commercial FCHV	58% Natural gas-H_2	50%
Based on US-market fuels and US combined fuel economy Source: Toyota		

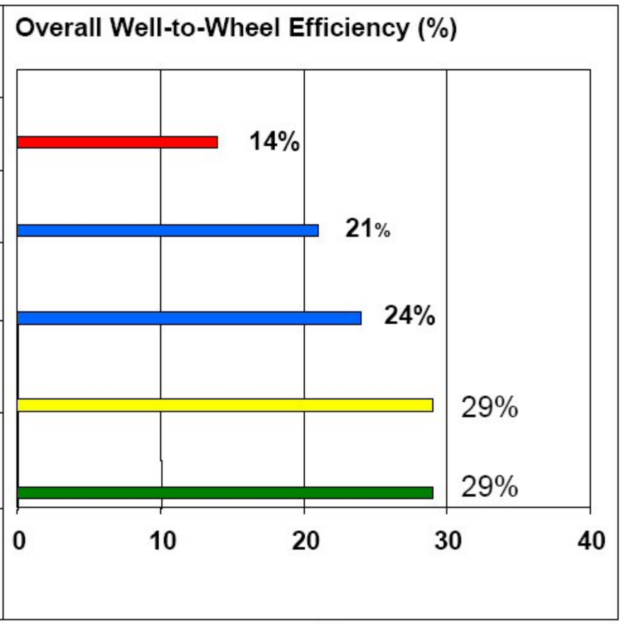

Figure 4.3: Well to wheel efficiency of the vehicles

We see that hybrid electrical vehicles are the most effective way of improving the efficiency and they do not need a new infrastructure. But, as the hybrid vehicles utilize extra electrical components and need major research, deciding an investment is a considerable issue. It is obvious that a hybrid electrical vehicle will cost more than an ICE vehicle. This investment should be amortized in an acceptable time.

Hybrid electrical vehicles consume less fuel than their ICE equals. Amortization is calculated by the save of this fuel. Thus, before deciding hybridization in a vehicle the possible drive cycle of the vehicle should be considered. A hybrid favorable drive cycle should include more stop and go operation and also more low speed operation. Highway operation is not favorable in hybrid applications.

Slopes in the driving cycle are another consideration. A plain driving cycle does not have a big effect in hybrid operation but a driving cycle which includes hills will be affected. Vehicles may use the same amount of fuel when climbing the hills, but when driving downhill, hybrid vehicle may be used to save the energy which is probably be lost by braking or engine compression and use that electrical energy where needed.

While these key issues are considered, vehicles used in the city traffics, especially light duty commercial vehicles including delivery cars, personnel and student service vehicles and taxies, will be the major candidates for hybridization.

It is possible to say that Istanbul can be a good pilot city for hybrid vehicles. The city is divided with the Bosporus and two sides are connected to each other by two bridges. People that live in one side of the city may have to commute to the other side of the city and have to cross the bridge every day. The bridges and the connection roads are not able to cover the heavy traffic everyday, thus it results in a stopped or very slow traffic. Also, city is built on hills and up-hill and down-hill operation is very common. The vehicle manufacturers should consider entering the market with at least a mild hybrid function in Istanbul. Light commercial vehicles and taxis would be good hybrid applications. In addition, as there are a lot of historical buildings in Istanbul, it is important to protect these buildings from corrosive effects of emissions of ICEs. Electric only driving of HEVs might be a solution to this problem.

Series hybrid vehicles have some major functions that result in good fuel saving performances. While new components add some weight in the vehicle, it will affect the fuel consumption to increase about 5%. In hybrids, engine can be smaller than the same kind of ICE vehicle. For example, Prius hybrid has an engine of 1.5lt which can offer the same performance of 1.8lt engine, with the electric motor assist. Also, as the engine always runs in its optimum operation area, consumption is even lesser.

Instant cranking is another good function to stop the car in red lights or jammed traffic and instantly re-runs the engine. Actually, a full hybrid vehicle is able to run by the electrical machine, so vehicle saves fuel in slow traffic conditions. The energy covered by the regenerative energy is one of the most important benefits of hybrid electrical vehicles, which result in a good amount of fuel save. In a series parallel hybrid vehicle, by using these functions, it is possible to use about 25% of fuel in a normal urban driving cycle. [15] In Figure 4.3, fuel savings of each function can be seen.

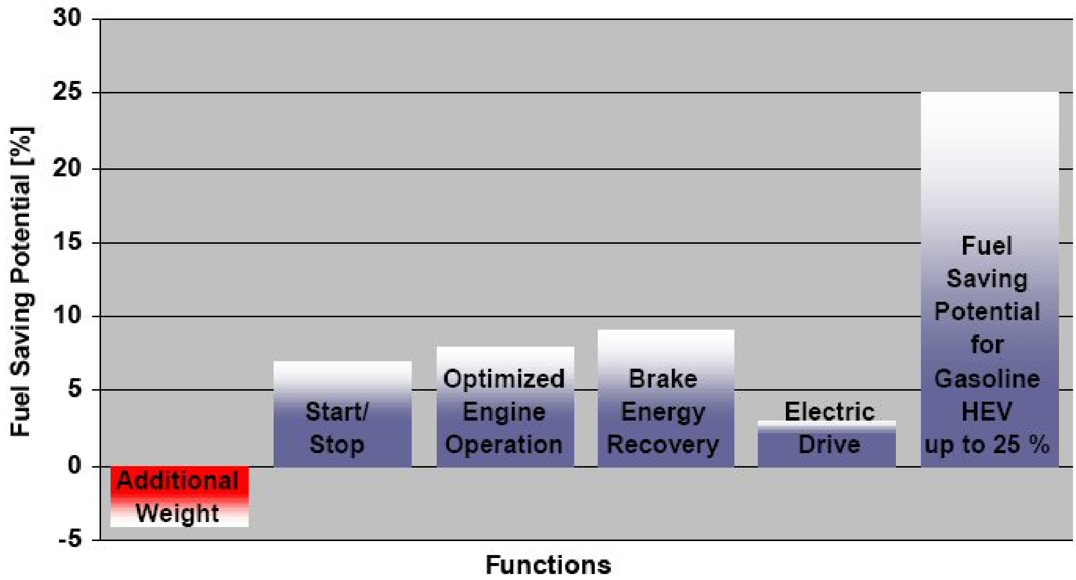

Figure 4.3 Fuel saving potentials vs. hybrid functions [15]

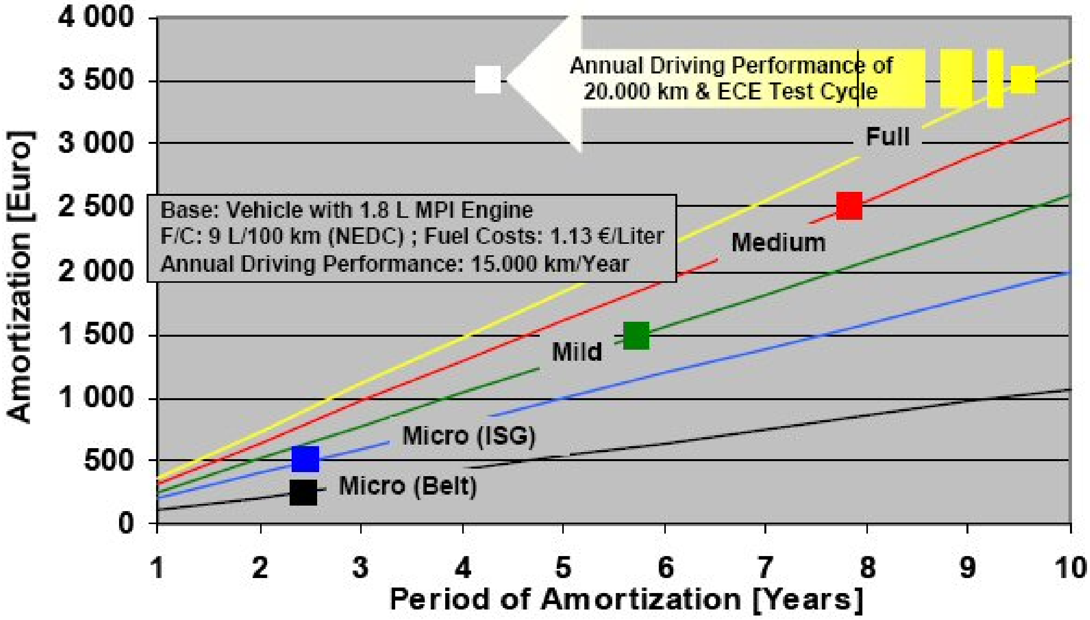

Figure 4.4 Period of amortization of a hybrid electrical vehicle investment

While calculating the amortization period, amount of driving should also be estimated. In Figure 4.4, amortization estimation of a 1.8lt ICE vehicle for various levels of hybridization is seen. Please note that that vehicle is considered 15000km annual driving. A full hybridization investigation is amortized more than 9 years but if the driving performance is increased to 20000km per year, it gets no more than 4 years. To give a better point of view, 9lt/100km is considered as the average fuel consumption of today's vehicles and commercialized hybrids, for example Toyota's serial parallel hybrid application Prius has a consumption rate of 4.2lt/100km. Hybrid vehicle manufacturers discuss in their websites that how a customer can save energy and amortize their new hybrid vehicle.

5. MODELING OF SERIES PARALLEL HEV

In the simulation part, model of a series parallel hybrid electric vehicle is going to be built and it will be run on various driving cycles to define a good energy management system.

For the simulation of the vehicle, Matlab R13 is used. Vehicle is built on Simulink and all the test were run on this program.

5.1 System Definition

The model vehicle will be a mid-size family sedan. It will utilize an internal combustion engine, one driving electrical machine and one starter/generator machine. Engine power will be divided between the generator machine (MG1) and the driving shaft, by the power split device. Power split device is actually a planetary gear. Driving electrical machine (MG2) will be connected to the driving shaft. Driving shaft runs the wheels through some reduction gears. Generator machine is able to charge up a battery block or assists driving machine in case of a high electrical power demand. Driving machine is fed through the battery block or by the Generator machine or by both. Vehicle is front-driven. While braking, driving machine generates electricity from the vehicle's kinetic energy. Generator machine also acts as a starter motor in start-up.

5.2 Vehicle Dynamics

For modeling the vehicle dynamics, Toyota Prius' body is chosen. This vehicle has the parameters which can be seen in Table 5.1. This table also contains the abbreviations for the total vehicle load modeling. With the help of these parameters, it is possible to calculate the load forces that apply to the vehicle.

In Figure 5.1, forces on vehicle are seen. Four main forces that apply to vehicle are:

- Wheel rolling resistance : $F_t = c_t.m.g.\cos\alpha$ (5.1)
- Drag resistance : $F_r = 0.5.c_r.\delta.A_f.V^2$ (5.2)
- Gravitational force due to the slope : $F_e = m.g.\sin\alpha$ (5.3)
- Accelerating force : $F_a = m.dV/dt$ (5.4)

Table 5.1: Vehicle body parameters

Abbreviation	***Definition***	***Value (unit)***
c_t	*Wheel rolling resistance*	0.01
m	*Total mass of the vehicle*	1300 *Kg*
g	*Gravity*	9.81 m/s^2
α	*Slope of the road*	- º
c_r	*Drag coefficient*	0.3
δ	*Air density*	1.17 kg/m^3
A_f	*Vehicle's frontal area*	1.746 m^2
V	*Vehicle speed*	*m/s*

The equations are used in the Simulink model block, which can be seen in Figure 5.1. It is also possible that the mechanical brake can be modeled as an extra load while mechanical braking is needed. Thus, Mechanical Brake model is added to load block which is also seen in Figure 5.1.

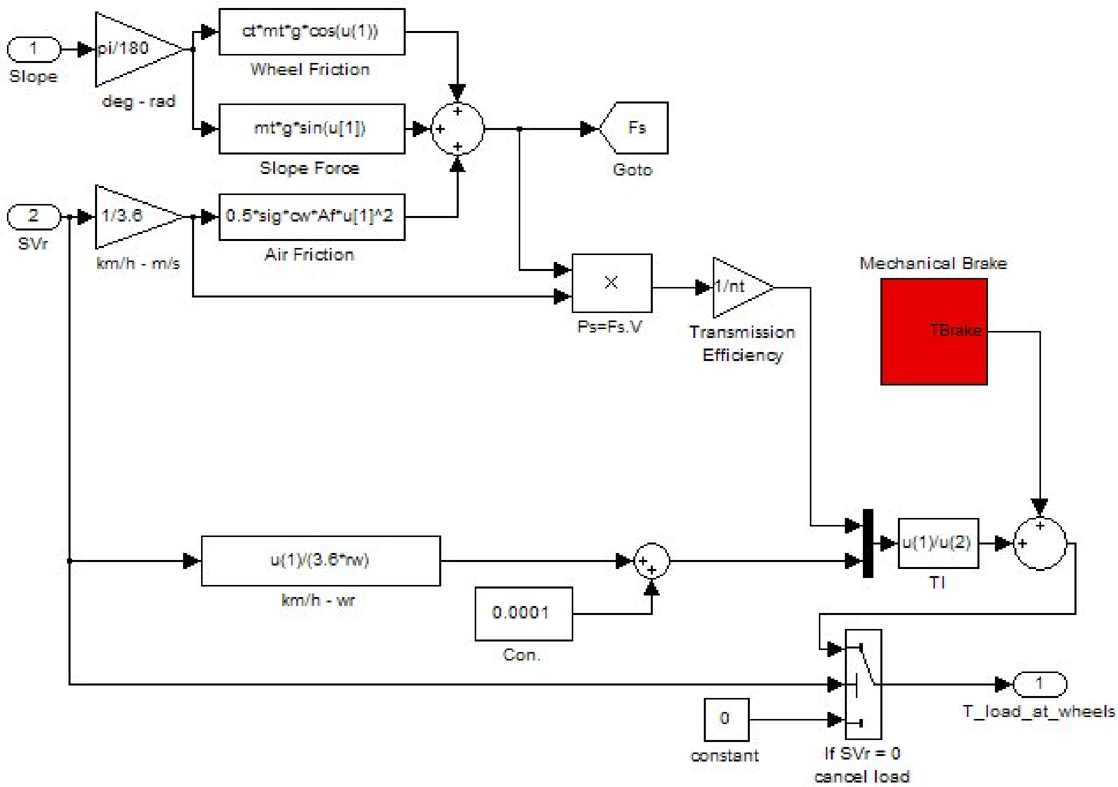

Figure 5.1: Load and mechanical brake model

Model block has the inputs of Slope and Actual Vehicle Speed (SVr). Parameters in Table 5.1 are defined in an external “m” file, named “parameters.m”. With these parameters, load forces are found using Equations 5-1 to 5-3. If F_T is the total load force we can calculate the total load power (P_T) as follows:

$$F_T = F_t - F_r - F_e \tag{5.5}$$

$$P_T = F_T \cdot Vr \tag{5.6}$$

Here, Vr is the vehicle speed. As the mechanical connections between the load and the driving elements are the wheels, it is convenient to model the system as it was loaded on and driven by them. So, total load power is multiplied by the wheel revolution speed, which was calculated from the real vehicle speed. Thus,

$$\omega_w = \frac{Vr}{3.6 \cdot r_w} \text{ rpm} \tag{5.7}$$

$$T_L = \frac{P_T \cdot n_t}{\omega_w} \text{ Nm} \tag{5.8}$$

In these equations, ω_w, the wheel revolution speed and T_L, total load torque is calculated. Parameters r_w, wheel radius (0.282m) and n_t, transmission efficiency (90%) are defined in the "parameters.m" file. Transmission efficiency in automobiles is about 90%. It can be considered 100%, if direct driving is applied. [11] Lastly, there is a very little constant added to wheel speed, added to avoid "divided by zero" error. Mechanical brake block applies an optimum amount of brake power, in case it is needed. This load and mechanical brake block has the output of load and mechanical brake torque with respect to the wheels.

It is seen that the load model does not contain an acceleration component. Instead of defining the acceleration component here, only static and speed based loads are mentioned in this block. Acceleration component will be calculated and taken into account in Transmission and Wheels block, where all the torque components are summarized and speed of the vehicle is calculated.

5.3 Internal Combustion Engine Model

As detailed modeling of an internal combustion engine is not a primary objective of this thesis, it is convenient to model the performance of the engine by using look-up tables. The engine that used is a 1.3lt engine with the torque-speed characteristics are as seen in Figure 5.2. The model engine is a Fiat engine, which is used in Albea, Palio and Doblo models. Table 5.2 also shows the values taken from Fiat and interpolated to form the figure.

Table 5.2 Torque vs. speed of the engine

Engine Speed (rpm)	Torque (Nm)
1000	84.08
1250	104.71
1500	156.69
1750	175.25
2000	175.32
2500	165.48
3000	150.96
3500	135.12
4000	118.71
4500	101.70
5000	82.93

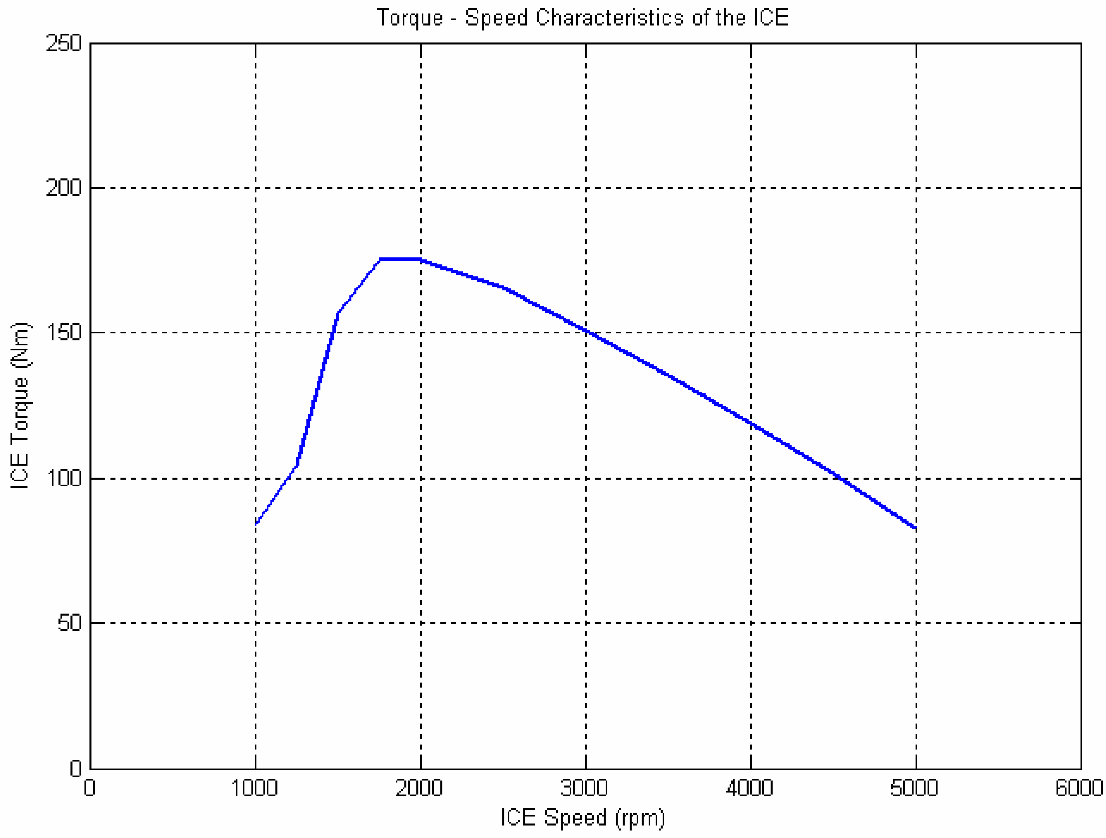

Figure 5.2: Torque speed characteristics of the engine

By using the table above, ICEs performance is modeled as seen in Figure 5.3.

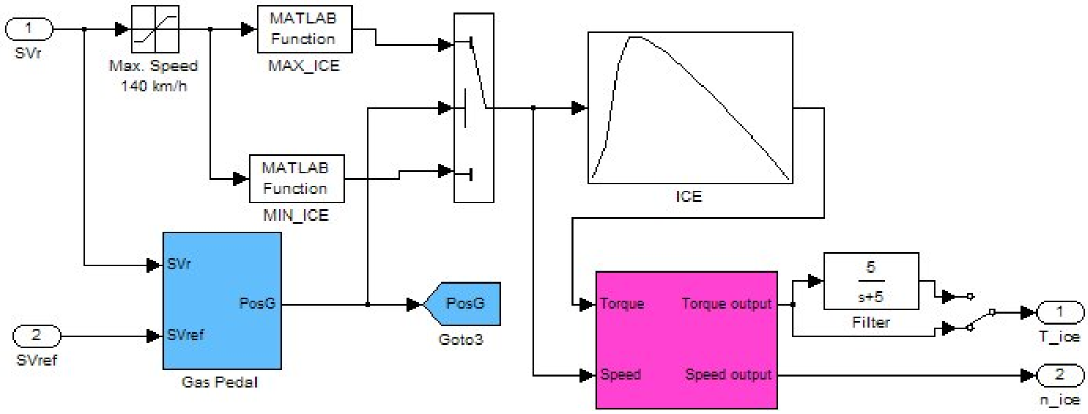

Figure 5.3: ICE performance model

Inputs of this block are actual vehicle speed (SVr) and reference vehicle speed (SVref). Actual vehicle speed is maximum 140 km/h. Gas pedal block, which can be seen in Figure 5.4, determine whether the gas pedal is pressed or not, by comparing the reference vehicle speed with actual vehicle speed and finds out the positive, negative or zero acceleration. It sends out 1 signal when positive acceleration is demanded. As the engine output is connected to a power split device, it should be in a certain boundaries in certain speeds for not to violate the speed boundaries of generator machine, which is connected to the output of the power split device. MAX_ICE and MIN_ICE blocks determine the ICE speed boundaries. Detailed information on the power split device can be seen in Chapter 5. After the proper ICE speed is determined, ICE lookup table is used to find out the ICE torque produced in that speed. Control block, which can be seen in Figure 5.5, is used to determine where the engine is on duty and lets out the calculated speed (n_ice) and torque (T_ice) in operation. The logic in the control block will be explained in the "Control Logic" part of this chapter.

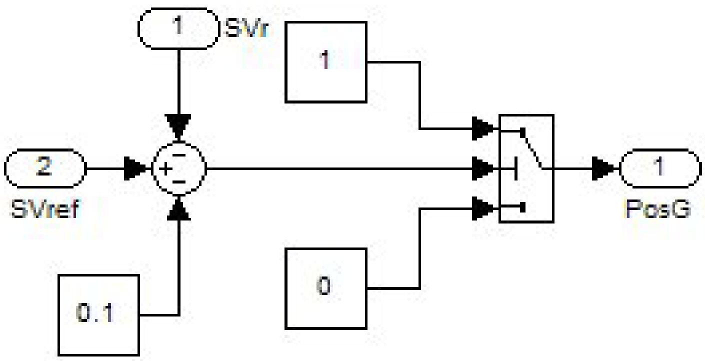

Figure 5.4 Gas pedal block

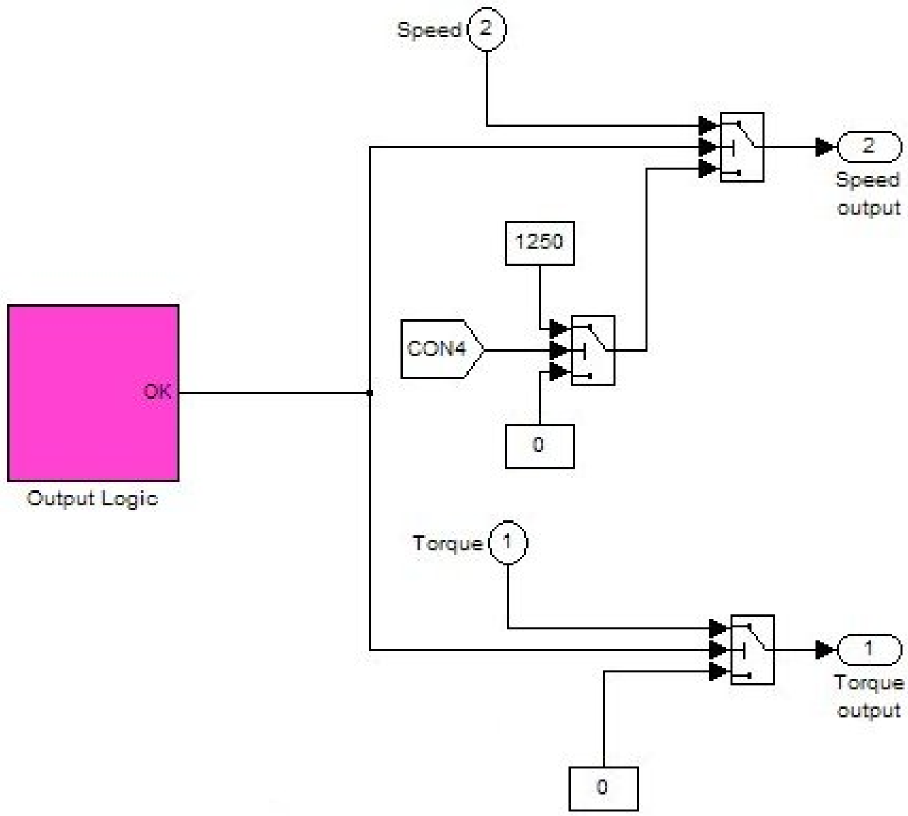

Figure 5.5: ICE control block

5.4 Driving Electrical Machine Model

The series parallel hybrid vehicle utilizes a driving electrical machine, which is able to run the vehicle in low speeds (i.e. up to 40km/h). Keeping this in mind, a brushless DC motor performance is modeled. In Figure 5.6 and Figure 5.7, torque speed and power speed characteristics of the model machine are seen. This data is set in "parameters.m" file and loaded in a look-up table in Simulink then MG2 performance model, seen in Figure 5.8, is built. This block has the inputs of driving shaft speed (n_MG2), which is also equal to the speed of the driving electrical machine's shaft, and electric power which is produced by generator machine (Pe_MG1). Look-up tables determine the power and torque values for each speed value. Control blocks, which can be seen in Figure 5.9 and 5.10, lets the power and torque values out in case of an operation. As this electrical machine runs in regenerative braking and accelerating conditions, each control block has two different algorithms to be used in acceleration and deceleration operations. Detailed information about the control algorithms will be given in "Control Logic" part of this chapter. In the CON6 tag, it is defined whether the vehicle accelerates or decelerates and proper control is utilized. The CON0 tag in the torque control block cancels out the output as it may cause some errors in zero speed.

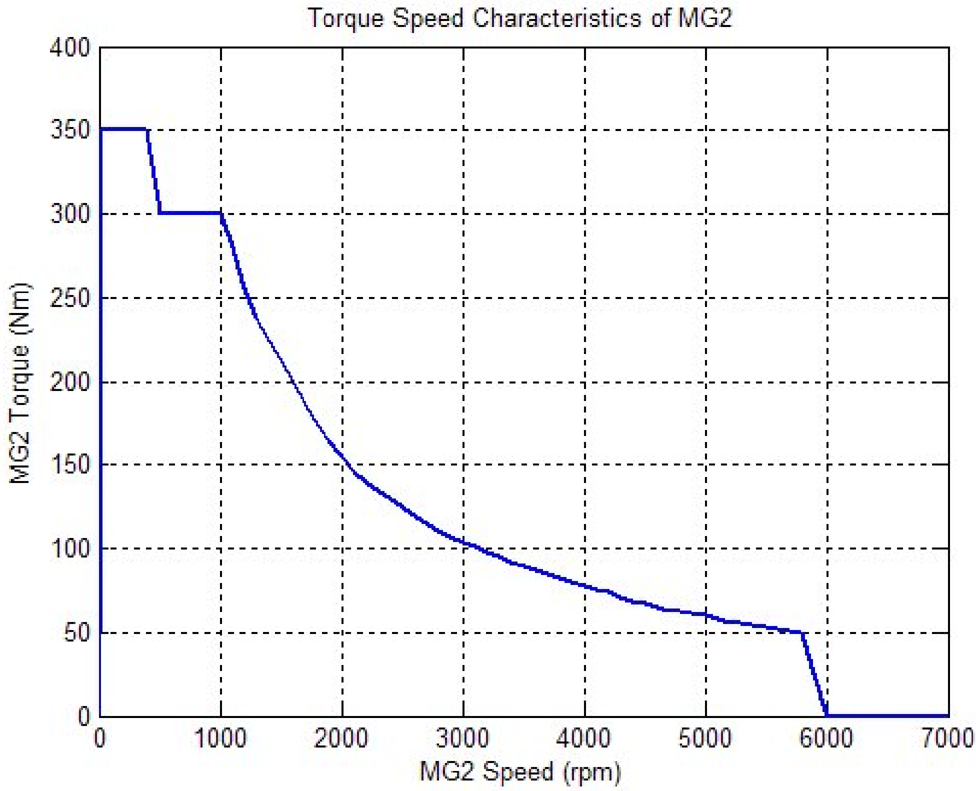

Figure 5.6: Torque – speed characteristics of the driving electrical machine

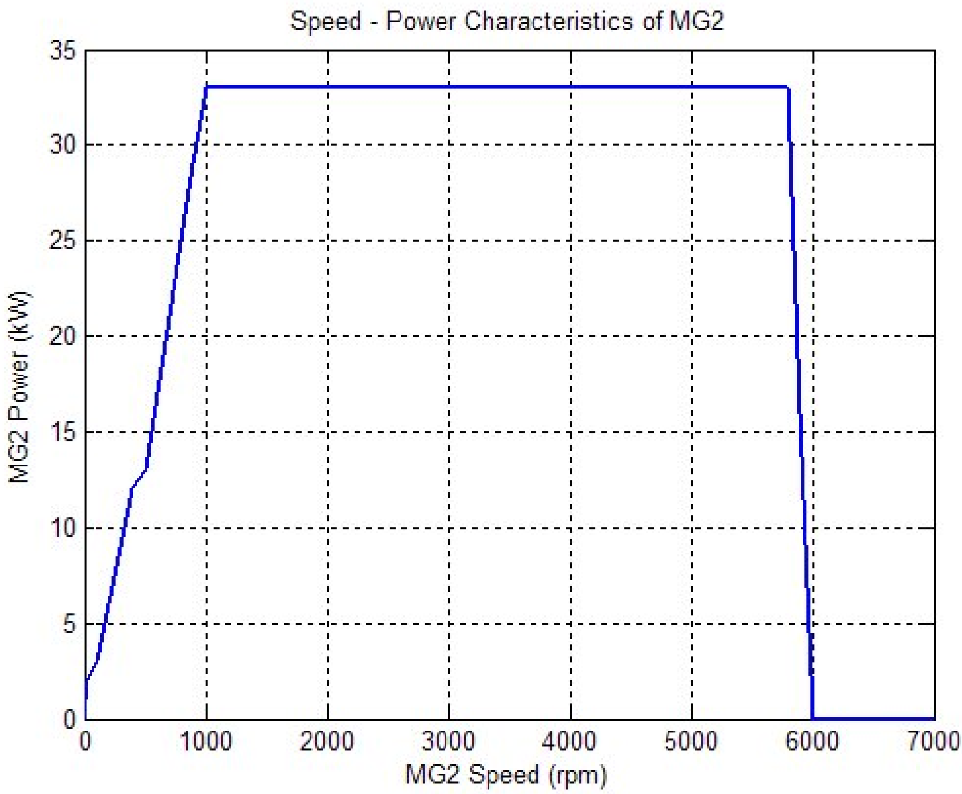

Figure 5.7: Power – speed characteristics of the driving electrical machine

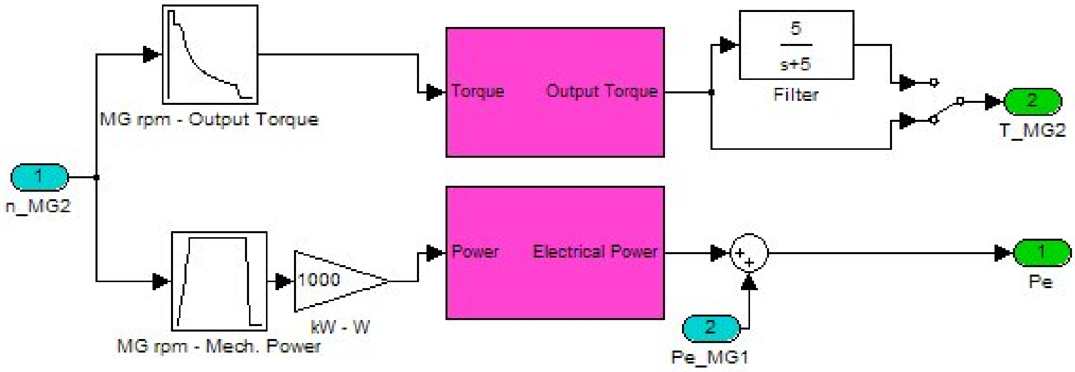

Figure 5.8: Driving electrical machine model

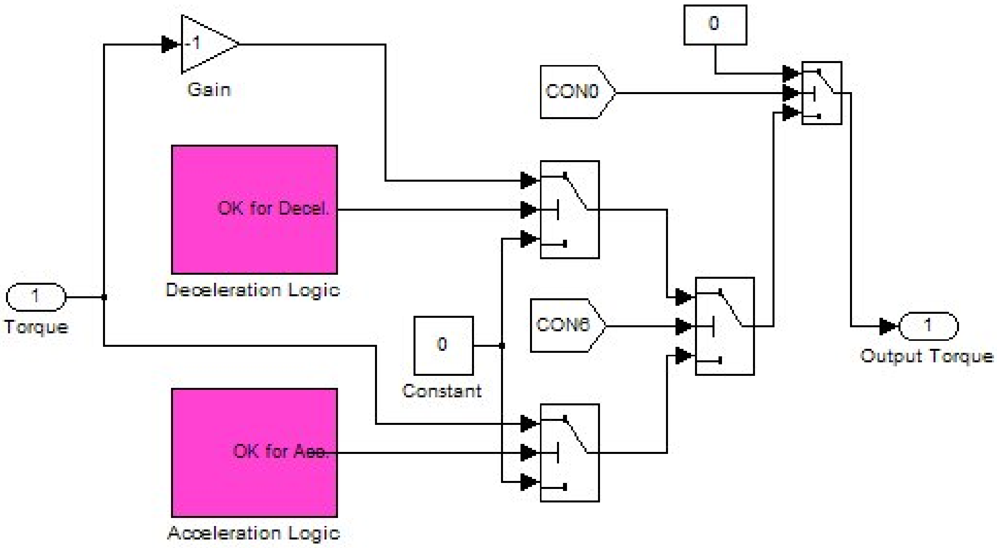

Figure 5.9: Torque control for driving electrical machine

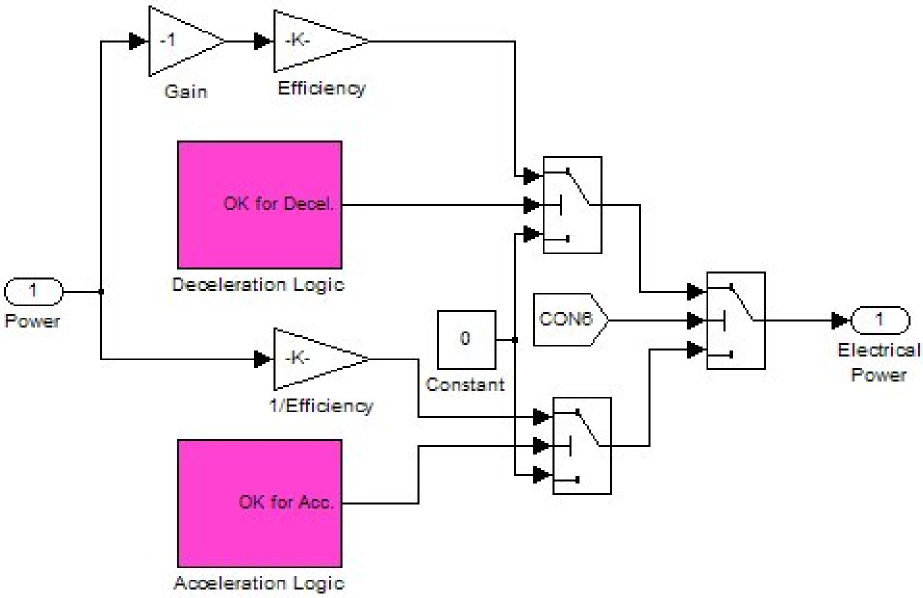

Figure 5.10: Power control for driving electrical machine

In the output of this model block, the electrical power consumed or regenerated and torque that applies to the driving shaft is calculated. Power element includes the power generated by the generator machine, too. The filter element seen in the output of the model block is used if the simulation is stalled by the change of parameters.

5.5 Generator Machine Model

The series parallel hybrid electrical vehicle also includes a generator machine which is connected to the power split device and driven by the engine. This machine is effective in many ways. It helps to adjust the gear, as it is a parameter in planet gear equations. It generates electrical power from the engine's excess production, as the engine's operation in efficient range is granted. It helps out the batteries in full throttle, where the driving electrical machine runs in full power. Thus, it helps to reduce the battery size.

Generator machine (MG1) is not as powerful as driving electrical machine. It runs in full power only in full throttle mode. Keeping battery power and driving motor full power in mind, the generator power can be chosen 15kW as it is in Toyota Prius. The torque speed and power speed characteristics are seen in Figure 5.11 and 5.12.

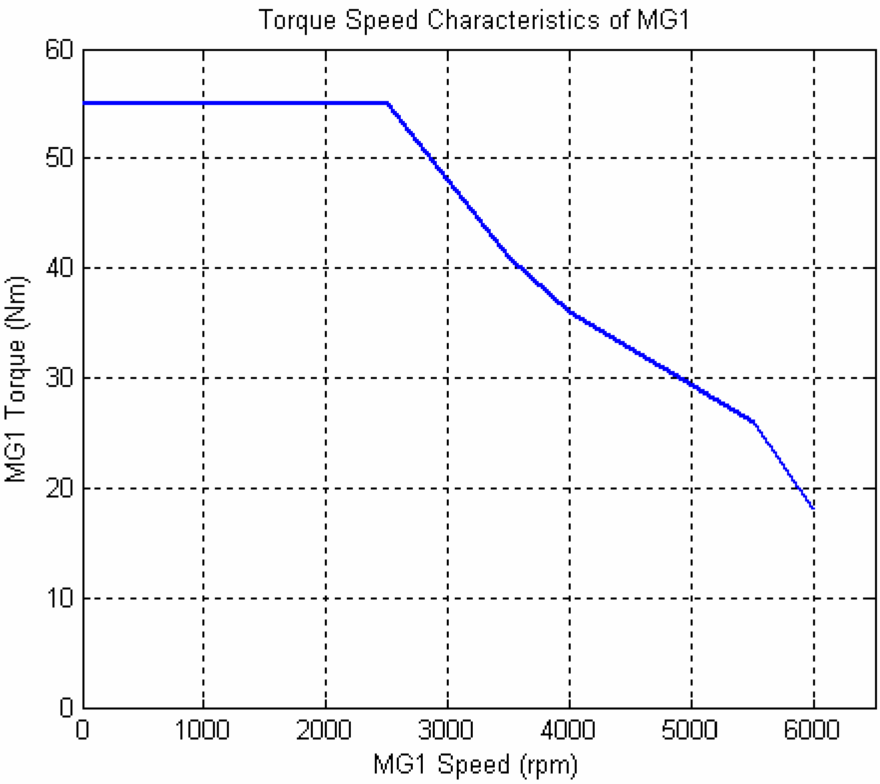

Figure 5.11: Torque-Speed characteristics of generator machine

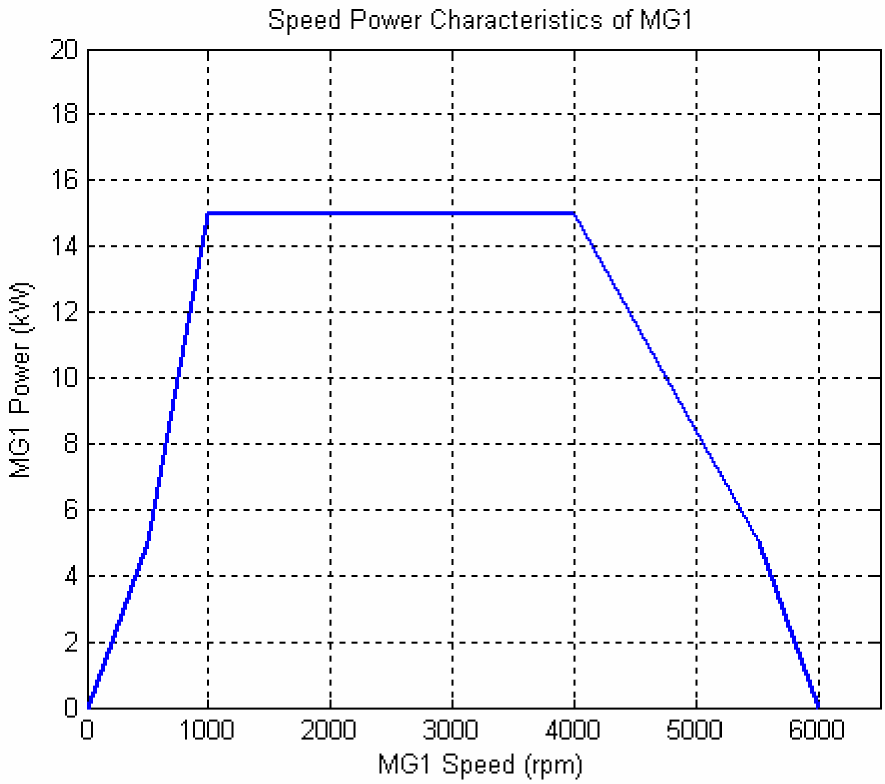

Figure 5.12: Power-Speed characteristics of generator machine

Parameters for the generator machine are set in the “parameters.m” file. These parameters are loaded to look-up tables in Simulink and generator machine performance model is set up as seen in Figure 5.13. The block has the generator machine speed (n_MG1) as an input, which has been calculated in the power split device block. As it can revolve in positive or negative direction, an absolute value operator is used in the input. In the look-up tables torque and power values for each speed is determined. In the control block, calculated values are let out in case of an operation. The control block can be seen in Figure 5.14. Detailed information about the control logic will be given in the related part of this chapter.

As it is seen in the model, the generator machine is also used in starting up of the vehicle. The start-up block generates the torque desired for stating up. Detail of this block is seen in Figure 5.15. CON10 and CON3 tags define that vehicle is at rest and in start-up mode. If this occurs, this block generates the starting-up torque for an instance.

The outputs of this model block are the power generated (Pe_MG1) and torque demand (T_MG1) from the engine.

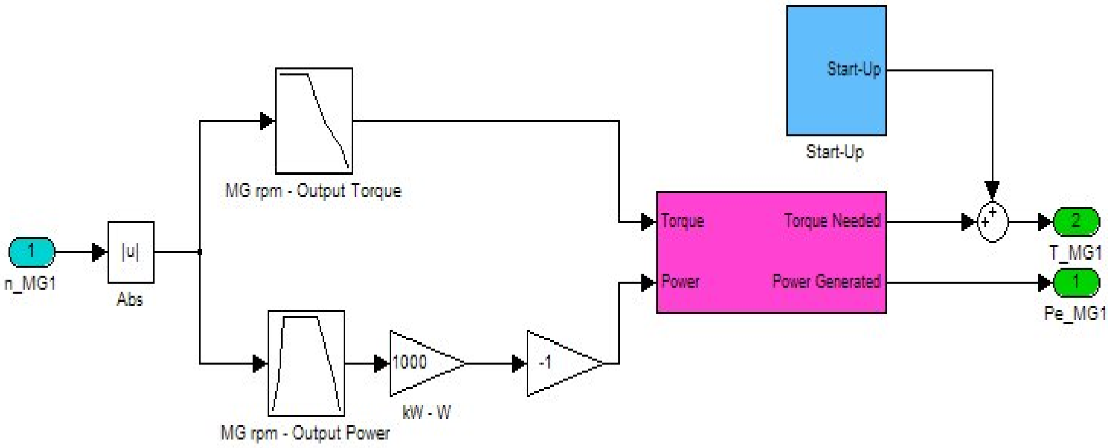

Figure 5.13: Generator machine model

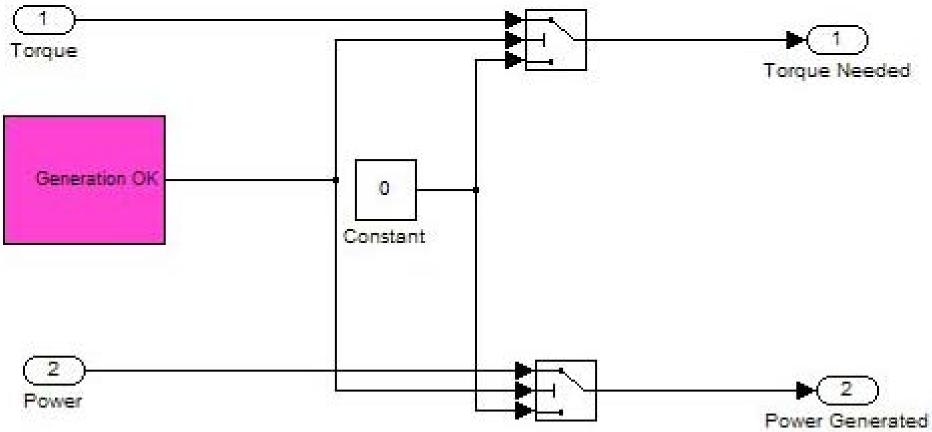

Figure 5.14: Power and torque control for generator machine

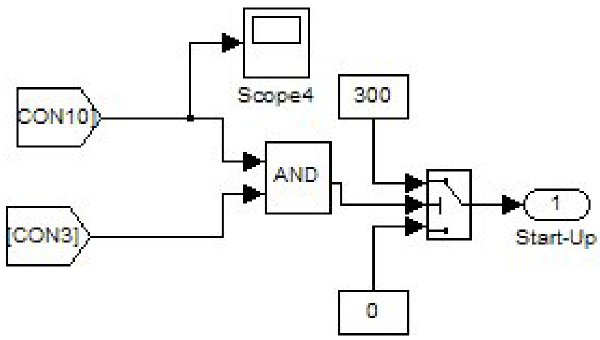

Figure 5.15: Start-up block

5.6 Power Split Device Model

The engine power is divided between the generator and the drive shaft by the power split device. This device is actually a planetary gear connected to engine, generator and drive shaft as seen in Figure 5.16. Power split device is controlled by the electronic control unit (ECU) of the vehicle and acts as an electronically controlled continuous variable transmission (E-CVT). Thus, with the reduction gears after the drive shaft, vehicle does not utilize any other transmission (See Figure 5.17).

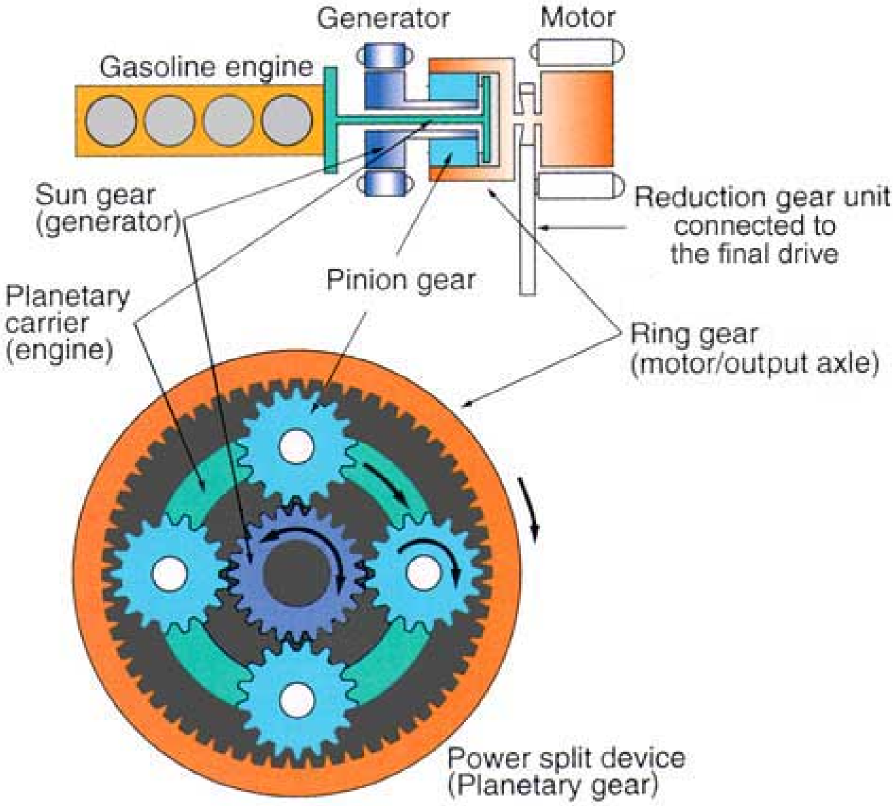

Figure 5.16: Planetary gear and its connections [10]

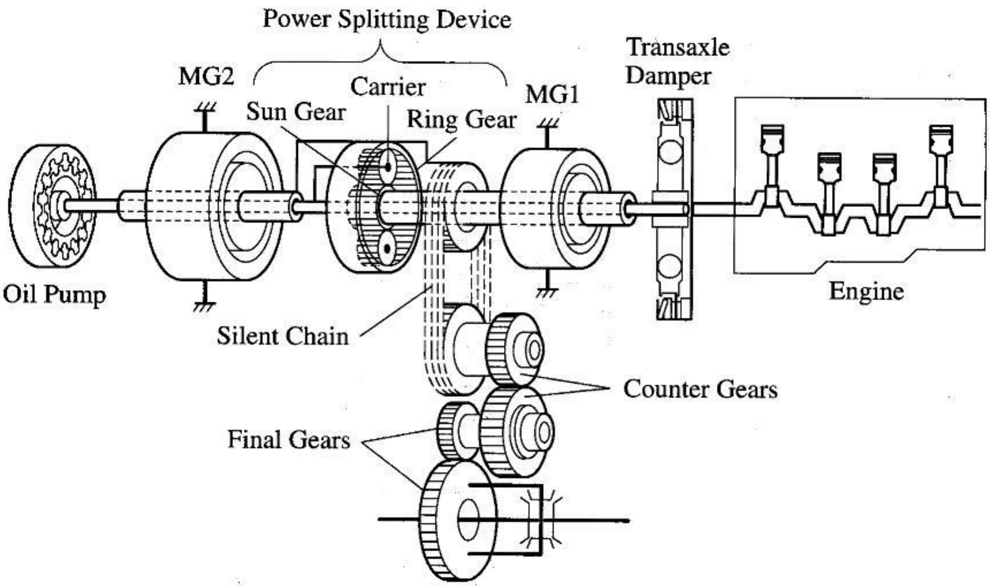

Figure 5.17: E-CVT in series-parallel hybrid electric vehicle [10]

As seen in Figure 5.16 and 5.17, engine is connected to the planetary carrier of the power split device. Power is divided between sun gear, where the generator machine is connected, and the ring gear, where the drive shaft is connected. In this vehicle, the sun gear has 30 teeth, each planet has 23 and the ring gear has 78 teeth on the inside. By holding each component still each time, below equation for the planet gear is derived.

$$n_{engine} = \left(n_{generator} + 2.6 \cdot n_{driving}\right)/3.6 \tag{5.9}$$

As seen in Equation 5.9, by adjusting the speed of each component, virtually unlimited gear ratios can be obtained. To understand the gear adjustment better, a nomograph as seen in Figure 5.18 can be plotted by using Equation 5.9.

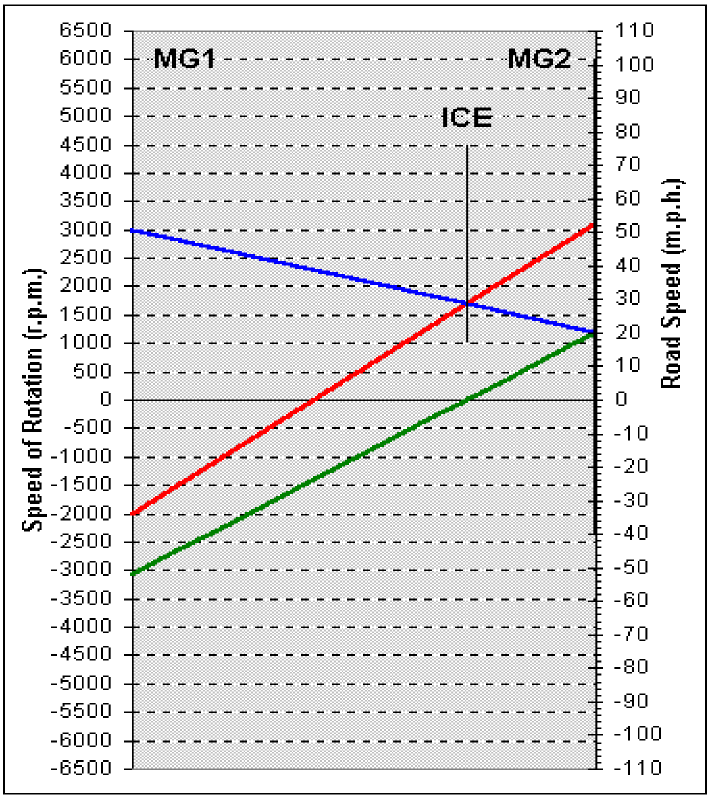

Figure 5.18: Nomograph for planetary gear

The working characteristics for each desired speed of the vehicle is optimized and adjusted by the electronic control unit of the vehicle. Having an optimized gear ratio has a positive effect in the efficiency. For modeling this complex planetary gear and electronically controlled continuous variable transmission, Simulink model seen in Figure 5.19 is built. This model block has the inputs of actual vehicle speed (SVr) and ICE speed (n_ice). As ICE speed value is calculated in ICE's block, we are able to find out the driving machine's and generator's speed. Driving electrical machine is connected to the wheels by some reduction gears. Thus, it is possible to calculate the driving machine's revolving speed. This calculation is done in power split device block. By using ICE speed and driving machine's speed and also by using Equation 5.9, generator speed is calculated. In the function blocks in power split device model, Equation 5.9 rearranged to find out the gear ratios for torque of ICE and generator machine as seen in Equation 5.10 and 5.11.

$$C_{T\_MG1} = \frac{(n_{ice} \cdot 9.36) - (n_{MG2} \cdot 6.76)}{(n_{ice} \cdot 3.60) - n_{MG1}} \tag{5.10}$$

$$C_{T\_ICE1} = \frac{(n_{ice} \cdot 3.6)}{0.722 \cdot (n_{MG1} + (n_{MG2} \cdot 2.6))} \tag{5.11}$$

Calculated torque coefficients are used in the transmission and wheels block to find out the torque affected on the wheels. Thus, from power split device model, we have coefficients to reduce the ICE and generator machine's torque to driving shaft.

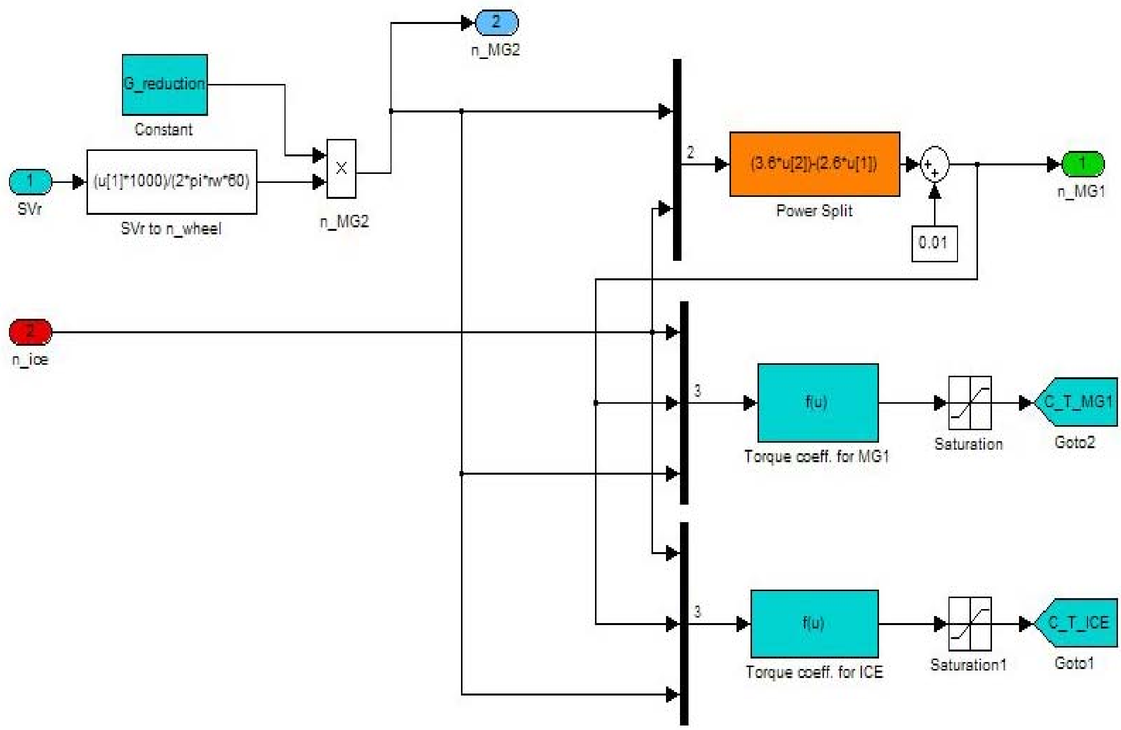

Figure 5.19: Power split device model

5.7 Transmission and Wheels

All the load and machine torque values are carried into transmission and wheels block to calculate the speed of the vehicle. This block can be seen in Figure 5.20. Engine's and generator machine's torque values are multiplied by the gear ratios calculated in the power split device model. After adding all these torque values and driving electrical machine's torque value in the driving shaft, calculated value is multiplied by the ratio of reduction gears. Reduction gear ratio is set to 3.905 in the "parameters.m" file. The result is multiplied by the transmission efficiency and the machine torque values effecting on the wheels are found. Load torque value is subtracted form this value and at last, total torque on wheels is found. By taking the whole vehicle as a single wheel model, we are able to run the following equation to find out the wheel speed. Then it is possible to find out vehicle's speed.

$$n_{wheels} = \frac{\int T_{total} \cdot dt}{M_{total} \cdot r_w^2} \tag{5.12}$$

In the above equation, n_{wheels} is representing the revolving speed of the wheels, T_{total} is the total torque value, M_{total} is the total weight of the vehicle and r_w is the wheel radius. These values are set in "parameter.m" file.

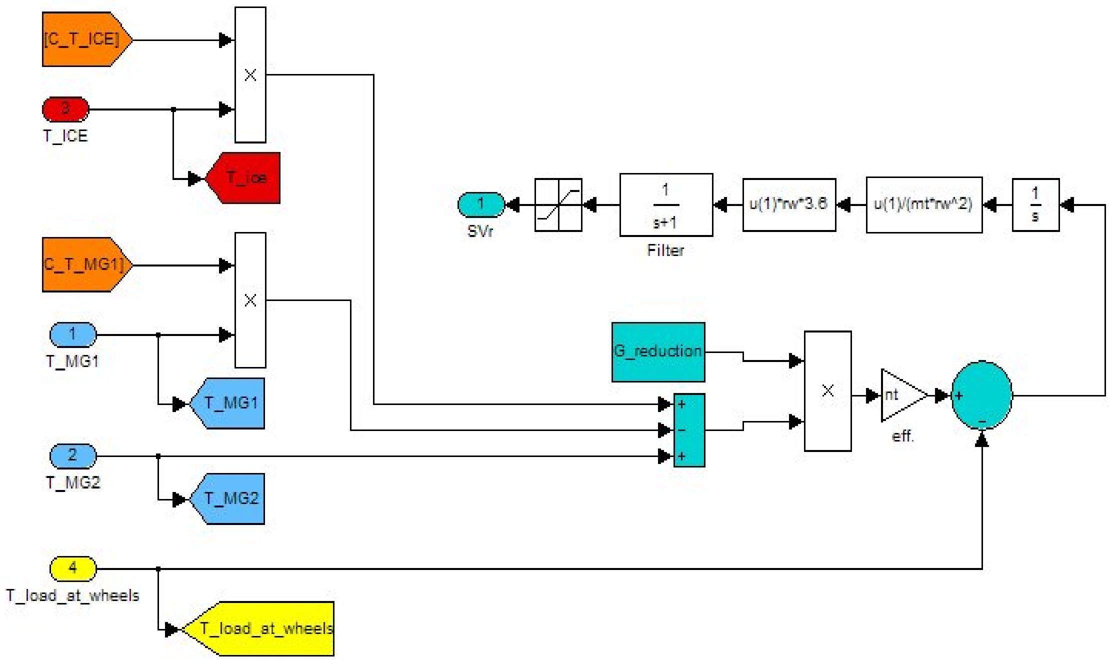

Figure 5.20: Transmission and wheels block

5.8 Battery

Battery is modeled as a voltage source and a resistance which changes with the power flow and load. Battery values are taken from a simulator program named Advisor [10]. SOC calculation, resistance and open circuit voltage are calculated in the sub-blocks. In the model, there are serially connected 55 Ah batteries. Number of batteries is set to 22 to obtain 274V of voltage. It is possible to adjust initial value of state of charge (SOC). The battery model can be seen in Figure 5.21.

In figure 5.22, the block to calculate the state of charge is seen. Battery power demand is used to find out the current demanded or supplied per hour. Integration of this value is added to available capacity of the batteries and new capacity level is determined. By dividing it with the full capacity, state of charge is found.

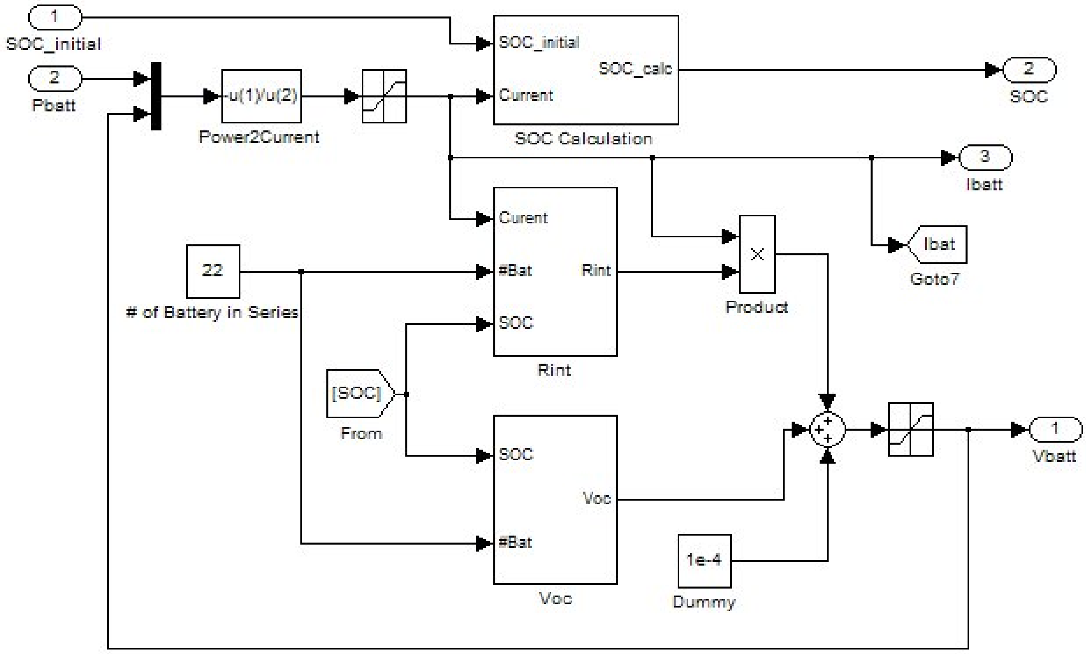

Figure 5.21: Battery model

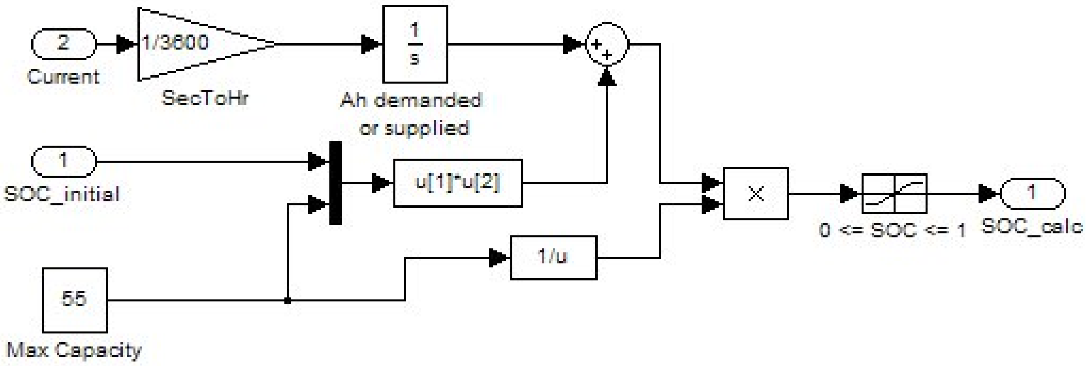

Figure 5.22: SOC calculation

The internal resistance of the batteries changes with the direction of the current and by the state of charge. Look-up tables are utilized to find out the internal resistance of one battery. Output is multiplied by the total amount of batteries to find out the total internal resistance as seen in Figure 5.23. In this model, temperature effect is neglected.

Open circuit voltage changes due to the state of charge. The block seen in Figure 5.24 calculates the open circuit voltage. Output of open circuit voltage block is added to voltage drop by the internal resistance and battery voltage is calculated at last.

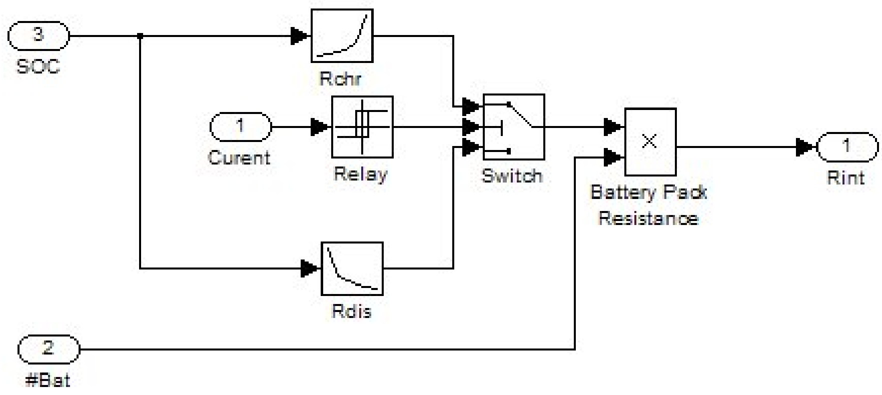

Figure 5.23: Internal resistance calculation

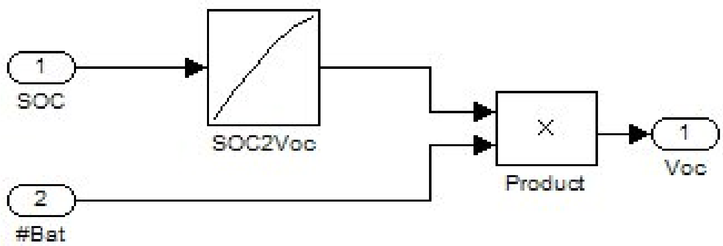

Figure 5.24: Open circuit voltage calculation

5.9 Control Logic

For the desired proper operation of the series parallel hybrid electrical vehicle, it is important to define good control logic. There are several aspects to be considered. These issues are mentioned in Chapter 4, abstract 4.1. In this part, the control logic with respect to those issues will be built. To be able to control the vehicle to run between 6 modes which are defined in that chapter, vehicle's speed and state of charge should be monitored.

In the simulation, vehicle runs only with driving electrical machine below a certain low speed level. This speed level is set by considering that the ICE operates inefficient in low speeds. By taking the heavy city traffic conditions and also start-stop actions in traffic lights, it is possible to use 40km/h as a low speed level upper limit where the vehicle runs in silent mode. Also, we must consider that in case of a high acceleration need, engine should turn on and run the vehicle. At this point, we need to define the high acceleration or full throttle mode. Acceleration and braking modes are to be considered, too.

Besides the vehicle speed and driver behavior like full throttle or braking, we also need to know the SOC of the batteries to define complete control logic. Aim of the control logic is to keep the SOC in a narrow band around 50% to avoid overcharge or undercharge. Thus, SOC is divided into 5 levels and in each level, proper energy management algorithms are utilized. The SOC levels can be seen in Figure 5.25.

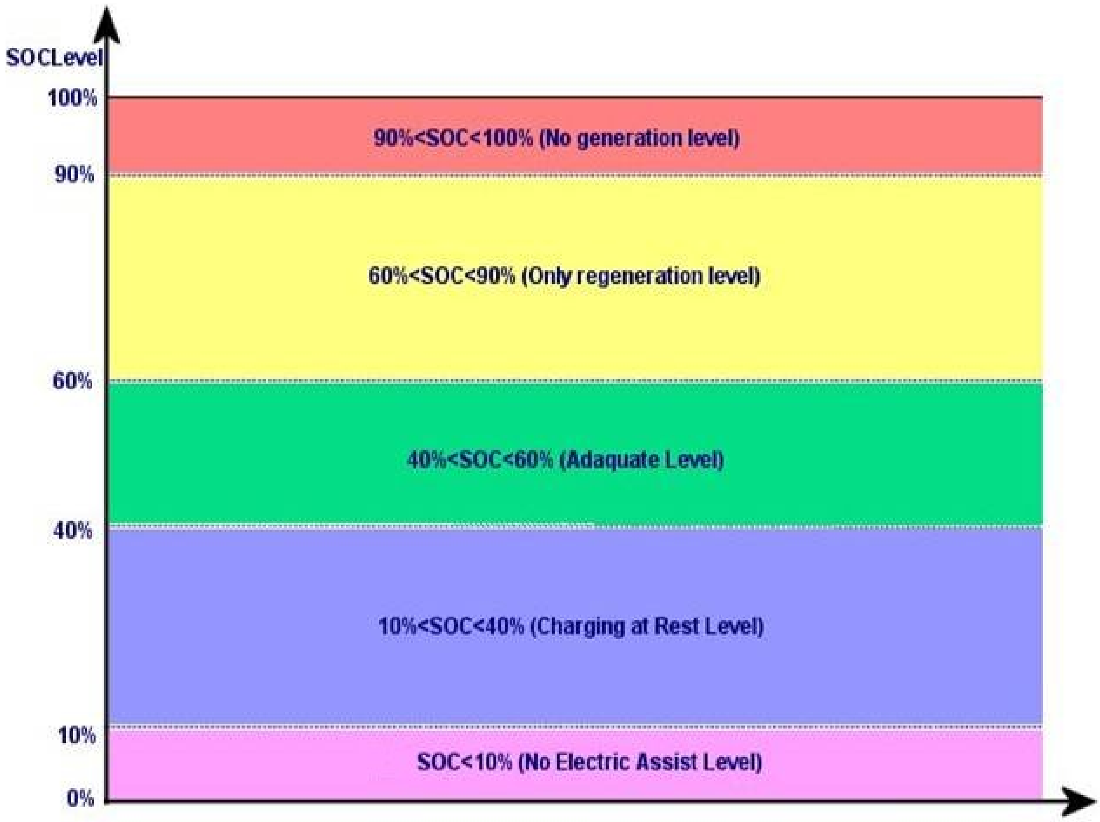

Figure 5.25: SOC levels

- Between 40% and 60%, the SOC is considered to be in adequate level. In this level, vehicle runs in silent mode below 40km/h, electric assist on full throttle is available, engine is run in its optimum point and excess power is used by the generator machine to charge up the batteries.
- When the SOC increase above 60%, up to 90%, electric consuming modes continue to operate as it was in the adequate level but energy is only saved by regenerative braking. This means that engine excess power is used by the generator only to power the driving electrical machine.
- When SOC increase above 90%, critical overcharge level is reached. After this level, no regenerative braking or any energy generation occur. The vehicle uses energy as usual.
- When SOC is below 40% but more than 10%, silent mode is cancelled. As the ICE is not efficient in low speeds, it is run in its efficient points but the excess power is obtained and used in generator to charge up the batteries. This occurs both in low speeds and at rest. Electric assist and regenerative braking occur as usual.

- When the SOC is below 10%, critical undercharge level is reached. In this level energy management system cancels all the electric assist and concentrate on regaining the proper SOC levels.

By considering the speed, driver demand and SOC issues, 11 control conditions are defined in control logic block. Inside of this block can be seen in Figure 5.26.

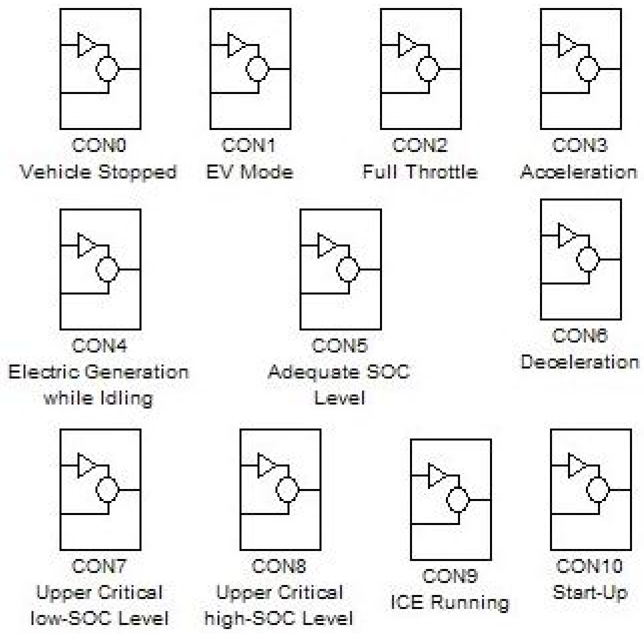

Figure 5.26: Control conditions

- CON0: Defines the vehicle is stopped. Reference vehicle speed and actual vehicle speed are equal to each other and value is zero. $(SV_{ref} = SV_{real} = 0)$
- CON1: Defines the vehicle can run in silent mode. Actual vehicle speed is under 40km/h and SOC is above 40%. $(SV_{real} \le 40km/h \,\&\, SOC \geq 0.4)$
- CON2: Defines the vehicle is in full throttle mode. Difference between actual vehicle speed and reference vehicle speed is more than 20km/h. $(SV_{ref} \geq SV_{real} + 20)$
- CON3: Defines the vehicle tends to accelerate. Gas pedal is pressed. $(PosG = 1)$
- CON4: Defines that vehicle should generate electricity while idling. It happens when SOC level is below 40% and vehicle is stopped. $(SOC < 0.4 \,\&\, SV_{real} = 0)$
- CON5: Defines the upper limit of adequate SOC level. $(SOC > 0.6)$
- CON6: Defines that the vehicle is decelerating. $(PosG = 0)$

- CON7: Defines the lower limit of adequate SOC level. $(SOC < 0.4)$
- CON8: Defines the overcharge level. $(SOC > 0.9)$
- CON9: Defines the minimum running speed of the ICE. $(n_{ice} \geq 1000)$
- CON10: Defines the vehicle is starting up. In this condition, vehicle's actual speed is 0 but reference speed is increasing. This mode continues when the vehicle speed reaches 5km/h. $(SV_{real} \leq 5 \,\&\, SV_{ref} > 0)$

When the control conditions are defined, it is possible to build up the control logic for each of the component in the vehicle. Control blocks allow the related component to go in action or stop in each operation mode. As a conclusion, the following modes of operation are defined.

- Start-up and low speeds: If the SOC is above 40%, driving electrical machine runs the vehicle up to 40km/h. If SOC is below 40%, vehicle is run by ICE and excess power is stored in the batteries.
- Normal driving: Both ICE and driving electrical machine runs the vehicle in speeds above 40km/h. Electric assist is stopped when the SOC is below 10%. As the generator machine supplies the driving electrical machine with the excess power of the ICE, batteries are not depleted.
- Sudden acceleration: If the SOC level is higher than 10%, battery energy and generator energy is used in the driving electrical machine and it is run in full performance. ICE is also runs in its full performance in this mode.
- Regenerative Braking: If the SOC is not higher than 90%, driving electrical machine works as a generator to regenerate power from vehicles kinetic energy in braking.
- Charging at rest: When the SOC is lower than 40%, ICE is run in an efficient point, i.e. 1250rpm, and generator machine charges the batteries while vehicle is stopped.

5.10 Integration of the Components

When all the components are defined, system is integrated to the model, seen in Figure 5.27. Input block includes the driving cycles that the vehicle will be running on. Measurements block is defined as seen in Figure 5.28 and vehicle speed, reference speed, ICE, MG1 and MG2 torques and powers, SOC, voltage and current of the batteries are monitored. Also there are three tools added in the measurement block to calculate the range, energy gained by regenerative braking and the amount of energy that the driving electrical machine has conducted to the system.

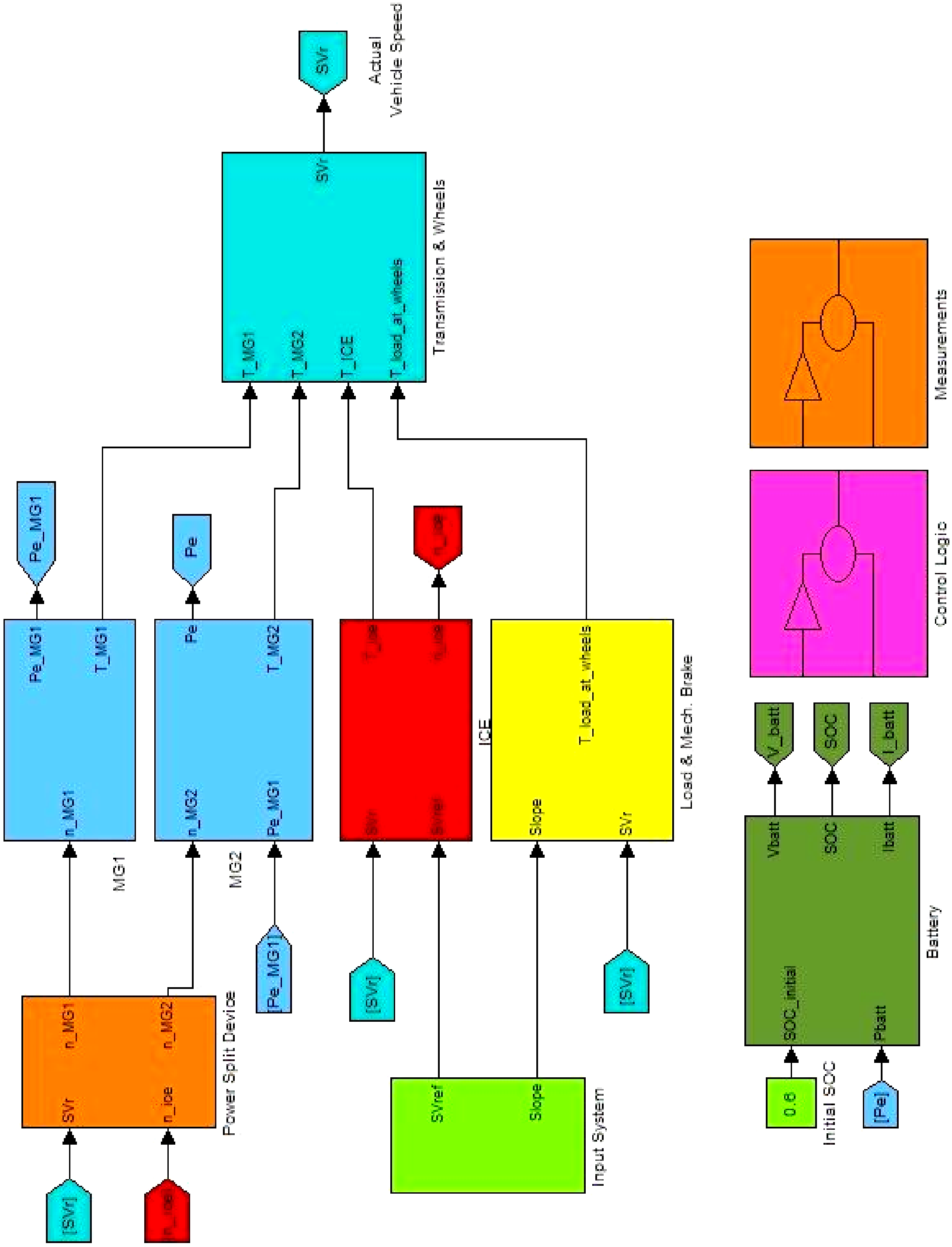

Figure 5.27: Series-Parallel Hybrid Electrical Vehicle Model

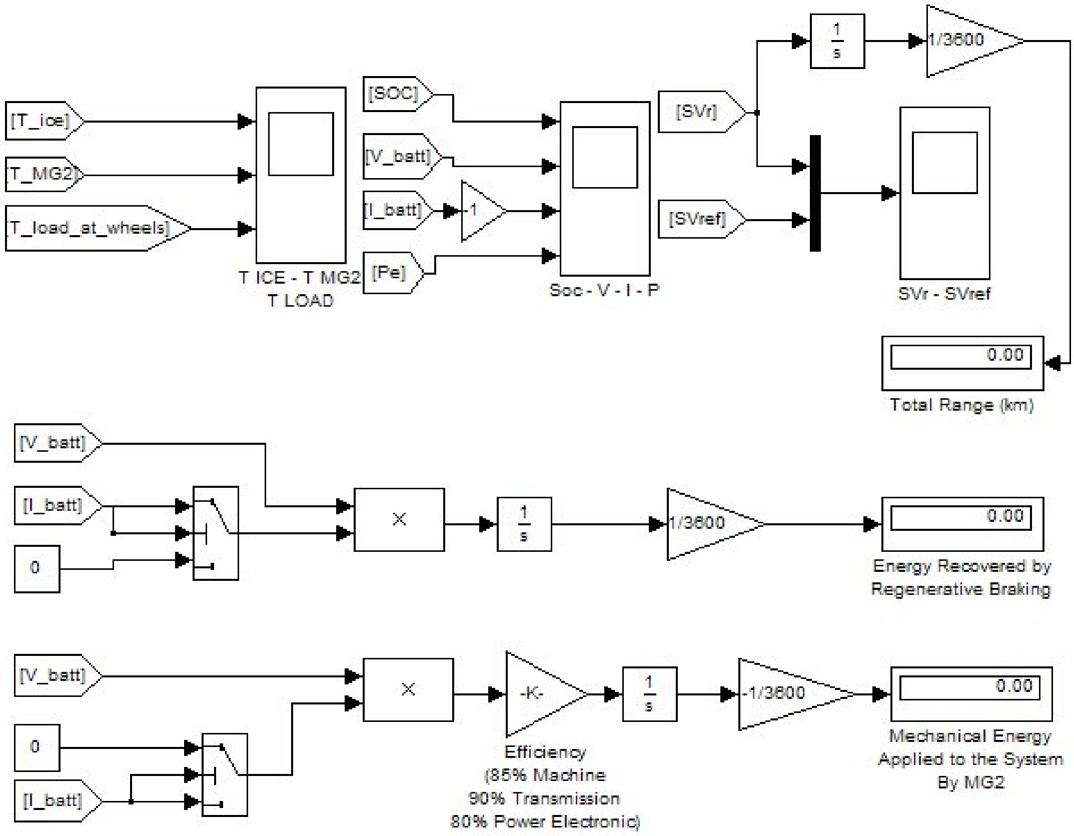

Figure 5.28: Measurements Block

In the measurements block, energy recovered by regenerative braking is calculated by taking the positive values of battery current (I_batt) and multiplying it with battery voltage (V_batt). The result of regenerative braking power and by integrating it, energy recovered and saved in the batteries are found. Similarly, the negative values of the battery current leads us to find out the energy taken from the batteries and used in the driving machine. Some of this energy is lost in the power electronic components (20%), mechanically in the machine (15%) and in the transmission (10%) and the result helps to drive the vehicle. These values give some information about the fuel save that might have been occurred by using this hybrid system and calculated values will be explained in the results.

6. SIMULATION

The series parallel hybrid electrical vehicle model has been built on Matlab R13 using Simulink 5. Parameters of the vehicle are loaded with “parameters.m” file which can be seen in Appendix C. Initial SOC has been taken 60%. Model has been run on UDDC and US06 driving cycles.

6.1 Urban Driving Cycle (UDDC)

This cycle is US Federal Test Protocol (FTP-75) Urban Dynamometer Driving Cycle. It has been developed in mid 70’s from a real driving pattern of an urban route. The cycle can be seen in Figure 6.1. It consists of many peaks, which rarely exceeds 50 km/h. The reason that this route was taken is that it was derived from a real pattern.

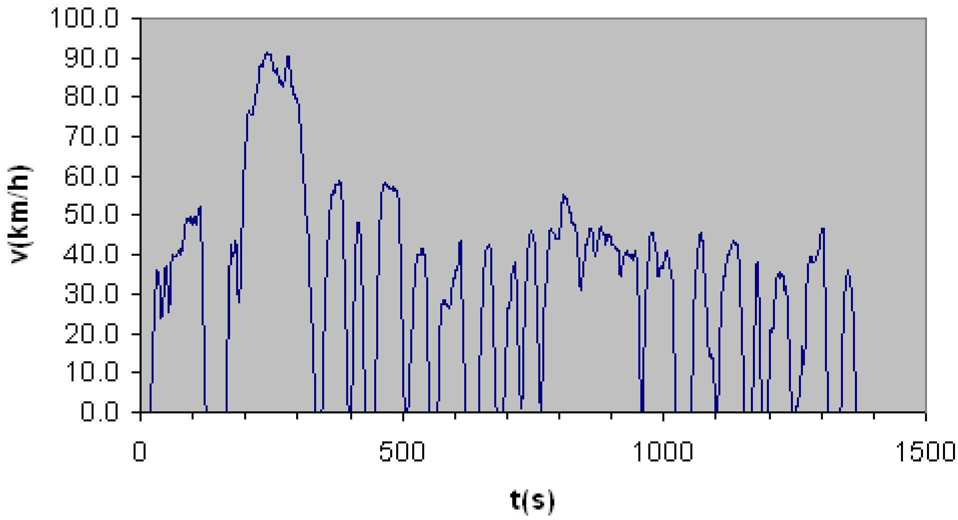

Figure 6.1: UDDC Driving Cycle

The results of this cycle can be seen in Appendix A. After the UDDC, it is seen that the vehicle has recovered 3.77kWh energy from regenerative braking and electric propulsion has conducted 2.87kWh of energy to the system. The SOC has dropped 15% because vehicle has run in silent mode in low speeds, consuming battery energy. While overall range of the cycle is 12km, the drop of SOC can be considered reasonable.

While the overall vehicle performance is considered, it can be said that the vehicle was able to reach the reference speed, as it can be seen on Appendix A. As this cycle is not very performance demanding, we should look at the highway driving cycle to comment on chosen motor and engine, if they are able to meet the demands.

Developed energy management system tested in respect to SOC management in this cycle and it can be said that the developed vehicle is able to run proper ranges in city conditions and also able to save energy, in terms of fuel, as a result.

6.2 Highway Driving Cycle (US06)

US06 highway cycle is an aggressive driving cycle. It is developed to describe a driving pattern with high loads. As UDDC, it was developed from a real driving pattern. In Figure 6.2, US06 driving cycle is seen.

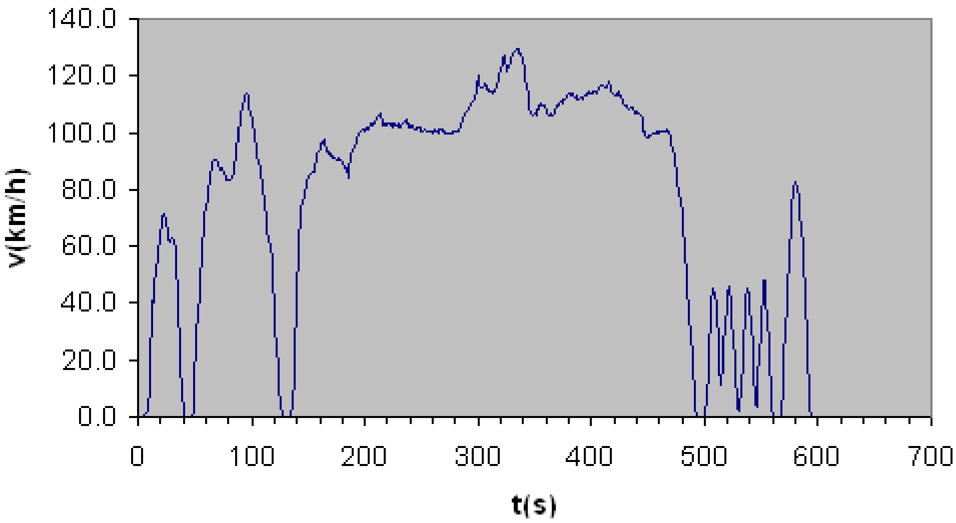

Figure 6.2: US06 Driving Cycle

This driving cycle has been run twice and 26km is driven. The results can be seen in Appendix B. After this cycle, 4.36kWh of energy is recovered through regenerative braking and electric propulsion has conducted 2.43kWh of energy to the system. The SOC has been dropped only 2.5% because vehicle generally used electrical energy in full throttle accelerations by using the driving electrical machine as an assist motor. Also, by regenerative braking, the kinetic energy of the vehicle, mainly gained from engine, is recovered to charge up the batteries.

Overall driving performance which can be seen in Appendix B is considered, it could be said that vehicle was able to meet this driving cycle's aggressive demands so motor and engine is thought to be adequate in performance.

CONCLUSION

In this thesis, electrical vehicle concept is defined. Electrical propulsion systems and electrical energy storages are explained. Energy management of a hybrid electrical vehicle is considered and amortization of the hybrid investment is discussed. As a practical part, a series parallel hybrid electrical vehicle is modeled and its simulation is run in Matlab R13/Simulink 5 mathematical modeling computer program.

The commercial and educational vehicle simulation programs are considered to be closed boxes and it not possible to build up an innovative energy management system. The developed simulation can be diversified by installing new type of engine, electrical machine and battery models; also it can be run on any driving cycle developed. Also, it offers a base to complicated models, which can utilize more detailed engine models, defining the fuel consumptions and calculating the emissions.

Developed model is optimized to develop new topologies as well as building up energy management strategies. Resulted simulation is thought to be an optimized full series parallel hybrid electric vehicle. By obtaining proper results for two different characterized driving cycles supports this.

Until a breakthrough in fuel cell or battery technology occurs, hybrid electrical vehicles will be the most popular new vehicle trend for some decades. Increase of the prices in petroleum is also supporting this trend. These vehicles are controlled by computer programs and it is possible to develop tailor made energy management systems for each vehicle in each driving conditions. So, it is best to describe different and optimized energy management systems for different drive cycles. For a further work, an optimization tool for different drive cycles, including Istanbul drive cycle can be built and more effective amortization scenarios, for a certain region and certain driving habits, can be developed. It is thought to be a good information source for automotive producers and users, and even governmental or civil organizations to realize the potentials of hybrid electrical vehicle benefits.

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APPENDIX A – URBAN DRIVING CYCLE RESULTS

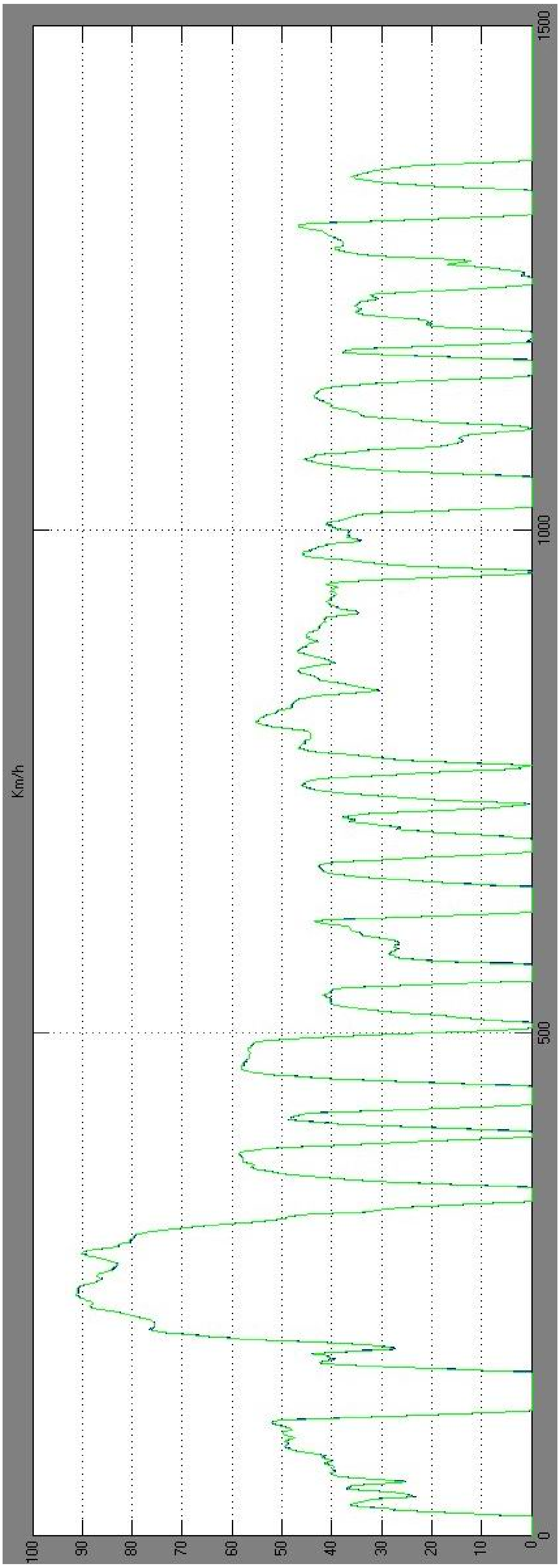

Figure A.1 Speed vs. Time graphic for UDDC

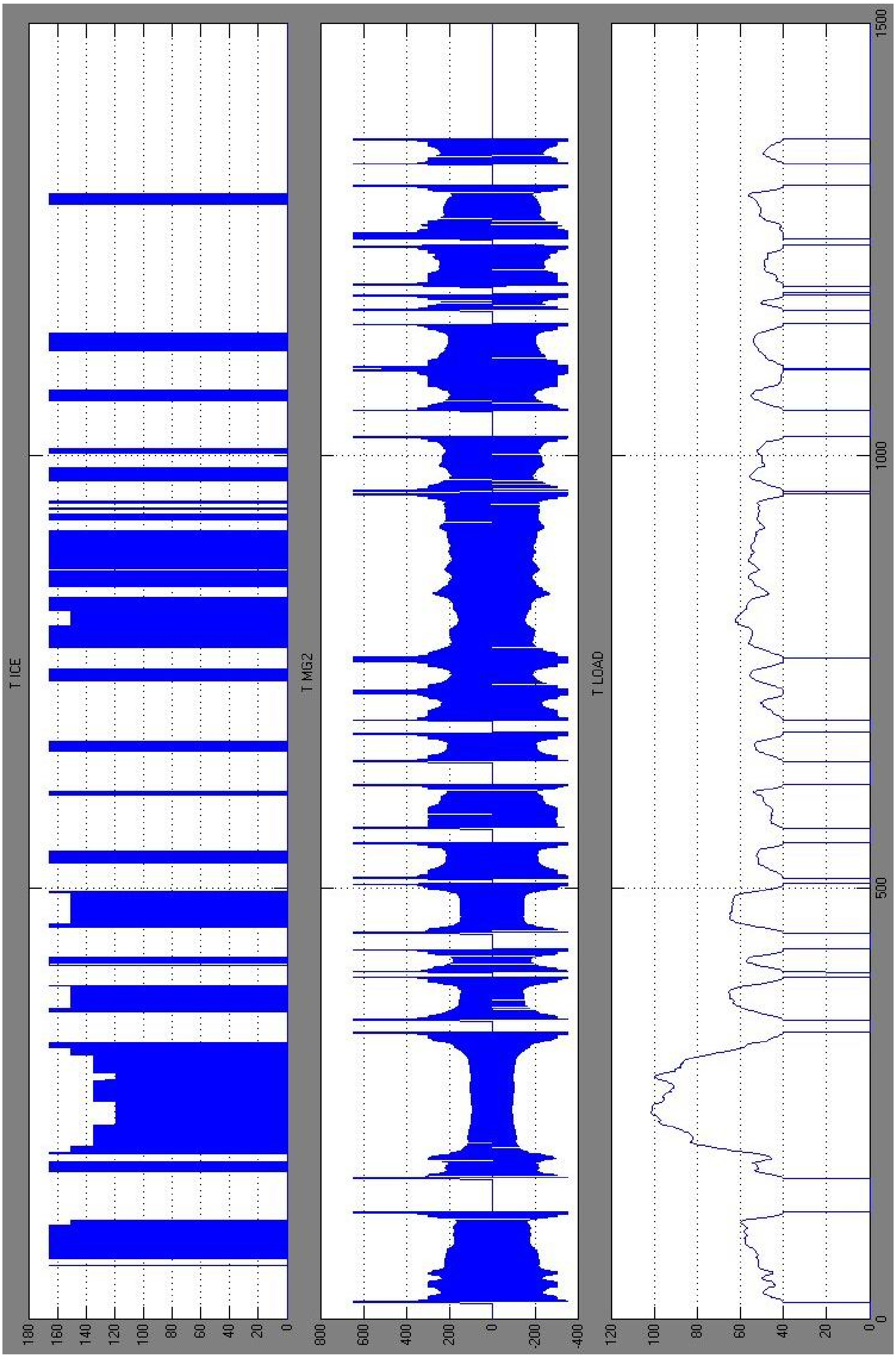

Figure A.2 ICE, MG2 and Load Torque Values during UDDC

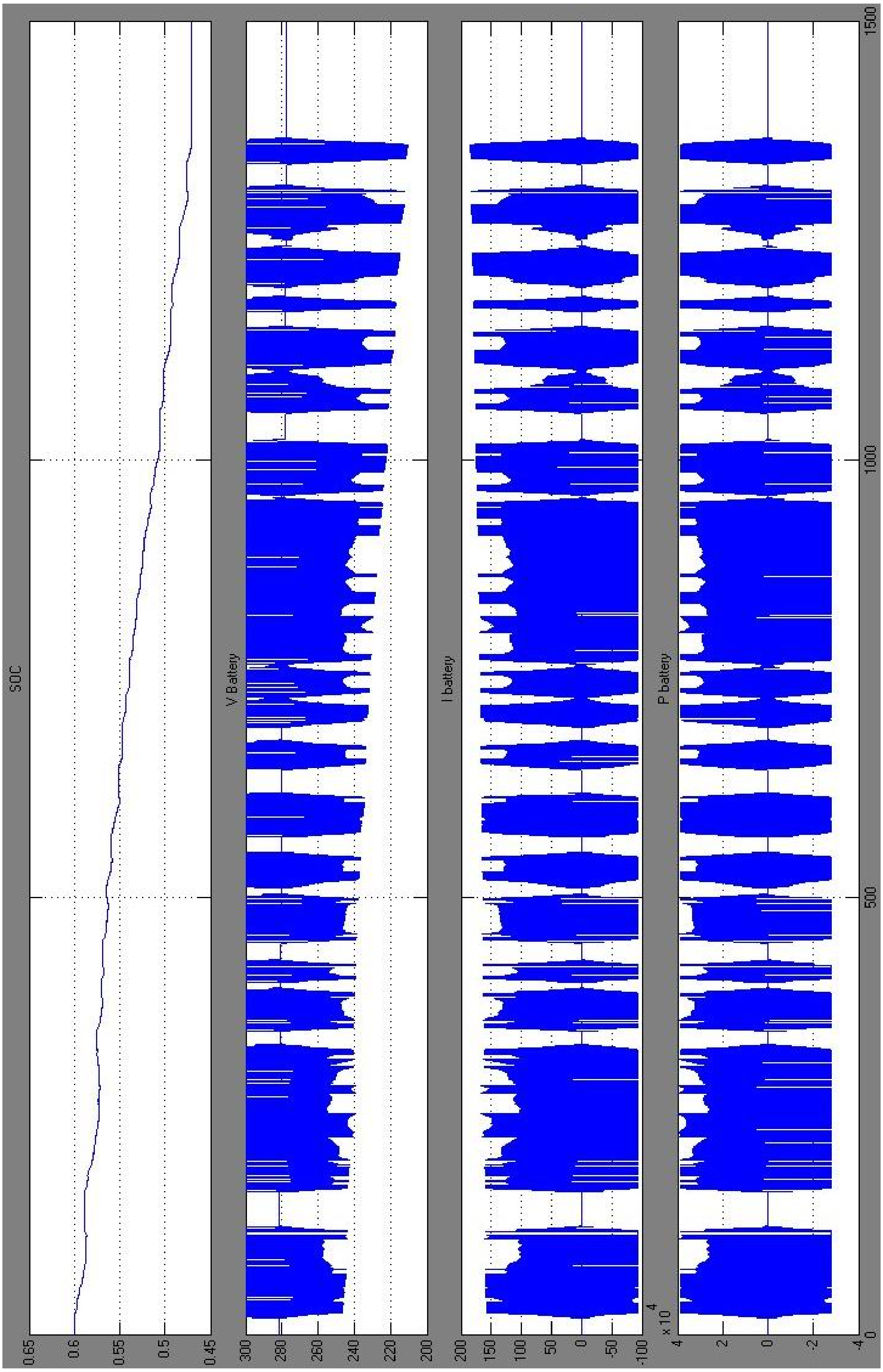

Figure A.3 SOC, Battery Voltage – Current and Power during UDDC

APPENDIX B – HIGHWAY DRIVING CYCLE RESULTS

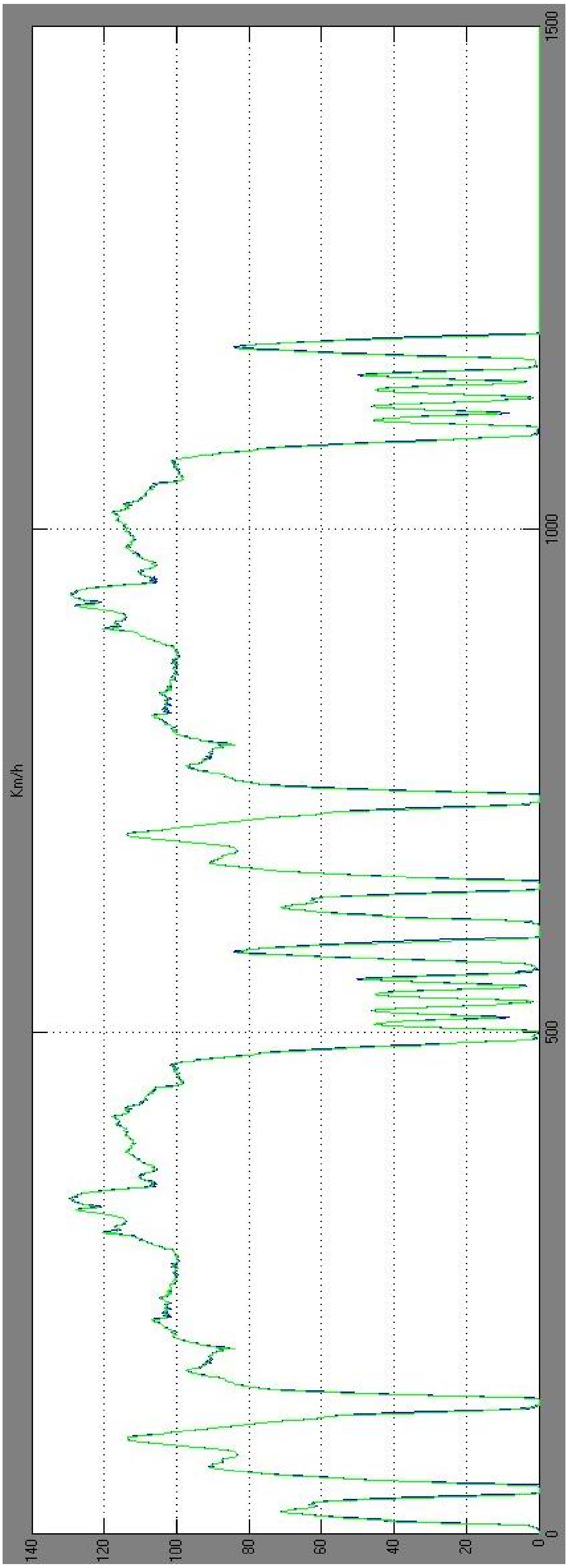

Figure B.1 Speed vs. Time for US06

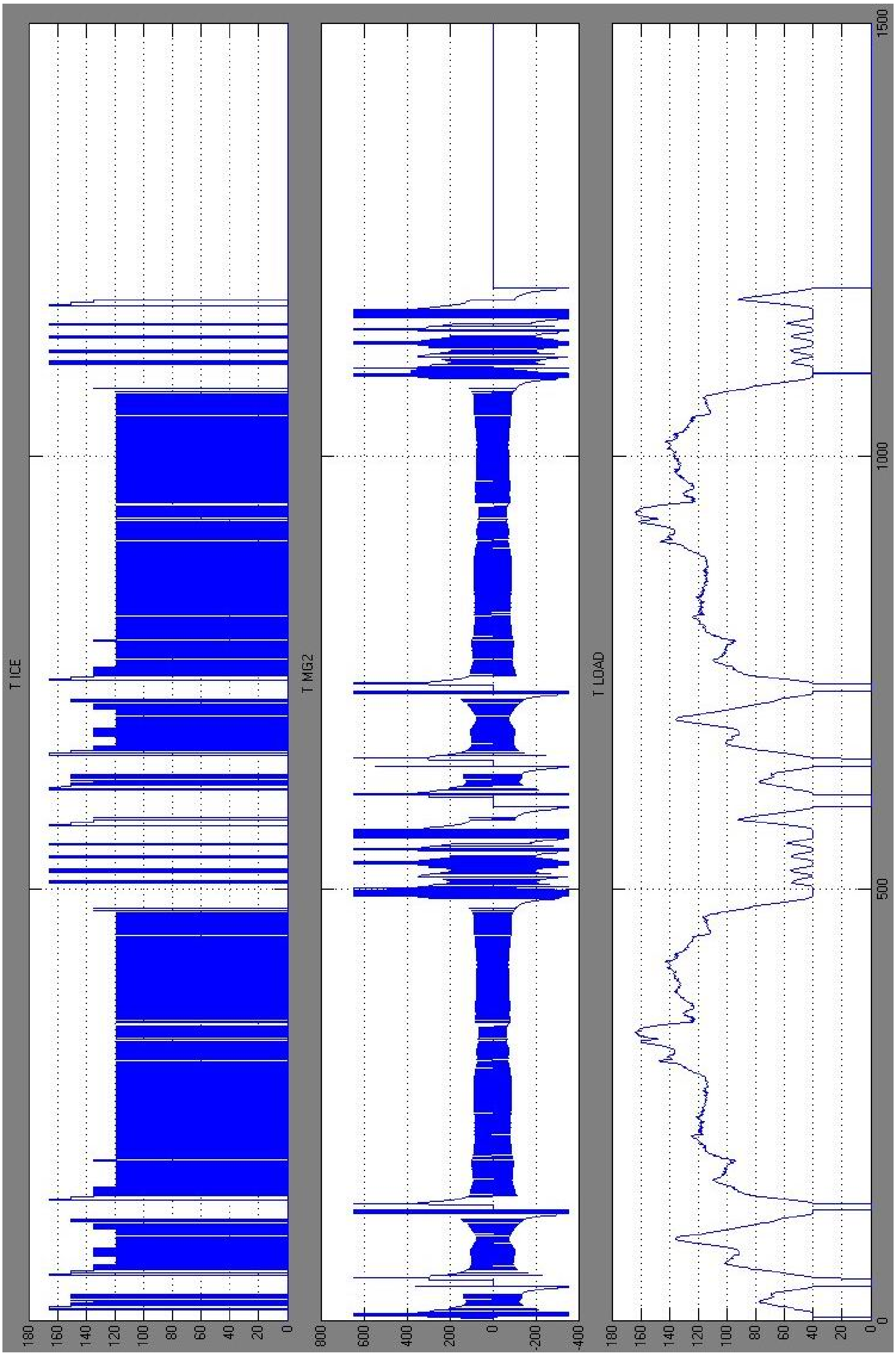

Figure B.2 ICE, MG2 and Load Torques during US06

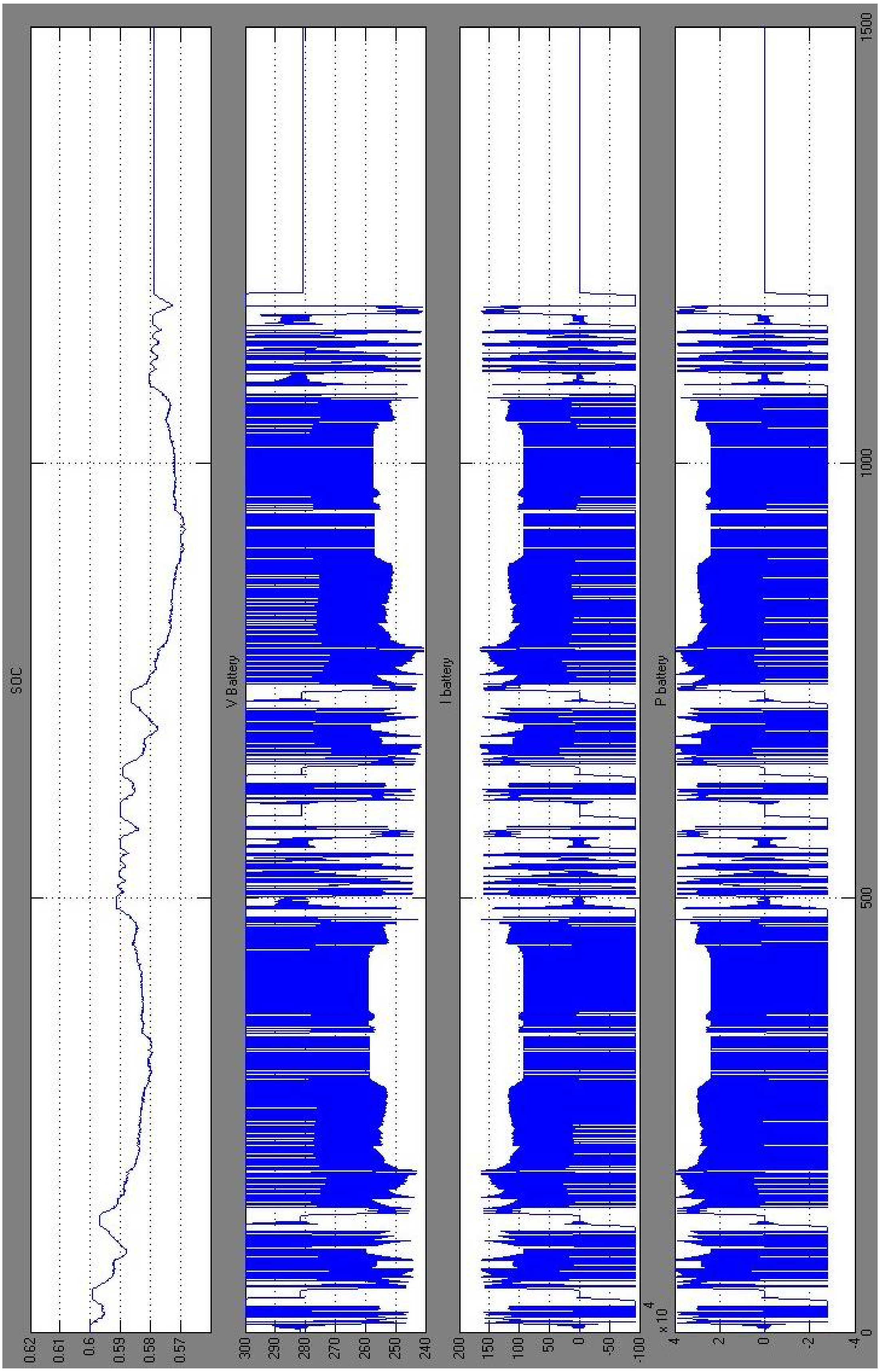

Figure B.3 SOC, Battery Voltage – Current and Power during US06

APPENDIX C – PARAMETERS OF SERIES PARALLEL HEV (PARAMETERS.M FILE)

ct = 0.01; % Rolling Resistance Coefficient

sig = 1.17; % Air Density (kg/m3)

cw = 0.3; % Drag Coefficient

Af = 1.746; % Frontal Area (m2)

nt = 0.90; % Transmission Efficiency (Non-CVT)

g = 9.81; % Gravity (m/s2)

rw = 0.282; % Wheel Radius (m)

G_reduction=3.905; % Reduction Gear Coefficient

mt = 1300; % Total Weight of the Vehicle (kg)

Vbus = 274; %Nominal Bus Voltage (V)

EFF_CVT=1; % CVT Efficiency

EFF_MG=0.85; % MG1 and MG2 efficiency

% Below are the data for MG2 (Motor / Generator)

MG2_RPM = [0 10 20 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 2500 2600 2700 2800 2900 3000 3100 3200 3300 3400 3500 3600 3700 3800 3900 4000 4100 4200 4300 4400 4500 4600 4700 4800 4900 5000 5100 5200 5300 5400 5500 5600 5700 5800 5900 6000 7000];

MG2_T = [0 50 350 350 350 350 350 300 300 300 300 300 300 280 255 238 225 212 200 186 175 164 155 146 140 135 130 125 120 115 110 107 104 101 98 95 92 90 87 85 82 80 78 76 74 71 69 67 65 63 62 61 60 58 56 55 54 53 52 51 50 25 0 0];

MG2_P = [0 1 2 3 6 9 12 13 17 21 25 29 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 33 16 0 0];

%Below are the data for MG1 (Generator)

MG1_RPM = [0 500 1000 1500 2000 2500 3000 3500 4000 5500 6000];

MG1_T = [55 55 55 55 55 55 48 41 36 26 18];

MG1_P = [0 5 15 15 15 15 15 15 15 5 0];

RESUME – ÖZGEÇMİŞ

Can Gökçe was born in 1980, Eskişehir. He has finished high school in Antalya Private Science High School, in 1998 and started Istanbul Technical University, Electrical Engineering Program in the same year. He had graduated as an electrical engineer in 2002 and started Electrical Engineering Master Program in İ.T.Ü. in the same year.

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Can Gökçe 1980 yılında Eskişehir'de doğdu. Lise eğitimini Özel Antalya Fen Lisesi'nde 1998 yılında tamamladıktan sonra yine aynı senede İstanbul Teknik Üniversitesi'nde Elektrik Mühendisliği eğitimine başladı. 2002 yılında elektrik mühendisi olarak mezun olduktan sonra yine aynı sene içerisinde İTÜ'de Elektrik Mühendisliği Yüksek Lisans Programı'na başladı.

Nisan 2004'ten bu yana da Mekatro Ar-Ge ve Tic. A.Ş.'de araştırmacı olarak görev yapmaktadır.