ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Serpil AĞYEL

COMPUTER SIMULATION FOR SERIES HYBRID ELECTRICAL VEHICLE

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

ADANA, 2011

ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

COMPUTER SIMULATION FOR SERIES HYBRID ELECTRICAL VEHICLE

Serpil AĞYEL

MSc THESIS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on 10/02/2011.

…….....	……..	…….....
Asst. Prof. Dr. Murat AKSOY	Assoc. Prof. Dr. Ulus ÇEVİK	Asst. Prof. Dr. Mutlu AVCI
SUPERVISOR	MEMBER	MEMBER

This MSc Thesis is written at the Department of Institute of Natural And Applied Sciences of Çukurova University.
Registration Number:

Prof. Dr. İlhami YEĞİNGİL
Director
Institute of Natural and Applied Sciences

Not: The usage of the presented specific declarations, tables, figures, and photographs either in this thesis or in any other reference without citiation is subject to "The law of Arts and Intellectual Products" number of 5846 of Turkish Republic

ABSTRACT

MSc. THESIS

COMPUTER SIMULATION FOR SERIES HYBRID ELECTRICAL VEHICLE

Serpil AĞYEL

ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Supervisor : Asst. Prof. Dr. Murat AKSOY
Year: 2011, Pages: 115
Jury : Assoc. Prof. Dr. Ulus ÇEVİK
: Asst. Prof. Dr. Mutlu AVCI

With increasing oil price and mounting environment concerns, cleaner and sustainable energy solutions have been demanded. At present transportation constitutes a large portion of the energy consumed and pollution created. The work presented here deals with evaluation and optimisation of the tractive system in hybrid electric buses. The work is based on analytical simulation models that are verified via measurements. The subject of this thesis is the control of the load distribution between the power sources in the hybrid electric powertrain. The control problem is to choose the distribution of power from the electric buffer and primary power unit that minimizes the fuel consumption in the long run. To solve this problem the efficiency characteristics of the components in the powertrain must be considered. It is the advantage of hybrids to have the extra degree of freedom because of the buffer so that the primary power unit can be driven independent of the transient traction demand of the vehicle powertrain. Using a simple model of the power flows, energy levels and a regression model of the future driving, the resulting policy minimizes the expected fuel consumption with respect to the prediction model of the future driving conditions.

Key Words: Series Hybrid Bus, Modelling, Simulation

ÖZ

YÜKSEK LİSANS TEZİ

HİBRİT ELEKTRİKLİ ARAÇLAR İÇİN BİLGİSAYAR SİMULASYONU

Serpil AĞYEL

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
ELEKTRİK – ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI

Danışman :Yrd. Doç. Dr. Murat AKSOY
Yıl: 2011, Sayfa: 115
Jüri : Doç. Dr. Ulus ÇEVİK
: Yrd. Doç. Dr. Mutlu AVCI

Yükselen yakıt ve montaj fiyatlarıyla birlikte çevresel kaygılar, daha temiz ve sürdürülebilir enerji çözümlerini talep ettirmiştir. Şu anki ulaşım çevre kirliliği yaratmakta ve çok büyük oranda da enerji tüketimi oluşturmaktadır. Burada sunulan çalışma hibrit elektrik otobüslerindeki çekiş sisteminin optimizasyonu ve evaluasyonuyla ilgilenmektedir. Bu çalışma, ölçümlerle doğrulanan analitik simülasyon modellerine dayanmaktadır. Bu tezin konusu aracın güç ihtiyacını içten yanmalı motor ve elektrik depolama ünitesi gibi farklı kaynaklardan karşılayarak uzun vadede yakıt tüketimini en düşük seviyeye indirmektir. Bu problemi çözmek için sistemdeki elemanların verim karakteristiklerinin bilinmesi ve kullanılması gerekmektedir. Hibritlerin avantajı ise elektrik depolama ünitesinin ekstra serbestlik derecesi sayesinde tahrik sistemi elemanlarının verimliliklerinin yüksek olduğu işletim bölgelerinde çalıştırılabilmeleridir. Sürücü tarafından gelecekte talep edilecek güç değerlerinin tahmininin zor olması en iyi yapma problemini güçleştirmektedir. Bu tezde hesaplamalarında kullanılmak üzere gelecek tahminleri yapılmaktadır. Güç akışlarının kontrolü, gelecek hız tahminleri ve verimli işletim bölgelerinin kullanımı yakıt tüketiminin azaltılmasına yardımcı olmuştur.

Key Words: Seri Hibrit Otobüs, Modelleme, Simülasyon

ACKNOWLEDGEMENTS

Foremost, I would like to express my gratitude to my supervisor Asst. Prof. Dr. Murat AKSOY. This thesis would not have been possible unless his limitless patience, knowledge, guidance and kind support.

I would like to send my greatest thanks to Mr. Andreas BAUMANN from TEMSA Global A.Ş. for their support, advice and time.

I am deeply grateful to Burak KİRAY, Sibel KAFTAR and Deniz ERDOĞAN for their support and help during my studies.

I owe a great and special thanks to Yusuf IŞIKLI for his never-ending encouragement, support and help.

Finally, I would like to thank my family for their endless love and encouragement throughout my life.

CONTENTS **PAGE**

ABSTRACT I
ÖZ II
ACKNOWLEDGEMENTS III
CONTENTS IV
LIST OF TABLES VIII
LIST OF FIGURES X
LIST OF ABBREVIATONS XII
1. INTRODUCTION 1
1.1. Background 1
1.2. The Need of Hybrid Electric Vehicles 1
1.3. Main Results 3
2. PRELIMINARY WORK 5
2.1. Contemporary Vehicle Powertrain Technologies 5
2.2. Internal Combustion Engine Vehicles 37
2.2.1. Conventional Vehicles 37
2.3. Electric Vehicles 9
2.3. Hybrid Vehicles 10
2.4.1. Introduction 10
2.4.2. HEV Classifications by Power Source 11
2.4.2.1. Internal Combustion Engine Based HEV 11
2.4.2.2. Fuel cell Based HEV 11
2.4.3. HEV Classifications by Drivetrain Architectures 12
2.4.3.1. Series hybrid 12
2.4.3.2. Parallel Hybrid 16
2.4.3.3. Power Split Hybrid 19
2.5. Review on Hybrid Electric Vehicles Energy Storage System 21
2.5.1. Research Issues in Hybrid Electric Vehicles Design 21
2.5.2. Energy Storage System 22
2.5.2.1. Sizing Considerations of Energy Storage System 22

2.5.2.2. ESS Power and Capacity Rating 23
2.5.2.3. ESS for an Electric Vehicle 25
2.5.2.4. ESS for a Hybrid Electric Vehicle 26
2.5.2.5. ESS for a Plug-in Hybrid Electric Vehicle 28
2.5.3. Advance of Energy Storage Technologies and Hydrogen Fuel Cells 29
2.5.3.1. Sealed Lead Acid Battery (SLA) 30
2.5.3.2. Nickel Metal Hydride Battery (Ni-MH) 30
2.5.3.3. Lithium Ion Battery (Li-ion) 31
2.5.3.4. Ultracapacitors 32
2.5.3.5. Hydrogen Fuel Cells 33
3. MATERIAL AND METHOD 35
3.1. Vehicle Simulation Tools 35
3.2. ADvanced VehIcle SimulatOR (ADVISOR) 35
3.2.1. ADVISOR Background 35
3.2.2. ADVISOR Modeling Approaches 36
3.2.3. ADVISOR Interface 37
3.2.4. Models in ADVISOR 41
3.2.4.1. Internal Combustion Engines and PEM Fuel Cells Models 41
3.2.4.2. Energy Storage Model 41
3.2.4.3. Electric Motor and Motor Controller Models 41
3.3. The flexible ELFA System (Electric Low Floor Axle (ELFA), ...42
3.3.1. Background 42
3.3.1.1. Range from hybrid drive up to pure electric drive 43
3.3.2. ELFA: advantages at a glance 44
3.3.2.1. Sensible: Braking energy is regenerated and stored 45
3.3.2.2. Increased degree of cost effectiveness and flexibility 45
3.3.2.3. For buses around the world: Tailored and system-based solutions 46
3.3.2.4. The standard: Systems with rugged induction motors 46
3.3.2.5. The alternative: Sys. with permanent-magnet synchronous motors 46
3.3.2.6. The generators: mechanical unit together with the traction motor.....47
3.3.2.7. The traction converters: Compact and can be used in a modular.....47

3.3.2.8. The open-loop control software – tailored customer solutions 47
3.3.3. A real milestone for urban bus traffic 48
3.3.4. Energy mix for ELFA applications 48
3.3.4.1. Hybrid drive with internal combustion engine 49
3.3.4.2. Hybrid drive with fuel cell 49
3.3.4.3. Battery drive 50
4. RESEARCH AND DISCUSSION 51
4.1 Modelling the Vehicle Dynamics in Series Hybrid System 51
4.2 Simulation Model 53
4.2.1. Introduction to the Program-model 54
4.2.2. User Interface of the Program 55
4.2.3. Program Model 57
4.3. Series Hybrid Vehicle Architecture 57
4.3.1. Mechanical Dynamics 59
4.3.2. Electric Traction Motor 61
4.3.3. Ultracapacitors 62
4.3.3.1. Ultracapacitor Power Charts 62
4.3.3.2. Specification 63
4.3.3.3. 125 Volt Transportation Modules 63
4.3.3.4. Features 64
4.3.3.5. Benefits 64
4.3.3.6. Advantages In Hybrid Vehicles 64
4.3.3.7. Implementation 65
4.3.4. ICE in Test Bench 65
4.4. Series Hybrid Bus Operation 66
4.4.1. UCAP State of Charge 66
4.4.2. BRAKING 67
4.4.3. ACCELERATION & CRUISING 67
4.4.4. IDLE 68
4.5. Drive Cycles 68
4.6. Simulation Parameters 69

4.7. Vehicle Dynamics Results 70
4.8. Optimization Method Results 73
4.8.1. Classical Road drive cycles; 73
4.8.1.1. Case 1 73
4.8.1.2. Case 2 75
4.8.1.3. Case 3 76
4.8.2. Metropolis Drive Cycle 78
4.8.2.1. Case 1 79
4.8.2.2. Case 2 80
4.8.2.3. Case 3 82
5. CONCLUSION 87
REFERENCES 89
CURRICULUM VITAE 93
APPENDIX A: MATLAB/SIMULINK 94
APPENDIX B: Ultracapacitors (Maxwell Technologies, 2009) 96

LIST OF TABLES **PAGE**

Table 2.1. Characteristic of a Benchmark EV.....25
Table 2.2. ESS Sizing for a Benchmark EV 26
Table 2.3. Specs of Ni-MH on a 2004 Toyota Prius 27
Table 2.4. ESS Sizing for a HEV 27
Table 2.5. UC-battery Hybrid ESS for Prius 1.....28
Table 2.6. UC-battery Hybrid ESS for Prius 2.....29
Table 2.7. Battery Performance Characterizes for HEV and EV.....32
Table 4.1. Maxwell ultracapacitor module specifications 63

LIST OF FIGURES **PAGE**

Figure 2.1. Current vehicle powertrain technology categories 6
Figure 2.2. A conventional vehicle driveline 7
Figure 2.3. Conventional Vehicle Engine Operating Points 8
Figure 2.4. An electric vehicle drivetrain 9
Figure 2.5. Series hybrid vehicle 13
Figure 2.6. Series hybrid vehicle engine operating region 14
Figure 2.7. Power flow in series hybrid vehicles 15
Figure 2.8. Paralel hybrid vehicle 17
Figure 2.9. Pre-Transmission Parallel HEV Configuration 17
Figure 2.10. Post-Transmission Parallel HEV Configuration 17
Figure 2.11. All Wheel Drive Parallel HEV Configuration 18
Figure 2.12. Complex hybrid vehicle 20
Figure 2.13. The planetary gear 21
Figure 2.14. Power/Energy Ratio of Vehicle Demand and ESS Capability 24
Figure 3.1. Flow Chart of a Backward Modeling Approach 37
Figure 3.2. ADVISOR/Simulink Block Diagram of a Two-mode Truck 37
Figure 3.3. ADVISOR Vehicle Input Interface 39
Figure 3.4. Simulation Setup Interface 39
Figure 3.5. Simulation Result Window 40
Figure 3.6. Siemens ELFA system diagram 43
Figure 3.7. ELFA operating range of series hybrid 49
Figure 4.1. A typical P_{aux} (w) curve 53
Figure 4.2. User interface of the hybrid bus simulation program 56
Figure 4.3. The highest level in the simulation program Simulink 57
Figure 4.4. Vehicle Architecture 1 58
Figure 4.5. Vehicle Architecture 2 58
Figure 4.6. Vehicle Hybrid System Structure 59
Figure 4.7. The mechanical level in the simulation program 60
Figure 4.8. The efficiency of an electric motor 61

Figure 4.9. Ultracapacitor power discharge profiles 62
Figure 4.10. The emissions from the Cummins natural gas ICE 66
Figure 4.11. Serial Hybrid energy savings potential 67
Figure 4.12. Classical Road Drive Cycle 68
Figure 4.13. Metropolis Drive Cycle 69
Figure 4.14. Grade Profile used for the drive cycles Classical Road and Istanbul City 70
Figure 4.15. Speed, Distance and Demanded Traction Power for Classical Road drive cycle 71
Figure 4.16. Energy Consumption with / without Regenerative Braking 72
Figure 4.17. Speed, Distance and Demanded Traction Power for Metropolis drive cycle 72
Figure 4.18. Energy Consumption with or without Regenerative Braking 73
Figure 4.19. SoC, fuel consumption and generator power for Classical Road drive cycle case 1 74
Figure 4.20. Optimization results for Classical Road drive cycle case 1 75
Figure 4.21. Optimization results for Classical Road drive cycle case 2 76
Figure 4.22. SoC, fuel consumption and generator power for Classical Road drive cycle Case 3 77
Figure 4.23. Optimization results for Classical Road drive cycle Case 3 78
Figure 4.24. SoC, fuel consumption and generator power for Metropolis drive cycle Case 1 79
Figure 4.25. Optimization results for Metropolis drive cycle Case 1 80
Figure 4.26. SoC, fuel consumption and generator power for Metropolis drive cycle Case 2 81
Figure 4.27. Optimization results for Metropolis drive cycle Case 2 82
Figure 4.28. SoC, fuel consumption and generator power for Metropolis drive cycle Case 3 83
Figure 4.29. Optimization results for Metropolis drive cycle Case 3 84

LIST OF ABBREVIATONS

ABS : Anti-Lock Brake System
ADVISOR : ADvanced VehIcle SimulatOR
AER : All electric range
BSFC : Brake specific fuel consumption
CAN : Controller Area network
CVT : Continuously variable transmission
DOH : degree of hybridization
ELFA : Electric Low Floor Axle
ESS : Energy storage system
EV : Electric vehicle
FC : Fuel Cell
HEB : Hybrid Electric Bus
HV : Hybrid vehicle
ICE : Internal combustion engine
ICEV : Internal combustion engine vehicle
IMA : Integrated Motor Assist
L-A : Lead acid
Li-ion : Lithium Ion Battery
M/G : Motor/Generator
NCV : Net calorific value
Ni-MH : Nickel Metal Hydride
Ni-MH : Nickel Metal Hydride Battery
NREL : National Renewable Energy Laboratory
PEM : Proton Exchange Membrane
PHEV : Plug in hybrid electric vehicles
PZEV : Partial- zero-emission vehicle
SLA : Sealed Lead Acid Battery
SOC : State of Charge
TCU : Transmission control unit

UCAP : Ultracapacitor

UPS : Uninterrupted power systems

ZEV : Zero-emission vehicle

1.INTRODUCTION

1.1. Background

In the more than 100 years since its inception, the internal combustion engine vehicle (ICEV) has transformed modern civilization. Many benefits have been derived from the freedom and convenience these vehicles have provided. The technology has not been without its negative effects, however. For instance, the highway and road infrastructure to accommodate the increasing number of vehicles has placed a severe financial burden on governments for initial construction and subsequent maintenance (Wishart, 2008). In the United States, for example, $80 billion dollars are spent each year on maintenance and upgrading of the interstate system (Micklethwait, 2006a). Despite these drawbacks, vehicles are certain to become even more ubiquitous in the future, especially in developing nations. It is forecast that the number of cars per hundred people in China and India will increase from two in 2006 to 29 and 21, respectively, by 2040, adding some 720 million new cars to the current population (Micklethwait, 2006b).

1.2. The Need of Hybrid Electric Vehicles

Electric traction of vehicles is an old technique and has been used for example 1894 in an electric train. Electrical motors have higher torque density than an ICE (internal combustion engine), and thus the electrical traction system can have a more compact design than the ICE counterpart, e.g. the electrical motor can be mounted in the wheel. The life cycle on an electrical machine is longer than that of an ICE, they do not need oil change and do not generate any emissions. Another advantage in a vehicle is that they can regenerate the kinetic energy when braking. As a traction motor, the electrical machine is more suitable than any ICE.

The problem with an electrical driven vehicle is the amount of energy that must be brought with the vehicle to reach a reasonable driving distance. The main energy storage is electro chemical (batteries), electro mechanical (flywheels) and

electro static (super capacitors). No electric bus equipped with these energy storages can store an amount of energy on the bus that is comparable to e.g. the energy in the diesel tank of a pure diesel bus.

An important trend for the future of electric vehicles is the use of fuel cells that allow for direct conversion of a high-energy medium (gas of fluid) to electricity. In the future, the fuel cell vehicle may compete with conventional ICE vehicles.

One solution to the electrically driven vehicle's energy storage problem is to bring along an ICE and a generator, which can assist the electro chemical energy storage with electric energy from chemical energy with high energy density. From a driving distance point of a view, such a vehicle has the sameadvantages as the pure ICE driven vehicles. From an emissions point of view the hybrid vehicle also has similar disadvantages as the ICE driven vehicle. But, there is a small and important difference, the ICE does not have to produce all the instantaneous power for driving, and there is a freedom to choose operating point for the ICE to keep the state of Charge (SOC) of the batteries within reasonable limits.

The battery assists with the difference between the total power used in the vehicle (including tractive power) and the power produced by the ICE-driven generator. The possibility of choosing the working points of the ICE more freely in a hybrid vehicle makes it possible to optimise some parameters. The energy consumption is one parameter and emissions another. To optimise the composition and use of a hybrid electrical vehicle, it is necessary to start by defining what qualities and performance or what combinations of these that is regarded as optimal.

Electrical hybrid vehicle can be built in any conventional type, like trucks buses and small cars. The electrical vehicle's qualities with a silent and emissions free (the ICE turned off) operation are particularly interesting in the centre of the city (Andersson, 2001).

This thesis describes a scientific evaluation of a commercial hybrid bus, with special focus on the simulation and control of the traction system including the batteries, combustion engine and electrical machines.

There are several commercial simulation programs available for electrohybrid vehicles. They are often made for specific customers or for specific hybrid structures,

and do not allow the kind of changes in detail and/or topology that we anticipate to need.

For all simulation programs a lot of parameters are requested like efficiency, consumption and emissions. The manufacturer of the components in a particular vehicle could supply these parameters, but often the manufacturers are not willing to supply key parameters, like the efficiency of their product. It is also required to have a good knowledge about the components in the vehicle as well as the driving cycle. This has been obtained in this work by measurements on the hybrid bus, both on the bus in traffic and directly on some of its components.

1.3. Main Results

The work performed for this MSc. research began with a thorough survey of the current trends in HV development, with a documentation of the state of the art of hybrid vehicle research. With a clear view of the path chosen by industry to development of this powertrain technology, the research focused on the development of virtual prototypes of hybrid vehicle powertrains through the use of design tools. Dynamic modelling of the selected designs is used to accurately describe the powertrain mechanisms' functions. Simulations are conducted to predict the performance of the developed models. An optimization of one of the powertrain components is performed to demonstrate the potential of optimization to improve designs. Finally, experimental validation of the results of the modelling and simulation is conducted to confirm or refute theoretical predictions. These steps are crucial aspects of the development of the virtual prototype. A virtual prototype is indispensible in the competitive industry of automotive development because it allows for design change effects to be measured quickly and easily and without the need to manufacture expensive physical prototypes with each change.

The authors' main contribution with the work presented in this thesis is:

· A simulation program for a HEB (Hybrid Electric Bus), verified via measurements, taking all major power conversion processes into account, modelling efficiency and emissions, given a particular drives cycle and vehicle specification.

· A predictive charging strategy that utilizes the repetitive nature of a bus route to predict the power need and thus allow a smoother use of the ICE

2. PRELIMINARY WORK

2.1. Contemporary Vehicle Powertrain Technologies

There are three main categories of powertrain technologies: (1) ICEVs, (2) Electric vehicles (EVs), and (3) Hybrid vehicles (HVs). The vehicles in these categories (with appropriate names and acronyms included) are presented in Figure 2.1 below. It should be noted that experimental technologies, such as compressed air propulsion systems, which are being pursued sporadically in research and development have not been included in this survey.

Several of the entries in Figure 2.1 are often written to include the term 'ESS'. ESS refers to an energy storage system, which can be a battery, an ultracapacitor, a flywheel or a combination of the three. The flywheel technology is rarely used in vehicular applications because of the danger associated with a large, heavy mass spinning with considerable angular momentum being unleashed in the event of an accident. As such, they are not included in this dissertation.

Due to the increasing problems of continued unfettered fossil fuel usage in vehicular applications, an interest in the development of partial- and zero-emission vehicles, known as PZEVs and ZEVs, respectively, has arisen. A PZEV is defined as a vehicle that is 90% "cleaner" than the average new model year vehicle, while the ZEV is 98% cleaner than the average new model year vehicle (driveclean.gov, 2006). However, there exists considerable confusion in the literature nomenclature for classifying the types of powertrain technologies of PZEVs and ZEVs.

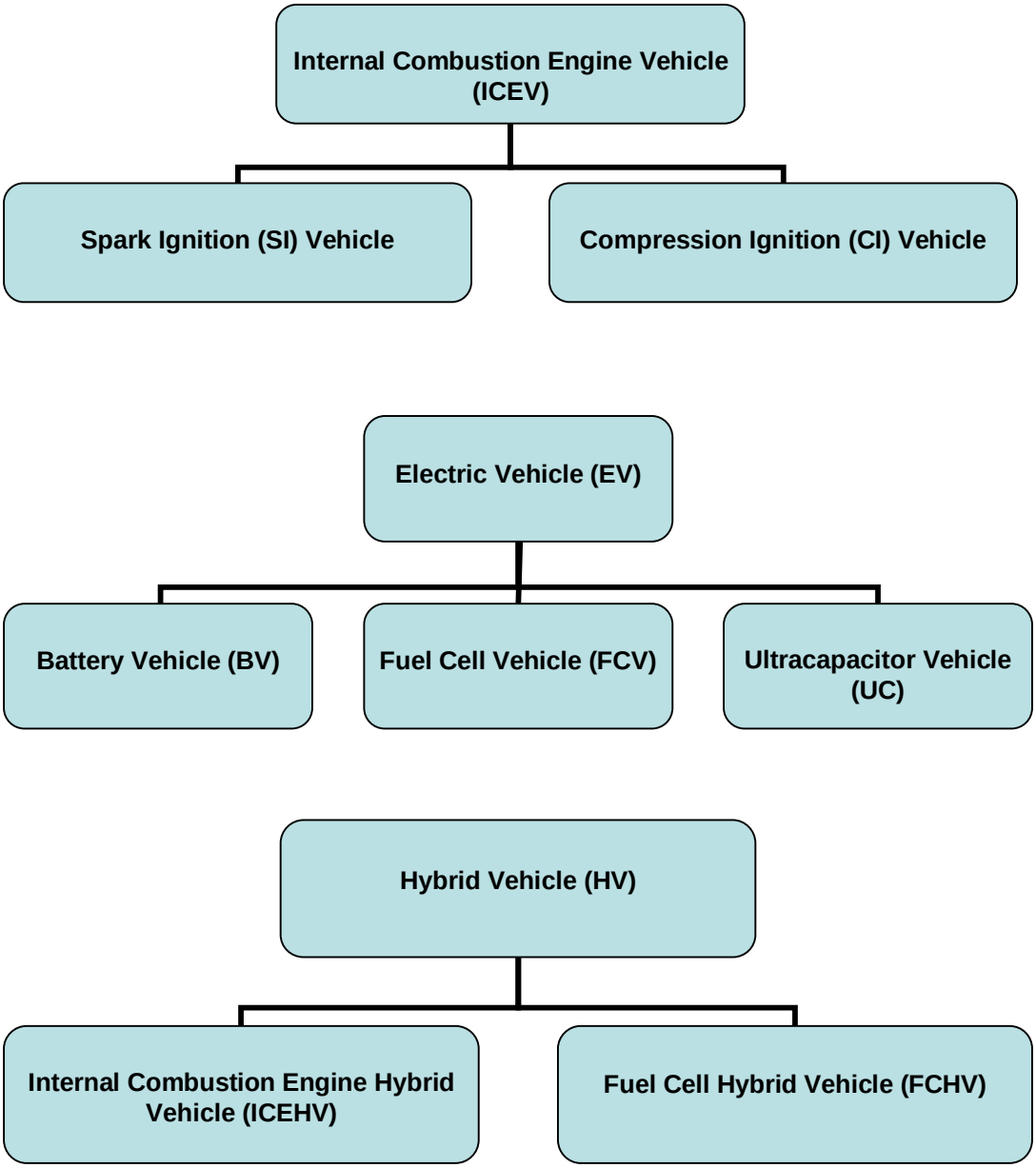


Figure 2.1. Current vehicle powertrain technology categories

2.2. Internal Combustion Engine Vehicles

2.2.1. Conventional Vehicles

Although everybody is familiar with conventional vehicles, their features are summarized here to form a basis of comparison. Figure 2.2 shows the layout of a conventional vehicle drivetrain.

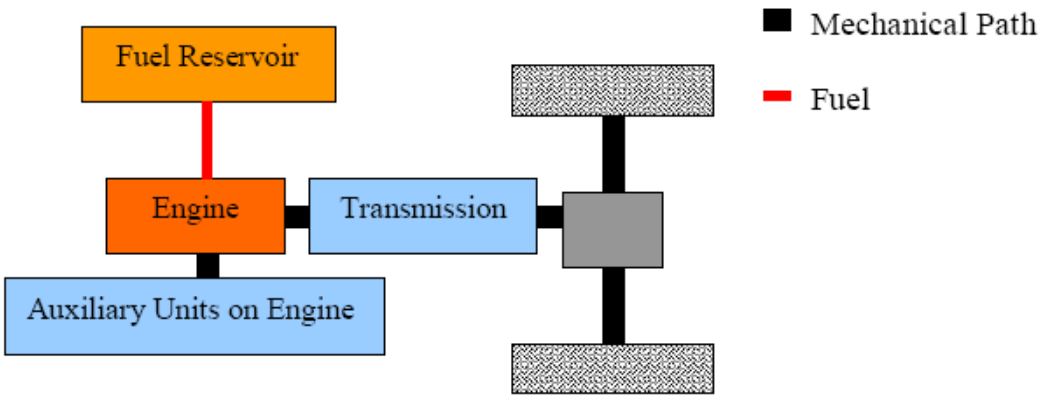


Figure 2.2. A conventional vehicle driveline (Okan, 2008)

In a conventional vehicle an internal combustion engine drives a transmission that drives the differential that drives the wheels. The internal combustion engine (ICE) can be diesel or gasoline. The transmission can be manual, automatic or continuously variable transmission (CVT). A conventional vehicle is relatively cheap and easy to control. It does not require extra control besides the engine control unit (ECU) and the automatic transmission control unit (TCU) if an automatic transmission is applied.

In conventional vehicles, operating points of the engine are concentrated in the inefficient regions of the brake specific fuel consumption (BSFC) maps. This is due to the mechanical coupling between the engine and the final drive and it is inevitable.

To identify the engine optimal operating points, it is common to use an engine efficiency map which is illustrated in Figure 2.3. It is a projection of a 3D

surface onto the speed-torque plane. Contours indicate the boundaries of the efficiency regions.

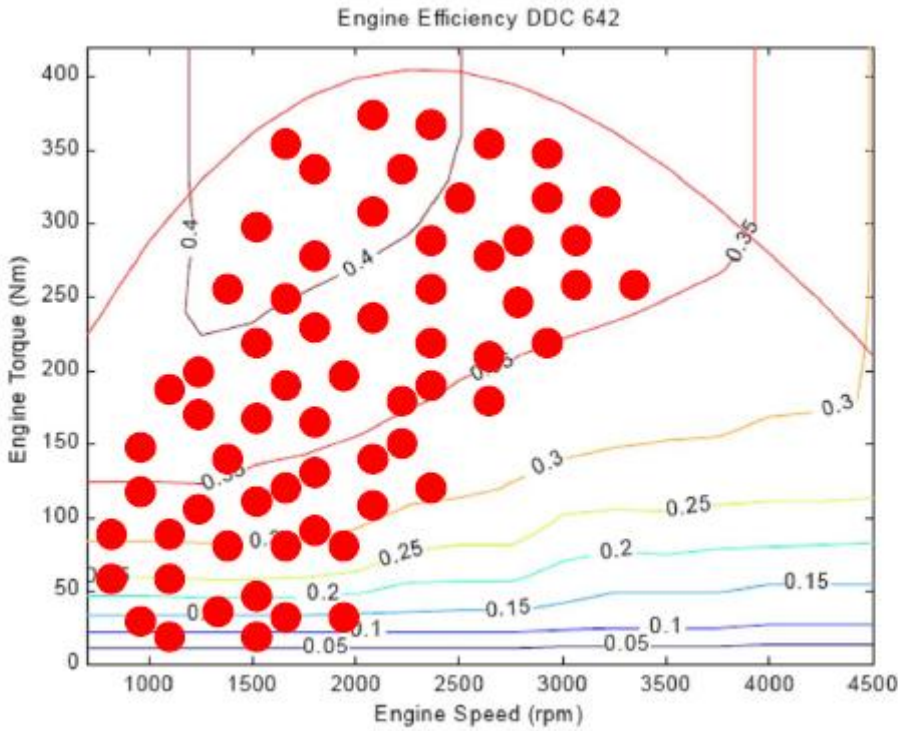


Figure 2.3. Conventional Vehicle Engine Operating Points (He, Parten and Maxwell, 2005)

Engine efficiency maps are presented using contours indicating either efficiency or fuel consumption in terms of mass per unit energy. The red curve at the top is the maximum torque limit. The red dots in Figure 2.3 indicate the periodically recorded operating points of a conventional vehicle (He, Parten and Maxwell, 2005). It should be noted that more than half of the points lie under the contour of 35% efficiency. The operating range mostly lies within the part of the graph where efficiency is low.

In a conventional vehicle the braking torque is generated via friction which dissipates the energy as heat. There is no storage mechanism to recuperate the brake energy (Okan, 2008).

2.3. Electric Vehicles

An electric vehicle (EV) has a powertrain consists of an electric motor, an energy storage device and a controller. The electric motor provides the power required to propel the vehicle. The energy storage device stores the electrical energy and supplies it to the electric motor. Although the energy storage device could be an ultracapacitor system as well as a battery pack or a combination of both. Figure 2.4 shows the layout of a typical electric vehicle.

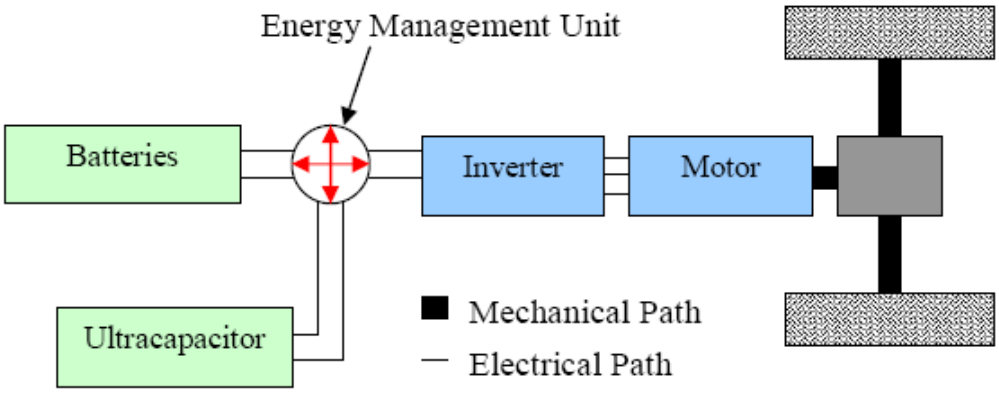


Figure 2.4. An electric vehicle drivetrain (Okan, 2008)

The main advantage of EV is that they don't emit exhaust gases. They are called zero emission vehicles (ZEVs), but it is important to mention that the generation of electrical power may not be free of emissions. According the "wells to wheels" concept, the emissions of the vehicle must be increased by the emissions of any kind related to the vehicle such as production and transportation.

The other advantage of EVs is their noiseless operation. EVs would decrease the noise level in cities significantly. EVs are competitive with conventional vehicles in complexity and price and even less complicated to control.

On the other hand, the disadvantage of the electric vehicle is its short range. It is limited by the capacity of the battery pack. Present battery technology may provide up to a certain mileage on a single charge depending on vehicle size, battery size and capacity and driving conditions.

The short range of EVs is not actually the main problem. While conventional vehicles can be refilled in few minutes, batteries of EVs need several hours of charging once they were fully discharged. Consumers are not used to being without their vehicles for hours every day. As a conclusion it may take a lot more to recharge the batteries as it takes to fill up the fuel tank for the same trip (Okan, 2008).

2.4. Hybrid Vehicles

2.4.1. Introduction

A definition of the entity hybrid vehicle is given by Michael Tamor at Ford Motor Company:

"A Hybrid vehicle is a conventionally fueled and operated vehicle that has been equipped with a power train capable of implementing at least the first three of the following four hybrid functions:

1) Engine shutdown when power demand is zero or negative.

2) Engine down-size for improved thermal efficiency

3) Regenerative braking for recovery and re-use of braking energy

4) Engine-off propulsion at low power (when engine is inefficient)"

A power train that fulfills at least the first three of the four functions above can be composed in a number of different ways, where series hybrid, parallel hybrid and variants of these are the most common. The ICE can be of different types, e.g. Otto, Diesel, Stirling etc. The electric energy storage can also be of several different types, like electro chemical (batteries), electro mechanical (flywheels) and electro static (super capacitors). The electrical machines can also be of several different types, although they are all rather alike in terms of efficiency (Andersson, 2001).

2.4.2. HEV Classifications by Power Source

There are many ways to classify hybrid electric vehicles. One way is based on principal power sources. Two major principal power sources for HEV are ICE and fuel cell system.

2.4.2.1. Internal Combustion Engine Based HEV

In an ICE based HEV, the engine is coupled with electric machine(s). This modification creates integrated mechanical and electrical drive trains that merge power from both the ICE and the electric motors to drive the vehicle. By using the energy storage system as a power buffer, the ICE can be operated at its most efficient condition and reduced in size while maintaining the overall performance of the vehicle. In this type of vehicles, fossil fuel, however, is still the sole energy source to the vehicle system, (except for plug-in HEV where electricity obtained from electrical grid provides another power source). The charge of the battery is maintained by the ICE and the electric machines. As a consequence of the reduced engine size, more efficient engine operation, and recovered braking power, fuel usage and emissions of the vehicle are considerably lower than comparable conventional vehicles (Zhou, 2007).

2.4.2.2. Fuel cell Based HEV

A fuel cell hybrid electric vehicle operates solely on electric power. The fuel cells continuously produce electrical power while energy storage devices buffer the power flow in the electric power train. A fuel cell system is an electric power-generating plant based on controlled electrochemical reactions of fuel and oxidant [Carlson, Kopf and Sinha, 2005). In principle, fuel cells are more efficient in energy conversion and produce zero emission. Due to many attractive features, such as low operation temperature, compact structure, fewer corrosion concerns, and quick start-

up, the Proton Exchange Membrane (PEM) fuel cells serves as an ideal power plant for automotive applications (Zhou, 2007).

2.4.3. HEV Classifications by Drivetrain Architectures

One of the most common ways to classify HEV is based on configuration of the vehicle drivetrain. In this section, three major hybrid vehicle architectures introduced are series, parallel and series-parallel. Until recently, many HEV in production are either series or parallel. In terms of mechanical structure, these two are primitive and relatively simple. A series-parallel powertrain brings in more degrees of freedom to vehicle engine operation with added system complexity.

2.4.3.1. Series hybrid

The buses in the project are series hybrids. In this combination of the hybrid vehicles electrical machines supply all the tractive energy and there are no mechanical connections between the ICE and the wheels. The ICE drives a generator that charges the battery and supplies the traction motor with power, as shown in Figure 2.5 An advantage is that the ICE can be switched off when driving the vehicle in no-emission zones. The working point of the ICE (speed and torque) can also be chosen freely when running the ICE. (van Mierlo, 1999).

A drawback is that the prime energy from the ICE has to pass two electrical machines and power electronics on its way to the wheels. This makes the system efficiency relatively low. The energy may also have to be stored in a battery, which further reduces the system efficiency. Another drawback is that the traction motors have to be able to convert the peak traction power.

An electrical vehicle supplied with a small ICE and generator as a range extender can be considered a simple series hybrid vehicle. Most of the existing hybrid buses are series hybrids. One reason is the way they run with many starts and stops. Another reason is that electric wheel motors do not need a rear axis; this makes it possible to design the bus with a low floor even in the back.

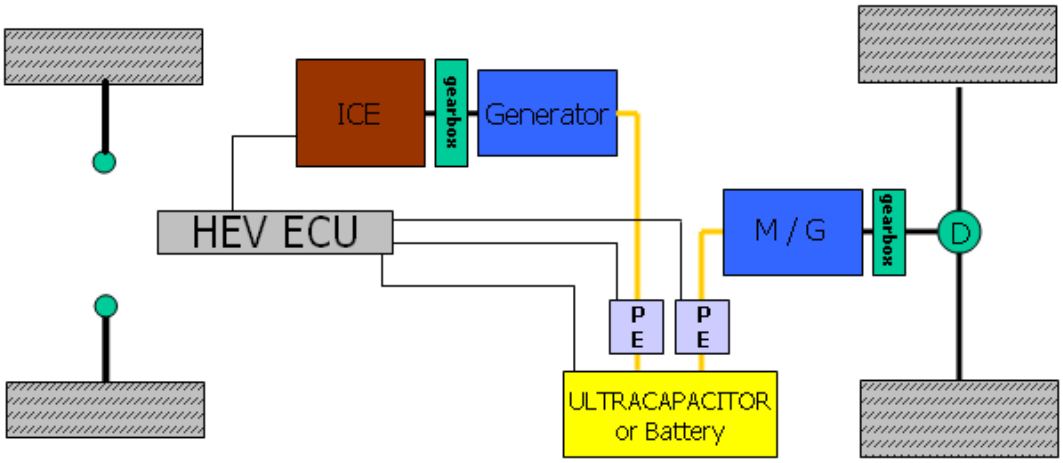


Figure 2.5. Series hybrid vehicle

HEV ECU: Hybrid Electric Vehicle Electronic Control Unit,

M/G: Motor/Generator

PE: Power Electronic

ICE: Internal Combustion Engine

D: Differential

A series hybrid vehicle engine operating points on an efficiency map is illustrated in the Figure 2.6

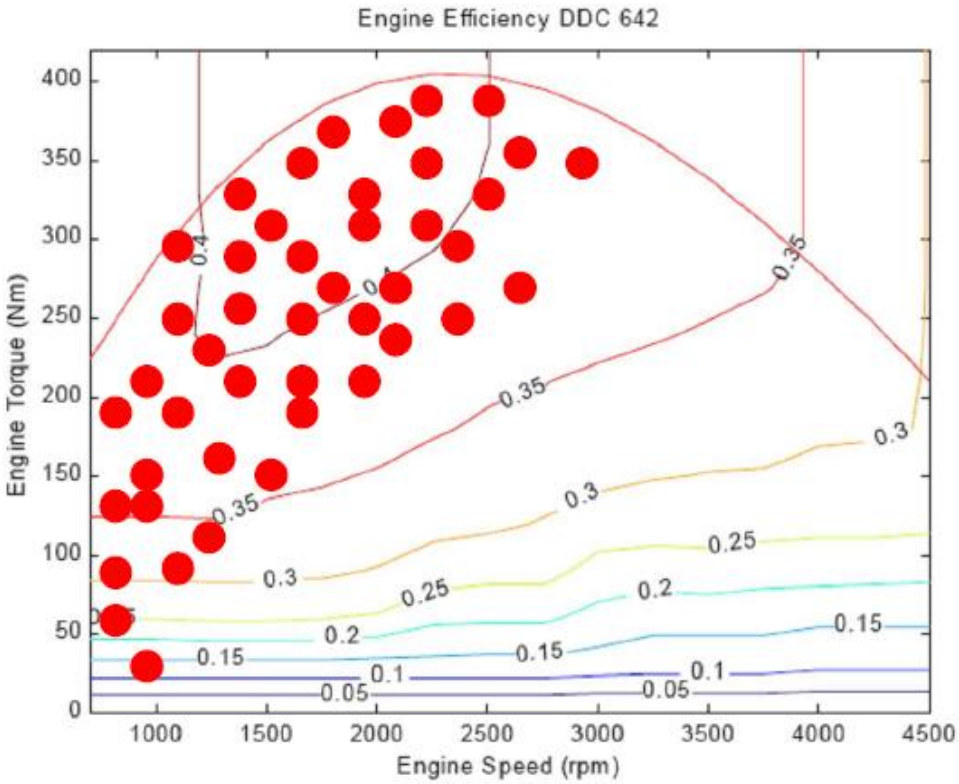


Figure 2.6. Series hybrid vehicle engine operating region (He, Parten and Maxwell, 2005)

The fact that the engine can operate in its most efficient region compensates the energy conversion losses and results fuel economy improvement that is significant in the city and moderate on the highway. The design also offers regenerative braking to capture the braking energy and store it in the battery instead of wasting it on the brake disks in the form of heat.

The hardware of the series hybrids is more expensive than the hardware of EV or conventional vehicles because it requires two electric machines and an engine. In addition to that its control of it is more complicated than the control of electric and conventional vehicles.

The control strategy is developed in such a fashion that the battery is always charged on board, and thus the driving distance is never limited by the life of the battery. As mentioned previously, the capacity of the battery is the biggest disadvantage of the electric vehicle and by charging the batteries on board, this disadvantage is eliminated. The control strategy, which causes the engine to run at a

desired torque and speed condition, is also supposed to ensure that the battery remains charged to a certain level at all time.

When large amounts of power are required, the motor draws electricity from both the electrical energy storage and the generator. A transmission is not needed at all. Some vehicle designs have separate electric motors for each wheel. Series hybrids can also be fitted with an ultracapacitor to store regenerative braking energy, which can improve efficiency by minimizing the losses due to high power transmission.

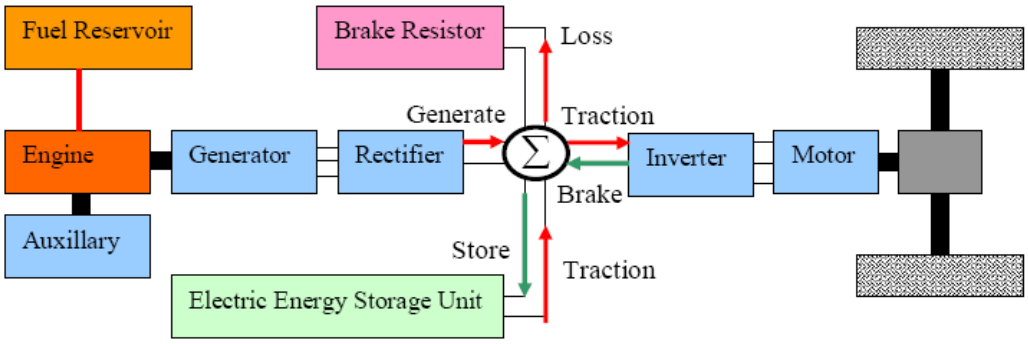


Figure 2.7. Power flow in series hybrid vehicles (Okan, 2008)

During long-distance highway driving, the combustion engine will need to supply all of the energy, in which case a series hybrid will be less efficient than a conventional system because the power from the combustion engine must run through both the generator and electric motor, so due to the prolonged conversion path the engine-to transmission efficiency becomes 70% - 80%, which is less than a conventional mechanical drivetrain having an engine-to-wheel efficiency of 90%. It is clear that the real advantage of hybridization lies within the ability to recuperate the kinetic energy of the vehicle back to electrical energy during braking and in supplying transient peak energy requirements where the engine operates in an inefficient region.

2.4.3.2. Parallel Hybrid

The parallel hybrid is another HEV type that has been closely studied. In parallel configurations, both the engine and the motor provide traction power to the wheels, which means that the hybrid power is summed at a mechanical node to power the vehicle. As a result, both of the engine and the motors can be downsized, making the parallel architecture more viable with lower costs and higher efficiency. Some early developments of parallel hybrid vehicles include the BMW 518, Citroën Xzara Dynactive and Saxo Dynavolt, Daimler-Chrysler ESX 3, Fiat Multipla, and the Ford Multiplia and P2000 Prodigy (Westbrook, 2001).

The parallel hybrid vehicles usually use the same gearboxes of the counterpart conventional vehicles, either in automatic or manual transmissions. Based on where the gearbox is introduced in the powertrain, there are two typical parallel HEV architectures, named pre-transmission parallel and post-transmission parallel, as shown in Figure 2.9 and Figure 2.10, respectively.

In a pre-transmission parallel HEV, the gearbox is located on the main drive shaft after the torque coupler. Hence, gear speed ratios apply on both the engine and the electric motor. The power flow is summed at the gearbox. On the other hand, in a post-transmission parallel hybrid, the gearbox is located on the engine shaft prior to the torque coupler. The gearbox speed ratios only apply on the engine. A continuous variable transmission (CVT) can be used to replace conventional gearbox to further improve the engine efficiency.

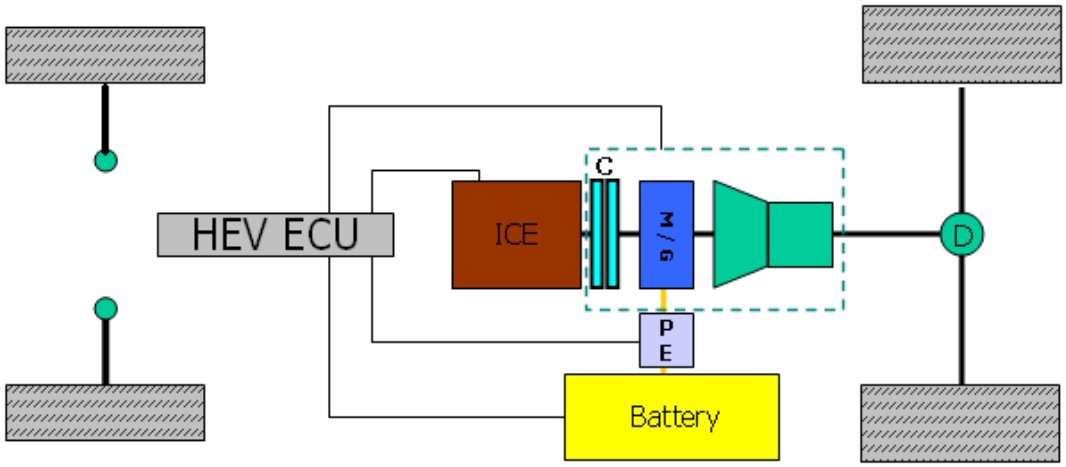


Figure 2.8.: Parallel hybrid vehicle

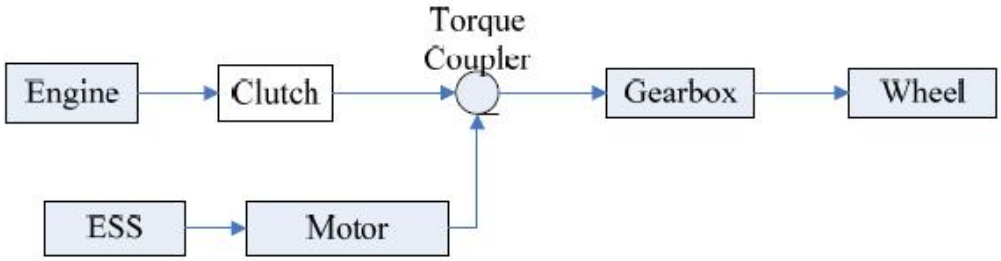


Figure 2.9. Pre-Transmission Parallel HEV Configuration

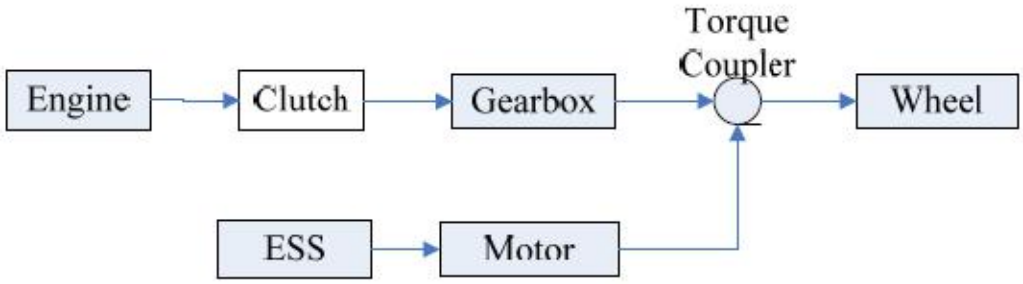


Figure 2.10. Post-Transmission Parallel HEV Configuration

In a pre-transmission configuration, torque from the motor is added to the torque from the engine at the input shaft of the gearbox. Contemporary mild parallel hybrid vehicles employ this strategy exclusively. In a post-transmission, the torque from the motor is added to the torque from the engine delivered on the output shaft

of the gearbox. A disconnect device such as a clutch is used to disengage the gearbox while running the motor independently (Miller, 2004).

Post-transmission electric hybrids can also be used in hybrid vehicles with a higher degree of hybridization. Hydraulic power can be used on launch-assist devices in heavy-duty trucks and commercial vehicles.

There are attempts from different perspectives to improve the operation of a parallel HEV. One possibility is to run the vehicle on electric machine alone in city driving while running engine power alone on highways. Most contemporary parallel vehicles use a complex control system and special algorithms to optimize both vehicle performance and range. The flexibility in powertrain design, in addition to the elimination of the need for a large motor, of parallel hybrids has attracted more interest in HEV development than the series hybrids.

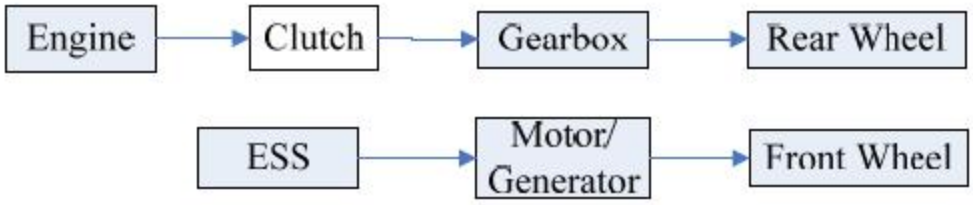


Figure 2.11. All Wheel Drive Parallel HEV Configurations

One unique implementation of the parallel hybrid technology is on an all wheel drive vehicle as shown in Figure 2.11. The design is most beneficial if the ICE powers the rear wheels while the electric motor powers the front wheels. The more weight borne by the front wheels during braking will result in more power captured during regenerative braking. The design is also effective on slippery surfaces by providing vehicle longitudinal stability control that is not as easy with other types of hybrid designs. The power to each axle is manipulated by a single controller, although this requires a fast data communication. It is unclear whether any automotive OEM has planned to incorporate this design into real vehicles.

The Honda Insight was the first commercialized hybrid vehicle, although the vehicle line was discontinued in September 2006. The Insight was considered as a

test vehicle to gauge public opinion on hybrid technology, and the 18,000 USD price tag is estimated to be 10,000 USD less than the actual production cost (Westbrook, 2001). Despite the cost distortion, the Insight never became a commercial success largely because of its two-seater format. Honda has promised a replacement to arrive in 2009 (Jong-Seob, Langari, and Ehsani, 2005)

The Insight is a mild-hybrid, with the electric motor being the key to the Integrated Motor Assist (IMA) technology that boosts the engine power. The engine is an inline 3 cylinders 0.995 litre gasoline engine that delivers 50 kW peak power at 5700 rpm, and 89 $N.m$ peak torque at 4800 $N.m$ with a manual transmission. When the IMA system is activated, these numbers rise to 54.4 kW and 107 $N.m$ for the manual transmission and 53 kW and 121 $N.m$ for the CVT. The electric motor is a permanent magnet machine that supplies 10.4 kW of power at 3,000 rpm with a manual transmission, and 9.7 kW of power at 2,000 rpm in a CVT model. The ESS consists of 120 cells of Nickel Metal Hydride (Ni-MH) batteries of 1.2 V each, for a total voltage of 144 V with a rated capacity of 6.0 Ah. The schematic of the Insight is similar to Figure 2.9 on a pre-transmission parallel HEV.

2.4.3.3. Power Split Hybrid

It is possible to combine the advantages of parallel and series hybrid vehicle (Stridsberg, 1998) or by using a planetary gearbox (Kimura, 1999), as illustrated in Figure 2.12. Such a constellation uses two electrical machines and one ICE in connection to a planetary gearbox.

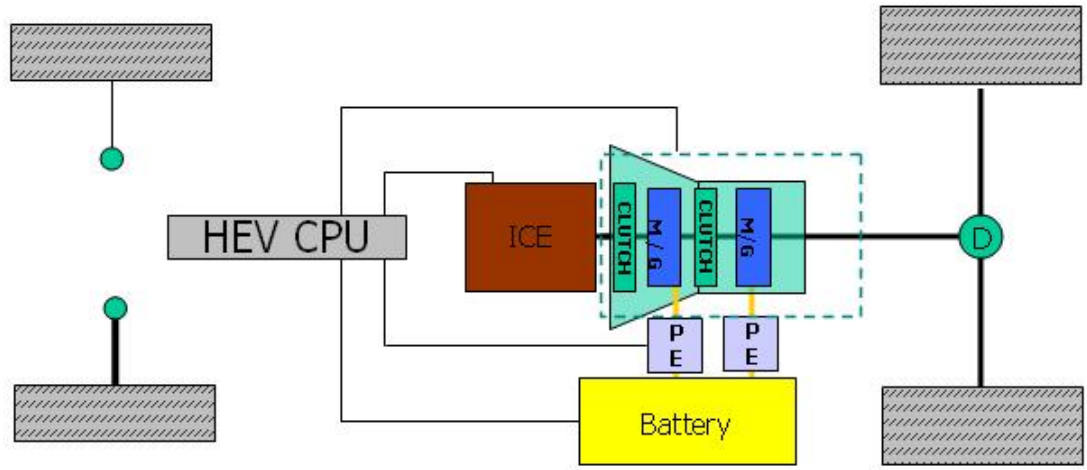


Figure 2.12. Complex hybrid vehicle

In the complex (power split) hybrids the ICE is connected to the planet carrier wheel, see Figure 2.13. The output axis is connected to the ring wheel. The electrical machines are connected to the solar wheel as well as the ring wheel. Both electrical machines are connected via separate power electronics to the battery. If the components in the drive train are well designed this technique allows the ICE to operate at optimal torque and speed for best efficiency. Only at one specific speed all the power from the ICE goes directly to the wheels and it acts like a parallel hybrid. In all other cases it acts more or less like the series hybrid. The choice of configuration depends on what performance the vehicle is designed for, and which complexity that is desired for the drive train.

The first passenger car in series production with this type of gearbox was Toyota Prius, with a 44 kW ICE and a 30 kW electrical motor, produced in 1998 (Hellman, Peralta and Piotrowski, 1998).

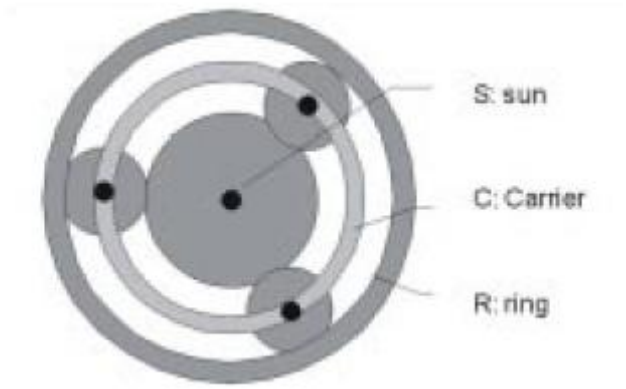


Figure 2.13. The planetary gear

2.5. Review on Hybrid Electric Vehicles Energy Storage System

2.5.1. Research Issues in Hybrid Electric Vehicles Design

The focus of HEV design is mostly on powertrain efficiency. This efficiency depends on contributions from the engine, motor, battery, and mechanical transmissions. The peak efficiency of an ICE can be as high as 36% (based on 1998 Prius 1.5L Gasoline Engine), while the overall efficiency of its operation, on the other hand, is usually no more than 20% (Zhou, 2007). Therefore, the objective of HEV design is to improve the overall vehicle efficiency by optimizing the sizes operations of its powertrain components. Although there is a great potential to improve the vehicle fuel economy and drive ability in principle, present control strategies based on engineering intuition frequently fail to capture these potentials. Due to the existence of multiple power sources on these vehicles, an overall fuel consumption and emission control strategy needed be developed.

2.5.2. Energy Storage System

2.5.2.1. Sizing Considerations of Energy Storage System

For different types of vehicle technology, the electrical energy storage system (ESS) is utilized differently. HEV are classified into three categories following the types of power source: electric vehicles (EV), hybrid electric vehicles (HEV), and plug in hybrid electric vehicles (PHEV). An EV uses ESS as the sole energy source. Technically an EV would not be considered as a HEV; it is discussed here in order to compare with the other two types. The ESS on an EV, usually a battery pack, is only charged from grid electricity except for during regenerative braking. The vehicle range with one charge is directly related to the energy capacity of the ESS. A HEV on the other hand, has more than one energy sources. The ICE or FC is usually hybridized with an ESS on a HEV. The ESS would be charged by the ICE or FC during the vehicle operation according to power demand, and no external power source is necessary to charge the ESS. A plug-in hybrid electric vehicle is also a HEV with its ESS being charged either by the on board power source, such as ICE and FC, or the stationary grid power.

In HEVs, the size of the ESS is determined to provide sufficient energy storage (*kWh*) capacity and adequate peak power (*kW*) ability. In addition, appropriate cycle life and hardware cost have to be considered. The size requirement of ESS varies significantly depending on the characteristics of different vehicle's powertrains (EV, HEV and PHEV) (Balch, Burke, and Frank, 2001). This requirement can be obtained once the vehicle is specified and the performance target is established. However, what is less straightforward and more challenging is to find an optimal ESS design that would satisfy the special characteristics of vehicle power requirements. Normally, energy storage units are primarily sized by either the energy or power capability. Charging-discharging efficiency is also considered. In this study, a comparison of the performance characteristics (*Wh*/*kg*, *Wh*/L, W/*kg* etc.) of various energy storage technologies for different vehicle power requirements is made to guide the ESS design.

2.5.2.2. ESS Power and Capacity Rating

ESS can consist of various types of batteries, ultracapacitors, and their combinations.

An expression $P_{peak} = V_o^2 / 4R$ is commonly used to rate the peak power of the battery, where V_o is the nominal voltage of the battery and R is the battery's internal resistance. The efficiency at the peak power of the battery is relatively low (close to 50%). A generic expression of battery power and efficiency is given by the following equation

$$P_{peak} = h \times (1 - EF) \times V_o^2 / R \tag{2.1}$$

where h is the efficiency at peak power pulse. It is assumed that the peak power occurs when $V_{peak} = V_o \times h$. For an efficiency of 85%, the peak power will be reduced by 1/2 from the peak power at lower efficiency.

Ultracapacitors are also sized by power and energy. Energy storage capacity (*Wh*) is usually used to size ultracapacitors due to their low specific energy (5-10 *Wh*/*kg*). The useable peak power from an ultracapacitor is given by Eq. (3.2):

$$P_{peak} = 9/16 \times (1 - h) \times V_o^2 / R \tag{2.2}$$

The peak power occurs at a voltage of $3/4V_o$, where $I = P_{peak} / 3/4V_o$. As internal resistance of an ultracapacitor is considerably lower than that of a battery, the peak power is much higher. Figure 2.14 shows specific power and energy of the most popularly used energy storage devices, including lead acid batteries, Ni-MH batteries, Li-ion batteries and ultracapacitors. With the differences of battery chemistry, there are tradeoffs between energy density and power density.

The specific energy and power of the batteries thus vary over a range, as illustrated by the shaded area shown in Figure 2.14. The size of ESS on different

types of vehicles is determined by the specific energy and power demands. In sections 2.5.2.3 – 2.5.2.5, three typical hybrid vehicles were analyzed. The ratio of their specific power and energy needs were calculated. Reference lines were drawn in Figure 2.14 to represent the ESS demand characteristics of these vehicles. For a HEV, the reference line for the ESS power/energy ratio appears between the specific power and specific energy regions of ultracapacitor and batteries. Therefore, for a HEV, the size constraint of a battery based ESS is the specific power while the size constraint of an ultracapacitor based ESS is the specific energy. An ideal match of both energy and power would be a combination of battery and ultracapacitor. For PHEV and EV, the ESS specific power/energy ratio lines appear in the battery regions, and the size constraint of ESS is the specific power of the batteries. Ultracapacitors with much lower specific energy are normally not considered; however, it may still be beneficial to added ultracapacitors to the batteries to extend the operation life of the battery (Stienecker, Stuart and Ashtiani, 2006).

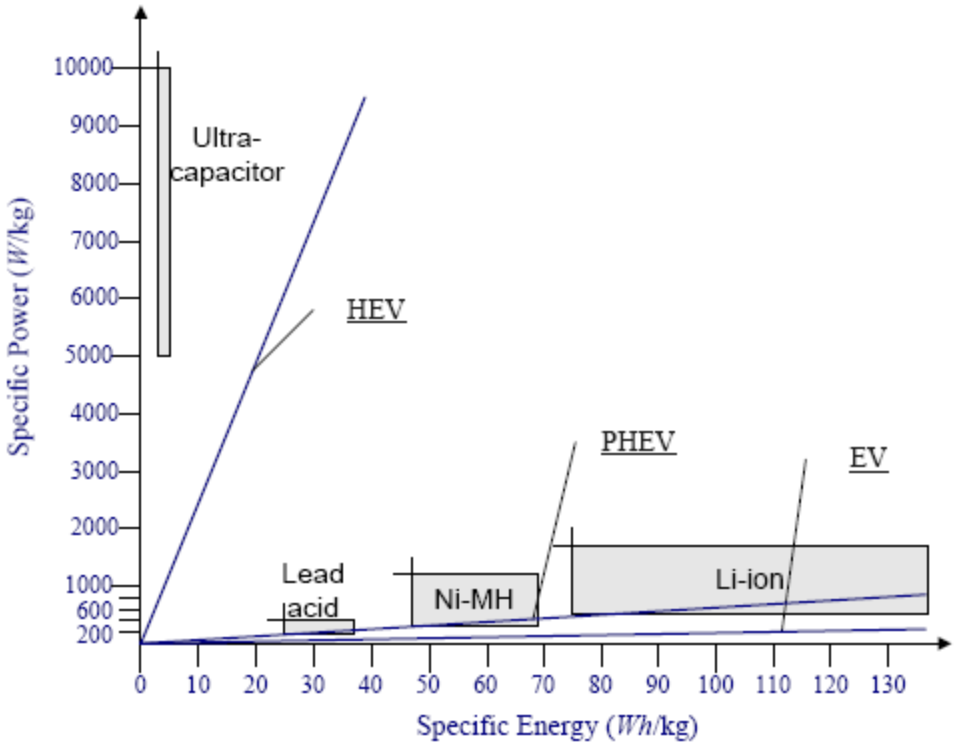


Figure 2.14. Power/Energy Ratio of Vehicle Demand and ESS Capability

2.5.2.3. ESS for an Electric Vehicle

The focus of an EV design tends to be the acceptable range with a single charge. Therefore, the ESS is sized to meet the designed range of the vehicle. For battery powered vehicles, the size of batteries is determined by its energy requirements (*kWh*/*kg*) as power requirements (*kW*/*kg*) can be easily satisfied for a reasonable vehicle acceleration performance need. The load cycles of batteries on an EV are usually deep discharging and charging. The shortened life of deeply discharged battery is a major consideration since the minimum battery life has to be satisfied.

Battery charging time is another major consideration as this time is significantly longer than refilling a gasoline tank. An alternative is to replace the discharged battery pack with a fully charged one at a battery station with a reasonable cost of service charge. However, certain challenges arise for battery replacement such as weight and volume, especially for the heavier and bulkier lead-acid batteries. Meanwhile, ultracapacitors are not likely to be employed in EV at present due to their characteristically low energy density. In order to quantify the power and energy consumption on an EV, a performance characteristics benchmark is used, as given in Table 2.1. The fuel consumption of 100 MPG is accepted as a benchmark for passenger vehicles. The gasoline consumption is translated into battery energy using net calorific value (NCV).

Table 2.1. Characteristic of a Benchmark EV (Zhou, 2007)

Peak Power	100 *kW*
Range	300 *km*
Fuel Economy (Equivalent)	0.024 *L/km* (100 *MPG*)
Discharge Depth	70%

The energy consumption (*kWh*) is calculated from fuel economy equivalent using the following equation.

$$E = \frac{300km \times 0.024L/km \times 0.73kg/L \times 42,900kJ/kg}{1W \times 3600s/hr \times 0.70} \approx 89kWh \qquad (2.3)$$

As a result, an ideal energy/power ratio of 0.89 (89 *kWh*/100 *kW*) or lower (for longer ranged) is necessary for an EV. A reference line for the EV was drawn in Figure 2.14. It is shown that all types of batteries are able to satisfy this power demand with the requested energy capacity. The main criterion for sizing an EV is energy rather than power capability. For EV applications the objective should be to develop batteries with high energy density and acceptable power density. The weight and capability of batteries for EV are shown in Table 2.2. As battery power is mostly sufficient for vehicle power demand, ultracapacitors are unlikely needed to boost power.

Table 2.2. ESS Sizing for a Benchmark EV (Zhou, 2007)

	Energy	**Power**	**Weight**	**Volume**
Lead acid	89 *kWh*	122 *kW* @ Ef. 95%	2602 *kg*	High
Ni-MH	89 *kWh*	114 *kW* @ Ef. 90%	1308 *kg*	Medium
Li-ion	89 *kWh*	108 *kW* @ Ef. 90%	635 *kg*	Low

2.5.2.4. ESS for a Hybrid Electric Vehicle

For a hybrid electric vehicle (HEV) using either an engine or fuel cells as the primary energy source, the ESS is sized differently depending on the degree of hybridization (DOH) and power management strategy of the vehicle. As the operation cycles of ESS on a HEV are significantly longer than on an EV, the life of ESS therefore will be a main concern. One approach to extend battery life is "shallow charging" which confines the battery operation at relatively narrow state-of-charge range (5%-10%). Reference (Karden, 2007) showed shallow cycle life can be greatly enhanced to satisfy consumer expectation on a HEV. Even though not

used in commercialized vehicles yet, ultracapacitors have the potential to be used in a HEV due to its much longer life cycle that passes 500,000. Reference (Douglas and Pillay, 2005) reviewed ultracapacitor applications and provided guidelines for sizing ultracapacitors on HEV. Due to the vehicle dependent nature of ESS on HEV, it is difficult to standardize the generic power demand for a HEV. The ESS on a 2004 Toyota Prius (Staunton, 2006) was set as reference while other ESS technologies were explored.

Table 2.3 Specs of Ni-MH on a 2004 Toyota Prius (Staunton, 2006)

Type	Module Volt.	Capacity	Cells	Power Specified
Ni-MH	7.2 *V*	6 *Ah*	168	21 *kW*@60%

The energy capacity of Prius is 1209.6 *Wh*. According to the shallow charge operation condition on battery, the useable energy is 60 *Wh*-120*Wh*. The battery efficiency at 21 *kW* is 60%. There is a distinct difference on cycle life between a battery and an ultracapacitor. Battery size is greatly influenced by the amount of power needed and its normal state of charging, related to battery cycle life. Ultracapacitor sizing, on the other hand, is only related to the usable energy.

Table 2.4 ESS Sizing for a HEV

	Rated Energy (*Wh*)	Usable Energy (*Wh*)	Power	Weight
Lead acid	1419 *Wh*	71 *Wh*-141 *Wh*	21 *kW*	54 *kg*
Ni-MH	1209 *Wh*	60 *Wh*-120 *Wh*	21 *kW*	27 *kg*
Li-ion	1200 *Wh*	60 *Wh*-120 *Wh*	24 *kW*	15 *kg*
Ultra-capacitor power-match	13.35 *Wh*	13.35 *Wh*	24 *kW*	3 *kg*
Ultra-capacitor capacity-match	90 *Wh*	90 *Wh*	160 *kW*	20 *kg*

In this case, power demand can be easily satisfied. The result of the Prius example shown in Figure 2.14 used the same energy power ratio as that of the EV. Ideally, a combination of battery and ultracapacitor will reach a point at which both power and energy can be satisfied simultaneously. Table 2.5 shows a combination of batteries and ultracapacitors which reaches the same performance characteristics with much lower weight.

Table 2.5. UC-battery Hybrid ESS for Prius 1 (Zhou, 2007)

	Rated Energy (*Wh*)	**Power**	**Weight**
Ni-MH	78.2 *Wh*	1.9 *kW*	1.7 *kg*
Ultracapacitor	11 *Wh*	19 *kW*	2.4 *kg*
Total	90 *Wh*	21 *kW*	4.1 *kg*

2.5.2.5. ESS for a Plug-in Hybrid Electric Vehicle

The only difference of a PHEV from the HEV is its larger battery that allows energy to be charged from grid electricity. In addition to the power and energy demand of a HEV, additional ESS capacity requirement depends on its "all electric range" (AER). However, sizing the ESS for a PHEV is more complex for several reasons. First, in the AER, not only the energy but also the power is a concern, since the battery is the only source of power for most operations. Secondly, battery life is affected by the depths of charge and discharge. The depth of discharge on a PHEV is far more than that of a HEV with limited, shallow discharges. It is therefore more difficult to satisfy energy and power requirements with a reasonable life expectancy of the ESS. More detailed power and energy requirement on a parallel PHEV is discussed in (Markel and Simpson, 2005). To further explore the ESS characteristics of a PHEV, a hypothetical PHEV based on Prius is used.

The AER power is confined at 30 *kW* which allows limited speed and acceleration.

Table 2.6. UC-battery Hybrid ESS for Prius 2 (Zhou, 2007)

AER Power	30 *kW*
Range	20 *km*
Charging Depth	70%
AER Efficiency	100 MPG

The energy demand can be expressed in the following equation where the energy/power ratio is 0.2 (6 *kWh*/30 *kW*) [5].

$$E = \frac{20km \times 0.024L/km \times 0.73kg/L \times 42,900kJ/kg}{1W \times 3600s/hr \times 0.70} + 0.09kWh \approx 6kWh \qquad (2.4)$$

The energy/power ratio was shown in Figure 2.14. As a result, batteries are more appropriate to be used as the energy storage unit. However, there exists a possibility of using ultracapacitors when vehicle speed and acceleration demand is higher. The AER peak power will be higher than 30 *kW* and this demands a lower energy/power ratio.

2.5.3. Advance of Energy Storage Technologies and Hydrogen Fuel Cells

In this section, the technical backgrounds and state of art on the developments of battery and ultracapacitor are briefly reviewed. At present three types of batteries are widely used, including lead acid (L-A), Ni-MH, and lithium-ion (Li-ion) batteries. Following the same order are their improved performance, energy density, and increased cost. For economic reasons, L-A batteries were used in earlier production electric vehicles. Ni-MH is gaining popularities on present HEV. Meanwhile, Li-ion battery applications are mostly limited at present to smaller electronics devices due to its superior power density where cost is not as much of a factor. Li-ion batteries, as a promising technology for vehicle applications in the future, start to see applications in high-end low speed vehicles. A study to optimize

the cost and performance of batteries, considering three different vehicles, three types of batteries, and three powertrains was carried by (Balch, Burke and Frank, 2001). As an energy storage device, batteries have a number of drawbacks, including large size, limited power density, thermal impact, low efficiency, long charging time and relatively short life. A summary of battery characteristics for EV applications is shown in Table 2.7. The data was gathered from a number of sources (Ito and Ohnishi, 2003; Horiba, 2005; Taniguchi, 2001).

2.5.3.1. Sealed Lead Acid Battery (SLA)

The sealed lead acid battery is the most common battery currently been used to power electric bicycles, mainly due to its low cost per watt-hour. The SLA battery is also very robust and durable when used properly. The self-discharge rate of the SLA battery is also low, only losing ~5% of its charge per month if not used. The SLA battery does not have a memory effect like the NiCad battery. Problems with the SLA battery include low power and energy densities, and potential environmental impact, where the lead electrodes and electrolyte can cause environmental harm if not disposed properly at a recycling facility.

2.5.3.2. Nickel Metal Hydride Battery (Ni-MH)

The Ni-MH battery is the most widely used battery to power electric automobiles at present. The Ni-MH battery has a higher energy density than a SLA battery. Its specific energy (*Wh*/*kg*) can be up to four times that of a SLA battery; and 40% higher than Ni-Cad battery. The battery is also relatively environmentally friendly, as it contains very mild toxic materials that can be easily recycled. The main problem with the Ni-MH battery pack is its higher cost than a SLA battery pack. It also takes longer time to charge a Ni-MH than a SLA or NiCad battery and generates a large amount of heat during charging. It is also more difficult to determine when the Ni-MH battery is fully charged than with a SLA or NiCad battery, resulting in the need for more complicated and expensive chargers. The

recent effort of improving Ni-MH for HEV applications has been focused on reducing the resistance and increasing the power capability. The trade-off will likely be a lower energy density than those used on an EV (Karden, 2007).

2.5.3.3. Lithium Ion Battery (Li-ion)

Many automotive companies are in the process of developing advanced Li-ion battery technologies for vehicle related applications. Much interest is focused on high power batteries for HEV and high energy batteries for EV. For example, a lithium-ion battery for EV will have a specific energy up to 150 *Wh*/*kg* and that of a Ni-MH battery will be 70 *Wh*/*kg*. The major concern of using Li-ion battery on a hybrid vehicle is the over-heating problem during recharging (Congress, 2007).

Table 2.7. Battery Performance Characterizes for HEV and EV

Battery Technology	**App. Type**	**Capacity Ah**	**Voltage (V)**	**Spec. Energy Wh/kg**	**Resis. Ohm**	**Spec. Pwr W/kg**	**Useable SOC**
Lead-acid							
Panasonic	HEV	25	12	26.3	7.8	389	28%
Panasonic	EV	60	12	34.2	6.9	250	
Nickel Metal Hydride							
Panasonic	HEV	6.5	7.2	46	11.4	1093	40%
	EV	6.5	12	68	8.7	240	
Ovonic	HEV	12	12	45	10	1000	30%
	EV	85	13	68	10	200	
Saft	HEV	14	1.2	47	1.1	900	30%
Lithium-ion							
Saft	HEV	12	4	77	7.0	1550	20%
	EV	41	4	140	8.0	476	
Shun-Kobe	HEV	4	4	56	3.4	3920	18%
	EV	90	4	105	0.93	1344	
Ultracapacitor							
	V rated	**C (F)**	**Resis. (Ohm)**				
Maxwell	2.7	2800	0.48				

2.5.3.4. Ultracapacitors

Ultracapacitors are electrochemical capacitors. Energy is storied in the double layer formed at a solid/electrolyte interface (Kotz and Carlen, 2000). Advances in new materials and new ultracapacitor designs have considerably improved the energy storage capability and cost of this emerging electrical energy storage device. Compared with the conventional capacitors, ultracapacitors allow for more energy

storage for a factor of 20 times (Rufer and Barrade, 2001). Other unique characteristics of ultracapacitors include maintenance-free operation, longer operation cycle life, and insensitivity to environment temperature variation. The energy density of ultracapacitors is still limited compared with batteries. The goal for ultracapacitor development is a specific energy of 5 Wh/kg for high power discharge (Arulepp, 2006). Carbon-carbon ultracapacitor devices are commercially available from several companies, including Maxwell, Ness, and EPCOS. The capacitance of their products ranges from 1000-5000 F.

An experimental test was carried on a series hybrid Ford Escort with and without ultracapacitors as load-leveling devices for the batteries (Anstrom, 2005). Simulations of a series hybrid bus on the same test were also carried out on PSAT using data validated from the tests. Both experimental and simulation results suggest significant reduction to the RMS and peak battery currents.

A method for determine the size of batteries and ultracapacitors on a fuel cell powered SUV was presented in (Schupbach, 2003). The peak-to-average ratio was introduced as the sizing criteria. An optimization tool in ADVISOR is used to obtain the results. Cost analysis was also carried out. Life cycle was not considered in the study.

2.5.3.5. Hydrogen Fuel Cells

A fuel cell system is an electric power-generating device based on controlled electrochemical reaction of hydrogen fuel and oxidant air (Carlson, Kopf and Sinha, 2005). In principle, fuel cells are more efficient in energy conversion and much cleaner than ICE. Due to many attractive features, such as low operation temperature, compact structure, less corrosion concern and quick start time, the Proton Exchange Membrane (PEM) fuel cells serve as an ideal power plant for automotive applications. Dozens of fuel cells are bundled together to form a modular power unit, the fuel cells stack. To satisfy the need of power on a vehicle, multiple fuel cells stacks are connected in series. Together with various ancillary devices, fuel cells stacks form a fuel cell power system. Over the last decades, extensive efforts have

been devoted to improve the performance of fuel cell system and to lower its costs. There is also an interest in using fuel cells to build uninterrupted power systems (UPS). Since a fuel cell system is a capable energy conversion device, rather than an energy storage device as battery and ultracapacitor, it can continuously provide electric power as long as the hydrogen fuel is provided, either in the form of pure hydrogen, or reformed natural gas. This unique capability, plus its quiet operation, zero emission and high efficiency, makes it a promising alternative to the ICE.

One weakness of a fuel cell system is its slow dynamic response to power demand. According to an experiment (Santi, 2002), at the initial start-up, it takes 90 seconds for the fuel cells to reach a steady state; thereafter whenever there is a change of electric power demand, it take 60 seconds for the fuel cells to readjust and reach a new steady state. A fuel cells power system alone is not capable of dealing with the rapid power demand change to serve as the sore power plant in the UPS system. At present, most research applying PEM fuel cells to electric backup power systems are limited to smaller, mobile UPS systems for computers and communication equipments with built-in battery units to fill the need of dynamic power demands. Several other barriers exist to the widespread use of fuel cells as the electric power plant for an electric vehicle or backup power system. The most obvious one among them is cost. As with any new technology, fuel cells are expensive to develop and manufacture. The magnitude of the cost problem for vehicles and backup power systems is exacerbated by the low cost of the incumbent ICE and battery technologies. In order to improve the viability of fuel cells as an alternative power plant, some method of either reducing their cost or the cost of the total backup power system over life time is required.

3. MATERIAL AND METHOD

3.1. Vehicle Simulation Tools

Different platforms for programming were evaluated and complete programs for vehicle simulation were evaluated (Andersson 2001). In some programs it was difficult to make modifications in the simulation program, e.g. with the simulation program the flexible ELFA System **(**Electric Low Floor Axle (ELFA and was not availably by the beginning of the project. Other programs were too expensive. Matlab/Simulink and Advisor (Demo version) were as chosen as the platform for this simulation model.

Matlab is well known in the scientific world and has already been used for many hybrid and electric vehicle simulations. The hybrid bus is modularly designed in Simulink and fed with input values via Matlab. The simulation program is, after calibration by extensive measurements, used for structural sensitivity analysis and evaluation of charging strategy improvements.

3.2. ADvanced VehIcle SimulatOR (ADVISOR)

3.2.1. ADVISOR Background

ADvanced VehIcle SimulatOR (ADVISOR) was developed by the National Renewable Energy Laboratory of US in late 1990s. It was first developed to support US Department of Energy in the hybrid propulsion research. The model was set up in a backward modeling approach, although it was labeled as both forward and backward in the official documents. ADVISOR is widely used by auto manufacturers and university and institute researchers worldwide. Many users contributed new components and data to the ADVISOR library. With a friendly user interface, ADVISOR was created in MatLab/Simulink® which is a software module in MatLab for modeling, simulating and analyzing dynamic systems. It supports both linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two.

Systems can also be MultiMate, e.g. having different parts that are sampled or updated at different rates.

3.2.2. ADVISOR Modeling Approaches

ADVISOR employs both backward and forward modeling approaches (Santi, 2002). A backward approach starts from a given driving cycle at the wheels, and traces back the needed power flow through the powertrain model to find how much each involved component has to perform. A control flow chart of a backward model is shown in Figure 3.1. No driver behavior model is required in such a model. Instead, the power required at the wheels of the vehicle through the time step is calculated directly from the required speed trace (drive cycles). The required power is then translated into torque and speed that go up stream to find the power required at the power source, an ICE, for instance. Component by component, this power flow is calculated backward through the drivetrain, considering losses. At the end, the use of fuel or electric energy is computed for the given speed trace or drive cycle.

Vehicle simulations that use a forward-facing approach include a driver model and a similar powertrain model. A driver model compares the required speed and the present speed to decide appropriate throttle and braking commands (using a PI controller). The throttle command is then translated into a torque demand at the power source (engine or motors). While the brake commands will be translated to friction torque at the wheels. The torque provided by the power source goes through the whole drivetrain to the wheels. Vehicle speed will be calculated and sends back to driver model as the present speed.

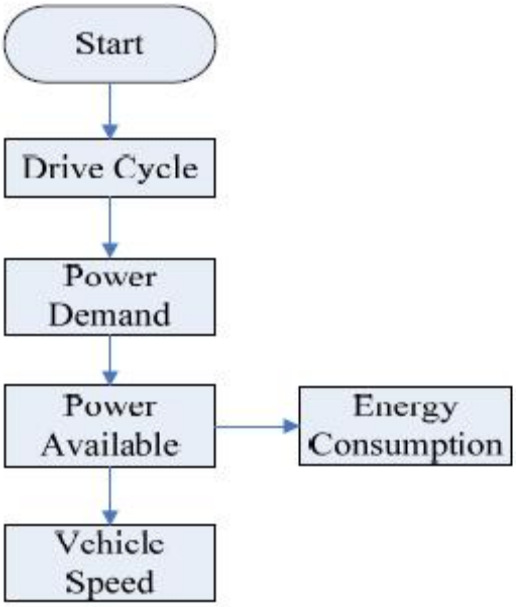


Figure 3.1. Flow Chart of a Backward Modeling Approach

Figure 3.2 shows the Simulink diagram of a two-mode hybrid vehicle model. The simplified function of this diagram is explained using the flow chart shown in Figure 3.1, as a so-called backward computer model.

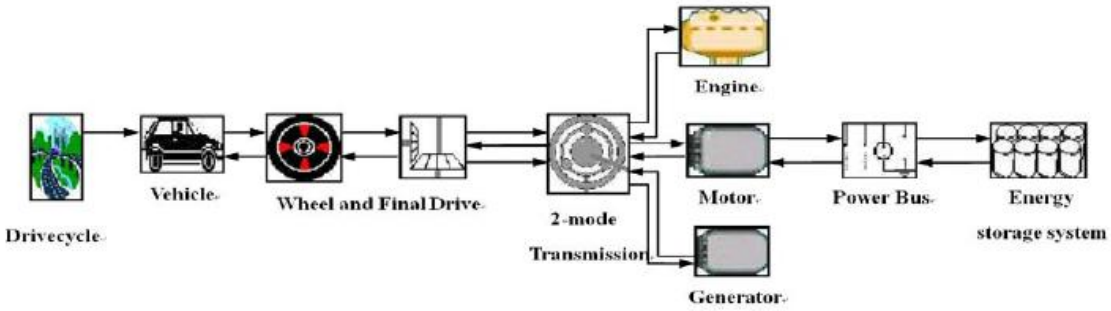


Figure 3.2. ADVISOR/Simulink Block Diagram of a Two-mode Truck

3.2.3. ADVISOR Interface

ADVISOR provides easy access and quick results to a trained user in vehicles modeling through a GUI interface. Three windows would guide users from the initial setting up toward the final results. The first window is used to enter data related to

the vehicle initial setup. The second window provides several simulation options one can select from. The last window shows selected simulation results.

In the ADVISOR vehicle input window Figure 3.3, the vehicle drivetrain configurations (e.g. series, parallel, conventional, etc.) is specified as well as the other key drivetrain components (Wipke, Cuddy and Burch, 1999).

Characteristic performance maps for various drivetrain components are accessible using the associated menus. The size of a component (*i.e.* peak power capability and number of modules) can be modified by editing the characteristic values displayed in the boxes. Due to its straightforward backward approach, ADVISOR is 2.5 to 8 times faster than forward looking approach (Guenther and Dong, 2005). Any scalar parameter can be modified using the edit variable menu in the lower right portion of the window. All vehicle configuration parameters can be saved for future use. After these vehicle input characteristics are specified, the next GUI interface is the simulation setup window.

In the ADVISOR simulation setup window as shown in Figure 3.4, a user defines the event over which the vehicle is to be simulated. Some of the events are driving cycle, acceleration test and other special test procedures. For example, when a single driving cycle is selected, the speed trace can be viewed in the upper left portion of the window and a statistical analysis of the cycle on the lower left portion. With simulation parameters configured, simulation can be run and results will be presented upon completion.

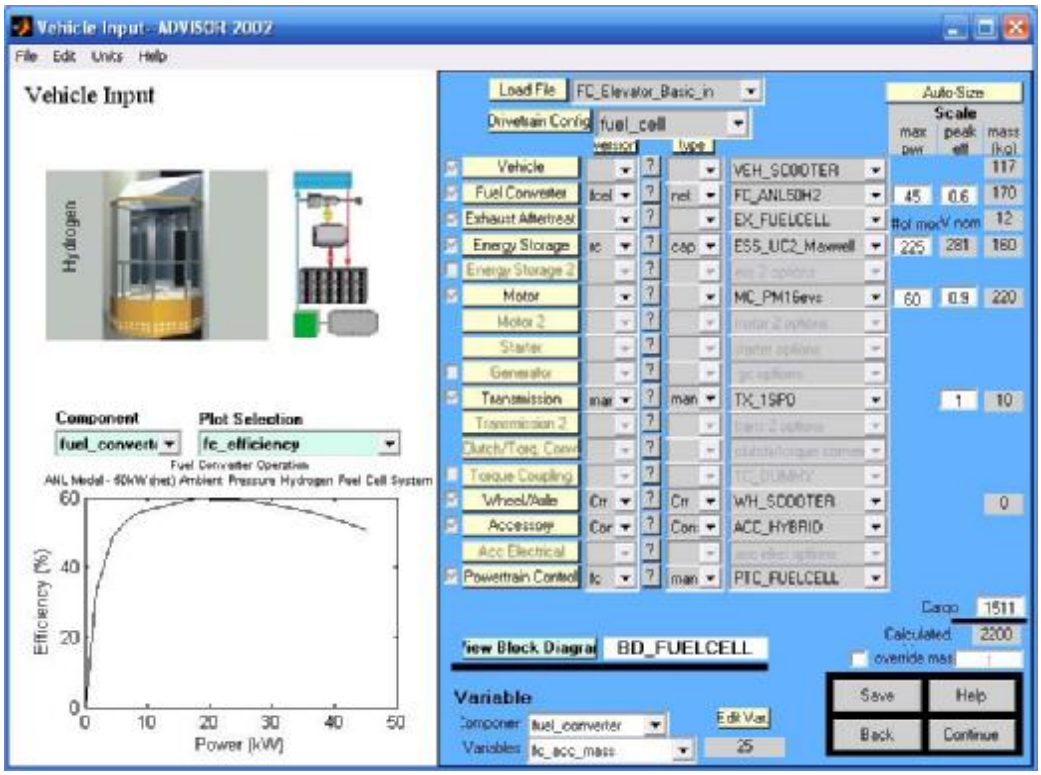


Figure 3.3. ADVISOR Vehicle Input Interface

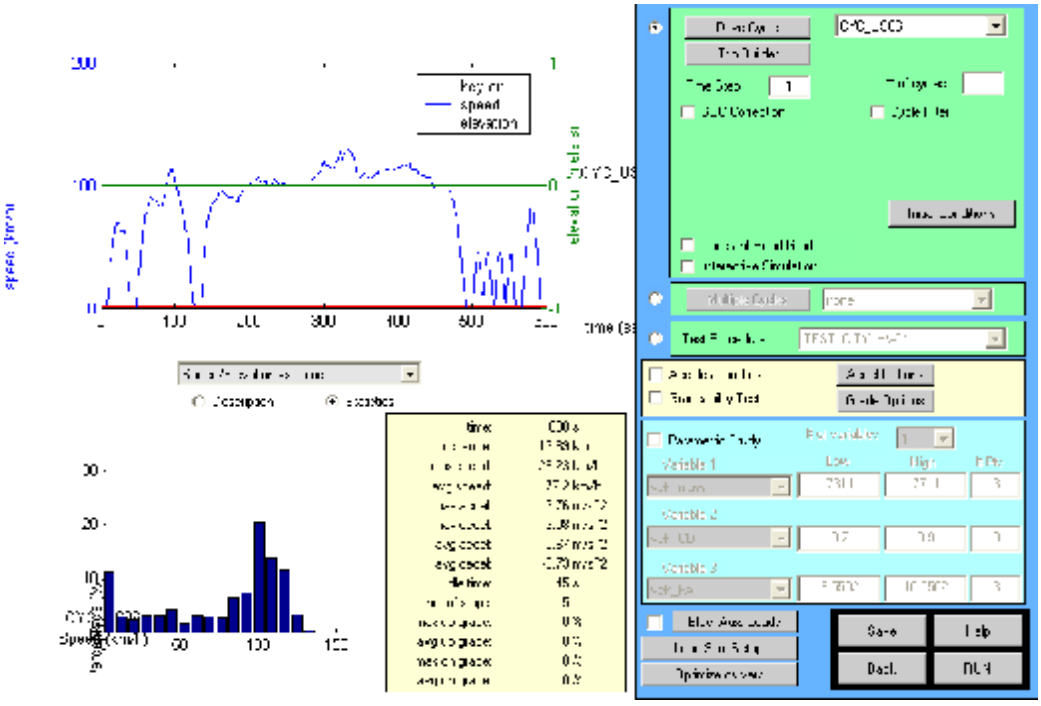


Figure 3.4. Simulation Setup Interface

The ADVISOR results window, shows in Figure 3.5, displays the review of vehicle performance, both integrated over a cycle and instantaneously at any point in the cycle. The results include vehicle performance, both integrated over a cycle and instantaneously at any point in the cycle, fuel economy, and emissions. Detailed time-dependent results can be plotted with options on different level of details (e.g. engine speed, engine torque, battery voltage, etc.) (Markel and Wipke, 2001). On the right portion of the window, summary results such as fuel economy and emissions are given. On the left, the detailed time-dependent results are plotted. These results can be dynamically changed to show other details (e.g. engine speed, engine torque, battery voltage, etc.) using the menus on the upper right portion of the window (Markel, 2002).

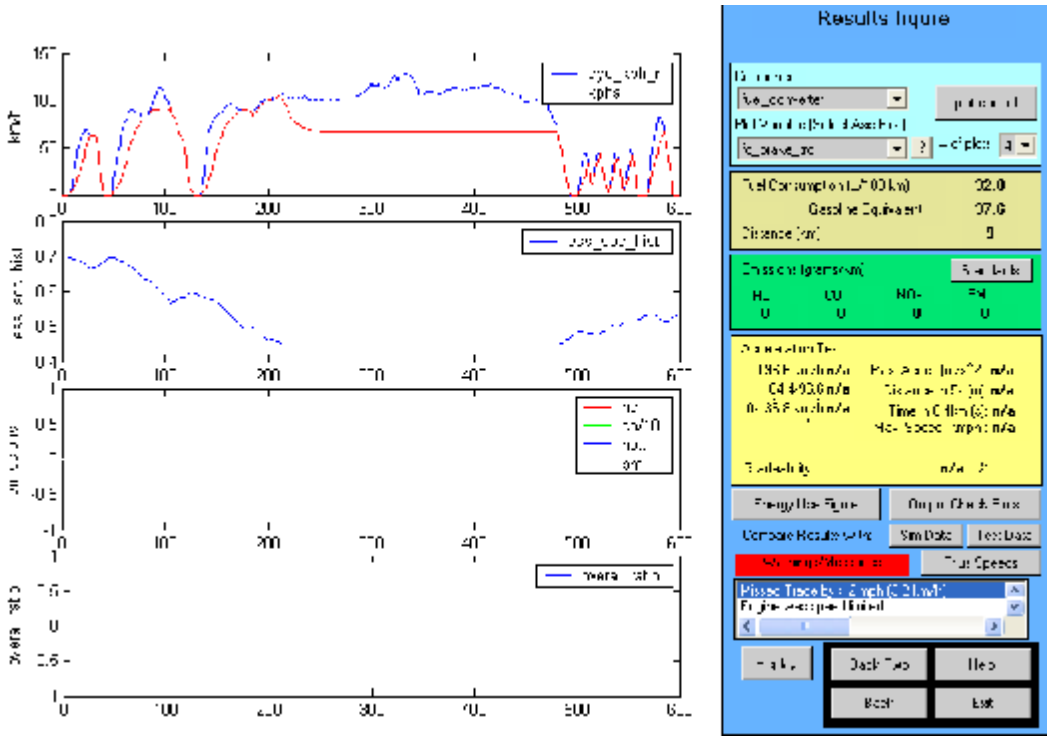


Figure 3.5. Simulation Result Window

3.2.4. Models in ADVISOR

3.2.4.1. Internal Combustion Engines and PEM Fuel Cells Models

A fuel converter is used in ADVISOR to convert indirect energy from fuel into direct energy such as electricity or kinetic energy to power the vehicle. The fuel converter for a motorized vehicle will be an ICE or fuel cells.

There are two categories of empirical, steady-state fuel cells models in ADVISOR. One simulates the performance of fuel cell system by mapping the system efficiency as a function of net power output. The other represents fuel cells performance based on a given polarization curve. Both models exclude thermal considerations and water management. Reformer and gas compressor are not included.

3.2.4.2. Energy Storage Model

There are several energy storage devices as build-in component models in ADVISOR library, including lead acid batteries, nickel metal hydride batteries, Li-ion batteries and ultracapacitors.

3.2.4.3. Electric Motor and Motor Controller Models

Several commonly used electric motors are preloaded in ADVISOR including induction motors, permanent magnet brushless DC motors, and switched reluctance motors. In terms of motor modeling for a vehicular drivetrain, two different approaches are used. One is the theoretical model based on physical principles. For a given motor geometry, material parameters and power electronics, the torque and speed of the motor are calculated. For example, the motor model for a brushless DC motor will be fundamentally different from the model of an induction motor.

The other modeling approach is more empirical data-driven, simply based on the static map of the drivetrain efficiency as a function of motor torque, speed and

voltage, as used at NREL. The empirical input data are obtained using a motor test stand. The latter cannot explain how the motor functions, but present more accurate motor performance behaviors and require much less computation, serving the system design task better. In this work, the latter approach was used.

3.3. The flexible ELFA System (Electric Low Floor Axle (ELFA)

3.3.1. Background

Siemens ELFA system claims to reduce energy consumption by up to 40% and allow emissions free operation in inner city areas and when buses are stationary. It is a series hybrid system designed for high flexibility and to be highly cost effective, and its modular design allows installation in many applications.

The ELFA traction system combines mobile energy generators, such as a diesel generator set or fuel cells, with high performance energy storage and regenerative braking. The use of a series hybrid principle allows a high degree of standardization such that the same electrical traction system can be operated in a diesel hybrid, fuel cell hybrid or battery powered electric vehicle. Therefore, a series hybrid can be easily adapted to new developments in diesel technology, energy storage devices and regenerative braking systems, as well as being able to utilize the latest technology in fuel cell development. The traction drive is completely decoupled from the energy generation source, usually a diesel engine today. This means that the diesel engine can be mounted in the vehicles such that it does not generate a torque reaction, and the drive torque does not have to be supported by the vehicle chassis. This significantly reduces the amount of noise and vibration and contributes to improved passenger comfort.

Siemens standard ELFA system uses liquid cooled AC induction motors with power ratings from 50 kW to 180 kW, with reduction gearboxes. This can be combined with electrical axle drive solutions and the electric motors are both extremely reliable and efficient, and easily packaged thanks to their small dimensions and low weights. Siemens can also incorporate permanent magnet

synchronous traction motors as direct drive units, providing additional efficiency in the lower speed range of operation. The use of synchronous motors allows the elimination of the step-down gear unit, delivering better fuel consumption and operating costs. Further components include standardized permanent magnet generators with radio dimensions that are the same as the traction motors, meaning they can be installed as a single unit. The system is completed by traction converters and control units using open loop control software (SupplierBusiness Ltd, 2010).

The vehicle manufacturer can freely select an internal combustion engine – or fuel cell and energy storage device. Furthermore the modules open a variety of combinations to adapt to the specific requirements of every vehicle (such as weight, acceleration, speed).

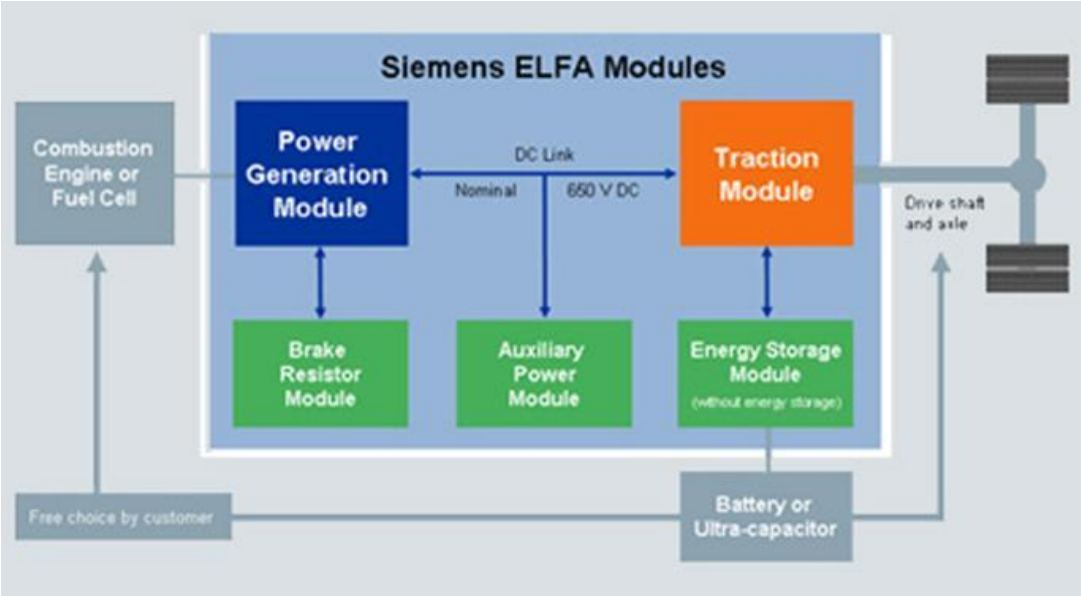


Figure 3.6. Siemens ELFA System diagram (Siemens AG, 2011)

3.3.1.1. Range from hybrid drive up to pure electric drive

ELFA® is a modular drive system therefore guaranteeing the highest degree of flexibility. This allows the vehicle manufacturer to configure the hybrid drive according to his individual requirements. As a result of the optimum combination coupled with intelligent energy management, fuel consumption and emissions can be

significantly reduced. Its flexible and modular system components the electric ELFA drive system can be used in commercial vehicles such as city buses employing the widest range of energy sources. In addition to internal combustion engines, these can also include electrical energy sources, such as e.g. battery, ultra capacitor and fuel cell (Siemens AG, 2010).

The decisive key to achieving significantly less energy consumption in bus traffic: The high amount of braking energy that occurs for typical stop and go operation. Here, savings of over 30 percent are definitely feasible – and has already been able to be proven in various applications. This braking energy is intelligently used with ELFA: Contrary to conventional buses where the energy is simply wasted, with ELFA, it is converted back into electrical energy by the regenerative operation of the traction motor and is fed into an energy storage device – i.e. in high performance capacitors or batteries. The energy yield is enormous, especially for city buses that are continually braking and accelerating. Depending on the bus type and the application conditions, operating companies can profit from significant cost savings. This makes it quite clear why an investment in an ELFA traction drive has an extremely short payback time (Siemens AG, 2007).

3.3.2. ELFA: advantages at a glance

• Up to 40 percent less energy consumption and exhaust emission
• Emission-free operation possible in inner city areas and at bus stops
• Noticeably more quiet
• Higher degree of comfort for passengers as the bus accelerates a lot more smoothly
• Extremely reliable and low-maintenance traction systems
• All components from a single source – motor, generator, traction converter and control
• Series hybrid system concept for maximum degree of flexibility and cost effectiveness
• Can be adapted to all city bus types as a result of the modular design
• Proven thousands of times over

3.3.2.1. Sensible: Braking energy is regenerated and stored

Always on the green route: Diesel engine operation with ELFA, the stored braking energy is always reused when starting: The diesel engine only has to be started at higher bus speeds or higher acceleration power. Depending on the storage capacity of the system, the bus can also be driven purely electrically, i. e. without any exhaust emission. This is especially important in environmentally sensitive inner city zones and at bus stops. A diesel engine can always be operated at a speed independent of the bus speed. This means that the engine can always be operated in a range that has the most favorable fuel consumption.

3.3.2.2. Increased degree of cost effectiveness and flexibility

The series hybrid ELFA systems utilize the series hybrid principle a superior concept with a whole raft of significant advantages for city buses: On one hand, the series hybrid can be standardized. This means that the same electrical traction system can be operated in a diesel hybrid, a fuel cell hybrid or a battery-powered vehicle.

As a consequence, a series hybrid can be easily adapted to new developments in the area of internal combustion engines and energy storage devices – the same also applies to leading-edge fuel cell technology. On the other hand, with the series hybrid, the traction drive is completely decoupled from the internal combustion engine. This means that the diesel engine can be mounted in the vehicle so that it does not generate a torque reaction and the drive torque doesn‘t have to be supported by the vehicle chassis. This significantly reduces the amount of noise and vibration therefore ensuring a significantly higher degree of passenger comfort. Additional advantages: A higher degree of latitude when designing the traction system and a higher degree of overall flexibility. This is because only the generator depends on the selected diesel engine. Thanks to its flexibility, the series hybrid can be perfectly adapted to upcoming innovation in the area of energy storage devices – associated with the future transition to Li-ion technology: More precisely – it is possible to use a smaller diesel engine than was previously used (down-sizing).

3.3.2.3. For buses around the world: Tailored and system-based solutions

With their unbeatable degree of flexibility, ELFA traction drives can be adapted to every bus type around the world, independent of individual special configurations and regions, climatic or topographical situations. The reason for this is its modular design: The complete system is assembled in a modular fashion from an extensive range of components – and is perfectly tailored to the specific requirement profile. We also offer many alternative possibilities for the mechanical integration – and certainly always the optimum solution for the specific project.

3.3.2.4. The standard: Systems with rugged induction motors

Rugged liquid-cooled induction motors with power ratings from 50 kW to 180 kW with reduction gearboxes are used as standard for ELFA traction systems. Also possible: Operation with electrical axle drive solutions. The motors are convincing thanks to their extremely high degree of reliability, high efficiency and space-saving design thanks to their small envelope dimensions and low weight for the particular power rating.

3.3.2.5. The alternative: Systems with permanent-magnet synchronous motors

Our latest development in the modular ELFA system: A permanent-magnet synchronous traction motor as direct drive. This distinguishes itself due to the efficiency that has been increased yet again in the lower speed range. Further, for this motor, a step-down gear unit is not required. This guarantees a further improvement in the efficiency eliminates the need to use gearbox oil – and when all is said and done – also reduces the fuel consumption, operating costs and exhaust emission.

3.3.2.6. The generators: Common mechanical unit together with the traction motor

Permanent magnet generators are used for all of the latest ELFA traction drive generation there are no exceptions. Their radial dimensions are exactly the same as those of the traction motor. This means that they can be mounted as a single unit. As a consequence, vehicle manufacturers can essentially keep their chassis design when changing over to hybrid traction technology and install the unit in the space previously occupied by the automatic gearbox.

3.3.2.7. The traction converters: Compact and can be used in a modular fashion

The traction converters play a key role in our ELFA traction systems. They control the traction motors, generators and auxiliary systems. Their compact, water-cooled aluminum frame corresponds to the environmental demands in the automobile sector and ensures the highest power density. This in turn significantly simplifies installation in the vehicle itself. The latest generation of traction converters completely fulfill the requirements placed on modularity. Alternative operation with 12 V and 24-V onboard supplies is also possible without requiring any modification.

3.3.2.8. The open-loop control software – tailored customer solutions

The complete ELFA traction system is controlled using just one standard traction converter software. A wide range of different applications can be parameterized at the system level using this software. In addition to the basic functions, various routines are integrated in the software – also customer-specific higher-level software modules that in conjunction with the standard software modules represent the system control. Using the set points from the driver, the traction control determines the torque and speed set points for the motors, generators and auxiliary systems – taking into account internal and external system limits. The required system performance is also determined in the traction control. This is the

input for the hybrid control that in turn determines the distribution of power between the internal combustion engine and the energy storage device for the various applications.

3.3.3. A real milestone for urban bus traffic

ELFA sets standards for hybrid powered city buses for bus manufactures, passengers and local municipalities. With our innovative series hybrid traction drive, you are benefiting from more than one hundred years of Siemens experience – the global market leader for large drives. In other words: You can profit from maximum reliability, highest efficiencies and a global service network whose experts are always there to provide you with competent support.

ELFA traction drives have already proven themselves thousands of times over. The first ones went into operation back in 1998 and in the meantime have many mil-lions of operating hours and kilometers under their belt reliably and economically. Together with bus manufacturers around the world, we are developing traction drive systems for city buses. This is based on our experience and competence in drive technology, our power of innovation and global presence and represents cutting edge technology when it comes to ecological and economic issues (Siemens AG, 2007).

3.3.4. Energy mix for ELFA applications

In addition to the electrical components, a hybrid drive generally comprises a power source - such as an internal combustion engine or a fuel cell - and an energy storage device such as a battery or an ultra capacitor. Using the ELFA traction system, vehicle manufacturers can address all of their requirements regarding the energy mix.

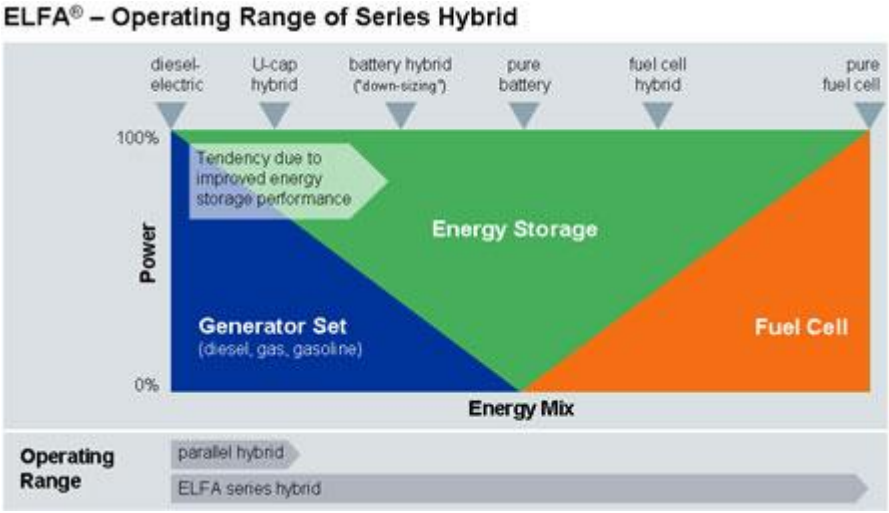


Figure 3.7. ELFA operating range of series hybrid (Siemens AG, 2010)

3.3.4.1. Hybrid drive with internal combustion engine

With this hybrid drive, the power comes from a generator, which is driven by an internal combustion engine. Energy storage devices are used to recover the braking energy. The power of the energy storage device, e.g. battery or ultra capacitor is combined with the traction motor and generator power. Innovative converter technology and intelligent energy management permit the fuel consumption and emissions to be significantly reduced. The attractiveness of the vehicle is further increased due to the fact that noise is reduced and the comfort level improved. An automated start-stop function for the internal combustion engine permits battery operation with no associated emissions - e.g. for sensitive inner-city areas.

3.3.4.2. Hybrid drive with fuel cell

With this hybrid drive, the energy is generated from a fuel cell. Energy storage devices are used to recover the braking energy. The power of the energy storage device (e.g. battery or ultra capacitor) is combined with the traction motor and the fuel cell power. Innovative converter technology and intelligent energy

management allow the fuel consumption to be significantly reduced. The attractiveness of the vehicle is further increased by a significantly lower noise level and improved levels of comfort.

3.3.4.3. Battery drive

For the battery drive, the energy is provided from just a battery. Modern high-energy batteries have a high power density; whereby it is especially important to note that the kinetic energy of the vehicle can be fed back into the batteries when braking. In conjunction with the innovative ELFA drive and converter technology coupled with an efficient concept for the auxiliaries, daily range targets for vehicles can be achieved without any intermediate charging. The battery drive has no emissions and also provides a very high degree of comfort as a result of the low noise levels.

4. RESEARCH AND DISCUSSION

4.1. Modelling the Vehicle Dynamics in Series Hybrid System

Energy management requires the knowledge of power flows between the hybrid electric vehicle components. The overall power flow can be described by:

$$P_{ICE} = P_{UC} + P_{TR} + P_{AUX} + P_{BR} \tag{4.1}$$

where:

P_{ICE} is power generated by the internal combustion engine
P_{UC} is the power flow into/out of the energy storage (ultracapacitor)
P_{TR} is the tractive power demanded by the driver
P_{AUX} is the auxillary units on the engine to run safety critical systems
P_{BR} is the dissipated energy through resistors if UC E is maximum

Then the generator power can be defined as the net power available to generate electricity:

$$P_G = P_{ICE} - P_{AUX} \tag{4.2}$$

The instantaneous tractive power required to cruise the hybrid electric vehicle at Velocity v is defined in (Gillespie, 1992):

$$\begin{aligned} F_{TR} &= m\frac{dv}{dt} + (F_{gxT} + F_{AD} + F_{roll}) \\ P_{TR}(t) &= F_{TR}(t)v(t) \end{aligned} \tag{4.3}$$

where:

m is the vehicle mass

F_{gxT} is the gravitational force
F_{AD} is the aerodynamic drag force
F_{roll} is the resistive rolling force
$\sin b$ is the grade

The above mentioned resistive vehicular dynamical forces are also defined in (Gillespie, 1992):

$$F_{gxT} = mg \sin b$$
$$F_{AD} = [mgC_1 + \frac{P}{2} A_F D_D]v^2 \quad (4.4)$$
$$F_{roll} = mgC_0$$

The power loss due to resistive dynamical forces can be expressed as:

$$P_{LOSS_MECHANICAL} = v(F_{AD} + F_{roll}) \quad (4.5)$$

Auxiliary Power Consumption can be modelled as a function of the engine speed as follows:

$$P_{AUX}(w) = P_{motoring}(w) + P_{hydrauics}(w) + P_{pneumatics}(w) + P_{A/C}(w) + P_{alternator}(w) \quad (4.6)$$

where:

$P_{motoring}(w)$ is the power consumption due to dynamics of the engine
$P_{pneumatics}(w)$ is the power consumption of the suspension and brake systems
$P_{A/C}(w)$ is the power consumption of the air conditioner unit
$P_{alternator}(w)$ is the 24V alternator power demand
$P_{hydrauics}(w)$ is the power consumption of the hydraulic steering system and the hydraulic cooling system for the engine and powertrain

The auxiliary units exhibit mostly linear behavior and it is advantageous that the power consumptions appear to be a function of the engine speed. An example power consumption curve of the auxiliary units can be given as follows.

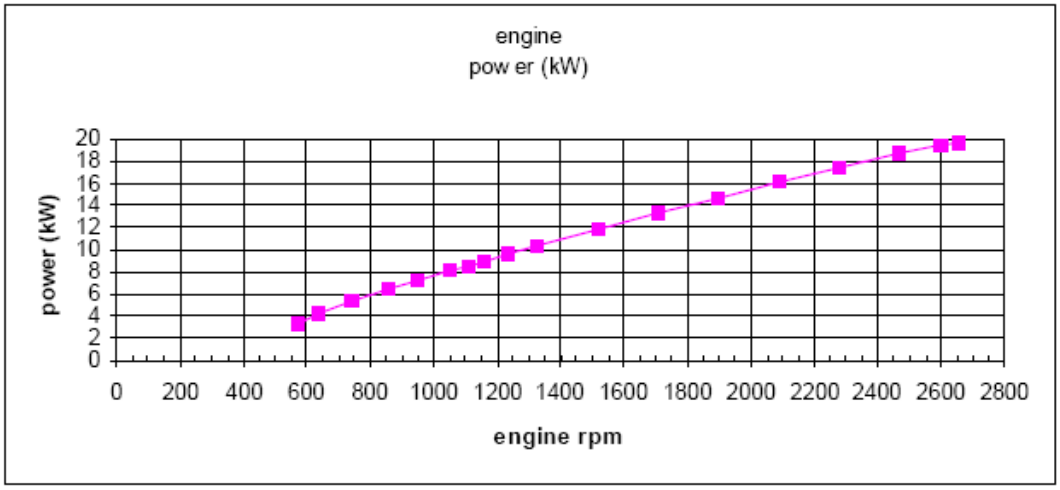


Figure 4.1. A typical $P_{aux}(w)$ curve

Since an engine on/off strategy is not considered for this project it is important to understand the behavior of the auxiliary units. Excessive power should not be spend to drive the auxiliary units. Therefore it is advantageous to drive engine in low speeds as much as possible. The idea is further discussed in the following section.

4.2. Simulation Model

The simulation model can be built in many different ways. To be able to use the model in as many situations as possible the model has to be based on physical principles. This gives more freedom to choose parameters in the model; not only to describe different choices of driving mode and components but also to be able to describe the way the vehicle operates.

In practical use two consecutive driving cycles on the same route are not equal. Stopping at a traffic light, a bus stop without passenger or stopping for a

pedestrian crossing the road are unique actions. The distance, the acceleration behavior and the total stops and starts during one cycle are approximately the same.

The “world model” means description of the external conditions around the bus operation. In principle the following types of information are necessary to supply:

1. the global movement of the vehicle which means acceleration, speed and position as the functions of time,

2. fuel consumption, emissions and the batteries state of charge as functions of time,

3. important components’ efficiency and losses as functions of time.

The model has to include the ICE, the electrical traction machines and the power electronics and consider an adequate description of the vehicle’s mechanic, electrical and ICE dynamics, efficiency and emissions.

The model does not consider things like temperature in the passenger compartment or the number of passengers. Actually, no difference was observed in the measurements between driving a bus filled with passengers and an empty bus. One of the reasons to this is that the bus itself is so heavy that the passenger’s weight does not significantly change the tractive work. Another reason is the relation between aerodynamic and friction forces and of course the altitude variation.

4.2.1 Introduction to the Program-model

Different platforms for programming were evaluated and complete programs for vehicle simulation were evaluated. (van den Bussche, 1998). In some programs it was difficult to make modifications in the simulation program, e.g. with the simulation program Advisor (Advisor) and was not availably by the beginning of the project. Other programs were too expensive. Matlab/Simulink was chosen as the platform for this simulation model.

Matlab is well known in the scientific world and has already been used for many hybrid and electric vehicle simulations. The hybrid bus is modularly designed in Simulink and fed with input values via Matlab.

The simulation program is, after calibration by extensive measurements, used for structural sensitivity analysis and evaluation of charging strategy improvements.

4.2.2. User Interface of the Program

The modules in the simulated vehicle constitute of batteries, ICE, generator, electric motor, power electronics, control block etc. Mechanical dynamics such as aerodynamics and rolling resistance components are modelled. All the components have been chosen to imitate the real bus and its conditions as good as possible. The electrical machines are modelled with look-up tables with current and voltage and efficiency as output parameter. The battery model includes a temperature depending resistance. In the simulation model the auxiliary load is considered a constant power.

The user-defined parameter that can be specified in the simulation model is:

- Choice of bus
- Driving cycle
- Charging strategy
- Size of the certain components

The choice of a special bus, defines the default value of ICE, battery and electric drive motor. These default parameters can then be scaled by reducing the number of cylinders, cells or using a scale factor.

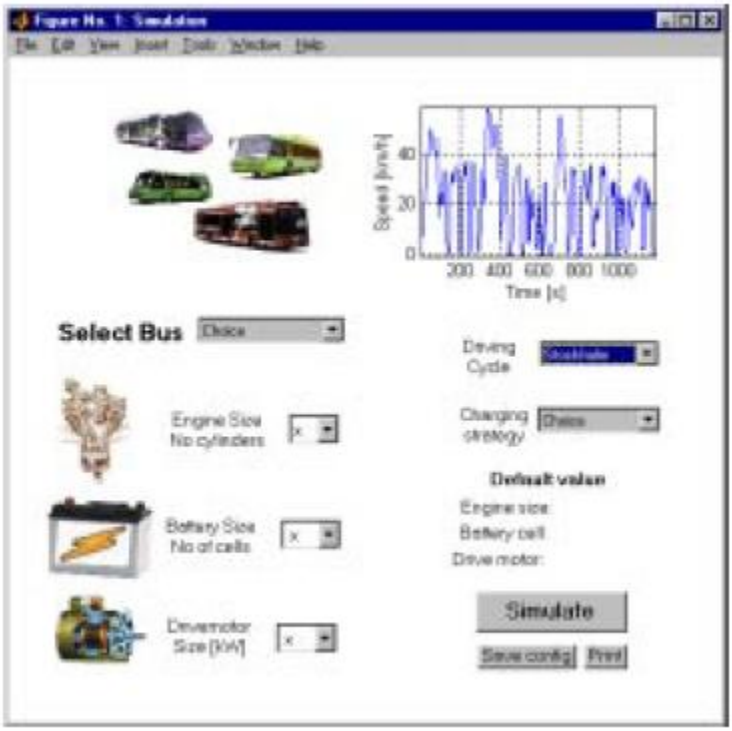


Figure 4.2. User interface of the hybrid bus simulation program.

The ICE simulation model includes all regulated emissions HC, CO and NOx as well as the fuel consumption.

The simulated driving cycles use velocity as a function of time or distance. Using velocity as a function of time can give a wrong result due to accumulated errors. If the speed differs from the desired speed too much due to low performance of the vehicle, the bus stop will occur at the wrong place after a while. If velocity is used as a function of distance this problem will not appear, but there might be a problem with the pause time at the bus stop. To make it possible for the passengers of the simulated vehicle to get on and off the bus at the bus stop, a time delay is added at all bus stops.

It takes 20 seconds to run a complete simulation of 1800 seconds simulation on a hybrid bus with an average PC.

4.2.3. Program Model

The program's structure can be seen in Figure 4.3. This is an overview of the highest level of the Simulink program. Each block can be opened and contains new structures. Here not all the details are described, but only the principal configurations are discussed. The full capability of the software is naturally experienced directly at the computer.

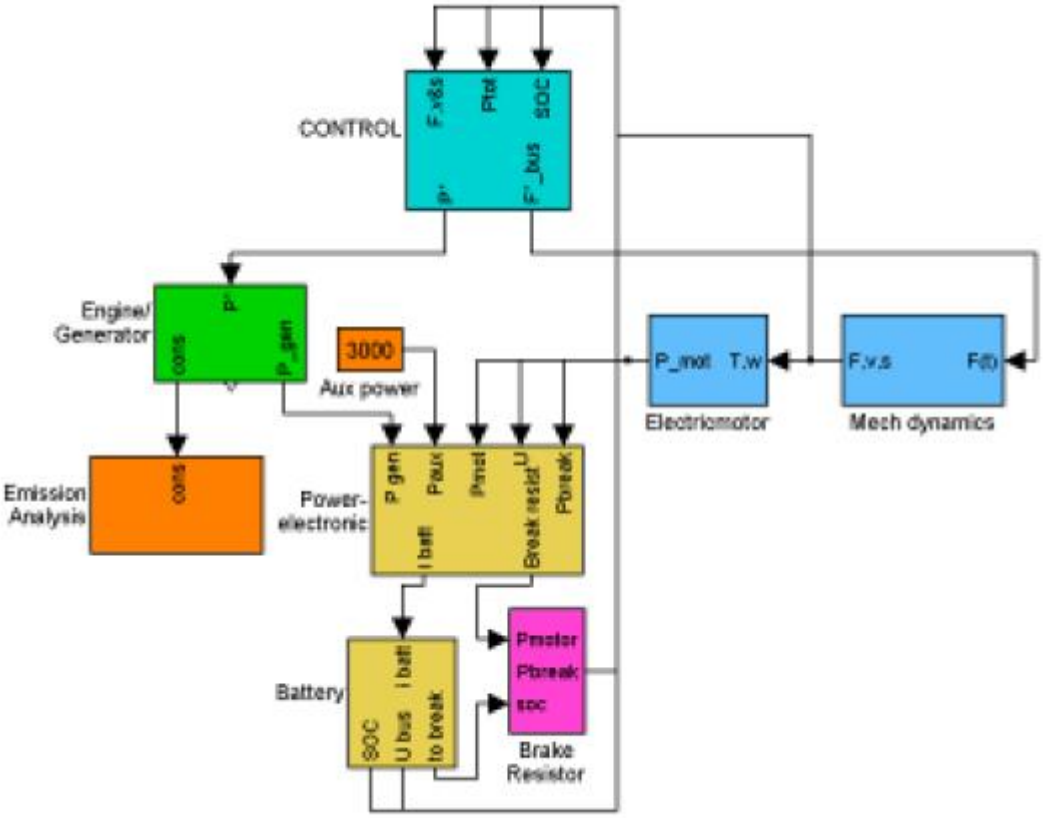


Figure 4.3. The highest level in the simulation program Simulink

4.3. Series Hybrid Vehicle Architecture

This first step of the design process quantifies the stock vehicle performance and develops a set of specifications that the vehicle design must achieve based on team goals and competitive vehicle analysis.

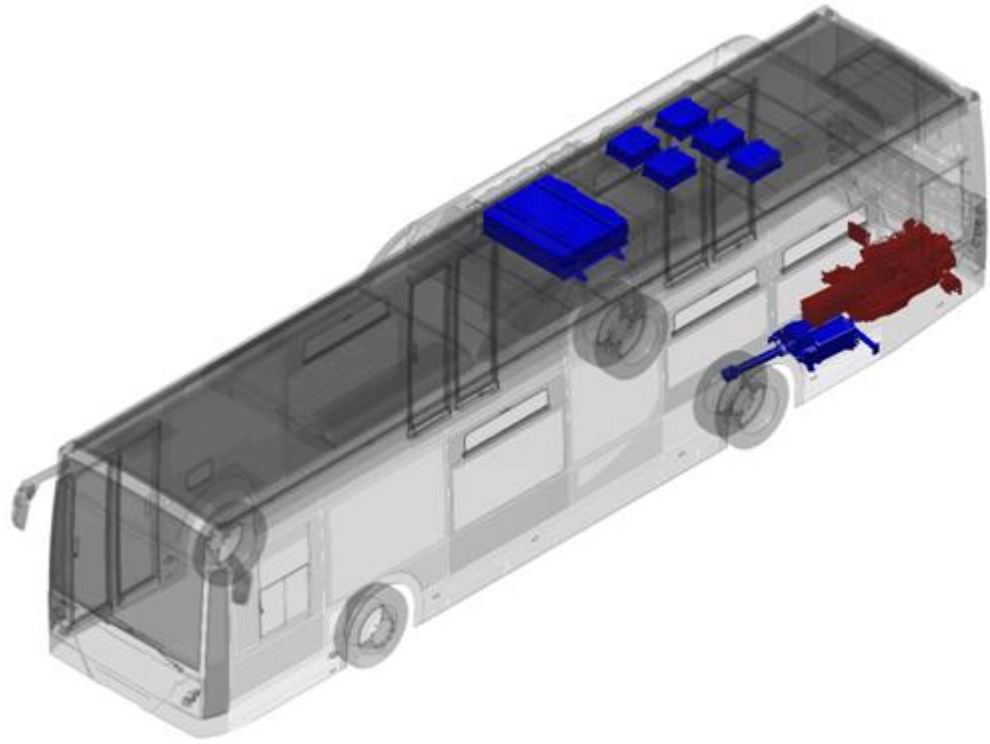


Figure 4.4. Vehicle Architecture 1

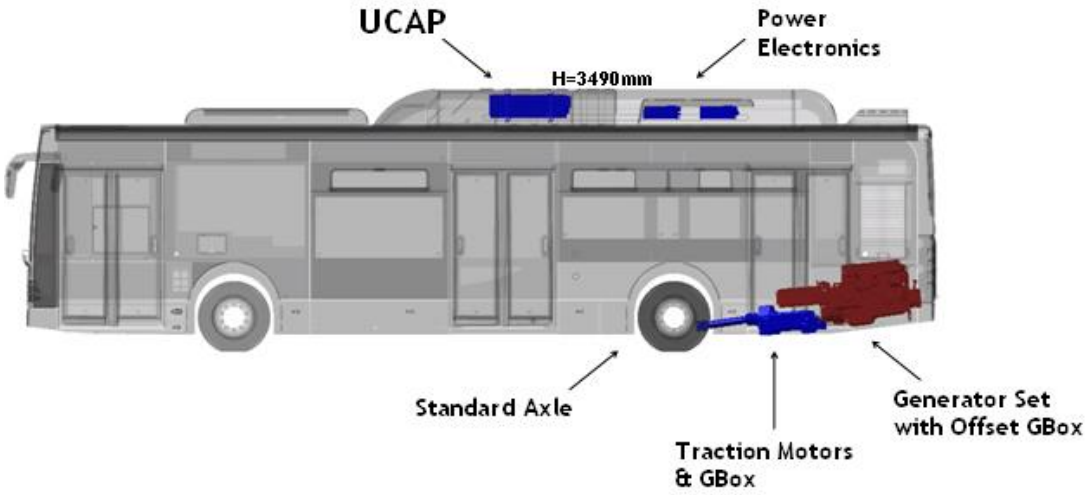


Figure 4.5. Vehicle Architecture 2

The bus is designed for very busy city traffic like in Istanbul, New York, London, etc. Actual bus will be tested in Istanbul to see if the following Theoretical Design Targets are met:

TARGETS

- Above 25% Gaseous Emission Reduction and Fuel Consumption Reduction (depending on Driving Conditions)
- Grade ability 22% (Max.) – 13% (Continuous)
- Maximum Speed 73kph

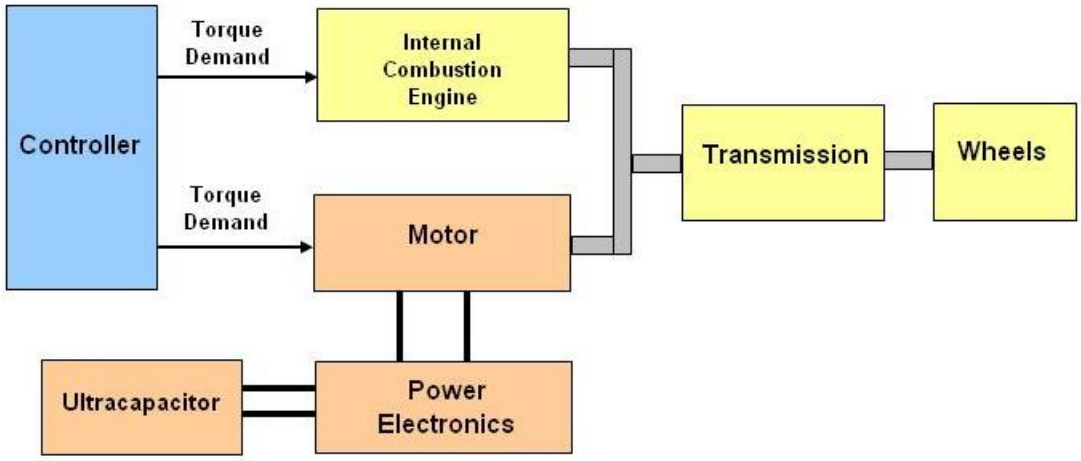


Figure 4.6. Vehicle Hybrid System Structure

4.3.1. Mechanical Dynamics

In the simulation block called *mech dynamics*, all the mechanical forces in the vehicle are summed up. There is no compensation for wind speed or number of passengers. The input variable for the block is the traction force from the vehicle, which in this case is the tractive force of the traction motor and the braking force from the mechanical brakes. The output variables from this block are the traction force, vehicle speed and travelled distance.

In the block the forces on the vehicle such as friction, aerodynamics and slope are summed up together with the traction force (Andersson, 2001).

$$F_R = F_{Traction} + F_{Friction} + F_{Aeoro} + F_{Slope} \tag{4.7}$$

where *Friction F* is a constant friction and *Aero F* is the air resistance of the bus. Acceleration is calculated through Newton's law.

$$a = \frac{F_R}{m_{buss}} = \frac{dv}{dt} \tag{4.8}$$

The acceleration is integrated to speed. The speed is integrated to distance.

$$v(t) = \int_{t=0}^{t} a(t)dt \Rightarrow s(t) = \int_{t=0}^{t} v(t)dt \tag{4.9}$$

The new distance that is reached, as well as the speed, is sent back to the Control block to be used for the new reference speed and tractive force calculation. The speed is used in the block *Electric motor* for calculation of the power use from the batteries and the motor losses.

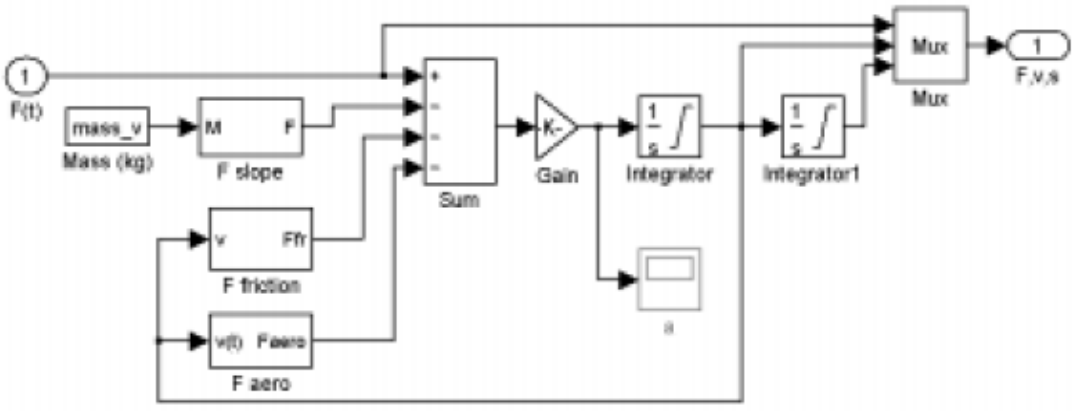


Figure 4.7. The mechanical level in the simulation program (Andersson, 2001)

4.3.2. Electric Traction Motor

The block calculates the power needed for driving the motor, the power on the motor-axis and losses of the electric traction motor. The efficiency of an electrical machine is rather high but is dependent on how it is driven. The losses are mainly of two types:

· Resistive losses caused by the current in the copper-windings. The losses are depending on the current in square.

· Losses caused by the speed when the magnetic flux is changing, eddy current losses and friction when the motor turns. Some losses are linear and some are quadratic to the speed.

The sum of all losses is low compared to an ICE when the motor works at nominal torque and speed. When the motor power is low, the relative losses are higher. This is illustrated in Figure 4.8.

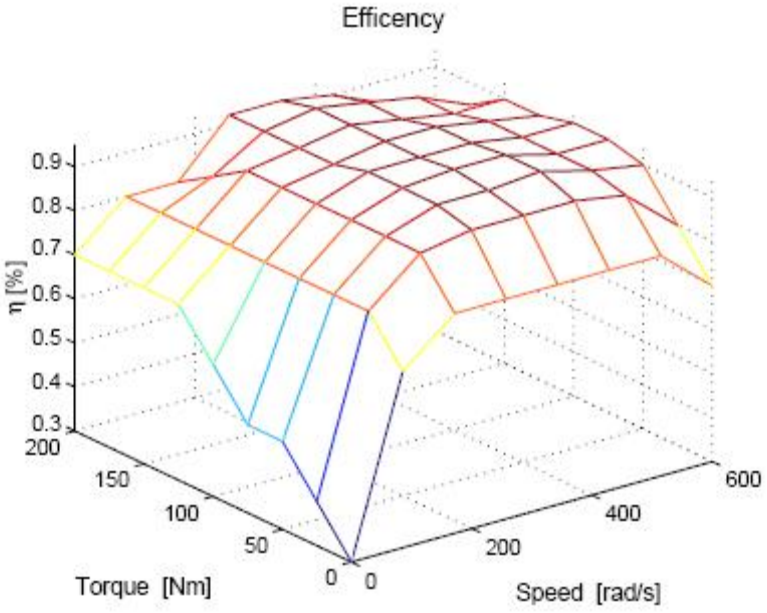


Figure 4.8. The efficiency of an electric motor (Andersson, 2001)

The traction force and speed of the vehicle wheels are converted to traction motor speed and torque. The traction motor speed and torque are used in look-up

tables for the efficiency of the traction motor and the electric input power is calculated. In Figure 4.8 the torque, speed and efficiency of a traction motor is plotted. Since the efficiency of well designed traction motors are very much alike, the same look up table for efficiency is used both for the generator and the traction motors.

4.3.3. Ultracapacitors

4.3.3.1. Ultracapacitor Power Charts

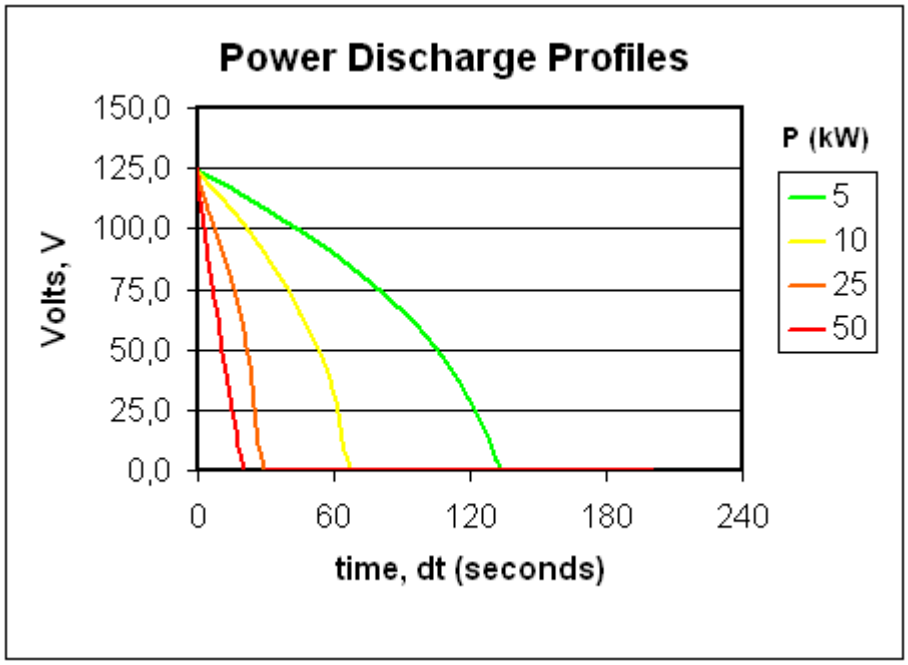


Figure 4.9. Ultracapacitor power discharge profiles (Maxwell Technologies, 2008)

Typical profiles for constant power discharge based on product specifications (Maxwell Technologies, 2008)

$$V = V_r - \frac{\left(\frac{V_r - \sqrt{V_r^2 - 4R_{dc}P}}{2R_{dc}}\right)}{C} dt - IR_{dc} \qquad (4.10)$$

where

V_r = 25 V

C = 63 F

R_{dc} = 0,018 ohms

4.3.3.2. Specification

Table 4.1. Maxwell ultracapacitor module specifications (BMOD0063 P125 B04 Standard module with CAN communications) (Maxwell Technologies, 2008)

Capacitance (F)	63
Rated Voltage (V)	125
Maximum Operating Voltage (V)	130
ESR, DC (mohm)	18
ESR 1kHz (mohm)	14.0
Ic (mA)	5.2
Max. Continuous current (A)	3,930
Weight (kg)	150
Energy Available (Wh)	58
Emax (Wh/kg)	137
Pmax (W/kg)	2.53

4.3.3.3. 125 Volt Transportation Modules

Maxwell Technologies' 125V Heavy Transportation series of ultracapacitor modules is a high performance energy storage product line for hybrid buses, trucks, trolleys, light rail, mining, construction and seaport cranes. Each model incorporates balancing, monitoring and thermal management capabilities to

ensure industry-leading charge/discharge performance, high reliability and long operational life.

4.3.3.4. Features

- Over 1 million charge/discharge cycles
- IP 65 environmental protection
- Operating temperature -40° C to +65° C
- CAN bus digital monitoring and communications
- Highest power performance available
- Temperature and voltage monitoring
- Series connection up to 1500V

4.3.3.5. Benefits

- Highest performance hybrid power systems
- Survive in nearly any weather/environmental conditions
- All in one solution with digital monitoring and built-in forced air cooling
- Digital feedback enables optimized hybrid control algorithms

4.3.3.6. Advantages In Hybrid Vehicles

- High power density
- Low impedance
- Virtually unlimited cycle life
- Rapid charging
- Reliable performance in harsh environments

4.3.3.7. Implementation

"An electric engine has a lot of torque at low revs —that is its main benefit — so it's ideal for fast initial acceleration. At higher revs, once you've begun to accelerate, nothing can beat an internal combustion engine. Our hybrid approach combines the best characteristics of both engines." Prof. Freymannfrom BMW (Vahidi, 2009).

Here, the Siemens generator is driven by a Cummins ISB 6.7e5, 6.7 liter engine modified to operate on pure hydrogen. It provides up to 184 kW of electric power in this series hybrid to drive a Siemens ELFA drive system. Excess energy, as well as energy recouped by regenerative braking, is stored in Maxwell ultracapacitors.

4.3.4. ICE in Test Bench

The stationary characteristics of the ICE's used in two dimension look-up tables in the simulation program are based on measurements from test bench driving. Torque (Nm) and speed (RPM) is used as the in parameter and for example NOx emission (g/kWh) as out parameter. The bench testing gives a good knowledge about how the ICE works in stationary operation, but is not valid when the ICE moves too fast in torque or speed.

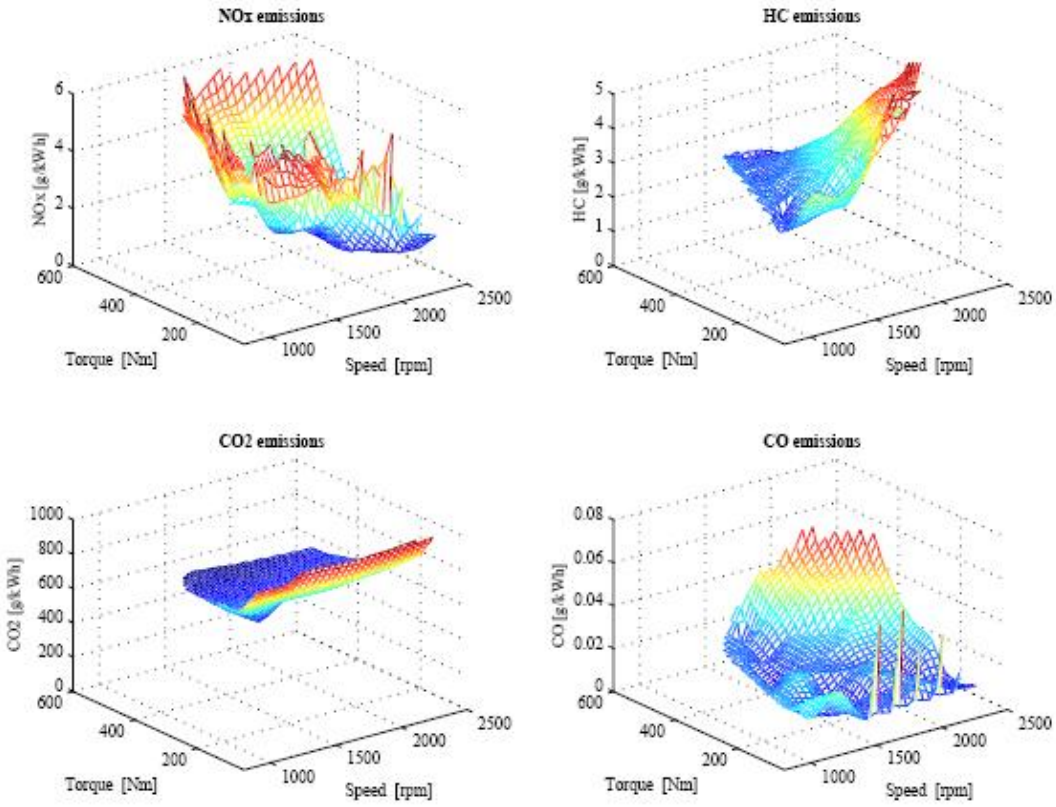


Figure 4.10. The emissions from the Cummins natural gas ICE

4.4. Series Hybrid Bus Operation

4.4.1. UCAP State of Charge

State of Charge (SOC) of the Energy Storage (UCAP) is a measure of the net energy stored in the UCAP. If SOC is LOW, Generator (generator coupled with the engine) charges the UCAP at Constant Charge Regime (e.g. at constant speed/torque). This enables the Engine (ICE) to run smoothly at efficient operation region. If SOC is HIGH, Generator stops charging.

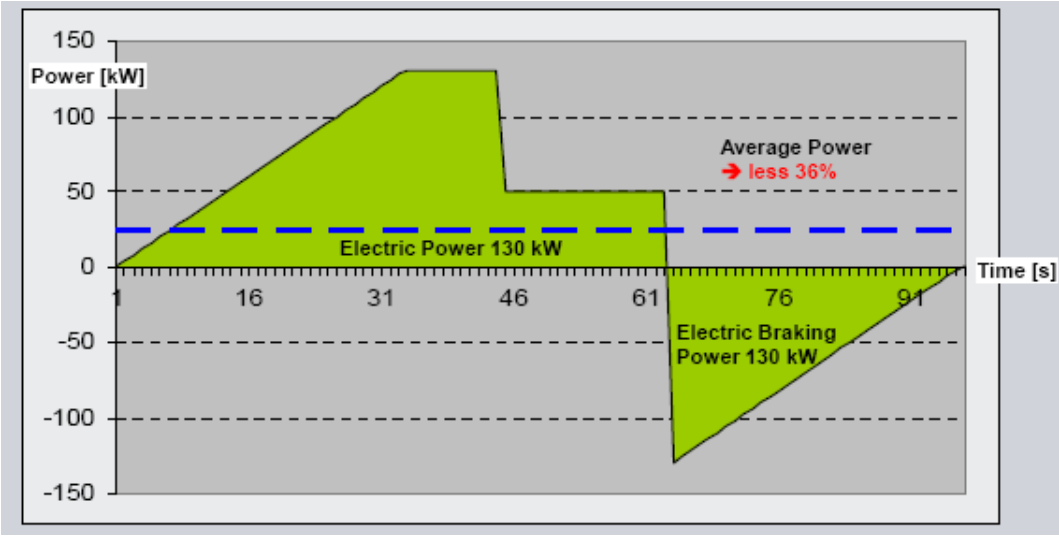


Figure 4.11. Serial Hybrid energy savings potential (Siemens AG, 2010)

4.4.2. BRAKING

When Braking, Energy Storage (UCAP) is charged by the Traction Motors (M/G) acting as Generators, in varying power levels to match the Driver's Braking Need. If SOC is high, excess energy is dissipated by a Brake Resistor in the System. If harsh brake is needed, Service Brakes of the Bus and ABS Systems gets into operation.

4.4.3. ACCELERATION & CRUISING

When accelerating, Power flows from Energy Storage to the M/G to drive the Bus to meet the Driver's Acceleration Demand. The Battery is charged when SOC is low.

When Cruising, the power demand by the M/G for driving the Bus is met by the Generator directly, thus there is minimal energy flow over UCAP.

4.4.4. IDLE

When the Bus has stopped and the engine is idling, the engine is stopped. When accelerator pedal is depressed the engine is started.

4.5. Drive Cycles

In urban areas, a vehicle can be driven on the road for different types of roadways (e.g. local roadways, arterial and freeway). A drive cycle is a series of data points representing the speed of a vehicle versus time. It is a trip defined as a driving path from an origin to a destination with a predefined travel speed, time, acceleration and deceleration. Drive cycles are produced by different countries and organizations to assess the performance of vehicles in various ways, as for example fuel consumption and emissions.

The Classical Road drive cycle which is 1 km long and takes approximately 160 seconds to complete. This cycle is composed of three accelerations with maximum speeds of 20km/h, 30km/h and 50km/h each.

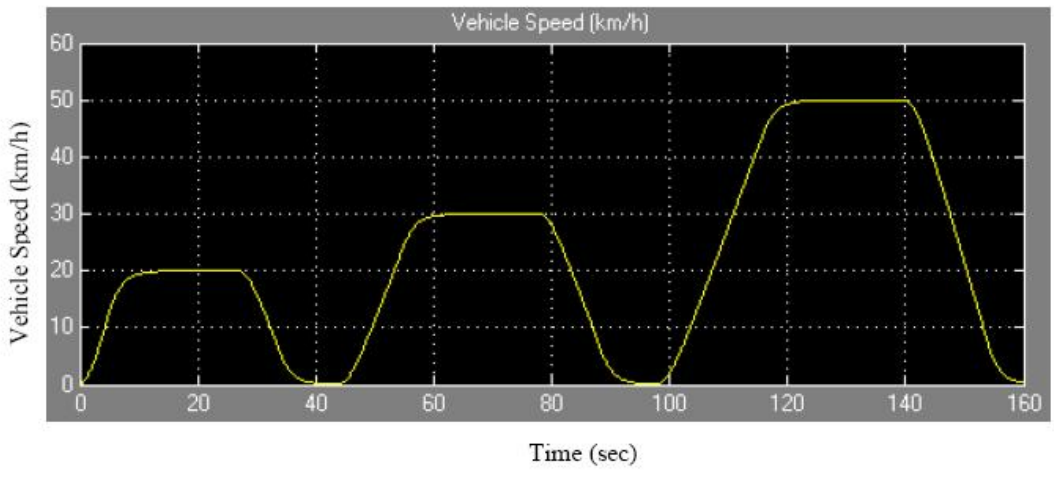


Figure 4.12. Classical Road Drive Cycle

The Metropolis drive cycle is representative of actual observed driving patterns of transit buses in Metropolis. It is a short test cycle characterized by

frequent stops, fast average acceleration, and low speed. Metropolis drive cycle is 1 km long and takes approximately 600 seconds to complete. Eleven accelerations of Metropolis are structured to simulate the real traffic conditions.

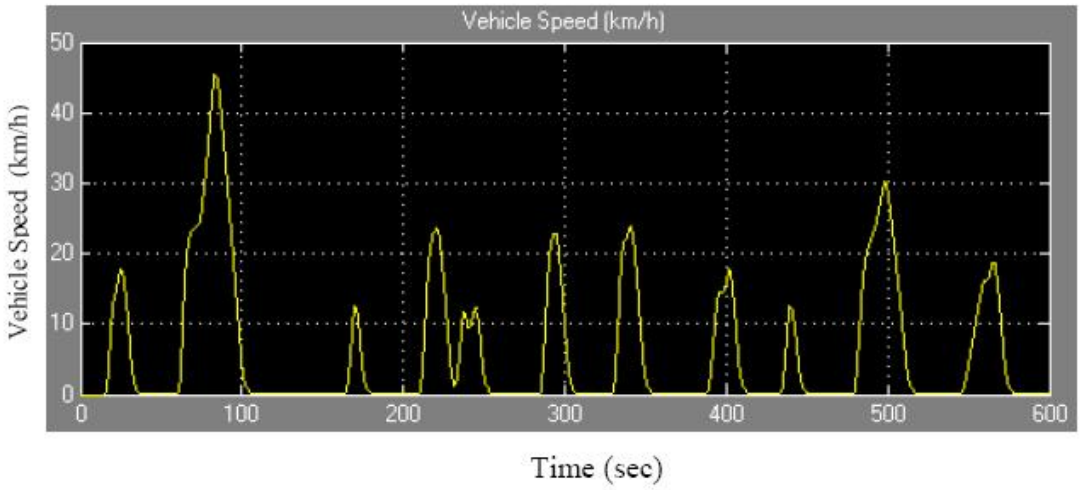


Figure 4.13. Metropolis Drive Cycle

Both Drive Cycles are independent of the traffic condition or the grade of the road and therefore frequently used as a reference for new vehicle testing.

4.6. Simulation Parameters

The vehicle studied in this project is a commercial 12m long citibus (18 ton maximum weight) with a 6 cylinder 185kW diesel engine.

The electric propulsion is composed of 2 x 85kW rated (2x150kW maximum) induction machines. The final driveline is assumed to have an efficiency of 0.9. The ultracapacitor system is capable of storing 1kWh energy and assumed to have an initial energy storage of 0.5 kWh. The charge/recharge efficiency is assumed to have an efficiency of 0.9.

To represent the performance of the methodology used in this thesis and produce results that are representative of real life conditions, road gradients were added to the drive cycles. The corresponding grade profile of the route is presented in Figure 4.14. The figure represents a hilly route in public transport systems with a maximum +-5% grade limit.

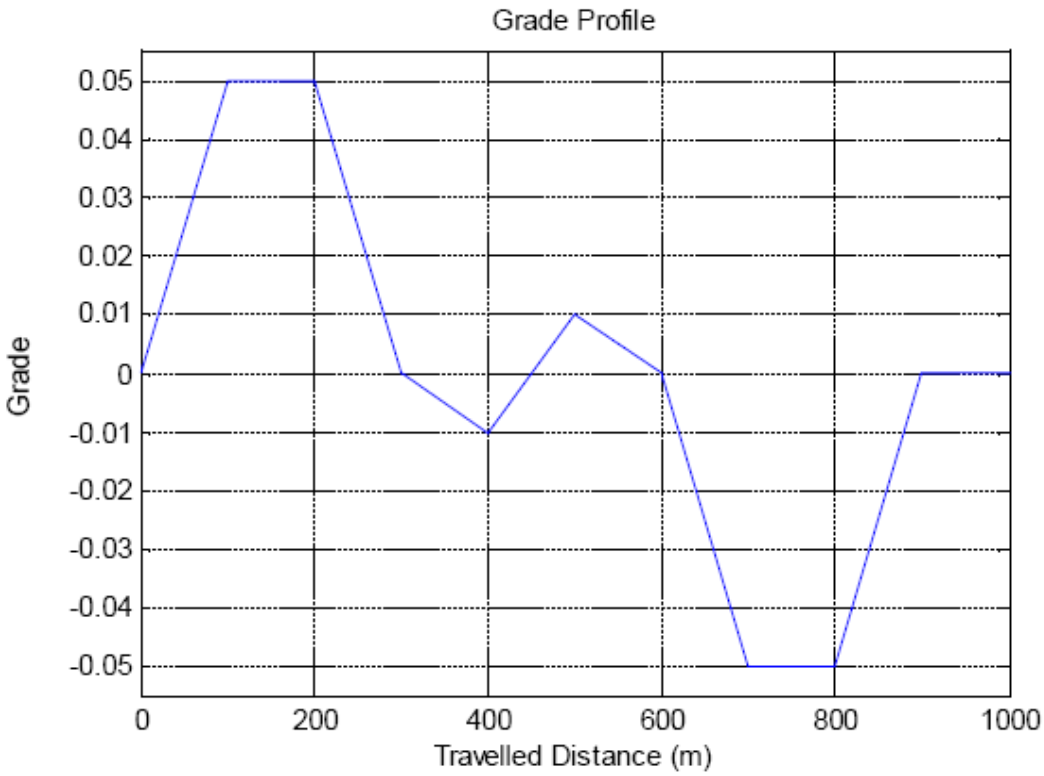


Figure 4.14. Grade Profile used for the drive cycles Classical Road and Metropolis

The above illustrated profile with a maximum +-5% grade limit is chosen regarding the fact that it represents a frequent hilly route in the public transport system.

4.7. Vehicle Dynamics Results

In this section the outputs of the simulated commercial citibus regarding the traction power will be presented.

The citibus is assumed to have a weight of 18000kg. The drag coefficient due to aerodynamic forces is taken as 2.6 which is reasonable for a bus. The rolling resistance is taken as 0.007 which is appropriate for an interaction between asphalt road and a tire with a heavy duty vehicle specification.

For Classical Road and Metropolis drive cycles the vehicle dynamic performance was recorded the speed profile, the total travelled distance and the traction power demanded to complete the cycle is presented in Figure. 4.15.

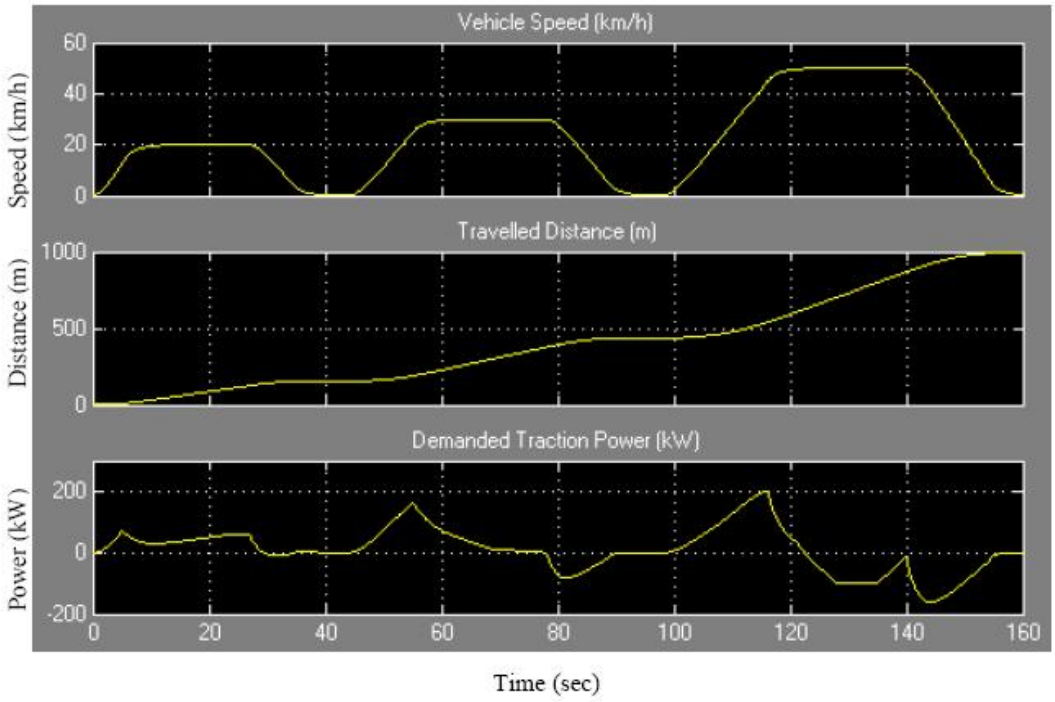


Figure 4.15. Speed, Distance and Demanded Traction Power for Classical Road drive cycle

It is important to note that the peak traction power demand is observed to be 200kW for Classical Road drive cycle with the given grade profile. It exhibits a good example for the performance of hybrid powertrains. A commercial vehicle would not be capable delivering this amount of propulsion power so the performance would be degraded.

The energy consumption in case of a hybrid powertrain and also in case of a commercial powertrain is graphed in the figure 4.16 to emphasize the difference due to the recuperated braking energy.

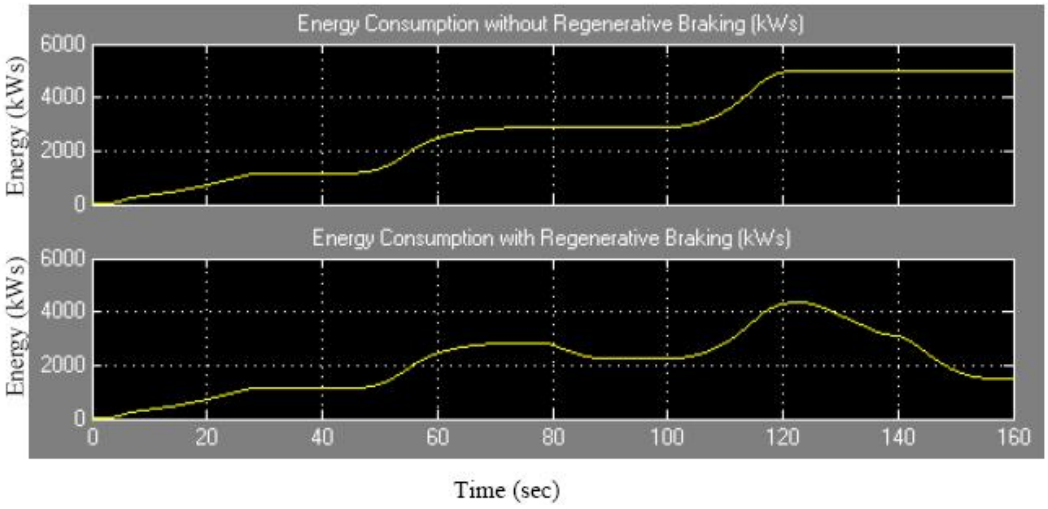


Figure 4.16. Energy Consumption with / without Regenerative Braking

In Metropolis Drive Cycle the peak demanded traction power (300kW) is even higher due to the fact that the second speed up with 50km/h maximum speed has a relatively high acceleration of 8 m/s.

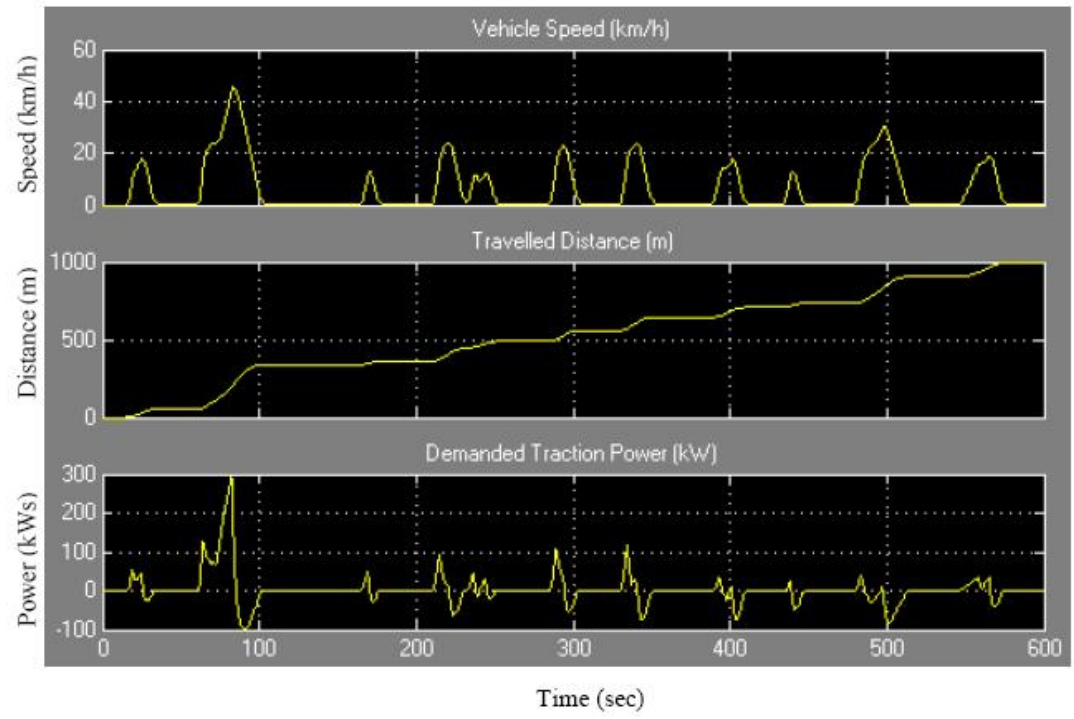


Figure 4.17. Speed, Distance and Demanded Traction Power for Metropolis drive cycle

After simulating the two cycles with different structural characteristics it should be noted that as the number of ramps within a drive cycle increases the total energy loss due to braking, ultracapacitor inefficiency and road loads increases also.

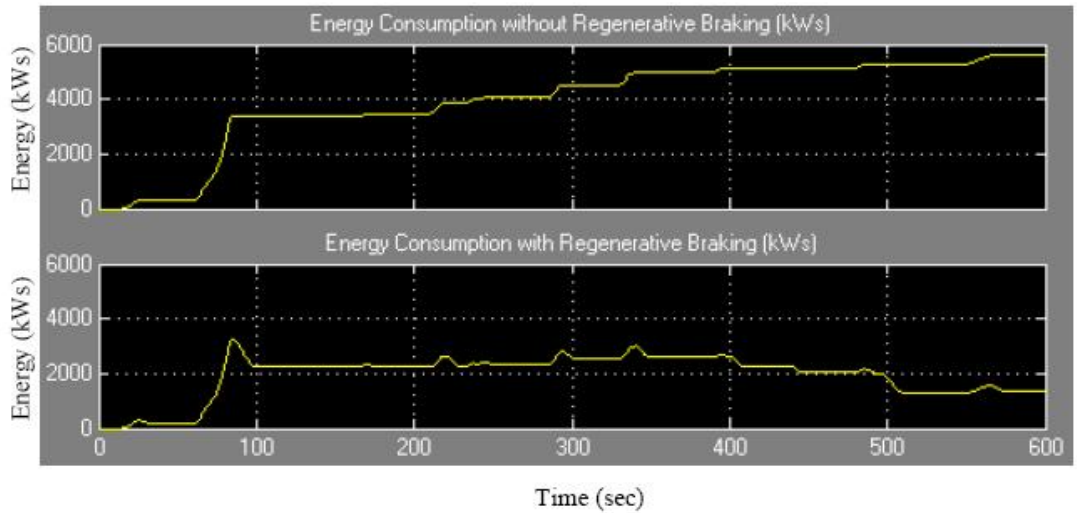


Figure 4.18. Energy Consumption with or without Regenerative Braking

4.8. Optimization Method Results

The SoC, fuel consumption, the constraints and the output of the dynamic optimization problem was recorded for the two drive cycles.

4.8.1. Classical Road drive cycles

4.8.1.1. Case 1

This case is assumed to be in its simplest form $0 \le E_{UC} \le E_{UC_\max}$. In other words, the ultracapacitor system is assumed to be capable of delivering 100% of its stored energy.

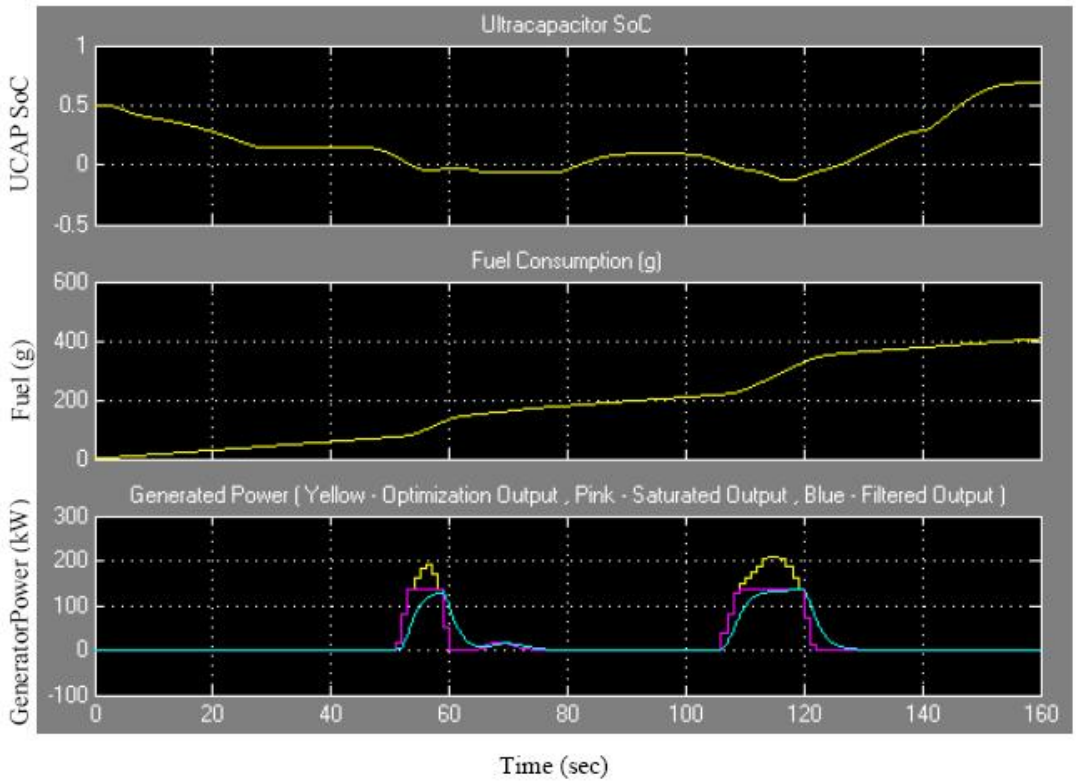


Figure 4.19. SoC, fuel consumption and generator power for Classical Road drive cycle case 1

The first graph presents the ultracapacitor SoC which depletes after 55 seconds due to the second acceleration of the vehicle. The constraint can not fulfill the requirement to follow the demanded speed profile. The second graph presents the fuel consumption of the vehicle. The yellow curve in the last graph presents the optimization output for generator power. As the ultracapacitor energy depletes, the generator power is observed to be increasing exceeding its physical limits. Therefore a saturated signal (magenta) represents the physical limitations of the generator power. The blue curve is both low-pass-filtered and saturated output. It simulates the time lag due to the fuel injection response and the dynamics of the ICE which is named as the ”slew rate”.

Figure 4.20 exhibits the behavior of the upper bound (yellow curve) and lower bound (magenta curve).

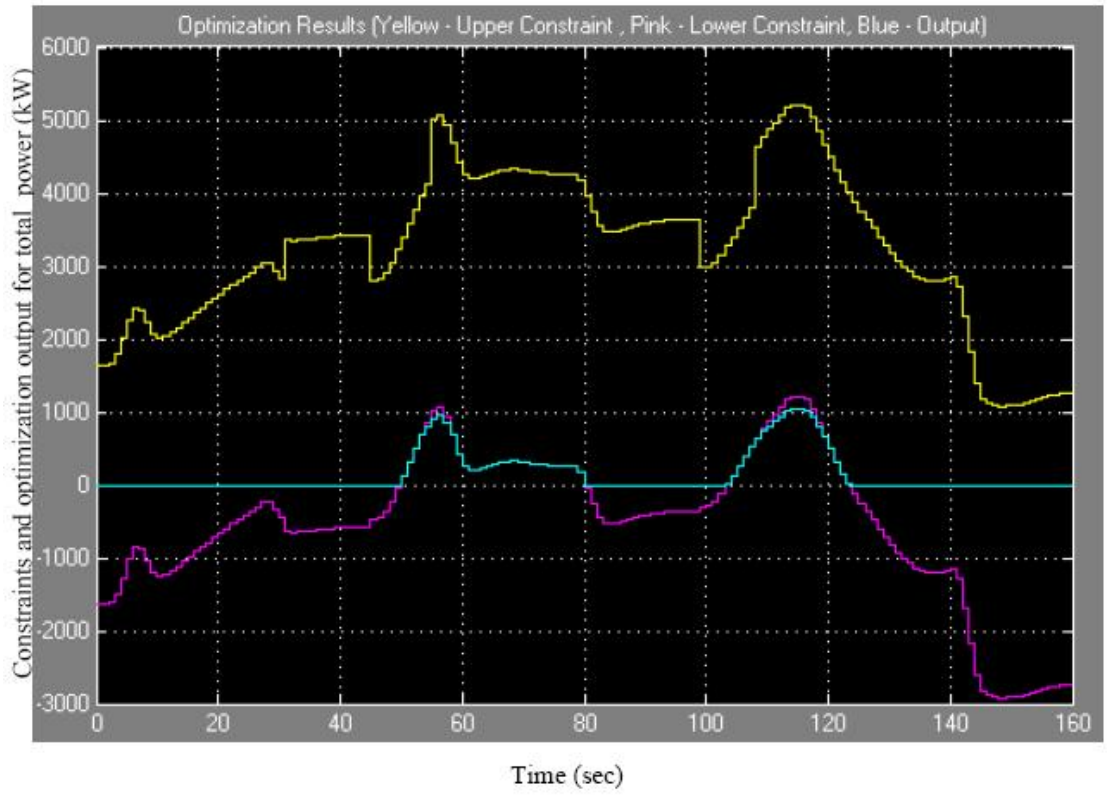


Figure 4.20. Optimization results for Classical Road drive cycle case 1

For the period in which the lower bound takes negative values, the blue line representing the optimization output generator power follows its lower physical limit which is defined as zero.

4.8.1.2. Case 2

In this case, the SoC output overshoots the upper bound (100%) because of the excessive regenerated energy recuperated during the last deceleration. It can be concluded that due to the fact that the constraint defined is not capable of adaption to changing load conditions. This insufficiency is valid for both case 1 and case 2.

In Figure 4.21, similar to Figure 4.20, an inconsistency between is observed between the curves of the lower constraint (magenta color) and the output total generator power (in blue color) at t=55 sec and t =110 sec.

It can be concluded that if the fuel consumption minimization problem is defined with static constraints, it is observed that the electric energy storage unit either depletes or overflows due to the unpredictable nature of the demanded traction power.

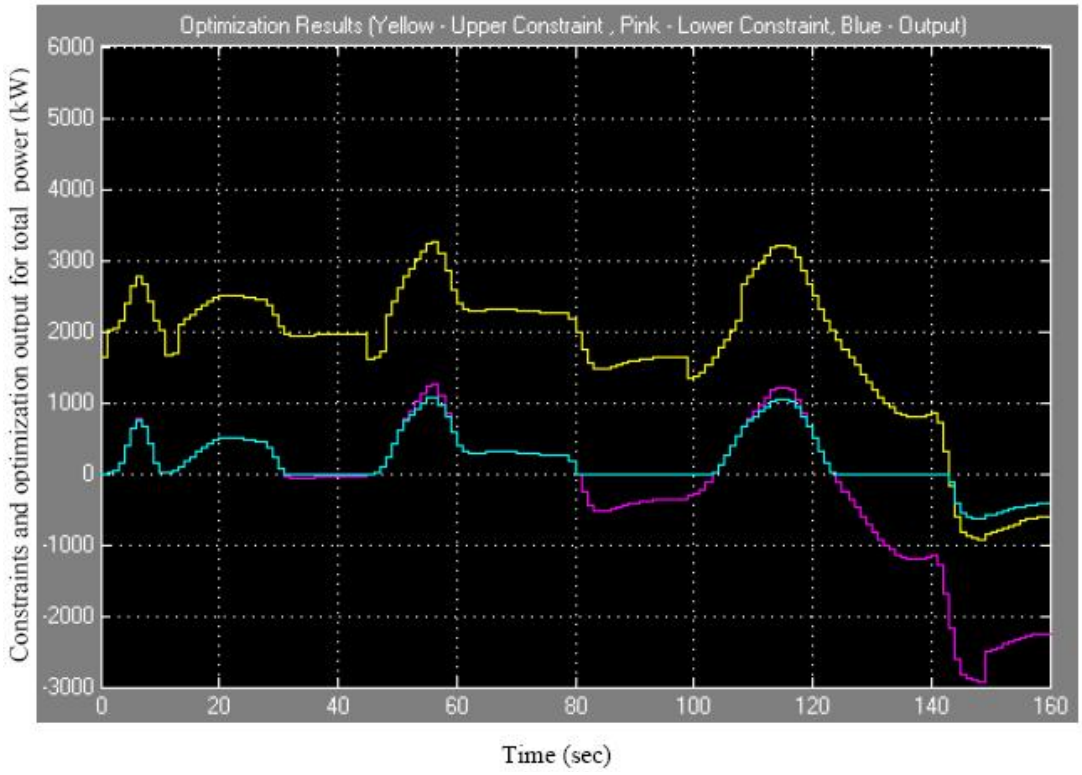


Figure 4.21. Optimization results for Classical Road drive cycle case 2

4.8.1.3. Case 3

The electrical energy in the ultracapacitor system can be defined as a function of vehicle speed and the road gradient. The sum of the electrically stored energy in the ultracapacitor, the kinetic and the potential energies of the vehicle is kept constant and is assumed to be less than or equal to the ultracapacitor energy capacity. For this reason, as illustrated in Fig 4.22, the SoC drops down to almost zero at t=115 and rises up to 90% after regeneration. The improvement in SoC output is due

to the increase of adaptability against the unpredictable road load conditions and driver traction demand.

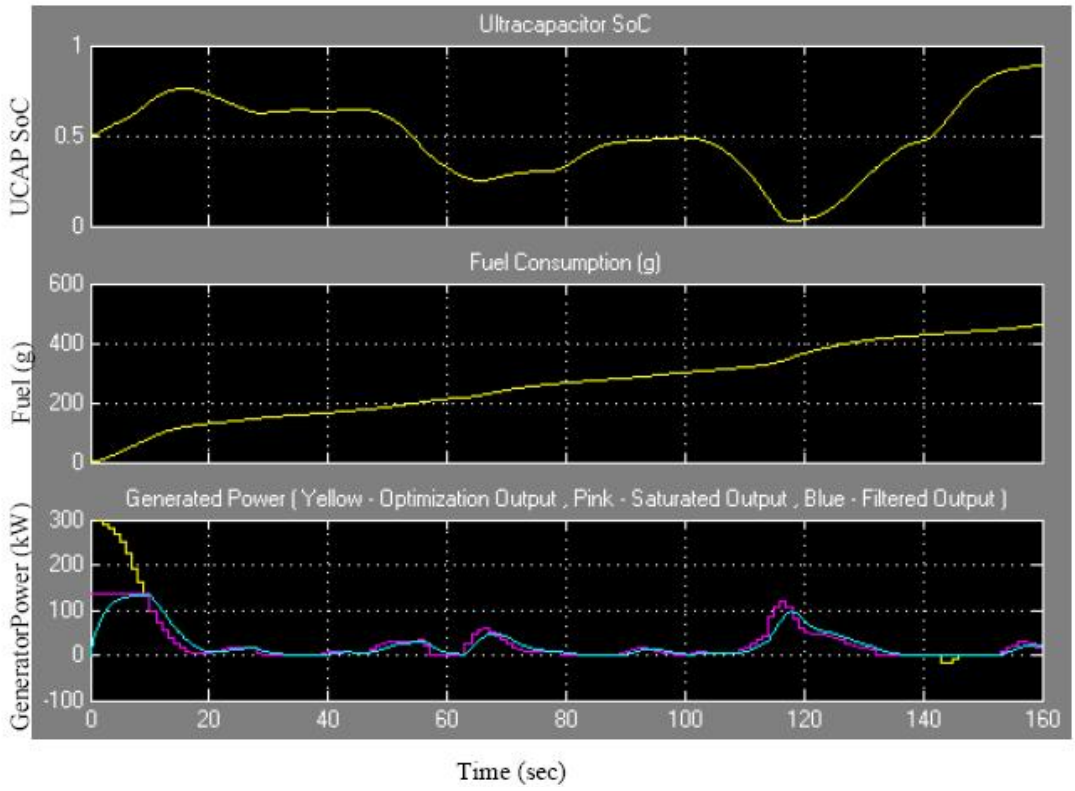


Figure 4.22. SoC, fuel consumption and generator power for Classical Road drive cycle Case 3

Total fuel consumption is less than the previous case 2 due to the fact that the storage capacity is fully exploited instead of a percentage (There is no static constraint on ultracapacitor energy). Another improvement to mention is the reduced transients of the ICE.

Compared to the previous cases the engine shows a more steady behavior which is in reality an advancement in terms of decreased transient dynamics due to excessive injection etc.

At the beginning of the simulation, the output total generator power falls below the lower constraint due to the saturated power generation. The dynamic constraint dictates to have a full energy storage when the mechanical energy (kinetic

and potential) of the vehicle is minimum, but intentionally for the simulation purposes the initial SoC was set to 0.5 to observe its effect.

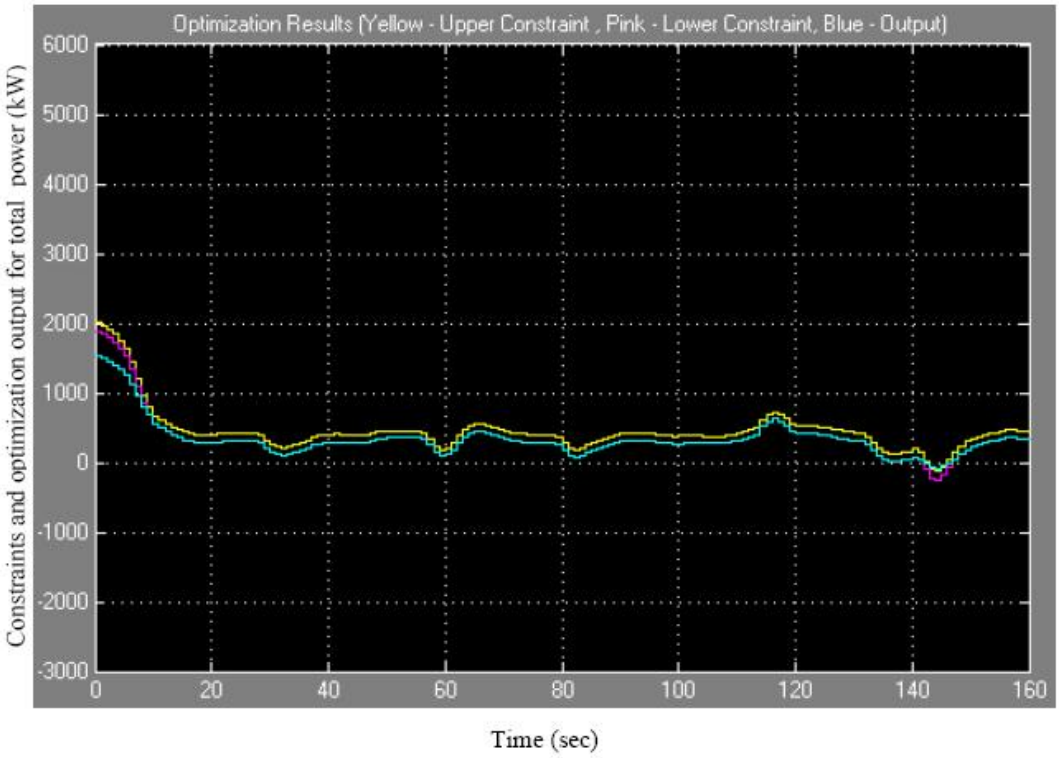


Figure 4.23. Optimization results for Classical Road drive cycle Case 3

As stated before the increasing behavior of the objective function forces the output of the optimization to overlap with the lower bounds.

4.8.2. Metropolis Drive Cycle

The 3 cases simulated with the Classical Road drive cycle are also applied to the Metropolis cycle to observe the outputs of the optimization method.

4.8.2.1. Case 1

Similar to the outputs in Classical Road cycle, with the simple constraint $0 \le E_{UC} \le E_{UC_\max}$ it is not possible to fulfill the requirements of the demanded vehicle propulsion to complete the mission. The SoC drops below zero within the second acceleration of the cycle.

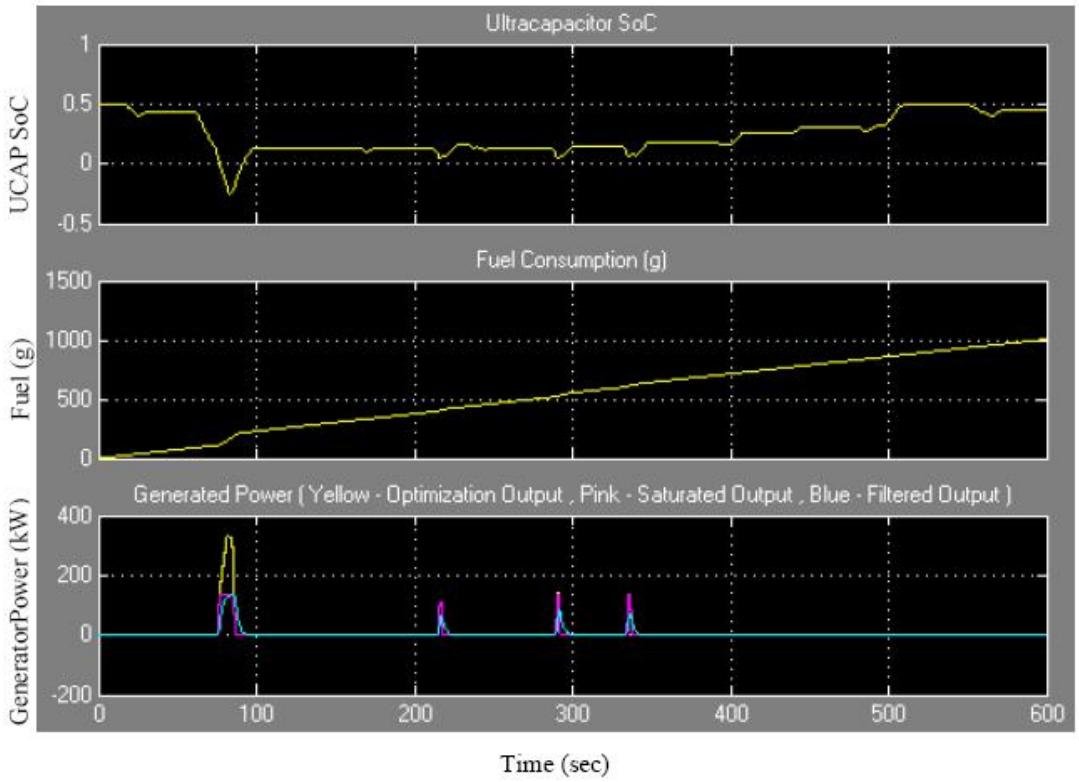


Figure 4.24. SoC, fuel consumption and generator power for Metropolis drive cycle Case 1

Similar to case 1 of the Classical Road the problem of SoC depletion is observed again for the 600 sec long Metropolis drive cycle. Total fuel consumption is observed to be 1000g.

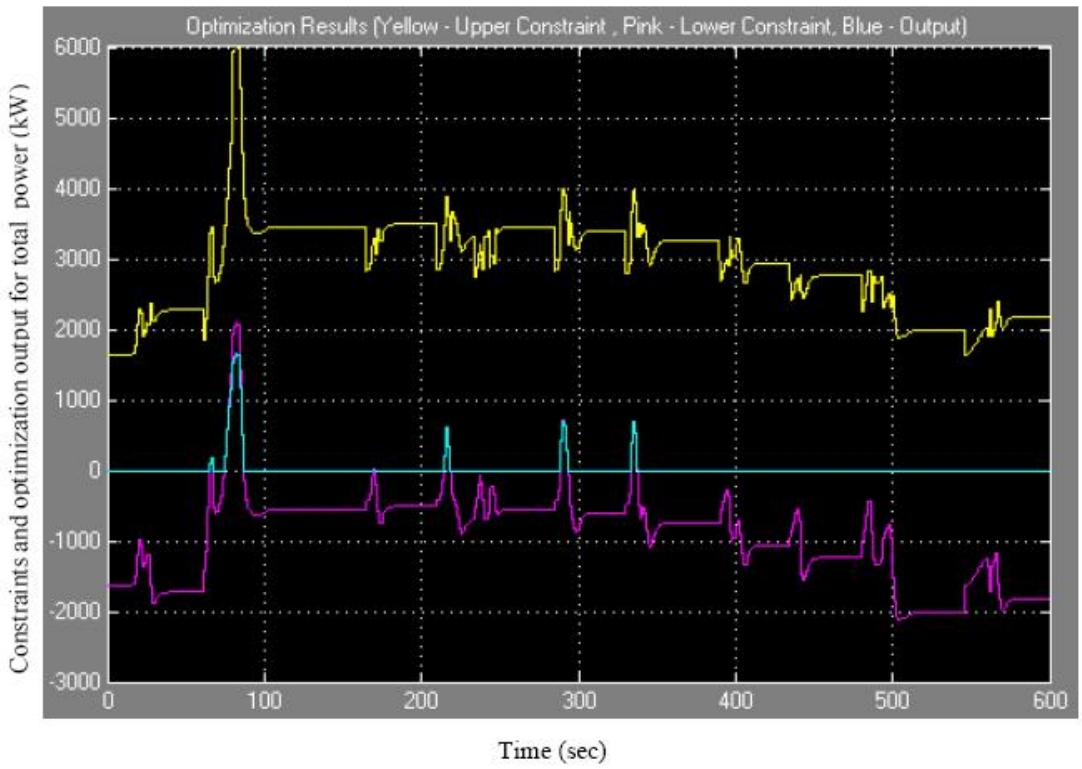


Figure 4.25. Optimization results for Metropolis drive cycle Case 1

4.8.2.2. Case 2

The following graph presents the outputs for the case 2, $0.5E_{UC_\max} \le E_{UC} \le E_{UC_\max}$

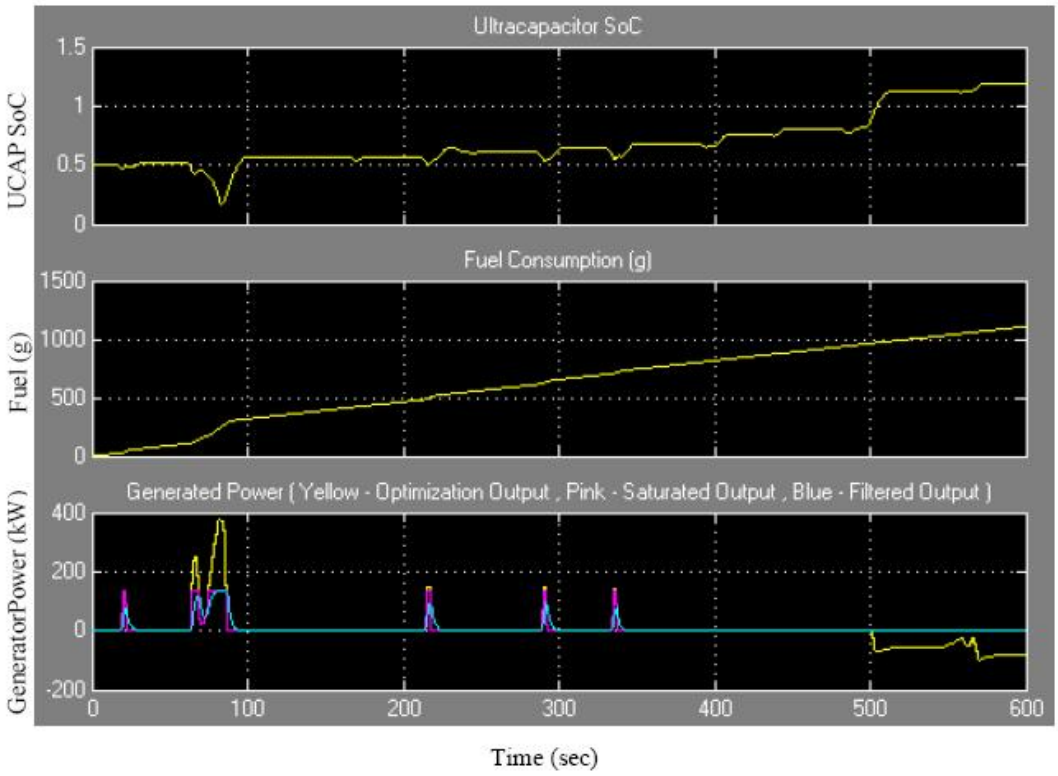


Figure 4.26. SoC, fuel consumption and generator power for Metropolis drive cycle Case 2

The SoC overflow problem is also observed at the end portion of Metropolis cycle composed of increased number of accelerations and decelerations. The SoC is observed to be exceeding the physical limits which would lead to deploy brake resistors to dissipate the excessive energy. Similar to case 1 the transients of the engine are observed to be high. High transients would lead to excessive fuel injection in real world scenario.

Figure 4.27 exhibits the inconsistency between the curves of the lower constraint (magenta color) and the output total generator power (in blue color) at t=61 sec and t =75 sec.

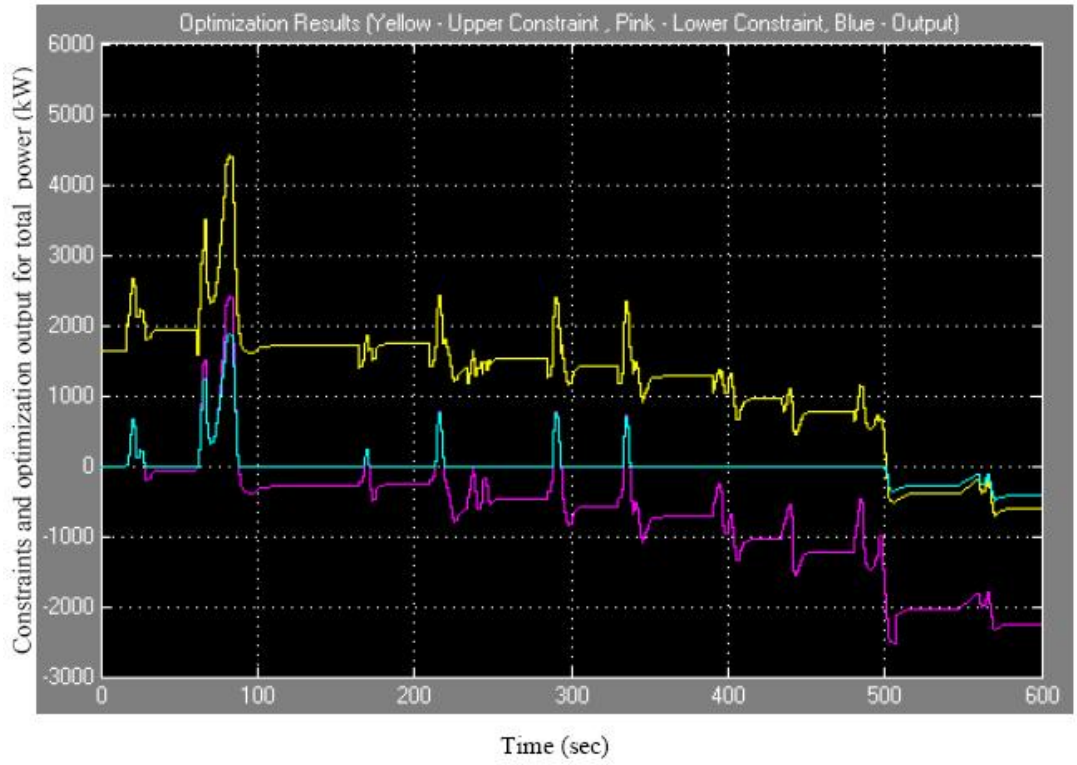


Figure 4.27. Optimization results for Metropolis drive cycle Case 2

4.8.2.3. Case 3

The following diagram presents the SoC output, fuel consumption and the generator power required to complete the Metropolis cycle.

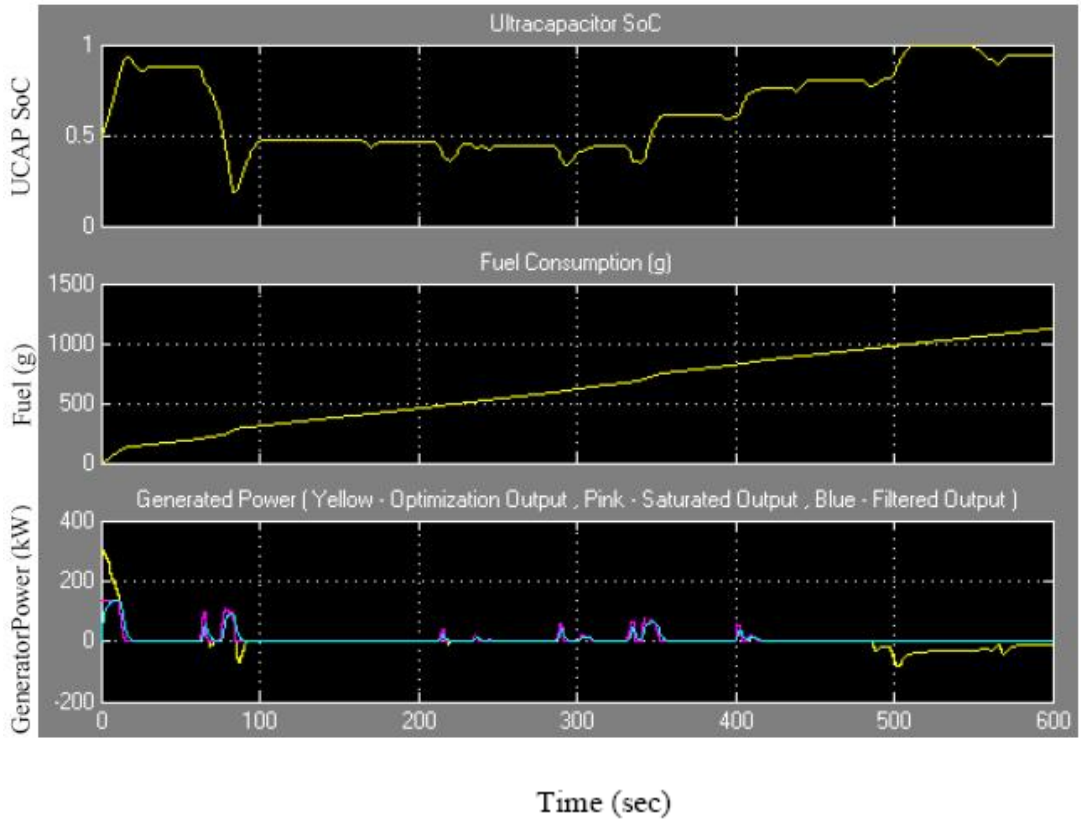


Figure 4.28. SoC, fuel consumption and generator power for Metropolis drive cycle Case 3

Unlike the case I and case 2 no overflow or full depletion is observed throughout the mission in terms of SoC. Fuel consumption is comparable to case 2 (~1000g). The transients of the engine are reduced. In simulation environment the increasing effect of transients on fuel consumption is another research topic. It is not covered in this thesis but the benefits of reduced transients are welcomed in automotive engineering applications.

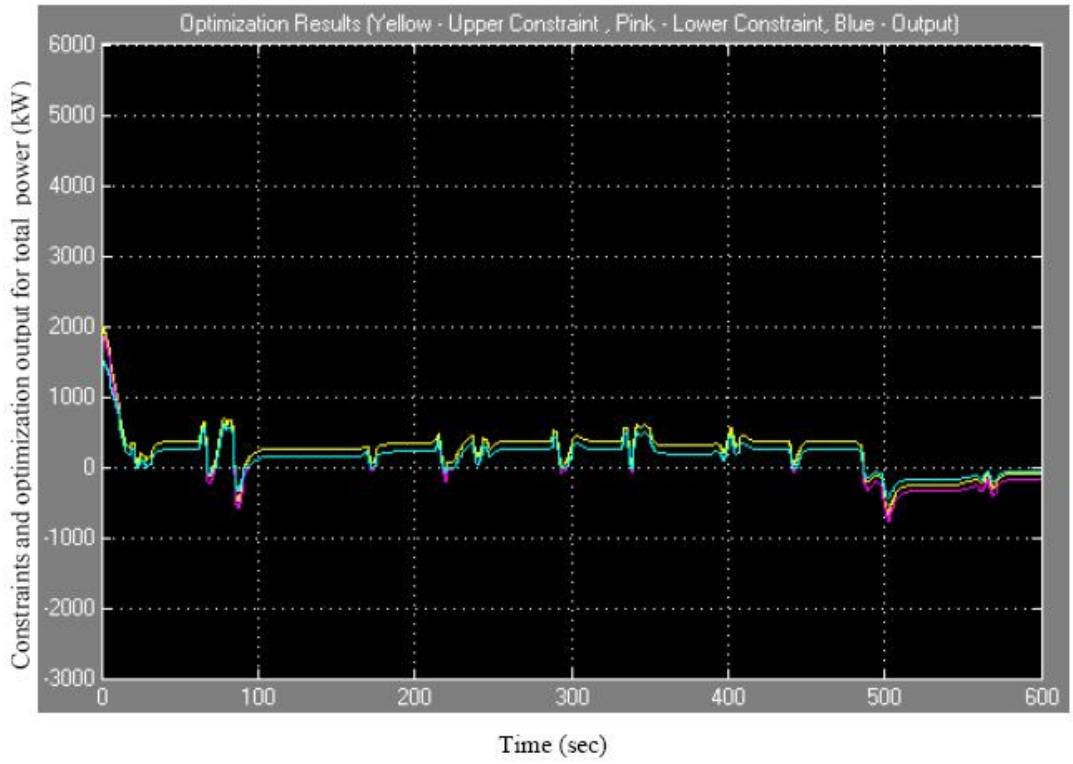


Figure 4.29. Optimization results for Metropolis drive cycle Case 3

In this chapter, a simulation study was conducted to assess the performance of a series hybrid vehicle configuration using two standard driving cycles, Classical Road and Metropolis. Simulation parameters were introduced and the simulated vehicle dynamical outputs were presented.

The results indicated that depending on the constraint type chosen, the SoC of the storage unit can be fully or partially used to reduce the fuel consumption of a series HEV in city cruising.

The problem is complicated due to the fact that the future driving demands are largely unknown. This uncertainty of the future driving makes it difficult, from a fuel efficiency viewpoint, to compare the cost of supplying the energy demand from the buffer or the fuel tank. In this thesis this problem is handled by using a prediction based information perspective. It allows utilization of a policy derived by Dynamic Programming. Using a simple model of the power flows, energy levels and a regression model of the future driving, the resulting policy minimizes the expected

fuel consumption with respect to the prediction model of the future driving conditions.

Additional information from GPS and digital maps or cooperation with the traffic infrastructure further enhances the optimization in terms of improved predictions and constraints and can be used to better schedule the use of the buffer so that further fuel consumption reductions are achieved.

5. CONCLUSION

The major conclusions are:

1. To be able to write “near optimal” specifications for a hybrid bus it is important to know the driving cycles, what kind of traffic, how steep hills and how many passengers the bus is expected to carry. Without such “a priori” knowledge, the hybrid drive train is likely to be overpowered with significantly less than optimal performance in terms of emissions, fuel consumption and battery losses. The ICE must be selected and purposefully designed with regard to average and peak power production. This in turn requires a well-defined charging strategy. The battery size must be limited to a minimum with respect to either the charging strategy or the minimum zero emission driving distance.

2. The charging strategy is important to minimize exhaust emissions and fuel consumption. The goal should be to supply instantaneous power to the traction and auxiliary systems, but without exceeding the limit for transient emission generation with the ICE. With such a goal, the battery will be minimized with respect to the charging strategy.

Since the driver's traction power demand depends the driving environment which makes it difficult to know the driving pattern exactly, the proposed policy minimizes the fuel consumption with respect to the predicted model of the future driving conditions using a simple model of the power flow, energy levels and a regression model of the future driving.

The solution methods were assembled for a detailed assessment of fuel consumption in various drive cycles via Matlab/Simulink. In order to monitor various strategies, a rather simple Classical Road drive cycle and a well known urban Metropolis drive cycle were taken into consideration in the fuel efficiency assessment. It can be concluded according to the detailed simulation results including vehicle speed, electric motor power, ultracapacitor SoC and average fuel consumption that HEVs have superior fuel consumption attributes if compared to the conventional vehicle in the urban cycle. The study also showed that selection of power management strategies in terms of optimization parameters and constraints

plays a key role in the fuel consumption dynamics as well as the state of charge of the ultracapacitor. Three different constraint sets were presented for both drive cycles. By analyzing the optimization results, an improved constraint based control strategy was developed.

The simulation system does not only allow investigating the influence of different energy management strategies, but could also be used to optimize the size of the electric energy storage unit by investigating its influence on optimization and power availability.

REFERENCES

ANDERSSON, C., 2001. Observations on Electric Hybrid Bus Design

ANSTROM, J.R., 2005. et al. Simulation and field-testing of hybrid ultra-capacitor/battery energy storage systems for electric and hybrid-electric transit vehicles.

ARULEPP, M., 2006. et al., The advanced carbide-derived carbon based supercapacitor. Journal of Power Sources. 162(2 SPEC ISS): p. 1460-1466.

BALCH, R.C., BURKE, A. and FRANK, A.A., 2001. The affect of battery pack technology and size choices on hybrid electric vehicle performance and fuel economy. , Jan 9-12. Long Beach, CL: IEEE.

CARLSON, E., KOPF, P., and SINHA, J., 2005. Fuel Cell seminar. Cambridge MA

CONGRESS, G.C., 2007 [cited 2007 7.1]; Available from: http://www.greencarcongress.com/2007/06/report_toyota_w.html.

DOUGLAS, H. and PILLAY, P., 2005. Sizing ultracapacitors for hybrid electric vehicles. Raleigh, NC, United States: Institute of Electrical and Electronics Engineers Computer Society, Piscataway, NJ 08855-1331, United States.

DRIVECLEAN.GOV., 2006. Webpage: www.driveclean.ca.gov/en/gv/home/index.asp, driveclean.gov. Accessed on September 15.

GILLESPIE, T.D., 1992. “Fundamentals of Vehicle Dynamics”, Society of Automotive Engineers, Inc.

GUENTHER, M. and DONG, Z., 2005. Modelling, Testing and Design Optimization of PEM Fuel Cell System for Low-speed Electric Vehicles. Department of Mechanical Engineering and Institute for Integrated Energy Systems.

HE X, PARTEN M, MAXWELL T., 2005. Energy Management Strategies for a Hybrid Electric Vehicles, Advanced Vehicle Engineering Laboratory, IEEE.

HORIBA, T., 2005. et al., Applications of high power density lithium ion batteries. Journal of Power Sources. 146(1-2): p. 107-10.

ITO, K. and OHNISHI, M., 2003. Development of prismatic type nickel/metal-hydride battery for HEV, in Proceedings of the 20 th Elec tric Vehicle

Symposium. Long Beach

JONG-SEOB, W., LANGARI, R. and EHSANI, M., 2005, An energy management and charge sustaining strategy for a parallel hybrid vehicle with CVT. IEEE Transactions on Control Systems Technology. 13(2): p. 313-20.

KARDEN, E., 2007. et al., Energy storage devices for future hybrid electric vehicles. Journal of Power Sources. 168(1): p. 2-11.

KOTZ, R. and CARLEN, M., 2000. Principles and applications of electrochemical capacitors. Electrochimica Acta. 45(15-16): p. 2483-2498.

MARKEL, T. and SIMPSON, A., 2005. Energy storage systems considerations for grid-charged hybrid electric vehicles. Chicago, IL, United States: Institute of Electrical and Electronics Engineers Computer Society, Piscataway, NJ 08855-1331, U.S.

MARKEL, T. and WIPKE, K., 2001. Modeling grid-connected hybrid electric vehicles using ADVISOR. in 16th Annual Battery Conference on Applications and Advances, Jan 9-12. Long Beach, CL: Institute of Electr ical and Electronics Engineers Inc.

MARKEL, T., 2002 et al., ADVISOR: A systems analysis tool for advanced vehicle modeling. Journal of Power Sources. 110(2): p. 255-266.

MAXWELL TECHNOLOGIES., 2008. Maxwell Ultracapacitors, 20080717_POWER_CHARTS_1.6.

_____2009. Product Guide – Maxwell Technologies BOOSTCAP Ultracapacitors– Doc. No. 1014627.1

MICKLETHWAIT, J. E., 2006. More of everything. The Economist, September 16th-22nd, pp. 18-19.

_____2006. Roads to Somewhere. The Economist, June 24th-30th, pp. 36-37.

MILLER, J., 2004. Propulsion Systems for Hybrid Vehicles, . Institution of Electrical Engineers: London, United Kingdom.

OKAN, R. Y., 2008. Energy and Power Managementin Series Hybrid Vehicles.

RUFER, A. and BARRADE, P., 2001. A supercapacitor-based energy storage system for elevators with soft commutated interface Sep 30-Oct 4 2001. Chicago, IL: Institute of Electrical and Electronics Engineers Inc.

SANTI, E., 2002. et al. A fuel cell based domestic uninterruptible power supply. in 17th Annual IEEE Applied Power Electronics Conference and Exposition, Mar 10-14 2002. Dalas, TX: IEEE Inc.

SCHUPBACH, R.M., 2003. et al. Design methodology of a combined battery-ultracapacitor energy storage unit for vehicle power management. Acapulco, Mexico: IEEE.

SIEMENS AG., 2007. ELFA hybrid drive system brochure.

_____2010. http://www.automation.siemens.com/mcms/large-drives/en/hybrid-drives/Pages/hybrid-drives.aspx

STAUNTON, R.H., 2006. et al., Evaluation of 2004 Toyota Prius Hybrid Electric Drive System. United States. p. Size: 4 Mb.

STIENECKER, A.W., STUART, T. and ASHTIANI, C., 2006. An ultracapacitor circuit for reducing sulfation in lead acid batteries for Mild Hybrid Electric Vehicles. Journal of Power Sources. 156(2): p. 755-762.

SUPPLIERBUSINESS LTD., 2010. The Hybrid Commercial Vehicles Report. p: 28

TANIGUCHI, A., 2001. et al., Development of nickel/metal-hydride batteries for EVs and HEVs. Journal of Power Sources. 100(1-2): p. 117-124.

VAHIDI, A., 2009. Ultracapacitor Assisted Powertrains, Capacitor Consortium Planning Meeting

WESTBROOK, M., 2001. The Electric Car:Development and future of battery, hybrid and fuel-cell cars. IEE Power and Energy Series 38, ed. A. Johns and D. Warne., London, United Kingdom: Institution of Electrical Engineers.

WIPKE, K.B., CUDDY, M. R. and BURCH, S.D., 1999. ADVISOR 2.1: A user-friendly Advanced powertrain simulation using a combined backward/forward approach. IEEE Transactions on Vehicular Technology. 48(6): p. 1751-1761.

WISHART, J., 2008. Modelling, Simulation, Testing, and Optimization of Advanced Hybrid Vehicle Powertrains.

ZHOU, Y. L., 2007. Modeling and Simulation of Hybrid Electric Vehicles

CURRICULUM VITAE

I was born on 10th of August, 1983 in Kars. I completed my high school education in Kars Fen Lisesi. After high school I attend to Electrical and Electronics Department of University of Çukurova in 2001. I graduated from the university in 2007. I worked at Fidancan Mühendislik A.Ş. between years 2007-2008. Later I worked in International Customer Services Department of Temsa Global A.Ş between years 2008-2010. And I continued Master of Science program at Electrical and Electronics Engineering Department of University of Çukurova between years 2008-2011.

APPENDIX A:

MATLAB/SIMULINK (The MathWorks, Inc, 2011)

1. Introduction

Simulink® is an environment for multidomain simulation and Model-Based Design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries that let you design, simulate, implement, and test a variety of time-varying systems, including communications, controls, signal processing, video processing, and image processing.

Add-on products extend Simulink software to multiple modeling domains, as well as provide tools for design, implementation, and verification and validation tasks.

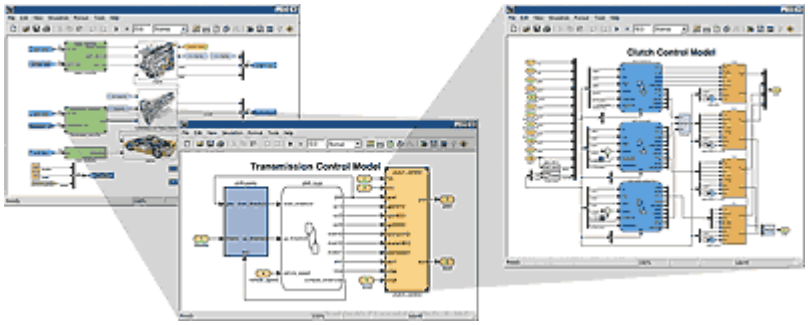
Simulink is integrated with MATLAB®, providing immediate access to an extensive range of tools that let you develop algorithms, analyze and visualize simulations, create batch processing scripts, customize the modeling environment, and define signal, parameter, and test data.

2. Key Features

- Extensive and expandable libraries of predefined blocks
- Interactive graphical editor for assembling and managing intuitive block diagrams
- Ability to manage complex designs by segmenting models into hierarchies of design components
- Model Explorer to navigate, create, configure, and search all signals, parameters, properties, and generated code associated with your model
- Application programming interfaces (APIs) that let you connect with other simulation programs and incorporate hand-written code
- Embedded MATLAB™ Function blocks for bringing MATLAB algorithms into Simulink and embedded system implementations

- Simulation modes (Normal, Accelerator, and Rapid Accelerator) for running simulations interpretively or at compiled C-code speeds using fixed- or variable-step solvers
- Graphical debugger and profiler to examine simulation results and then diagnose performance and unexpected behavior in your design
- Full access to MATLAB for analyzing and visualizing results, customizing the modeling environment, and defining signal, parameter, and test data

Model analysis and diagnostics tools to ensure model consistency and identify modeling errors



APPENDIX B:

Ultracapacitors (Maxwell Technologies, 2009)

1. Description of Double Layer Capacitors

1.1. Theory

Electrochemical double layer capacitors (EDLCs) are similarly known as supercapacitors or ultracapacitors. An ultracapacitor stores energy electrostatically by polarizing an electrolytic solution. Though it is an electrochemical device there are no chemical reactions involved in its energy storage mechanism. This mechanism is highly reversible, allowing the ultracapacitor to be charged and discharged hundreds of thousands to even millions of times.

An ultracapacitor can be viewed as two non-reactive porous plates suspended within an electrolyte with an applied voltage across the plates. The applied potential on the positive plate attracts the negative ions in the electrolyte, while the potential on the negative plate attracts the positive ions. This effectively creates two layers of capacitive storage, one where the charges are separated at the positive plate, and another at the negative plate.

Conventional electrolytic capacitors storage area is derived from thin plates of flat, conductive material. High capacitance is achieved by winding great lengths of material. Further increases are possible through texturing on its surface, increasing its surface area. A conventional capacitor separates its charged plates with a dielectric material: plastic, paper or ceramic films. The thinner the dielectric the more area can be created within a specified volume. The limitations of the thickness of the dielectric define the surface area achievable.

An ultracapacitor derives its area from a porous carbon-based electrode material. The porous structure of this material allows its surface area to approach 2000 square meters per gram, much greater than can be accomplished using flat or textured films and plates. An ultracapacitors charge separation distance is determined by the size of

the ions in the electrolyte, which are attracted to the charged electrode. This charge separation (less than 10 angstroms) is much smaller than can be accomplished using conventional dielectric materials.

The combination of enormous surface area and extremely small charge separation gives the ultracapacitor its outstanding capacitance relative to conventional capacitors .

1.2. Construction

The specifics of ultracapacitor construction are dependent on the application and use of the ultracapacitor. The materials may differ slightly from manufacturer or due to specific application needs. The commonality among all ultracapacitors is that they consist of a positive electrode, a negative electrode, a separator between these two electrodes, and an electrolyte filling the porosities of the two electrodes and separator.

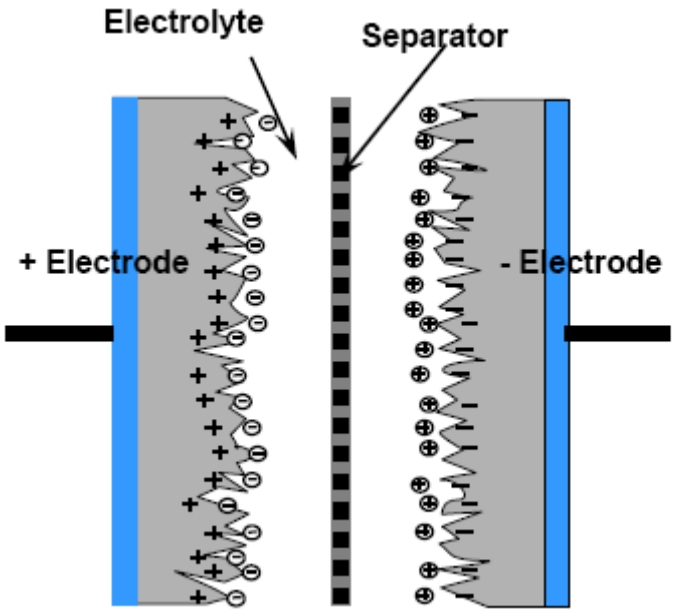


Figure 1. Ultracapacitor charge separation

The assembly of the ultracapacitors can vary from product to product. This is due in part to the geometry of the ultracapacitor packaging. For products having a prismatic or square packaging arrangement, the internal construction is based upon a stacking assembly arrangement with internal collector paddles extruding from each electrode stack. These current collector paddles are then welded to the terminals to enable a current path outside the capacitor.

For products with round or cylindrical packaging, the electrodes are wound into a jellyroll configuration. The electrodes have foil extensions that are then welded to the terminals to enable a current path outside the capacitor.

1.3. Typical Applications

Maxwell BOOSTCAP® ultracapacitors products are offered in a full range of sizes. This enables utilization of ultracapacitors in a variety of industries for many power requirement needs. These applications span from milliamps current or milliwatt power to several hundred amps current or several hundred kilowatts power needs. Industries employing ultracapacitors have included: consumer electronics, traction, automotive, and industrial. Examples within each industry are numerous [44].

Automotive – 42 V vehicle supply networks, power steering, electromagnetic valve controls, starter generators, electrical door opening, regenerative braking, hybrid electric drive, active seat belt restraints.

Transportation – Diesel engine starting, train tilting, security door opening, tram power supply, voltage drop compensation, regenerative braking, hybrid electric drive.

Industrial – uninterrupted power supply (UPS), wind turbine pitch systems, power transient buffering, automated meter reading (AMR), elevator micro-controller power backup, security doors, forklifts, cranes, and telecommunications.

Consumer – digital cameras, lap top computers, PDA's, GPS, hand held devices, toys, flashlights, solar accent lighting, and restaurant paging devices.

Consideration for the various industries listed, and for many others, is typically attributed to the specific needs of the application the ultracapacitor technology can satisfy. Applications ideally suited for ultracapacitors include pulse power, bridge power, main power and memory backup.

1.4. Pulse Power

Ultracapacitors are ideally suited for pulse power applications. As mentioned in the theory section, due to the fact the energy storage is not a chemical reaction, the charge/discharge behavior of the capacitors is efficient.

Since ultracapacitors have low internal impedance they are capable of delivering high currents and are often times placed in parallel with batteries to load level the batteries, extending battery life. The ultracapacitor buffers the battery from seeing the high peak currents experienced in the application. This methodology is employed for devices such as digital cameras, hybrid drive systems and regenerative braking (for energy recapture).

1.5. Bridge Power

Ultracapacitors are utilized as temporary energy sources in many applications where immediate power availability may be difficult. This includes UPS systems utilizing generators, fuel cells or flywheels as the main power backup. All of these systems require short start up times enabling momentary power interruptions. Ultracapacitor systems are sized to provide the appropriate amount of ride through time until the primary backup power source becomes available.

1.5. Main Power

For applications requiring power for only short periods of time or is acceptable to allow short charging time before use, ultracapacitors can be used as the primary power source. Examples of this utilization include toys, emergency

flashlights, restaurant paging devices, solar charged accent lighting, and emergency door power.

1.6. Determining the correct Ultracapacitor for the application

Determination of the proper capacitor and number of capacitors is dependant on the intended application. For sizing the system correctly a number of factors should be known. These factors include the maximum and minimum operating voltage of the application, the average current or power, the peak current or power, the operating environment temperature, the run time required for the application, and the required life of the application. All of these issues will be covered in detail in the "Performance Characteristics" section of this guide. For now, a general approach is described.

Each of the products has a rated voltage (VR). Since ultracapacitors are low voltage devices, this rated voltage is generally less than the application voltage required. Knowing the maximum application voltage (Vmax) will determine how many capacitor cells are required to be series connected. The number of series connected cells is determined by:

$$\#series_cells = \frac{V_{\max}}{V_R}$$

Next, by knowing the average current (I) in amps, the required run time (dt) in seconds and the minimum working voltage (Vmin), an approximate system capacitance can be calculated.

$$Csys = I.\frac{dt}{dV} = I.\frac{dt}{(V_{\max} - V_{\min})}$$

The total system capacitance is comprised of the capacitance of all the series connected capacitors for achieving Vmax. For capacitors connected in series the capacitance of the individual cells is determined by:

$$\frac{1}{Csys} = \frac{1}{C_1} + \frac{1}{C_2} + ... + \frac{1}{C_n}$$

where n = # series connected capacitors.

For C1=C2=…=Cn and rearranging equation 3, the cell capacitance (C) is determined by:

$$C = C_{sys}.n$$

This capacitance value can then be compared to the product data sheets to determine the appropriate capacitor for the application. If the capacitance calculated is not achievable by a single capacitor it will be necessary to place one or more capacitors in parallel to obtain the necessary energy. For capacitors connected in parallel the capacitance is determined by:

$$C = C_1 + C_2 + ... + C_n$$

Therefore, take the calculated capacitance and divide by the capacitance available from the data sheet and round up to the next whole number. This will be the number of capacitors required in parallel.

There are many other items to consider for properly sizing the application. This includes the internal resistance of the capacitor to account for the instantaneous voltage drop associated with an applied current, the ambient operating temperature which affects the internal resistance and the capacitor life, and the life of the

application. The ultracapacitor performance requirement at end of life of the application is necessary to ensure proper initial sizing of the system.

2. Performance Characteristics

This section describes the behavior of ultracapacitors under operating conditions such as temperature, dc charging, cycling and frequency. The data is represented in product specific format where applicable.

2.1 Temperature Effects, Initial Performance

The performance of Maxwell Technologies ultracapacitors is very stable over a wide operating temperature due to the chemistry and physical make up of the products. This behavior is common between all of the products lines due to the similar chemistry and construction. The following plot in figure 2 illustrates the relative capacitance and resistance change as a function of temperature between the operating temperature ranges of –40 to 65 oC.

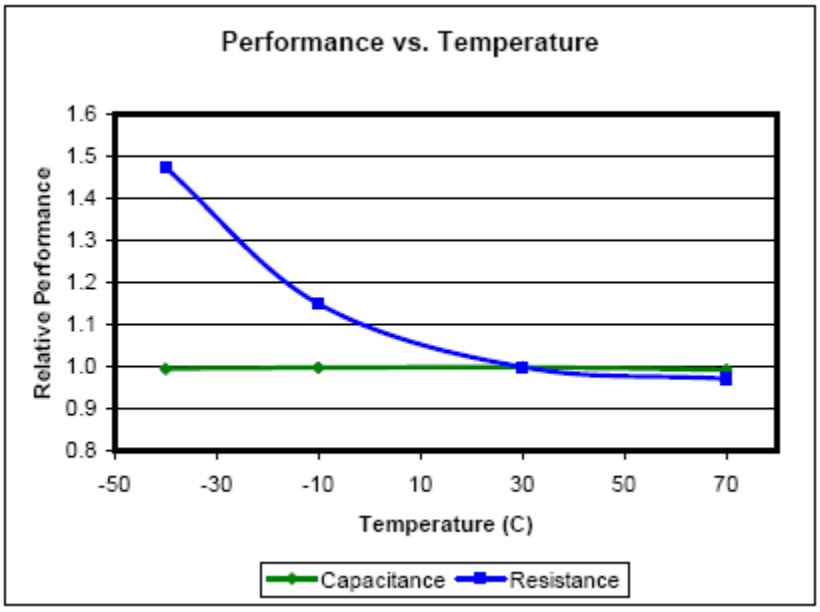


Figure 2: Relative ultracapacitor performance over operating temperature range

2.2 Voltage and Temperature Effects on Life

A common utilization of the ultracapacitors such as UPS applications is to maintain the ultracapacitors at working voltage until needed for the application. The following figures illustrate the influence of voltage on performance of the products when held at rated voltage and a lower voltage at its maximum rated environmental temperature.

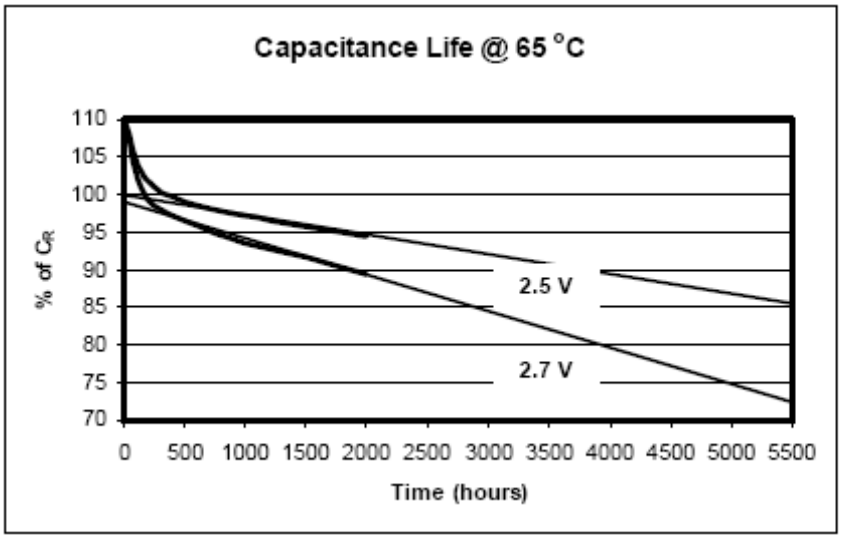


Figure 3: MC Cell Capacitance degradation at 2.7 V and 2.5 V at 65oC

Figure 3 represents the expected capacitance degradation relative to the product specification. The plot, along with the fact that the influence of temperature has a doubling effect for every 10 oC, can be used to predict the expected performance change for a variety of conditions. From this plot it is expected that a: 30% reduction in rated capacitance may occur for an ultracapacitor held at 2.7 V after

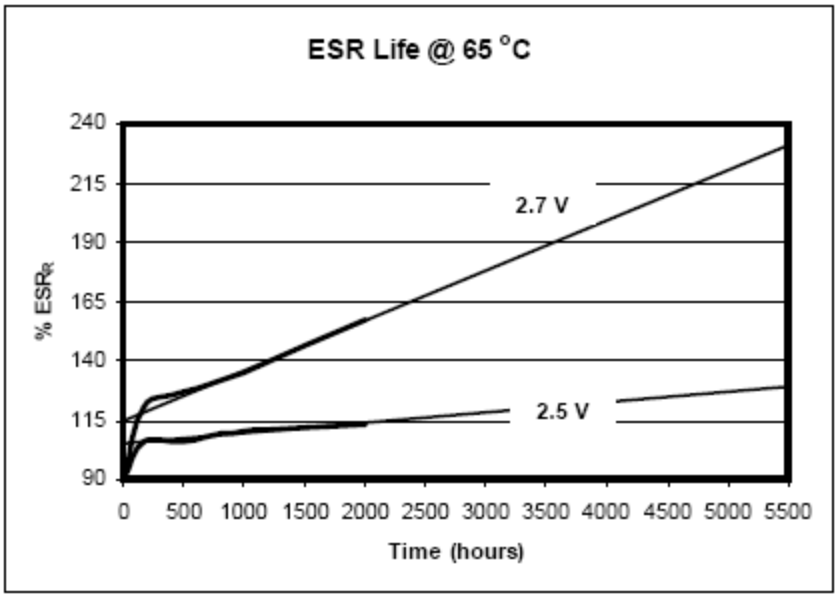


Figure 4: MC Cell Resistance degradation at 2.7 V and 2.5 V at 65oC

Figure 4 represents the expected resistance degradation relative to the product specification. The plot, along with the fact that the influence of temperature has a doubling effect for every 10 oC, can be used to predict the expected performance change for a variety of conditions. From this plot it is expected that a:

140% increase in rated resistance may occur for an ultracapacitor held at 2.7 V after

2.3 Cycling

Cycle testing is performed on the products to determine the degradation of ultracapacitor performance over cycling events. The cycle testing is performed at ambient temperature with no forced convective cooling. The cycles are performed at a continuous current as indicated on the data sheet from the rated voltage to half rated voltage. A 15 second rest is allowed between each charge/discharge cycle. The resulting duty cycle for this test is initially 70% reducing to approximately 50% at the product ages.

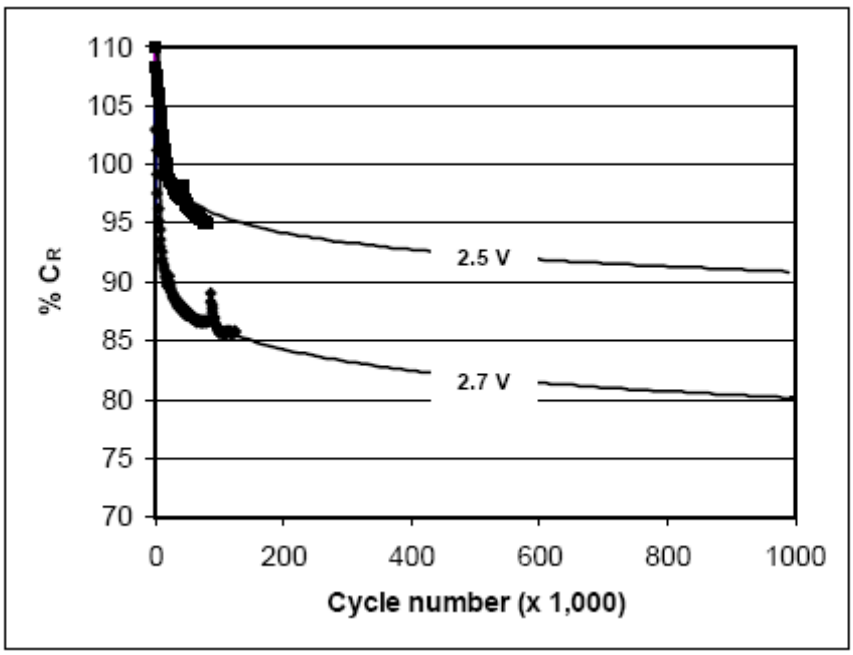


Figure 5: Capacitance change vs. Continuous cycling

From Figure 5 it is seen that under the conditions described the product is expected to provide in excess of 1 million duty cycles with an approximate 20% reduction in rated capacitance. Notice in the 2.7 V cycle data the capacitance recovery during a stoppage in testing. This characteristic is normal when the ultracapacitor is allowed to rest. For most applications a rest period is allowed thus the figure illustrates a worst-case application. Similar life improvements illustrated previously for DC charging are evident for lower voltage cycling.

2.4 Frequency Response

Ultracapacitors have a typical time constant of approximately one second. One time constant reflects the time necessary to charge a capacitor 63.2% of full charge or discharge to 36.8% of full charge. This relationship is illustrated in the following figure.

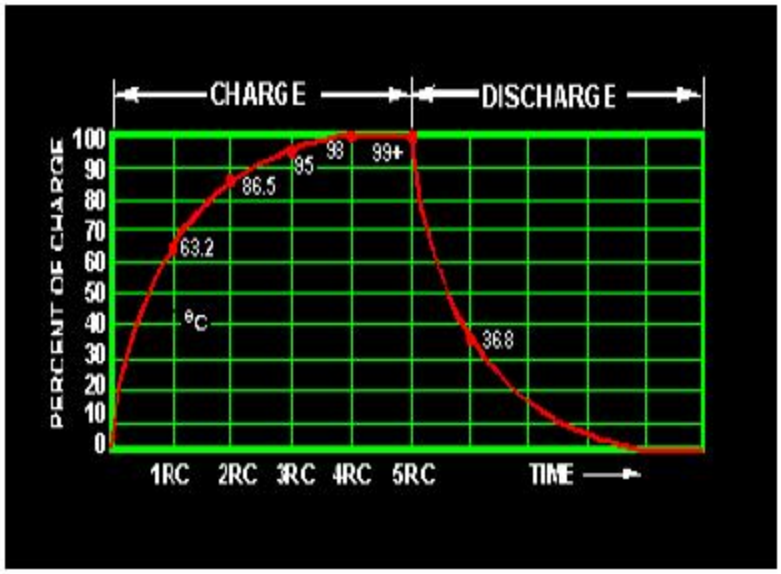


Figure 6: RC time constant relationship

The time constant of an ultracapacitor is much higher than that of an electrolytic capacitor. Therefore, it is not possible to expose ultracapacitors to a continuous ripple current as overheating may result. The ultracapacitor can respond to short pulse power demands, but due to the time constant the efficiency or available energy is reduced. The following figures illustrate the performance of the ultracapacitors at various frequencies. The drop off in capacitance is associated with response time necessary for the charged ions within the pores of the electrode to shuttle between positive and negative during charge and discharge. The drop in resistance is representative of the response time of the different resistive elements within the ultracapacitor. At low frequency all resistive elements are present where at high frequency only quick response elements such as contact resistance are present.

The test is typically conducted with no applied voltage. For this reason the capacitance appears to be much lower than what is stated at rated voltage as capacitance has a slight dependence on voltage.

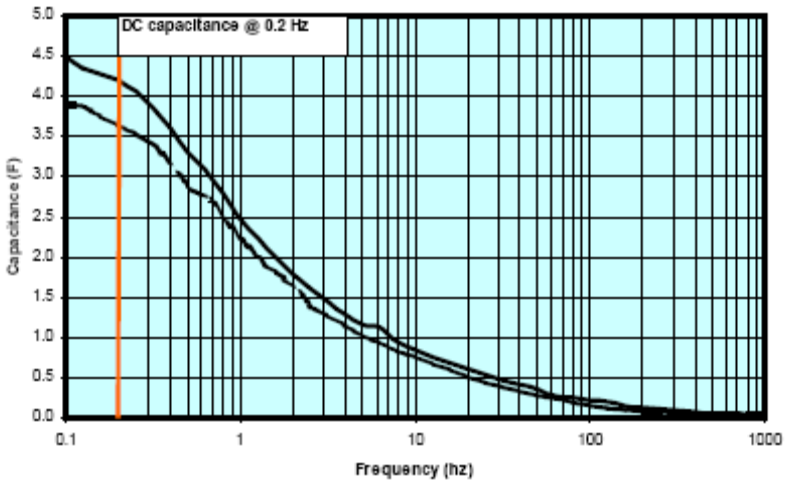


Figure 7: PC5 Capacitance vs. Frequency Response, 95% Confidence

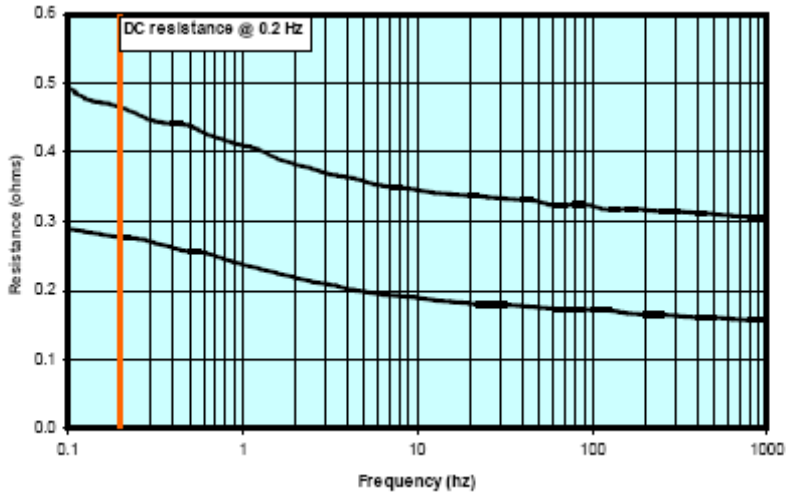


Figure 8: PC5 Resistance vs. Frequency Response, 95% Confidence

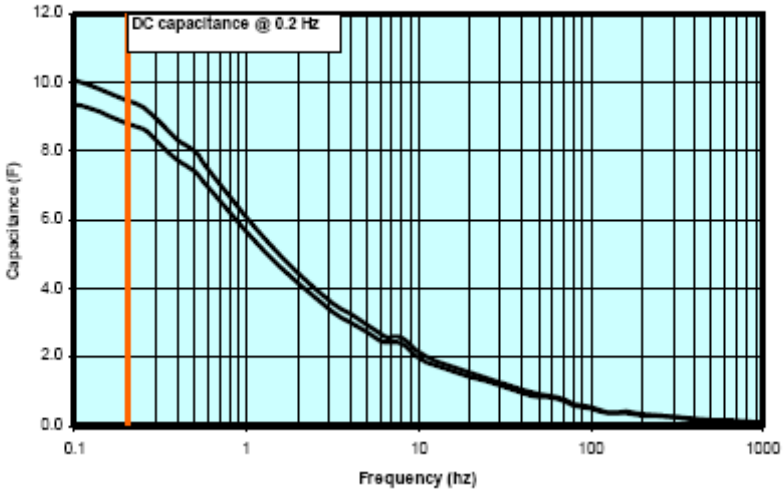


Figure 9: PC10 Capacitance vs. Frequency Response, 95% Confidence

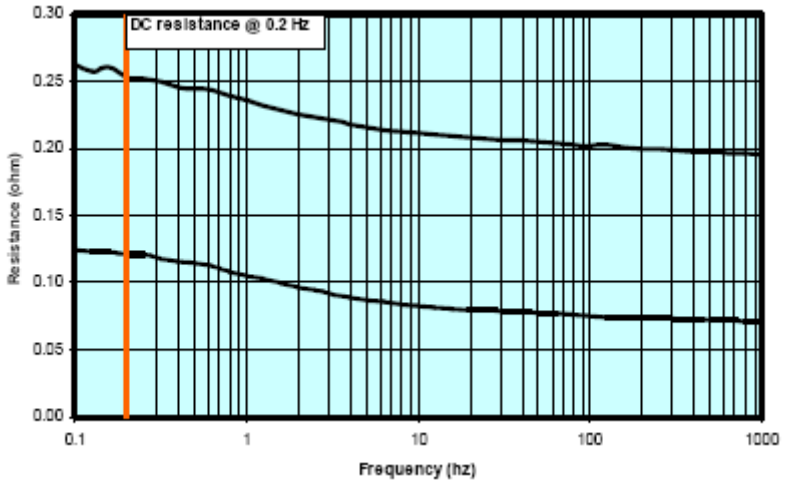


Figure 10: PC10 Resistance vs. Frequency Response, 95% Confidence

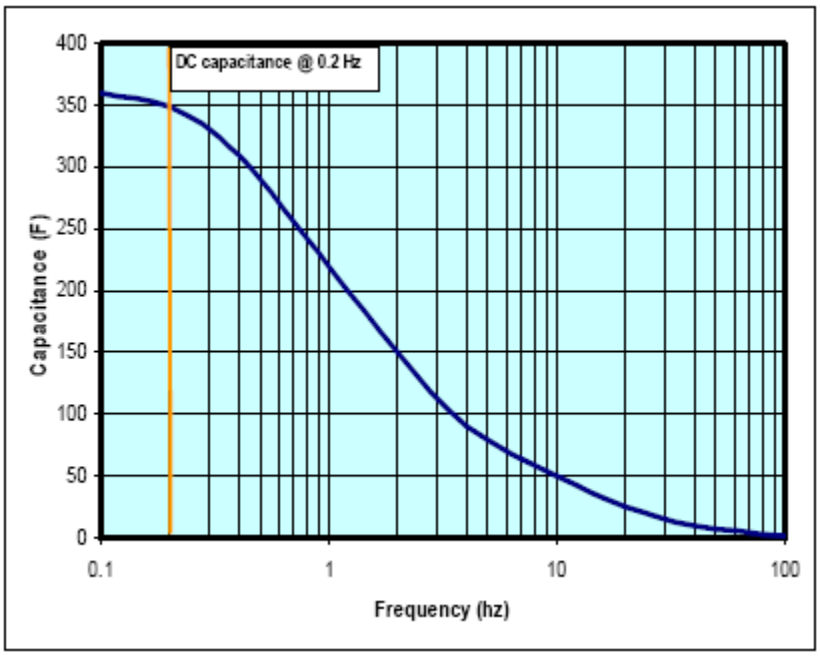


Figure 11: BCAP0350 Capacitance Frequency Response

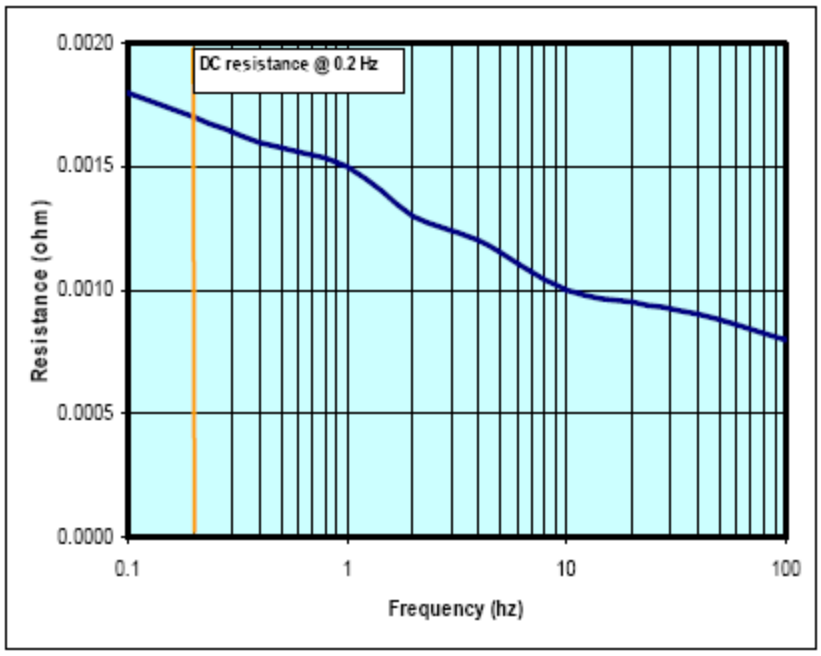


Figure 12: BCAP0350 Resistance Frequency Response

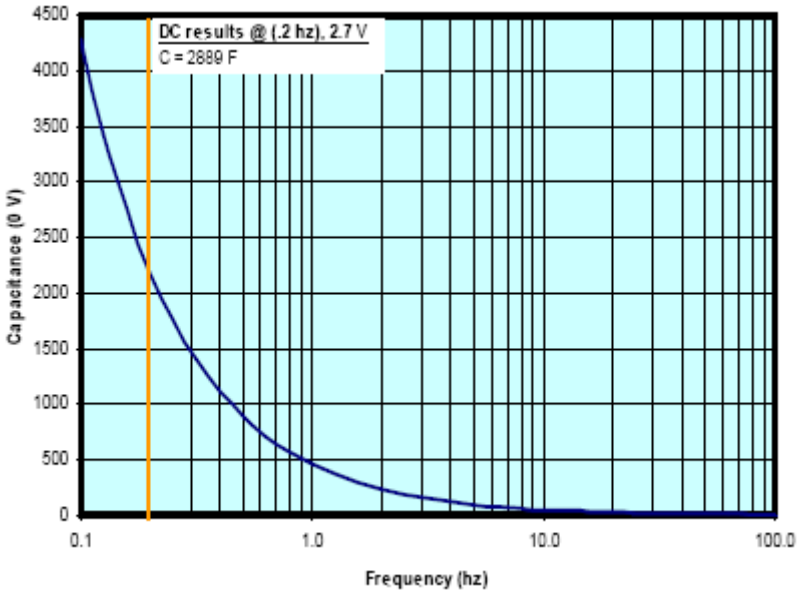


Figure 13: BCAP2600 Capacitance Frequency Response

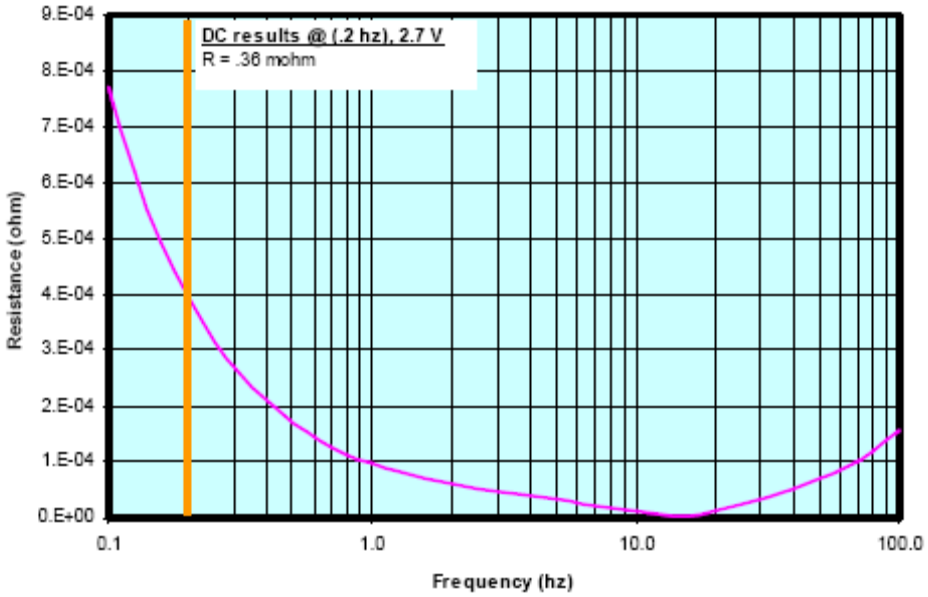


Figure 14: BCAP2600 Resistance Frequency Response

2.5. Charging of Ultracapacitors

Charging of ultracapacitors is simple while at the same time may present some unique challenges. Unlike batteries, ultracapacitors may be charged and discharged at similar rates. This is very useful in energy recovery systems such as dynamic braking of transport systems. Here are a few characteristics of ultracapacitors that should be kept in mind when integrating/designing a charging system for the intended application.

An ultracapacitor with zero charge looks like a short circuit to the charging source. Most low cost power supplies fold back the output current in response to a perceived short circuit, making them unsuitable for charging of ultracapacitors.

Ultracapacitors have a low series inductance allowing easy stabilizing with switch mode chargers. The RC time constant of passive charging networks is usually too long. Therefore, linear regulators are inefficient components for ultracapacitor charging. Covered in this application note are recommendations for constant current charging, constant power charging, and AC line charging.

2.6. Constant Current Charging

A DC-to-DC constant current regulator is the simplest form of active charging. Either a buck or boost regulator may be used depending on the application. A buck regulator is the preferred topology due to the continuous output charge current. The power losses or ultracapacitor heating is proportional to current squared times the duty cycle. Therefore, an ultracapacitor module with an I2 rating of 40,000 may be charged at 200 amps using a buck converter with low ripple current, whereas, the same module could only be charged at 141 amps from a boost converter at a 50% duty cycle (282A squared times a 50% duty cycle 40,000).

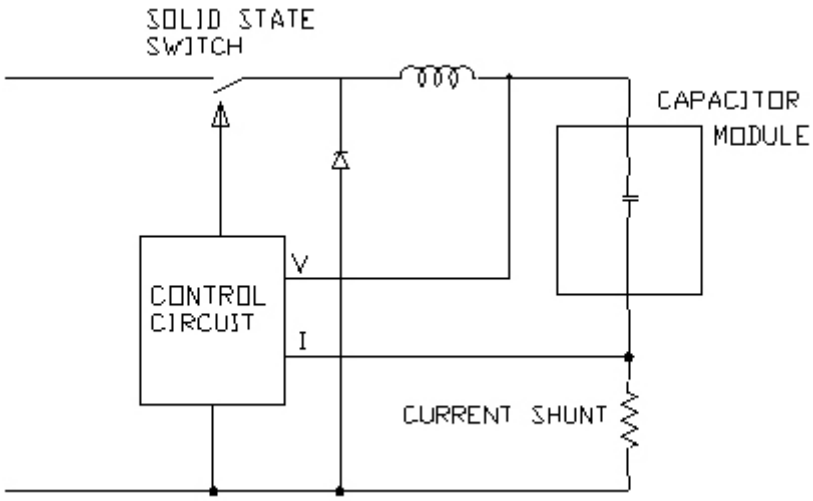


Figure 15: Constant Current Charging Schematic

A simple constant current charger may be built with standard power supply IC's. The current limit would be set to the required charge current and the voltage limit would be set to the maximum required voltage. An example circuit layout is provided in figure 1.

2.7. Constant Power Charging

When charge time is critical, constant power charging provides the fastest charge method. Constant power charging can transfer all the available power from the charge source into the energy storage capacitors.

Drawing a constant current from the source at a constant voltage is a simple implementation of constant power charging. This usually requires that a maximum switching current of 2.5 times the nominal be established to prevent overloading the switching circuitry when the ultracapacitor voltage is below 40% of maximum. An example schematic is provided in figure 16 (patent pending).

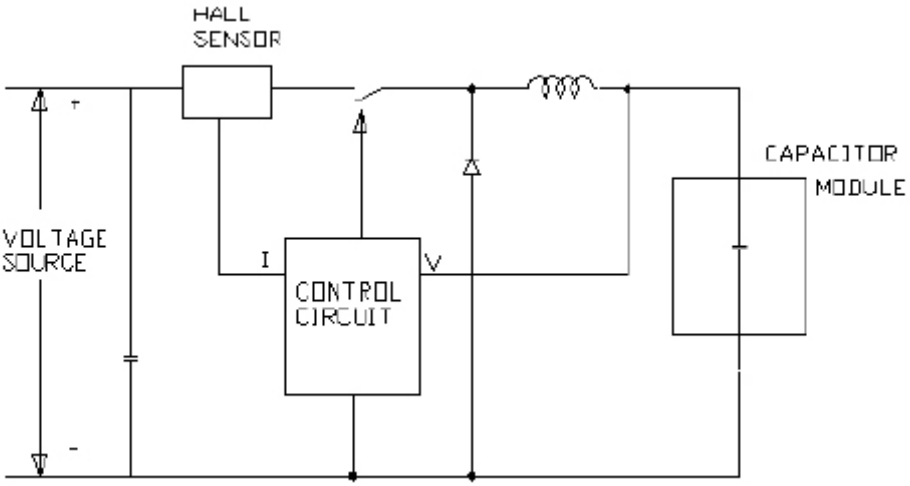


Figure 16: Constant Power Charging Schematic

To quantify the significance of constant power charging the following example is provided and illustrated in figure 3. A 100 farad, 50 V module is charged from a 50 V, 20 amp power supply. In the constant current waveform the module is charged at the maximum power supply current of 20 amps. In the constant power waveform the module is charged at a constant 1000 watts. The maximum charge current from the constant power charger was set at 50 amps. The constant 20 amp charge current required 250 seconds to charge the module to 50 volts. The 1000 watt constant power charger required 145 seconds to charge the module to 50 volts. For the constant power waveform 50 amps charging current was utilized until the ultracapacitor module voltage reached 20 V with this limit is set by the switching circuitry. Constant power charging is very useful in dynamic braking systems. This allows a constant power to be extracted from the vehicle's momentum and transferred to stored electrical energy.

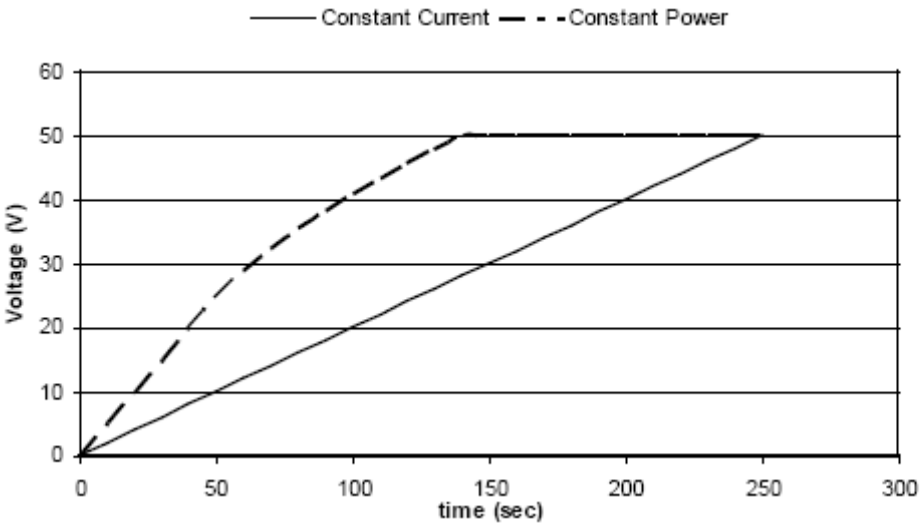


Figure 17: Constant Current vs. Constant Power Charging Time

2.8. Isolated AC Line Charging (U.S Patent 6,912,136 – Thrap)

It is often difficult to cover the wide dynamic range requirements for charging ultracapacitors from a varying AC power line. The circuit illustrated in figure 4 uses the L/V characteristics of the switching transformer to set the switching frequency permitting the circuit to provide full output current at zero volts with no risk of saturating the magnetics.

The switch Q1 turns on, charging the primary of T1 to a preset current limit. The switch Q1 then turns off permitting the energy stored in T1 to discharge through D1 into the ultracapacitor module, C1. When the secondary current has discharged to a preset lower limit then Q1 will turn on again repeating the cycle. The time required to charge T1 is inversely proportional to the instantaneous line voltage while the time required to discharge T1 is inversely proportional to the ultracapacitor voltage at C1. The combination of low line voltage and low ultracapacitor voltage will produce the lowest switching frequency. The highest switching frequency occurs at the peak of the AC power line at maximum voltage and full charge voltage on the ultracapacitor.

Depending on the application the switching frequency can cover a range of 20:1. When C1 reaches its maximum voltage then the voltage sensor will drive the control circuit into discontinuous operation.

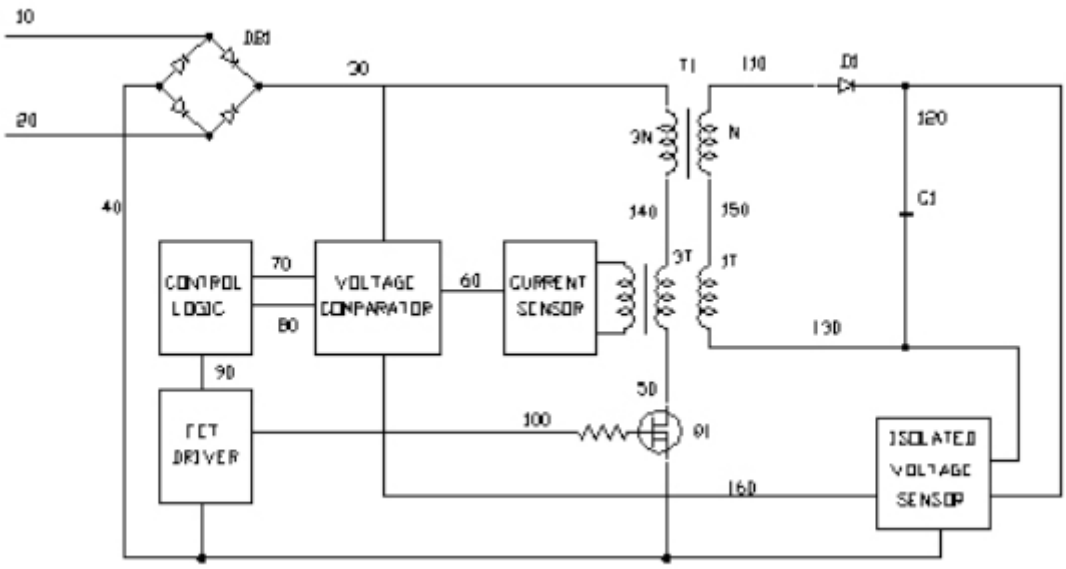


Figure 18: AC Charging Schematic