Peace-of-Mind
Series Hybrid Electric Vehicle Drivetrain

by

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Abstract

This study investigates a new series hybrid electric drivetrain concept for on-road vehicles in order to find a means of sustainable individual transport without decreasing quality of life for anybody and without putting the burden of high investments on future generations. The concept called Peace-of-Mind is based on existing technology and promises:

- Noticeable contribution to lower CO_2 emissions and less energy consumption.
- Improvements for local air quality in urban areas.
- Some improvements in other environmental impacts like noise or emissions.
- Fuel and energy supply within the existing infrastructure.
- Fuel-flexibility - that means the drivetrain can easily be adapted to other fuels without a complete new design.
- Ease of technology changes and improvements - that means new technologies (fuel cell) can be implemented without major redesigns.
- Near-term market introduction through mainly employing available technology.
- Affordability and desirability.

This thesis begins with a review of actual vehicle design considerations, energy considerations and technology considerations including battery issues.

The lithium-ion battery is a vital part of this concept and many other possible future car concepts. A new test procedure is proposed and the test-results are used for developing a new battery model.

The new series hybrid electric drivetrain concept is specified based on knowledge about available products and using fundamental equations for propulsion. The specified drivetrain is compared with existing vehicles using ADVISOR, a Matlab-based simulation package for drivetrains.

The drivetrain management requirements for this concept are discussed and the hardware for this management and in-vehicle data-acquisition is described.

The simulation results indicate that the proposed drivetrain concept is viable: the energy consumption is very low, it produces no local pollution in urban traffic, the performance is acceptable and the versatility of the car is comparable with actual vehicles. But simulation and first driving results also indicate that the battery is the key issue: it adds substantial cost, weight and uncertain behaviour.

The thesis concludes with suggestions for future work: A field-test with about ten vehicles will reveal cutting-edge knowledge on the changes of battery behaviour over their lifetime. The new battery model will be used to determine the battery behaviour.

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Introduction

1.1 Context of the investigation

The escalating number of vehicles on the road and the dependency on resources is raising awareness to vehicular environmental impacts and sustainability. The U.K. domestic goal is for a 20 % reduction in CO_2 by 2010 and road transport is responsible for 22 % of UK greenhouse gas emissions [1]. The conventional car with internal combustion engine running on gasoline or diesel has been developed over 100 years, but it may not meet future requirements regarding noise, emissions and energy consumption. This has provided a stimulus for research into future mobility solutions. The USA is investing US$ 127,000,000 in 2003 for "Freedom Car”, a large fuel cell project [2].

There are a wide variety of alternative fuels and alternative propulsion systems that might or might not be a solution for the future. Internal combustion engines could run on hydrogen or on LPG or on bio-fuels like ethanol. The conventional drivetrain could be substituted by battery electric, fuel-cell electric or by a large number of options and types of different hybrid electric drivetrains. But it has to be concentrated on meeting the targets with the lowest possible number of fuels and solutions. Otherwise, it will not be financially sustainable for all concerned – vehicle manufacturers, vehicle owners, vehicle users and fuel suppliers. Society’s needs of affordable and sustainable individual transportation cannot be met.

Hydrogen is considered as the most favorable future fuel and it is likely that the fuel cell will provide the electric power to propel an electric motor to drive the car at some point in the future. Using hydrogen as fuel in cars requires a new fuel supply infrastructure. The German project “Wasserstoff-Wirtschaft” was aiming for a countrywide hydrogen supply infrastructure in the year 2020, but the high cost of €120,000,000 are forcing to delay the aim till 2050. The UK aims for general availability of hydrogen/fuel-cell technology in transport from 2012 on [1]. The fuel-cell technology itself is far away from maturity and the energy source for producing the hydrogen is yet unclear. Hydrogen may be the future medium for energy transport and high-density energy storage in vehicles. But it must be produced by sustainable means that minimize production of CO_2 emissions. Otherwise, the case for hydrogen as the future fuel is undermined.

The dream of a sustainable hydrogen economy may be achieved within the next thirty to fifty years. This is too far away to just wait and hope and there is a distinct lack of short-term and mid-term solutions that fit into the pathway. Hybrid electric vehicles have been suggested to be this step stone. They are capable of reducing emissions and fuel consumption. Available products suffer from high prices and comparatively small environmental advantages if compared with efficient conventional vehicles. The hybrid electric drivetrain offers a large number of different configurations. Their advantages and disadvantages are well known, but it is uncertain, which configuration fits best into the pathway towards future individual transportation aims.

A key factor that is preventing the step change from today's petrol and diesel fuelled vehicle technologies to alternatives with lower environmental impact, is market competitiveness. IC spark-ignition and compression-ignition engines have benefited from many years of evolution and though very sophisticated devices, they have become highly cost-effective in design, manufacture and use. The cost of fuel refining and distribution is also relatively low. These are a result of large-scale investment in manufacturing and infrastructure, made over many decades. Economies of scale associated with high production volumes also contribute to the low cost. A change over either to alternative fuels or to alternative drivetrains require high investment cost that nobody is willing to pay for in our society that is based on cost calculations and competition.

1.2 Aims of the Investigation

This project investigates the question whether sustainable individual transport in cars can be achieved with existing knowledge and technology without decreasing quality of live for anybody and without putting the burden of high investments on future generations.

Several different ways and aims may help solving the impacts of transportation in general:

- Decreasing or limiting transportation
- Shifting to other means of transport
- Changing driver or customer behaviour
- Reducing vehicle size and mass
- Shifting to other energy sources and alternative fuels
- Employing alternative drivetrains

Only the right mixture of these attempts will achieve the next step forward to the vision of sustainable transport. Education for example is certainly the most sustainable way of changing customer or driver behaviour, but it requires far too much time. Raising fuel prices is probably the only way of giving energy a higher value and increase awareness. But trying to achieve a decrease in transport or a shift to other means of transport by employing this tool without offering appropriate alternatives leads to radical changes with unpredictable surges to economy and quality of life.

This thesis investigates alternative drivetrains. This should be understood as one attempt that has to work in cooperation with other major attempts rather than being in competition with them. The key objectives are:

1. One objective of this research is finding an alternative drivetrain that requires small time to market introduction, is affordable, provides acceptable vehicle performance, supports versatility of the vehicle, has low impacts on the environment, consumes drastically less fuel and provides some additional value to the customer.
2. Another objective is to explore the issues of this drivetrain technology and their potential solutions.

3. Batteries are likely to become very important in future drivetrains because their implementation promises advantages in terms of lower impacts and lower energy consumption. On the other hand they are blamed for being problematic and unpractical. It is likely that the battery is the key issue in the proposed drivetrain. Understanding and predicting the behaviour and managing it are objectives of this work.

The research question and the objectives were not conducted by a sponsoring company nor directed by other departmental research. Finding them formed a considerable part of the work that has been carried out. The research question has actual relevance and the answer is uncertain. The objectives are achievable if the research question finds a positive answer. They leave room for uncertainties and perceiving them contributes new knowledge to science.

1.3 Research Outline and Structure

The research question requires multidisciplinary considerations. Sustainability issues need to be understood as well as economical, social and psychological interactions. Technological background knowledge and actual statistical figures need to be present in order to perceive the research question. This suggests employing a breadth before depth strategy. This may suffer from being unfocused and too complex, but it prevents focusing on irrelevant details. The objectives suggest exploratory tactics because research on alternative drivetrains and on sustainability is comparatively young and not very well explored yet. Aim-driven tactics are more suitable for mature research fields with considerable in-depth knowledge like for combustion engines for example. The breadth-first strategy with exploratory tactics requires control in order to balance the exploration and answer the research question.

At first literature is reviewed in order to analyse the actual and the arising problems of individual transport requirements on one hand and environmental / social impact implications like energy issues on the other hand. A review of different types of drivetrains follows in order to identify technological options and their potentials. Batteries are likely to be the key issue in future drivetrains and a deeper investigation in battery technology is prepared in this review.

Li-Ion is a modern battery technology with promising performance figures. It is likely to take over in automotive applications. Knowledge about high-energy Li-Ion batteries is rare and tests require a lot of time and investment. Many cells need to be connected in series in order to achieve a suitable voltage. Monitoring and equalizing technologies are essential but not state of the art yet. General options are reviewed in order to identify limitations in the number of cells. A Li-Ion battery has been purchased in order to implement it in a test-vehicle. Chapter 3 describes the test of this battery using a newly developed shorter test-procedure. Data are analysed and results presented. Exploring the behaviour of the battery has revealed that existing models are not satisfactory and the design of a new model is described.

Though drivetrains are reviewed in chapter 2, a more detailed investigation in hybrid electric vehicle drivetrains is undertaken in chapter 4, in order to prepare the specification of a design template. This template is an abstract definition for the proposed hybrid electric vehicle drivetrain that can meet the criteria in the research question most likely. It is based on knowledge about available technology and performance of components. Chapter 4 also approaches an “optimal” configuration based on this template. This “optimal” drivetrain is assessed and compared with available drivetrain technology based on simulation work. A test-vehicle is currently under development in order to compare simulation results with real-world driving and also for exploring the real-world problems or demonstrating the viability of the concept. The configuration differs from the “optimal” one due to availability of components. It is described in the end of chapter 4.

Modern engines make use of an engine management system; modern cars comprise at least one bus-system for managing the drivetrain. The hybrid electric vehicle drivetrain is even more complex and a more sophisticated management is required in order to manage the cooperation of different power converters. It is essential to investigate these requirements for the proposed drivetrain, because it has to be determined how and if it can be managed at all and what cost may be involved. Chapter 5 discusses the management requirements for the proposed drivetrain.

Chapter 6 describes the hardware that is developed in order to manage the drivetrain. This hardware development will reveal whether practical implementation of the management is possible and what practical problems may arise. It is also used for data acquisition in the vehicle. Obtained data help understanding battery behaviour and vehicle behaviour. Both can be compared with simulation results.

First real-driving results and suggestions for the next evolutionary step are discussed in chapter 7.

This work describes the intermediate stage of the project with the mentioned objectives. Chapter 8 summarises all the potential for future research work that has been identified so far. It then proposes methods and specifies the future work that can be committed within this project in order to answer the research question and keep the exploration balanced.

2. Review of State of the Art and Future Trends

This chapter reviews all considerations that are essential basis for proposing a drivetrain and its energy management. A comprehensive study on energy issues is presented first, because it needs to be understood whether cars need to be more energy efficient or if a shift to renewable fuels should be in the focus instead. The second section reviews other design criteria and also potentials for market introduction, because cars cannot be sold on energy efficiency per se. Technology is focused next in order to understand possible achievements and limitations of different drivetrains. It is found that batteries become more and more essential in future cars. They are part of the last two sections of this review.

2.1 Energy and CO_2 Considerations

Energy consumption and CO_2 emissions of road transport are the main issues amongst all impacts. Cars run on fuel that is refined from oil. Oil reserves will run short within the near future, experts are just arguing about the time. CO_2 emissions threaten the world with climate-change. They are almost proportional to the amount of energy consumed if the source is fossil.

The Kyoto agreement requires a 12.5 % reduction in greenhouse gases (mainly CO_2) by 2012. The U.K. domestic goal is for a 20 % reduction in CO_2 by 2010. A reduction of 60 % is required by 2050. “In the next 20 years the current rate of utilization and cost of fossil fuels will be under considerable policy scrutiny by European member states as they tackle climate change.” [1] But so far, energy consumption is strongly related to quality of life and it is still steadily increasing. This indicates that these goals are essential and challenging if quality of life is not going to be decreased.

This thesis focuses on individual transport in vehicles. Road transportation is responsible for 22 % of UK greenhouse gas emissions – the third biggest. The ACEA (European Automobile Manufacturers Association) voluntary commitment targets for a CO_2 emission of 140 $^{g}/_{km}$ fleet European average for cars by 2008. This is equivalent to a 25 % reduction since 1995. They have achieved a reduction of 1.9 % per year in the past and 2.1 % are required in the future years for reaching that goal. [3] There is an expectation that the industry will subsequently be under further pressure to make significant additional reduction in CO_2. The number of cars on the other hand is still increasing. The growth of passenger car numbers in 2001 was 2.3 % per annum just for the European-15 member states. The deviation is between 0.5 % in Sweden and 8.2 % in Greece [4] and growth in many other countries like China, India or Eastern Europe states is much higher. Despite all the effort the growth still outpaces the improvements and no contribution has been made to the Kyoto agreement so far. The question is whether more radical solutions like the introduction of low-impact cars are required.

Hydrogen is frequently called the energy source of the future, but hydrogen is not a source itself, it is “just” a fuel that produces zero local emissions when combusted. Hydrogen needs to be produced first and this requires energy. It is yet unclear whether sufficient hydrogen can be produced sustainable to satisfy the needs of road transport at all [1]. The use of hydrogen is discussed later. The discussion about energy and CO_2 leads to some general questions:

- What will the energy source of the future be most likely?
- Can renewable energy sources satisfy the energy requirements without decreasing quality of life?
- Do we need to focus on other sources for energy or do we need to implement more efficient ways of using it?
- What will be the fuel for cars of the future?

It is essential to answer these questions in order to design a vehicle drivetrain that fits into future scenarios. The energy issue needs to be studied in general, not just for cars, because energy supports the whole life of human beings, not just transportation. The average power support for every human being is about 3600 W. In other words: human beings make use of 60 so-called energy servants per person. The mentioned questions are investigated in the following subsections.

2.1.1 Energy Sources Now and in Future

Oil, coal and natural gas are fossil fuels, which are mainly used to "generate" energy. They have been accumulated under ground for millions of years. The energy conversion process uses fossil fuels and O_2 to produce CO_2 and energy. CO_2 contributes to the greenhouse effect, which leads to global warming. Renewable fuels are "young fuels" – they contain energy that came down to earth recently and not over millions of years. These fuels overcome two main impacts of combusting fossil fuels:

1. Fossil fuels will run short or difficult to use within the next century – renewable fuels last forever.
2. Combusting renewable fuels will not produce CO_2: The CO_2 consumption that is necessary to form the fuel is in balance with the CO_2 production in the combustion process. This is called the carbon cycle.

The most important renewable fuels are:

- Bio-Ethanol (alcohol)
- Bio-Diesel
- Bio-Gas
- Wood

Bio-gas and wood are important for heating or stationary electric power plants. Alcohol and bio-diesel can be produced in sugar cane or rape plants. They are liquid and can be distributed through the existing infrastructure with some modifications in order to deal with the higher corrosive potential. Brazil for example runs a high percentage of cars on alcohol. Pure bio-diesel is 11 % oxygen by weight. It provides significant reduction in pollutants during combustion and the life-cycle production and use offers at least 50 % less carbon dioxide. Bio-diesel is claimed to provide a 90 % reduction in cancer risk. Significant increase in producing nitrogen oxides is an issue [1].

Used unblended, these bio-fuels are incompatible with most current in-service vehicles. In case of bio-diesel, the market is unlikely to be able to supply enough bio-diesel for more than a few percent of the total fuel demand. The maximum overall bio fuel substitution is usually considered around 8 % of present gasoline and diesel consumption if bio fuel production was restricted to the 10 % of agricultural land presently covered by the set aside regime. One hectare of land is required in the UK to produce one ton (1100 liters) of bio-diesel from rapeseed oil per year. It is estimated that availability of land in Europe is such that at best bio-diesel can only provide about 5% of the fuel demands [1].

All mentioned bio-fuels rely on biomass. Plants convert CO_2 into C by using sunlight. This process (photosynthesis) captures and stores sunlight energy in biomass. All mentioned biomass products are not capable of delivering sufficient energy to the world. Some figures will help to determine whether other plants or processes promise better results at all: The net primary production of plants capturing and converting energy is about 30 to 50 $\cdot 10^{20}\ ^{J}/_{a}$. The use of fossil fuels is 3.0 $\cdot 10^{20}\ ^{J}/_{a}$ – only 10 % of it. This sounds promising, but examining the situation from another point of view reveals that wood only forms less than 10% of total world energy consumption. The efficiency of plants in terms of capturing energy from the sun is comparatively bad: values above 5 % have not been reported and this means that huge land-areas would be required to satisfy energy needs for the whole world by biomass. To provide 50 % of U.K.'s present energy use on a continuous basis, over 400,000 km^2 of energy plantations would be needed. This is about 70% more than the country's total land area. Ethanol production from sugar cane plants in Brazil is another example. They are capable of producing 61.0 GJ/(a*ha) = 6.1 * 10^{12} J/(akm^2). That means 690,000 km^2 or 290 % of the United Kingdom's total land area is required to feed the world's energy consumption. [5] (Data from 1987) These land areas required are in competition with land for food production, living, working and industry, nature and recreation. Efficient crop production for fuel requires use of pesticides and nutrients. Biomass is an interesting way of direct fuel production, but it seems to be unpractical to feed the energy consumption in the world on its own.

The incoming short-wave radiation reaching surfaces of oceans or land cover is about 30,000 $\cdot 10^{20}\ ^{J}/_{a}$ this is about 10,000 times more than the actual consumption of fossil fuels. Table 2-1 compares different ways of exploiting this huge sustainable energy source. It focuses on the land use required to produce the electricity for the whole world or for United Kingdom, because land use is the main issue against biomass production.

Table 2-1: Comparison of Different Sustainable Energy Sources

	Sugar Cane	Wind	Solar Cells	Solar Steam
Source of information	*1	*1	*2	*2
Medium	Ethanol	Electricity	Electricity	Electricity
Energy exploitation in J/akm^2	$6.1 \cdot 10^{12}$	$1.5 \cdot 10^{14}$	$9.4 \cdot 10^{14}$	$1.4 \cdot 10^{15}$
Required area for world energy in km^2	$5.4 \cdot 10^{7}$	$2.2 \cdot 10^{6}$	$3.5 \cdot 10^{5}$	$2.4 \cdot 10^{5}$
Percentage of total land area	41 %	1.7 %	0.27 %	0.18 %
Factor of UK area	223	9.1	1.4	1.0
Area for energy in UK in km^2	$1.4 \cdot 10^{6}$	$56.3 \cdot 10^{3}$	$9.0 \cdot 10^{3}$	$6.0 \cdot 10^{3}$
Percentage of usable land in UK	579 %	23 %	3.7 %	2.5 %
Per capita area required in m^2	24,390	981	157	105

**1 [5]*
**2 [6]*
Photon: global radiation in Algeria: 2,000 kWh/(a·m^2) = 7.2 E15 J/akm^2
Efficiency of solar electricity generation: 13 %
*Direct normal radiation in Algeria: 2,500 kWh/(a*m^2) = 9.0 E15 J/akm^2*
Efficiency of thermal solar power plants: 15 % (improvements expected) [6]
World energy consumption: 3.3 E20 J/a,
Ttotal world land area: 131 E6 km^2 of which only <42.1 E6 km^2 usable [5]
U.K. facts (1989):
*Area excluding fresh water: 242 * 10^3 km^2*
*Population – total: 57.4 * 10^6*
*Energy consumption – total: 8.45 * 10^{18} J/a*

Table 2-1 reveals that other methods than producing bio-fuel promise much better efficiencies in land use. Only 0.27 % of the world land area needs to be covered with solar cells in order to satisfy the world's energy consumption. Figure 2-1 shows this area covered in Algeria: the largest quadrate is sufficient to generate the energy for the world, the second largest is sufficient for Europe and the small one is sufficient for Germany.

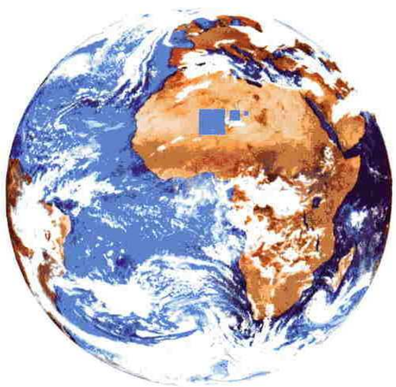

Figure 2-1: Requirements for the World Energy Supply with Solar Cells [6]

This seems to be a perceivable way forward and Table 2-1 also reveals, that solar steam generation promises even better results and smaller land areas. Table 2-1 shows the world energy figures, but the world energy consumption is steadily increasing, especially in developing countries. The figures focusing on the United Kingdom are presented because they can represent the requirements of all countries in the future once the developing countries reach the same level and so-called developed countries manage to sustain their consumption and USA manages to reduce it. An equivalent of 3.7 % of UK's land area needs to be covered with solar cells in order to satisfy UK's energy consumption. This is equivalent to 157 m^2 per capita. This is possible, but requires a massive investment. The following facts help to estimate the financial issues:

The German government supported photovoltaic between 1975 and 1997 with 1,200,000 DM = GBP 375,000. The resulting energy production covers about 0.001 % of Germany's electricity supply. In 2001 it was 0.011% and the actual "100.000-Daecher-Programm" will achieve 0.05 %. [6] Cost for electricity production is estimated with 20 Cent per kWh (after a cost reduction of 50% for photovoltaic production) for solar cells and 12 Cent per kWh for solar steam. [7] The cost for electricity production is acceptable in the end, but investment is very high. Return on investment is not attractive enough for investors yet until energy cost rise significantly. But not only financial investment or final energy cost is an issue. Also timescale and investment of energy need to be considered. Solar cells need time and energy for production and the question is whether both is still sufficient once investors find it attractive enough, but this is not part of this thesis.

Power generations from waves, tides or geothermal heat are other sustainable ways of energy generation, but they have not been reviewed so far.

Beyond renewable energy sources, there are some alternative sources to oil, like:

- Gas (LPG or Natural Gas)
- Coal
- Nuclear power or fusion reactors (under development)

They are already used in many applications like heating and power plants. They are not renewable, but can support renewable fuels or act as an interim step in order to gain time. There are vast reserves of natural gas, but these are often in remote areas that are too remote from pipeline and urban markets. Use of coal is contributing to global warming. Nuclear power is used for generating the base-load, because control is slow and makes the plants inefficient. Additionally it is more expensive than the use of coal and waste disposal or regeneration is always an unpopular issue.

It is likely that several different energy sources will be used in order to satisfy the energy consumption and certain other criteria like:

- **Energy security:** We always need energy, not just if the sun shines or the wind blows. Redundant generation is required in order to cope with failures or with unexpected circumstances.
- **Land usage:** Only a certain amount of the land can be used for energy generation as mentioned above.
- **Esthetics:** People already start complaining about too many windmills in some areas as one example.
- **Cost:** Some alternative sources like solar cells are very environmentally friendly but require considerable investments.
- **Impacts:** Discussions about the impacts of nuclear power generation are well known. Windmills are being accused for killing birds.

In conclusion, energy supply will be an issue in future and it is sensible not only to concentrate on new energy sources but also on a more efficient use of energy. It is likely that energy cost will go up in future and only the efficient use of energy can sustain quality of life. Smaller energy consumption helps introducing alternative and more expensive energy sources. Individual transport makes 22 % of the total energy consumption and cars need to be more efficient, because there number is still growing. The following subsection will show that energy storage on board of cars is an issue as well, making energy efficiency even more important.

2.1.2 The Paths for Energy Sources for Individual Transportation

The source is not the only issue on supplying energy. In order to propel a car, the energy needs to be converted, distributed and stored. The path for the energy depends on the type of power generation and the fuel that is going to be used in the vehicle. This section examines this issue.

Though there are vast reserves of natural gas, the direct use of natural gas in cars promises only small advantages compared to combusting conventional fuels in cars. Natural gas infrastructure is available but it needs to be compressed or liquefied. It is not a renewable source and CO_2 benefits are small. Hydrogen is frequently considered as the fuel of the future and the current infrastructure for gas is not compatible with hydrogen. This puts into question the role of natural gas as a direct path on the route to a hydrogen infrastructure [1]. It seems more suitable for stationary use like heating and cooking. The advantages of natural gas in automotive applications are too small for investing into a changeover.

LPG is a by-product from two sources: natural gas processing and crude oil refining. Used in combustion engines it shows 11 % reduction in CO_2, 44 % reduction in NO_x, 19 % reduction in total hydrocarbons if compared with a Euro IV gasoline car. Maintenance of an LPG vehicle needs more care and control and energy density is about 20 % smaller than gasoline [1]. LPG is a considerable interim solution.

Renewable fuels represent a reasonable alternative and overcome the problems of global warming and running short of fossil fuels, but production requires massive land areas as discussed in section 2.1.1. Other means of renewable power generation like solar cells for example are better in land use, but they do not produce a fuel that can easily be stored. Nuclear power, fusion reactors, tidal and wave generation, they all produce electricity as well. Electricity can easily be distributed through the existing infrastructure, but storage is an issue. Storage is required in order to match the generated power that cannot be controlled easily to the consumption. Better networking can minimize the need for storage in the electricity supply, but some storage will always be necessary. The individual transport with cars requires storage of energy inside the vehicle. It can be stored in batteries or as hydrogen. This is discussed in following paragraphs.

"Hydrogen is favored as the most suitable fuel for the future, because it is the only carbon free fuel that is potentially available to us." [1] But carbon free fuel does not necessarily mean there are no CO_2 emissions any more, because hydrogen needs to be produced somewhere and somehow. If produced with electricity that is generated in conventional power plants fired with coal, all the advantages of hydrogen fuels will be offset. Hydrogen is not an energy source; it is just a means of storing energy. It promises convenient ways of storing and releasing electrical energy in mobile applications like cars: Electricity is used for electrolyses. Water is split into O_2 and H_2. The energy is stored in hydrogen. The hydrogen can be distributed and stored in vehicle tanks. A fuel cell in the car can generate electricity directly from the hydrogen and an electric motor propels the car. Or – alternatively - the internal combustion engine could run directly on hydrogen. Hydrogen has a very high energy content per unit mass (120.7 kJ/kg). On mass basis it has 2.6 times higher energy than gasoline. On the other hand it must be liquefied (-253 °C) or compressed to contain sufficient energy per volume appropriate for a mobile applications. Liquefying absorbs 25 % of its energy content, using 5 kWh to liquefy each 0.45 kg [1]. The mass of the fuel storage device has to be added to the fuel mass and this is much higher for liquefied or compressed hydrogen than for naturally liquid fuels like ethanol or bio-diesel. It has to be mentioned, that fuel-cell technology, hydrogen infrastructure and hydrogen storage is not available yet. Massive investments are required as the following figures may demonstrate:
Experts estimate that the first series production fuel-cell cars will be available between year 2010 and 2020. The ambitious German project "Wasserstoff-Wirtschaft" ("Economy of Hydrogen") was aiming for a countrywide hydrogen infrastructure until 2020. Cost-estimations of about € 120,000,000 for this project have caused reconsidering and delaying the aim until 2050. [2]

Batteries are another means of storing electrical energy on board. Technology is almost available, electricity can be stored directly, infrastructure for distributing electricity is available and efficiencies are high (about 90% for Li-Ion batteries). They are ideal from this point of view, but the disadvantage is the comparatively poor energy storing capability. High mass and volume is required in order to store a certain amount of energy. One liter of gasoline generates about 8.866 kWh of energy. Latest battery technology can store about 200 $^{Wh}/_{kg}$ [8]. This means more than 44 kg of battery are required to store the same amount of energy as one liter of gasoline.

Not only on-board energy storage and distribution, but also the total energy efficiency of the technology is an issue. This has been shown in section 2.1. "Electric vehicles running on batteries have no local emissions, but the electricity needs to be generated somewhere. Current production and distribution efficiencies are such that overall efficiency is reduced to 17 % behind gasoline at 19 % and diesel at 21 %" [1]. This is an example of a well-to-wheel analysis. It is extremely misleading because it is not based on any future scenario. It is based on a conventional vehicle that runs on oil-products and this is compared with an electric vehicle that uses electricity generated from coal. If the fuel-cell vehicle had been compared in the same study it would have been even worse than the electric vehicle. This is not a sensible approach to the problem, because most alternative energy sources produce electricity. Well-to-wheel analyses need to be based on perceivable future scenarios and they need to include all possible drivetrain technologies. This subsection has revealed that three future scenarios are possible:

1. Electricity generates hydrogen and this provides the energy for the car.
2. Electricity is stored in on-board batteries.
3. Renewable liquid fuels propel cars.

All three scenarios comprise advantages, disadvantages and technological problems. Use of alternative fuels like for example LPG has not been included, because the advantages as an interim solution are without doubt, but they do not offer a sustainable transport and substantial CO_2 reduction.

If hydrogen could be produced directly from sunlight, this would help overcoming the problem of building a hydrogen infrastructure and all the losses in power-transmissions. H2SPC is a UK company that plans to commercialize a process that uses sunlight to produce hydrogen directly from water. They claim their product is cheaper and less energy intensive to manufacture than conventional silicon solar cells, but no figures were mentioned. Their cells could be site on something not hugely larger than a domestic garage to produce enough for an average car user's need. The efficiency of the process could be above 10 %, but cells will have between 5 % and 10 % because of lower material cost in that case. [9] The global radiation in England is about 1,000 kWh / (am^2). Technology with an efficiency of 10 % produces 100 kWh / (am^2). The average car travels about 7,000 miles/a or 10,000 km/a. A conventional car consumes about 80 kWh / 100 km, this equals to 8,000 kWh / a. This would require 80 m^2 of their "hydrogen-cells". This is four times more than the area of a typical domestic garage unless the car becomes much more efficient. Not to mention the problem of storing the energy for load leveling. Thus, direct hydrogen generation has not been included in the scenarios.

The different scenarios are based on different technologies in the drive train of the vehicle. Hydrogen can power either a fuel cell or a combustion engine with certain efficiencies. The well-to-wheel efficiency analysis is required in order to estimate the cost of this scenario. Electricity stored in batteries can only be sufficient in electric vehicles with very high efficiency in order to provide sufficient range. Electric vehicle technology needs to be reviewed in order to judge whether range can be sufficient at all. Vehicles need to be efficient if they are to be propelled on renewable fuels, because renewable fuels can be available in small quantities only. Most scenarios can be combined in order to achieve advantages. The combinations of scenarios with drive train technology are compared in section 2.3.

2.2 Vehicle Design Considerations

Energy and environmental factors are not the only considerations when designing a vehicle. In fact they were not considered at all for a long time. This thesis proposes a drive train for future individual transport and thus, all factors have to be considered in order to provide sustainable individual transport and quality of live in future. The factors can be categorized in two main groups:

- Factors focused on customer or driver requirements
- Factors considering social requirements

Factors focused on customer or driver requirements

Modern cars provide reliable operation over 160,000 km (100,000 miles) and more. Maintenance is required after every 20,000 km or longer. Most cars are extremely versatile: They can carry four or more passengers and goods or tow trailers. The range on a full tank is about 700 km and the tank can be refilled within minutes in almost any region of most countries around the world. It can operate in strong winter and hot summer and most cars provide climate control for comfortable temperatures inside the vehicle. All modern cars provide sufficient power for traveling on motorways, for overtaking other cars on highways, for acceleration on hills outside urban areas and for almost all gradients on public roads. Cars provide high comfort for tireless driving of several hours even on poor roads. Safety has been increased during the last fifteen years; modern cars have a structure that is designed for high protection in a crash. Big and small cars have been made compatible in crashes by designing the stiffness of the body. Different technologies like for example air bags, anti blocking system, electronic stability system have been implemented for increased safety. Most cars provide sufficient power not only for driving along but also for fun. The engine is oversized in order to keep engine noise and vibration low during normal operation. Driving a car with combustion engine, clutch and manual gearbox requires skills, but all drivers are trained in driving schools before they go onto roads. Most factors are exposed to inflation and customer expectations steadily increase. Every new model is sold by adding some new value to it, like higher safety, more comfort, more features, better drivability, higher versatility or a new appearance. The engine power for example has increased by 14.3 % between 1995 and 2000 [1]. Another factor is the cost of the vehicle: customers get increasingly higher value for money since cars have been invented. Existing vehicles with conventional combustion engine technology is arguably mature and there is little scope for improvements from the customer perspective.

Factors considering social requirements

The escalating number of cars on the road and the dependency on resources on the other hand has raised awareness to vehicular environmental impacts and sustainability. Future cars have to have smaller impacts on the environment: less noise, less local pollution, less global pollution, small CO_2 production and better compatibility with cyclists and pedestrians in terms of size and weight. They are also required to have reduced energy consumption in order to reduce dependency on oil and for offsetting the higher cost of renewable fuels. The energy issue is discussed in section 2.1. Disregarding these social factors is non-sustainable and quality of life for everybody would decrease in the future.

Unfortunately most of these social factors need to be traded off with the driver requirements as some examples may demonstrate: The high reliability and low cost of modern cars and the competition of automotive companies hinders fast exploration and introduction of alternative concepts. The high versatility and flexibility of modern cars prohibits the introduction of purpose design vehicles. The good drivability and power of modern cars leads to oversized engines that suffer from poor efficiencies in slow traffic. A smaller vehicle mass would help to reduce noise from tires, keep energy consumption low and increase compatibility with cyclists and pedestrians, but the higher the vehicle mass the higher the potential for comfort, shelter and safety inside the car. Equipment for comfort and safety is consuming substantial amounts of energy.

Car manufacturers are heading for added value in order to be competitive, whilst politicians try to establish social factors. International regulations regarding noise and emissions are committed, but these achievements are not sufficient when facing the facts about future transportation requirements and growth:

Individual mobility increases rapidly all over the world [10]:

“Today, world citizens move 23 billion km in total; by 2050 that figure grows to 105 billion. (All numbers per year) The average American's mobility will rise by a factor of 2.6 by 2050, to 58,000 km/year. (Rise measured from the year 2000) The average Indian travels 6000 km/year by 2050, comparable with West European levels in the early 1970s. Air quality will continue to improve as result of the replacement of older vehicles until about 2020, when it is predicted that the growth in vehicle mileage will start to offset the effects of cleaner vehicles. The average car mass of new cars has increased by 7.9% over the 1995-2000 period.” [1].

Sustainability in transport is required which may be achieved by government plans to raise cost and other obstacles for using cars, but this cannot be the ultimate solution because “The sale and use of cars has expanded in response to individuals’ desire for a lifestyle in which their friends, workplace and leisure activities may be geographically dispersed. This is taken quite for granted and young people imagine that people have always lived their life that way.” [11]. People are willing to spend only a certain amount of money and time for traveling. [10] Increasing cost or time for transport result in the decrease of quality of life for a certain number of people, which ultimately cannot be the aim of governments.

In consequence of what has been discussed so far, there will be a market for a car that just meets the demand for individual transport but reduces impacts on the society remarkably – the low-impact car. It needs to provide the following basic requirements:

- It must be affordable over the lifetime in future scenarios. Higher purchase cost can be offset by low running cost. It is likely that this sort of car is purchased on loan or it is leased.
- It needs to meet the state of the art standards in terms of safety, reliability and versatility.
- It must be powerful enough to cope with all traffic situations and provide some fun of driving.
- It needs to provide substantial advantages in terms of noise, emissions, and energy consumption. Advantages in terms of low weight are welcome but at least it should not be worse than actual cars.
- It should provide some added value, but not necessarily on the route of more power, higher comfort and increased safety.

Though there is a market for low-impact cars, the question remains, whether it can be introduced to the markets. The typical new-car buyer does probably not need to save money and big automotive companies find it increasingly difficult to make money with the small-car market anyway. But if running cost of vehicles – especially fuel cost – will increase, the typical second-hand buyer becomes more and more interested in buying a new low-impact car with low running cost instead of a second-hand car with high running cost. Doing so can shift the actual new-car buyer’s mind as well, because it becomes less likely that he can sell his car second-hand.

The following section investigate what drivetrain technology could propel such a low-impact car.

2.3 Review of Drive Train Technologies

This section is discussing different drive train options: conventional and alternative ones. The comparison is based on the energy considerations in section 2.1, because different drive train technologies require different energy sources and fuels.

2.3.1 The Conventional Car and Possible Improvements

The combustion engine has been developed since more than 100 years. It is well studied and has reached maturity. Mass production has been set up and economical use is proven. Main disadvantages are:

- Comparatively poor efficiency: The peak efficiency of modern diesel engines is about 38 %. Peak efficiency is reached at high loads and medium speed; they substantially decrease in other regions of operation. The engine is rarely used in its maximum efficiency region.
- Combustion noise
- Vibrations
- Local Emissions (depending on the type of fuel)

Internal combustion engines (ICE) can be powered on conventional fuels like diesel or gasoline. This is not sustainable and engines produce local and global exhaust emissions. By 2010, the quality of tail pipe emissions for new vehicles will be such that any further regulated reduction will have a minimal environmental impact. [1]

Following to the suggested scenarios in subsection 2.1.2, the ICE could be run on renewable fuels or on hydrogen. Running it on renewable fuels will not overcome the problem of local emissions. Both scenarios would suffer from poor drive train efficiency. Amount of renewable fuel production is limited due to land use or high investment cost. The storage of sufficient hydrogen on board is an issue, because the tank needs to be bigger and heavier for the same amount of stored energy if compared with renewable fuels. This can only be offset by lower energy consumption of the drive train. Future developments will make the following technological improvements a standard: direct fuel injection, variable valve timing, electrically engaged valves, electrically powered auxiliaries like power steering and climate control, start-stop automatic, cooling management including preheating and preheated catalysts. All these achievements focus on the main problem of ICE: the poor efficiency and poor emissions in urban traffic situations and cold engine runs. The peak efficiency will not be affected remarkably. Small high tech cars have been reviewed in order to estimate future improvements.

Make and model	Displacement in l	Maximum power in kW	Fuel consumption in $^{l}/_{100km}$
Opel Corsa Eco (gasoline)	1.0 (3 cylinder)	43	Urban: 6.5 Extra urban: 4.0
VW Polo FSI (gasoline)	1.4 (4 cylinder)	63	Urban: 7.8 Extra urban: 4.8
VW Polo 1.4 (gasoline)	1.4 (4 cylinder)	55	Urban: 8.9 Extra urban: 5.3
VW Polo TDI (diesel)	1.4 (4 cylinder)	55	Urban: 5.7 Extra urban: 4.1
VW Lupo TDI (diesel)	1.4 (3 cylinder)	55	Urban: 5.7 Extra urban: 3.6
VW Lupo 3l (diesel)	1.2 (3 cylinder)	45	Urban: 3.6 Extra urban 2.7

Table 2-2: Comparison of Fuel-Consumptions of Small High-Tech Cars

The Opel Corsa Eco is one of the most economical cars. The smaller engine with only 3 cylinders reduces wear; it also comprises four-valve technology. The automated transmission has gear ratios that are optimised for low fuel consumption and the automatic shifts gear optimal for fuel economy. Lowering the vehicle reduces the air-drag. Implementing direct fuel injection could make further improvements. The Polo FSI uses this technology and the improvements in terms of fuel consumption are about 12% if compared with the Polo 1.4. This improvement could make the Corsa Eco consume about 5.7 $^{l}/_{100km}$ in urban traffic. The real improvements might be lower, because the Polo FSI has additional advantages if compared with the Polo 1.4. The Corsa comprises them already and they have been double-counted. The new VW Polo TDI is probably the most fuel-economical diesel car in the same class as the

Corsa. Further efficiency improvements of up to 37% in urban traffic are possible as the comparison between the Lupo TDI and Lupo 3l ($^{l}/_{100km}$) reveals. The Lupo 3l uses fuel-saving technology almost without compromises. This would make the Polo consume about 3.6 $^{l}/_{100km}$. It has to be mentioned that all these high-tech fuel-economical cars are much more expensive than conventional technology. They are very rare on the roads and they are not available in many countries. Introduction may take a long time, but they can show the potential: 5.7 $^{l}/_{100km}$ for gasoline cars and 3.6 $^{l}/_{100km}$ for diesel cars in urban traffic.

2.3.2 The Battery Electric Vehicle (BEV)

The peak efficiency of the drive train in electric vehicles is about 70% (battery: 90%, motor controller 90% and motor 90%) and they are able to regenerate some energy back during braking. It has been reported that about one third of the energy can be regenerated in urban traffic. Including this regeneration, the peak efficiency of an electric vehicle drive train is close to 100% if compared with the conventional ICE drive train. Another advantage is that the efficiency map of the drive train is flat, that means most driving situations are close to the peak efficiency value. The electric drive train itself produces no local emissions, is silent and promises less maintenance.

The main problem is storing the electric energy. Batteries have a small energy capacity if compared with a fuel tank. The following relation is used in order to compare the amount of stored energy between batteries and fuel:

1 liter of gasoline generates about 8.866 kWh if combusted.

Equation 2-1: Energy Equivalent of One Liter of Fuel

A small car has a fuel tank with 45l of gasoline. This is equivalent to about 400 kWh of energy. A modern Li-Ion battery has an energy density of 330 $^{Wh}/_{l}$ or 165 $^{Wh}/_{kg}$. A battery equivalent to the 45l gasoline tank would require about 1.2 m^3 of space and 2,424 kg. Taking into account that the drive train of an electric vehicle is about 5 times more efficient would still require 240 liter and 485 kg of modern Li-Ion battery. This is an unreasonable high weight, space and cost. It leads to poor drivability, high tire noise, low versatility and no customer acceptance. The range of a pure electric vehicle with reasonable battery weight is limited to about 100 km. The creation of communal battery charging infrastructure could encourage the wider adoption of BEVs but it will remain to be a niche market, because people are used to more versatile products. They would not accept to spend the same amount of money for a vehicle that can just manage to drive 100 km and requires at least one hour for recharging.

2.3.3 Fuel Cell Electric Vehicles (FCEV)

The fuel cell is capable of directly producing electric energy from fuels like hydrogen, methanol or gasoline, without noise, combustion and conversion to mechanical energy between. Energy can be stored as a fuel with high energy-storage density and an electric motor can be used to propel the car. When using hydrogen as a fuel, the only exhaust will be water in theory. This technology promises to make use of the advantages of the electric vehicle drive train without being restricted to short range.

The theoretical efficiency of a fuel cell is up to 90 %. Between different types of fuel cells, the "proton exchange membrane fuel cell" (PEMFC) has the highest power density (>1 kW/l). Thus, the PEMFC is one of the favorites to be used in cars. The practical efficiency of this fuel cell system including gas purification is about 40 %. [12] This is much worse than a Li-Ion battery (90 %). The electric motor adds further losses. This is not much advantage to the combustion engine, though the fuel cell has better average efficiencies. This point changes if energy can be regenerated: assuming about 30 % regeneration, the drive train would reach about 70 % efficiency. This will require the implementation of a battery for storing the energy back.

Technology is not ready to combine all promising advantages of fuel cells in one practical system and infrastructure for hydrogen needs to be established. But the fuel cell appears to be the most reasonable solution in the far future. A shift towards hydrogen and fuel cells as the future solution is currently discussed and favored by industry and government. This would represent a dislocation of power-train technology and investment after over hundred years of evolution of the ICE fuelled by petrol and diesel. There are significant barriers to reaching the carbon free transportation era. The problem of on-board vehicle hydrogen storage, cost of fuel cell technology and the ability of such vehicles to compete on cost with conventional vehicles may prevent their introduction. Massive changes also would be needed to the fuel refining and distribution infrastructure to move to hydrogen. [1] Current fuel cells itself achieve to deliver up to 1.75 kW/litre, but they are generally intolerant of impurities in the fuel, have a relatively short life span and use large amounts of precious metals [1].

Direct methanol fuel cell is an option to overcome the problem of fuel storage, but methanol is dangerous, because it burns without a visible flame and it is extremely toxic to humans by ingestion or absorption through the skin (it attacks the optic nerve). These safety problems and also corrosion problems in the infrastructure are a significant issue to using methanol [1]. Storing petrol and reforming it in the vehicle is another option, but this scenario is unlikely in the future. The problem of storing hydrogen needs to be solved. The more efficient the drive train is, the smaller the problems of hydrogen storage become. Fuel-cell vehicles with regenerative braking and batteries are superior to pure fuel-cell vehicles and they are superior to combustion engine vehicles running on hydrogen.

2.3.4 Hybrid Electric Vehicles (HEV)

The HEV uses both, an electric motor and a fuel-converter. The challenge is to find the power-train configuration and energy-management that combines the advantages and cancels out the disadvantages and not vice versa.

The Toyota Prius (full size four-seated vehicle) and the Honda Insight (two-seated vehicle) were the first commercially available cars on the market. These cars achieve lower fuel consumption especially in urban driving cycles. The Toyota Prius for example achieves 61.4 mpg (3.8 $^{l}/_{100\ km}$) on urban driving cycle [13] while the VW Golf TDI 1.9 achieves only 40.4 mpg (5.8 $^{l}/_{100\ km}$) [14]. They have dramatically reduced exhaust emissions when compared to a conventional car. Toyota claims for "1000 % better CO emissions, 900 % better HC/NOX emissions and 90 % better

CO_2 emissions" than a comparable conventional car with automatic transmission [13]. Experts estimate that common internal combustion engines in cars will not be able to meet future regulations concerning tailpipe emissions and that hybridization will be necessary. However, hybrid electric vehicles in general have two main disadvantages:

<u>They still consume too much fuel.</u> The Toyota Prius achieves 58 mpg (4.1 $^{l}/_{100\ km}$) on the combined cycle [13]. Modern Diesel cars like VW Golf TDI achieve 52 mpg (4.5 $^{l}/_{100\ km}$) on the combined cycle but without hybrid drive train [14].

<u>They are expensive.</u> A comparable internal combustion engine (ICE) car costs less, because the hybrid electric vehicle needs more components. The Toyota Prius for example costs about £ 16,500 [13] and the VW Golf TDI costs about £ 13,500 [14]. It should be mentioned that Toyota looses money with every sold Prius at this price.

It has been proven difficult to sell cars that cost more but do not offer significant and **obvious** advantages. Experts rank hybrid electric vehicles only as a temporary solution, before the fuel cell cars and the hydrogen infrastructure are generally available.

2.3.5 Conclusion of the Drive Train Review

The conventional drive train with ICE meets consumer expectations very well but will not meet future requirements for sustainable transportation. [15] [16] Only radical new fuel and vehicle technologies can support environmental and sustainable objectives. They will not itself generate customer acceptance and demand [1]. They need to provide additional value to the customer and government action is required as a stimulus. **The battery electric vehicle is more efficient than any other type of drivetrain so far**. The battery is more efficient than a fuel cell and hydrogen needs to be produced from electricity first. The FCEV needs a battery (or other storage devices) as well to make use of regenerative braking. Unfortunately the range of pure BEVs is not sufficient for selling it to mass markets because of consumer expectations. Some sort of hybrid electric vehicle using the combustion engine first and the fuel cell in the future is the most likely solution. All solutions require rechargeable batteries. The following paragraph reviews available and future battery technology.

2.4 Batteries for Hybrid and Pure Electric Vehicles

Batteries are required in order to store electric energy on board of vehicles. Nowadays batteries are used for starting the engine and running some auxiliaries if the engine is switched off. Future cars will make more and more use of batteries for increased comfort, safety and efficiency. The 42 V system is going to be implemented soon. Hybrid electric vehicles and fuel-cell vehicles require batteries as well. The higher the share of battery storage capacity is the higher is the energy economy of the car. Batteries will be an important component in the car. The conventional lead-acid starter battery is very well understood, but future batteries require higher energy storage capacities and it is unlikely that the lead-acid battery will remain to be the implemented technology. Other chemistries like Nickel-Metal-Hydride (NiMH) or Lithium-Ion (Li-Ion) promise better performance, but their behaviour and applicability needs to be better understood, before implementing them in cars. This section focuses on the use of batteries in hybrid and fuel cell electric vehicles.

2.4.1 Terminology

Batteries use a chemical process to store energy. Different types of batteries are available and the electrochemical series defines the voltage of a single **cell**: the voltage per cell (VPC) is between 1 V and 4 V. The drive train of an EV requires higher voltages to keep the current low for a certain amount of power. For this reason, cells need to be connected in series. Most manufacturers of batteries produce **blocks** that contain some serially connected cells in one housing. The **battery** consists of several cells or blocks.

Every cell can store a certain amount of energy, but most batteries are specified by their **coulomb capacity** in Ah instead. This is more precise as the following example may demonstrate:
A "12 V – battery" with a coulomb capacity C has an energy capacity of:

$$E = C \cdot \overline{V_{terminal}}$$

Equation 2-2: Energy capacity of a battery, depending on coulomb capacity and average terminal voltage

The average terminal voltage $\overline{V_{terminal}}$ is the average of the decreasing terminal voltage during the whole discharging process. The average terminal voltage of a "12 V – battery" for example is not 12 V. It varies between 11 V and 12.5 V and is a complex function of many parameters such as temperature, discharge current, age of battery and history of use. Graphs need to be used for presenting the energy content of a battery as a function of different parameters. The coulomb capacity is not constant for all types of batteries. Lead acid batteries for example release less Ah on higher currents than on lower currents. The capacity C of Li-Ion cells on the other hand is fairly constant within certain conditions.

The delivery and intake of power and the current is limited for all batteries. The design of batteries can be optimized for high currents or for high energy content.

Energy, current and power of cells are usually a linear function of the capacity for a given type of battery. It makes sense to specify these values not in absolute measures but in relation to the cell capacity. The terms 3C or C/2 for example specify the current. It means 150 A respectively 25 A for a battery with a capacity of C = 50 Ah. Some **High-power cells** can deliver currents of more than 20C, they have a low internal resistance and a good current conducting internal structure. **High-energy cells** can store more energy, but deliver only about 5C peak or less and 1C continuous. They require high internal surface area. This is a trade-off to the strong structure required for high power.

Unlike a fuel tank, batteries loose their energy due to **self-discharge** during idle periods. The self-discharge rate depends on the battery type, age and temperature. An old NiCd battery in a BEV might fully discharge within 2 weeks due to self-discharge and small consumption of system-electronics. A new lead-acid battery discharges to 50% within 1.5 years at 25 °C [17].

Batteries are expensive items. The cost for a certain storage capacity is between USD 100 / kWh to USD 500 / kWh. Unlike the fuel tank, batteries might not last for the whole vehicle life and their performance deteriorates over their lifetime as well. The **life of a battery** is measured in cycles or years. For cyclic applications – every EV is a cyclic application – the cycle life is the more interesting specification. The cycle life of batteries is between 300 and 1,500, depending on the type of battery. Some variables influence this cycle life:

- The definition of "End of Life" (EOL)
- The depth of discharge in every cycle (DOD)
- The environment (e.g. temperature and shock)
- The treatment during charging, discharging and idle periods

The EOL is reached when the battery's holding capacity has decreased to 80 % of the rated capacity. This is the conventional definition, but the power capability of the battery is of more interest in some applications and EOL can be defined in other terms. The DOD for each cycle can be defined as well and is usually 80 %. The influence of temperature and shock on the battery life is determined by tests.

The treatment is difficult to define but the influence of this complex variable can be very significant, as some examples may demonstrate:
Frequent incomplete charging of a Hawker Genesis valve regulated lead-acid battery (VRLA) may result in a life of 30 cycles only instead of the usual 500 cycles. [18] Most battery manufacturers provide a charging scheme that is recommended for their cells or blocks but not for the whole battery string. Cell imbalances can reduce the life and performance of a battery dramatically [19]. They may cause 80 % reduction in cycle life. [19] The user of the battery (the driver of the car) is another considerable influencing factor, but very difficult to define. Vehicle manuals containing comprehensive information on "How to treat the batteries …" might prolong the battery's life but are not helpful to the user at all.

The actual **state of charge** (SOC) of a battery is measured in Ah or in percent of the maximum available capacity. It is comparatively easy to calculate it by Ah-counting for batteries with constant capacity like Li-Ion, but it becomes more difficult for lead-acid batteries. The self-discharge is difficult to take into account, because this parameter varies over lifetime and other conditions like age or temperature. Comparing and adjusting the calculated value with certain reference points can overcome this problem. Other attempts implement self-adjusting fuzzy-neural networks. This makes sense in applications without a full-charge reference point and with very dynamical use of the battery, because digital Ah counting becomes too inaccurate.

In conclusion, the battery is the component of an EV that adds substantial cost and uncertainties. Battery management is necessary for predicting SOC and to assure best possible treatment and longest lifetime without interfering too much with the driver. Better knowledge for predicting the battery life in EV applications needs to be gathered by implementing battery-monitoring equipment into vehicles.

2.4.2 The Charging of Batteries

The batteries in EVs are rechargeable. The charging can be compared with filling the fuel tank in conventional vehicles. The drawback is that it takes much longer: Filling the tank of a car takes a few minutes. That means refilling takes a couple of seconds for 100 km driving range. Charging a battery from a household 3-phase socket can "refill" with about 10 kW. This is equivalent to 1.1 l/h or about one hour for 100 km driving range in a small and efficient EV. The energy distribution network for recharging is available and charging can take place at home over night or during parking for shopping or at work. The speed of charging depends on the available electrical power and the type of battery. Some Li-Ion, NiMH and NiCd cells can be recharged within one hour or less, but they require a sophisticated charging control with temperature, voltage and current monitoring. Some HEV or FCEV are self-sustaining and they cannot be recharged from the mains.

A battery that is fully charged cannot store any more energy and the charging must be stopped. The battery needs to internally dissipate energy if overcharging occurs. Most batteries can deal with overcharging without damage up to a certain extend. If this energy dissipation is higher than the amount of energy used for charging in the end, the cell protects itself and the type is called **good-natured**. Lead-acid, NiCd and NiMN are good-natured. Li-Ion batteries are not good-natured and they require single cell observation.

The battery manufacturer usually provides the charging algorithm. Batteries can be charged with a DC or pulsed current. Charging can be categorized in different phases and purposes:

- Initial or bulk charging phase
- Absorption-charging phase
- Float charging phase
- Equalization charging
- Service

The **initial charging** returns the main amount of the discharged energy. The battery can accept the highest charging current in this phase. Manufacturers will usually specify the limits in temperature, current, voltage and time. VARTA for example recommends charging the Drymobil [20] in this phase with I_{charge} = C/5 and a voltage limit of 2.35 VPC.

The **absorption-charging** phase returns the last percentages of energy. It takes a comparatively long time, because the current is much smaller in order not to damage the battery. About C/140 should be applied 0.6 times as long as the initial charging phase to the Drymobil [20]. Though this phase returns only a small amount of energy, it is essential for most lead-acid batteries to prolong their life. NiCd and NiMH batteries can be recharged much quicker, because this phase is not required in a fast charging algorithm.

The **float charging** maintains the battery in a fully charged state. This phase reverses all self-discharge processes. The problem is that the self-discharge rate is not constant; it depends on the age of the battery and the temperature. Unmatched float charging can shorten the life of the battery and consume significant amount of energy in practical use. Recharging on demand is preferable to float charging in EV applications.

Some types of battery require an **equalizing charge** to fully and equally charge all cells in a series string. This phase makes use of the internal energy dissipation in good-natured battery types. It usually requires small currents and takes a long time. It becomes less effective in old battery packs with growing cell imbalances. Active equalization can speed up this process; it works better in older batteries and becomes essential in not good-natured battery types like Li-Ion. Methods for active equalizing are discussed in section 2.5.

Some applications and some battery types require **service charging**. Service charging is launched regularly or only if indicated. The special charging or cycling procedure helps to measure and maintain the battery performance. It is launched rarely. Cycling NiCd batteries from time to time for example can reduce their memory effect. Proper charging and use of the batteries can minimize the demand for service charging. Any need for service charging of Li-Ion or NiMH batteries has not been reported.

There are different **charging regimes** for batteries:

- Constant current (CC or I charging)
- Constant voltage (CV or V charging)
- Constant power (CW or W charging)

Most manufacturers specify the charging algorithm for their batteries with combinations of these methods. An IVIa or CC-CV-CC-a charging algorithm for example means charging with constant current (CC) up to a certain voltage in the initial charging phase. Continuing with this constant voltage (CV) for a certain time or till a certain current is reached. Followed by a constant current (CC) charge regime in the absorption-charging phase, which will automatically be terminated (a).

In conclusion, charging of batteries is not only a comparatively slow process due to the power limitation of the mains and the charge acceptance of the battery, but also a complex procedure. The combination of fast charging and high cycle life is a challenge for battery manufacturers and charger designers. It requires a battery management system (BMS).

2.5 Battery Cell Equalization

The battery of hybrid and pure electric vehicles consists of many electrochemical cells electrically connected in a series string. The characteristics of each cell, like capacity, internal resistance, self-discharge or end-of-charge-voltage are never precisely equal. Even new cells have differences. Charging them in a series connection will always result in one to be the first and one to be the last fully charged. [21] Either the first cell is being overcharged or the last lacks to be fully charged or both. This effect dramatically rises with the number of discharge-charge cycles of the battery leading to reduced performance and shorter battery life. This effect will increase if the cells are on different temperatures. Battery equalization can reduce or eliminate these effects and reviewing them is essential for prolonging the life of the batteries and keeping the running cost low. Complex equalization systems on the other hand can increase the purchase cost of vehicles significantly.

Figure 2-2 shows a string of three old Hawker Genesis blocks in a series connection while charging, discharging and idle periods without an equalizer. The figure shows the three block voltages and the charging current. It can be seen that block 1 is not fully charged while block 3 is overcharged (valve openings result in voltage bursts).

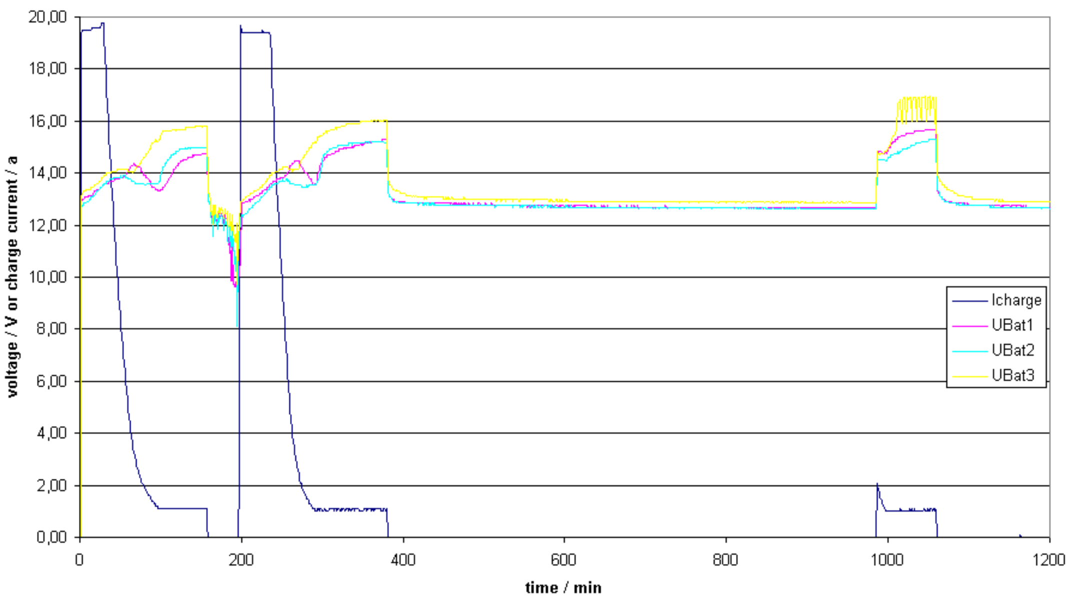

Figure 2-2: Charging of Three Old Battery Blocks in Series without Charge Equalization

There are different methods and topologies for equalizing the cells in a series connection. They are discussed in the following subsections.

2.5.1 Equalization Methods

The **string equalization** method is the natural method for all good-natured chemistries. It is based on the rise of internal energy dissipation once a cell is fully charged. It works by a long and careful overcharge until all cells are fully charged. It cannot be applied to Li-Ion batteries.

The idea of **dissipative equalization** or **current shunting** is to draw energy from the fullest cells or blocks and dissipate it in a resistor or transistor. Figure 2-3 shows this principle. The control circuit controls this device to keep all cells in the battery string equalized.

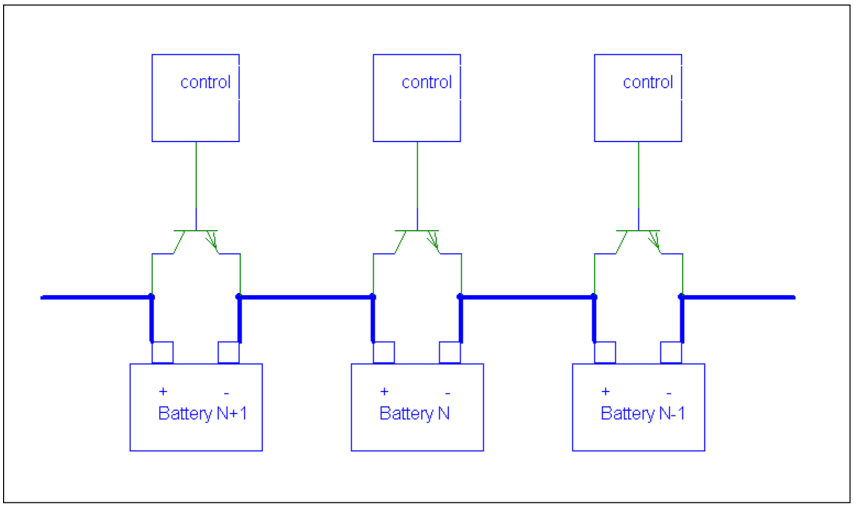

Figure 2-3: Working Principle of a Dissipative Equalizer

The main advantages of this method are simplicity and low cost, but the equalizing current is very limited.

The method of **switched reactors** is based on transferring energy from the cells with higher voltage to its neighbor with lower charge. This method works bi-directionally, usually comparing two neighboring blocks. A Daisy Chain assures all blocks are equalized. High equalizing currents are achievable without large heat sinks. Figure 2-4 shows one circuit of a switched reactor in principle. It equalizes two batteries. N-1 circuits in a Daisy Chain are needed to equalize N batteries. The transistor next to the block or cell with higher charge is controlled with a PWM. When switched on (phase 1) it draws current from this block through a reactor, which “stores this current”. When switched off (phase 2), the neighbored block is charged with this small amount of stored energy.

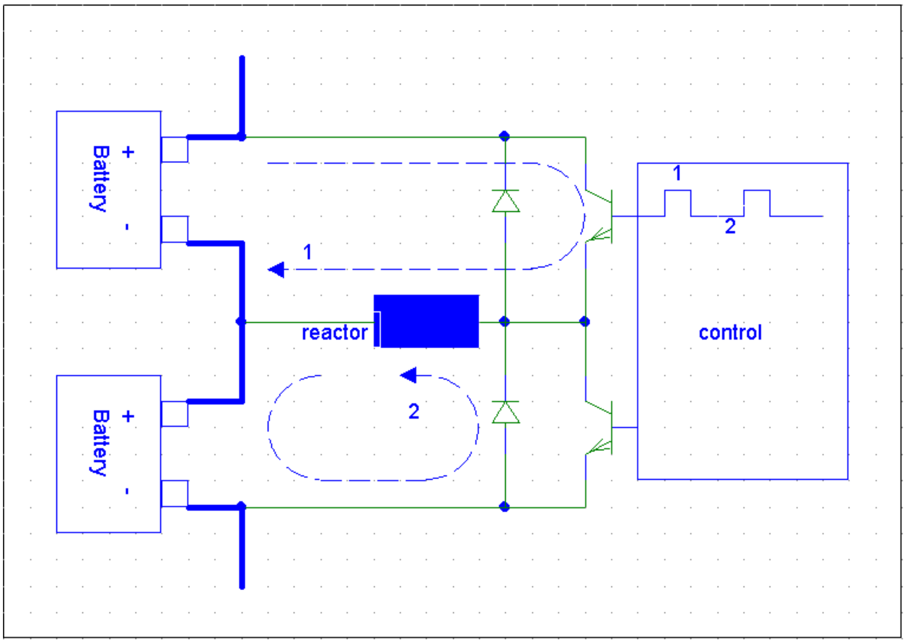

Figure 2-4: Working Principle of Equalizing with Switched Reactors

The main drawback of this method is the higher complexity and the fact that the cell voltages are compared with their neighbors and not with a reference.

Figure 2-5 shows the method of **flying capacitors** in principle: The switches switch back and fro with a certain frequency. The capacitor "between" two blocks reaches the average voltage of these blocks. It discharges the block with higher voltage in first step and charges the block with lower voltage in the second step.

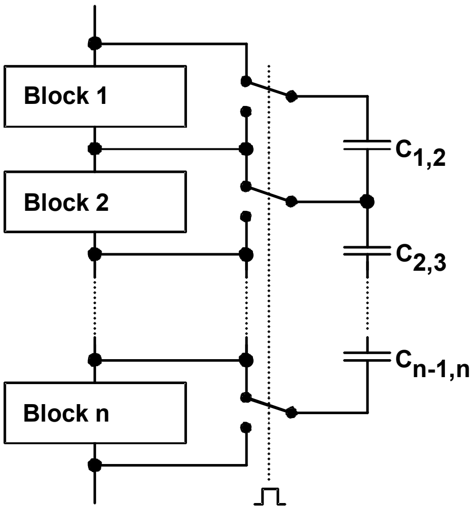

Figure 2-5: Working Principle of Equalizing with Flying Capacitors

This technology is comparatively complex and it will not achieve high equalizing currents. The control algorithm is very simple, but cell voltages can never be fully equalized due to the exponential charge/discharge characteristic of capacitors. The circuit can be simplified for smaller cell numbers by using only one capacitor that is switched among all cells using a multiplexer. This would be a very low-cost solution for up to 16 cells in series.

Another method is to charge each cell or block separately with its own charger or to distribute additional small amounts of energy to some cells/blocks when necessary. Providing a single charger for each cell or block of course means very high complexity, space, wiring (high current cables) and cost. Distributing only small amounts of energy to the low cells or blocks can be combined with cell or block voltage measurement, using the sensing cables.

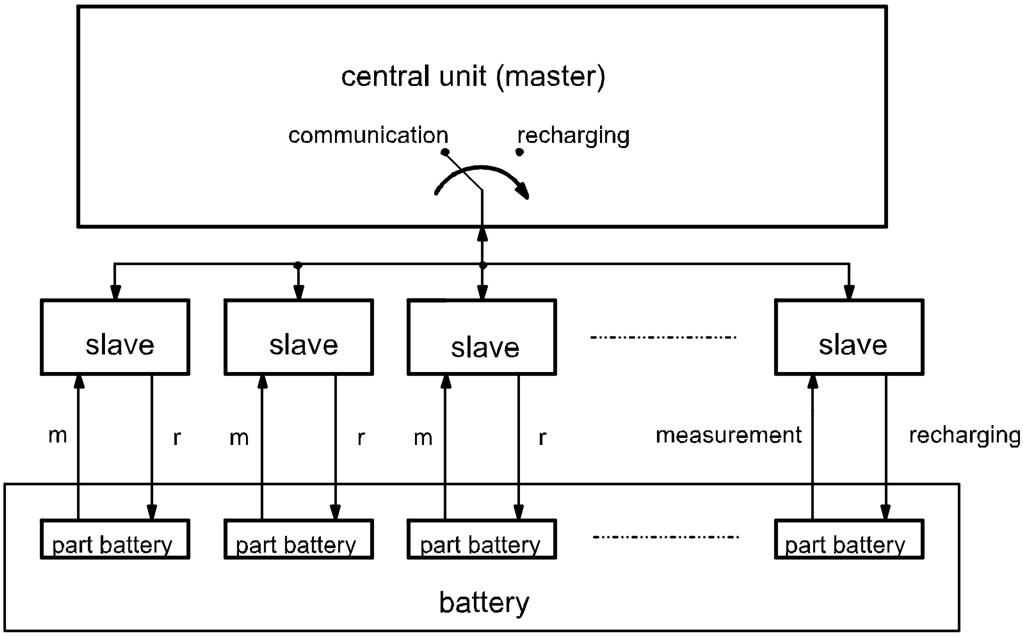

Figure 2-6: Isolated Distributing Equalizer Circuit [22]

Figure 2-6 shows a circuit using a bus system. High frequency transformers are used for communication and for distributing small amounts of energy for equalizing. These methods are very complex but provide the fastest equalization and charging.

2.5.2 Topology of Equalizer

There are different possible topologies for battery equalizing systems:

- Centralized Equalizer
- Partly centralized Equalizer
- Modular Equalizer
- Master-Slave Architecture

All might provide an interface to the charger, driver or other components or might be without any interface. The partly centralized equalizer and the modular equalizer can or cannot be linked for communication.

The **centralized solution** does not need a link like a bus-system for communication between modules. It has to cope with high voltage drops in one housing, if applied to a battery with many blocks and it is not scalable to the number of blocks in different batteries.

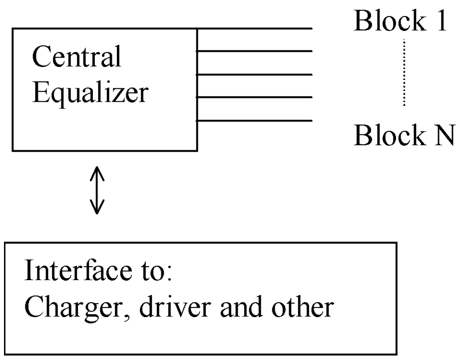

Figure 2-7: Central Equalizer with Interface

The centralized equalizer as shown in Figure 2-7 is a simple and reliable solution for batteries with a few cells and comparatively low voltages up to 70V. High production volumes for a certain number of blocks, like the new 42V system in cars, will favor this solution due to its lower price.

Having a battery with a higher voltage and more blocks requires the equalizer to be split into several parts, as shown in Figure 2-8. This topology requires an isolated interface or bus system between the modules, if communication or external interface is needed. The BEMU from SKI [23] uses this topology.

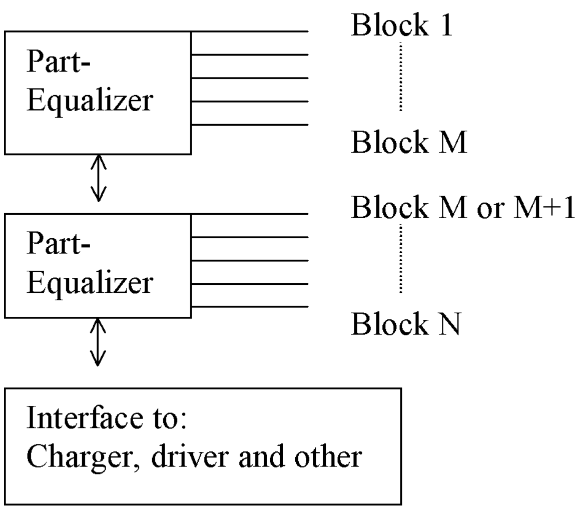

Figure 2-8: Partly Centralized Equalizer with Interface

In some cases like for the PowerCheq from PowerDesigners [19] without any communication or interface it is sensible to have a topology with one standalone module per block or between two blocks. This **modular** approach as shown in Figure 2-9 makes the system fully scalable with the number of blocks in any battery, thus reducing cost because of higher possible production volumes. No long wires are required and the temperature gradients on long battery strings can easily be taken into account by attaching the equalizer to each cell. If any interfacing or communication is required on the other hand, this topology will suffer from higher complexity and thus higher cost.

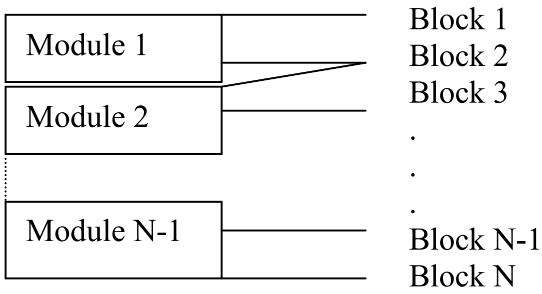

Figure 2-9: Modular Equalizer without Interface

Master-Slave architectures combine some advantages of the modular and the centralized topology. The central solution becomes scalable to the number of blocks or cells and the modular solution receives capabilities like interface and communication without high cost.

The suitable topology of the equalizer does not influence the quality or the results of equalization. It needs to be chosen regarding cost, number of blocks to be equalized, battery voltage, production volume, circuit design, interfacing, equalizing method and battery type. The general requirements for battery cell equalization depend on several factors:

- The battery technology (chemistry, size, type)
- The application
- Number of cells in series connection
- Charging methods

2.5.3 Equalizer for Li-Ion Batteries

Li-Ion batteries require comparatively small equalizing currents, because the equalization needs to offset the differences in self-discharge rates only. The cell voltages are monitored anyway in order to prevent damage to the batteries.

The central solution with flying capacitor method is the simplest and most promising solution for battery strings up to 8 or 16 cells. One capacitor can be connected to the output of an off-the-shelve multiplexer with 8 inputs. This multiplexer is required for connecting the chosen cell to the cell monitoring system. The internal resistance of available multiplexer is above 50 ohms and limits the equalizing currents. Cells with very high capacity on the other hand might require higher equalizing currents. It needs to be found, what cell size requires what equalizing current over the lifetime.

The central solution with current shunting method is preferred for small cell number of up to 16 cells. This method will also work for larger capacities, because currents can easily be in the order of 120 mA and this is much more than the self-discharge rate for Li-Ion batteries. A resistor in parallel to the cell with the highest voltage can be switched on till this cell-voltage equals the lowest cell-voltage in the string. The current drawn is small enough not to influence the cell-voltage instantaneously. The voltage drops slowly through reducing the state of charge.

Current shunting is also suitable for higher cell numbers, but master-slave architecture is required. Available cost-effective multiplexer can handle up to about 70V or 16 Li-Ion cells, communication is required for monitoring cell-voltages and temperatures and interfacing to a battery management system. It is sensible to keep the number of cells in the battery as low as possible in order to minimize the complexity and cost for the equalizing system.

3. Preliminary Test of the Li-Ion Battery

The battery is the most crucial component within the proposed drivetrain. It adds cost, weight and uncertainty of vehicle operational behaviour. Good knowledge about the battery is an essential part of hybrid, fuel cell or electric vehicle. Unfortunately the Chinese manufacturer of our Li-Ion battery provides insufficient information about their batteries. Thus, testing of the battery is required. The behaviour of batteries depend on several parameters like state of charge, temperature, charge or discharge current, duration of applied current, age of battery, cycles of battery, battery vibration and so on. Some parameters are difficult to assess or non-repeatable like for example the treatment during former cycles.
Good test-equipment, many battery cells and a lot of time is required for testing batteries comprehensively - especially if the influence of age is to be investigated.
Equipment, time and many cells are not available for extensive tests like these. The ISEA in Aachen (Technical University of Aachen) offered us using their battery test equipment (Digatron) for three days free of charge. A special method for testing the most interesting parameter within this very short time has been developed. This method and the results are presented in this chapter.

3.1 Description of Battery Test Equipment

Tests are carried out using a Digatron battery tester. The tester is capable of charging and discharging batteries with up to 100 A and between 0 V and 18 V for charging or 0 V … 15 V for discharging. The Digatron measures voltages with an absolute error of ± 5 mV. The accuracy of current measurements is ± 0,5 % of set value for current between 10 A and 100 A or ± 50 mA below 10 A. The error of the temperature measurement is smaller than ± 0.1 K. The test arrangement is shown in Figure 3-1.

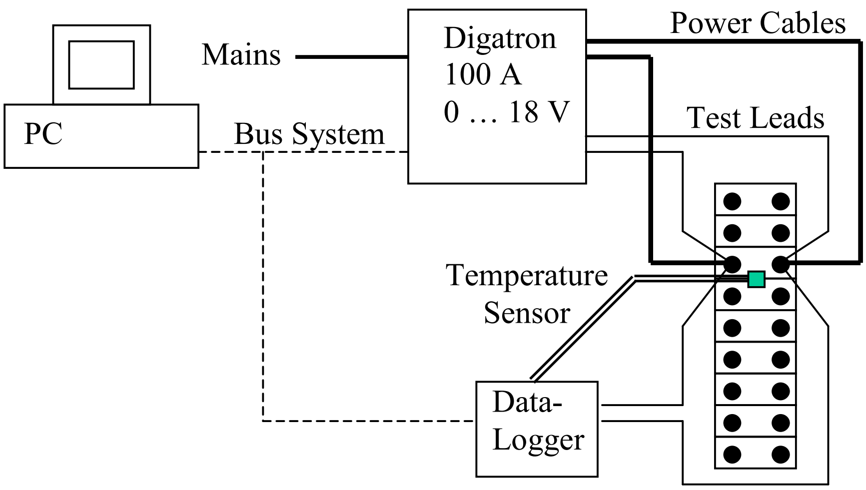

Figure 3-1: Arrangement for Testing the Li-Ion Battery on the Digatron Tester

The Digatron is connected to the third cell using 10 mm^2 power cables. Cables with higher cross-section area are recommended for 100 A testing and long cable runs, especially if the battery voltage is small. The test procedure is halted if the Digatron is not able to maintain the current because of high voltage drops across the cable. Cell three is chosen for testing, because other cells surround it and temperature rises higher than on the outer cells. The battery is placed on a plastic grid to allow airflow and for isolating it from the ground temperature. The battery temperature can rise and fall naturally and it is decoupled from most surrounding circumstances except surrounding temperature. This allows modeling the temperature behaviour of the battery. The ambient air temperature is 21 ^{0}C during the tests. The test leads for measuring the cell voltage are separate from the power cables to avoid measuring voltage drops. The data logger DLP 24C is capable of measuring fourteen channels 0 … 20 V DC, three channels 0 … 100 mV DC, one channel 0 … 300 mV DC and six temperature channels. Channel one is used to verify the voltage measurement of the Digatron and channel nineteen is used for temperature measurement. The temperature probe is placed between cell three and cell four. The Digatron and the data logger are connected to a PC through a bus system. The Digatron software allows programming the test-procedure and logging data like time, current, voltages, power, temperature, watt-hours and ampere-hours. The sampling time, limits and start/stop criteria can be programmed. The test procedure is described in section 3.2.

3.2 Description of the Battery Test Procedure

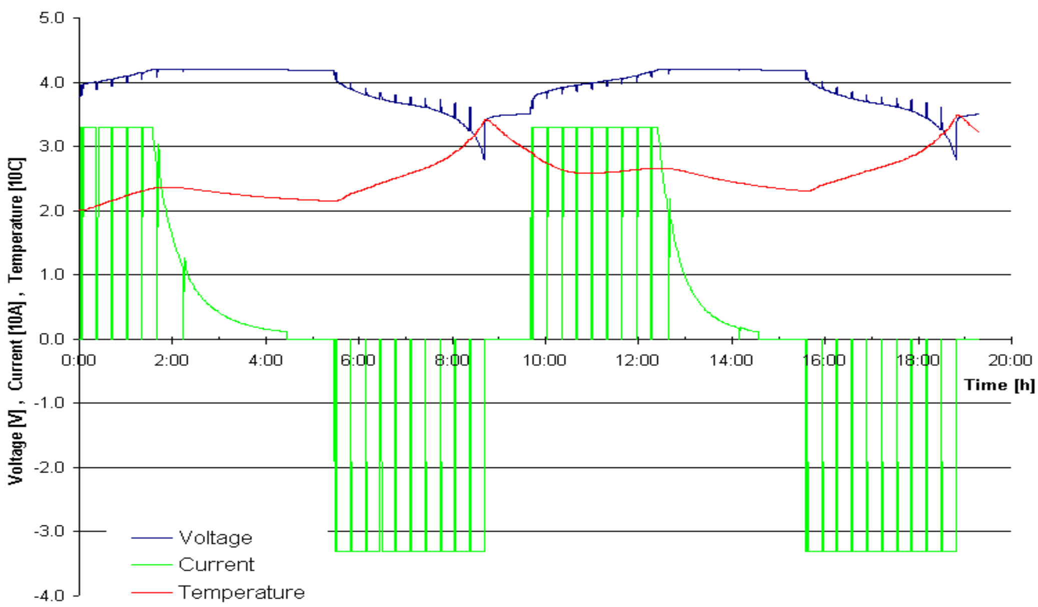

Figure 3-2: First Test-cycles of the Thunder Sky TS-LP 8582B 100Ah Li-Ion Cell

Figure 3-2 shows the first test cycles of the Thunder Sky TS-LP8582B 100Ah Li-Ion cell. The cell is first fully charged and then discharged, charged and discharged again. The discharging current is constant 33 A till cell voltage reaches 2.8 V and then stopped for one hour before charging it again. The charging is a constant current – constant voltage regime (CC-CV-charging) with 33 A till cell voltage reaches 4.2 V and then with decreasing current and constant voltage till the charging current reaches 1.0 A. This is the charging procedure that is recommended from Thunder Sky, the manufacturer of the battery.

A rest for one hour is applied after charging before next discharging. Current, voltage and battery temperature are recorded every minute during charging and discharging. A short brake for one minute is applied every 10 Ah during charging and discharging and records are taken every second in this pause. The battery temperature is not maintained constant during tests and the ambient temperature is 20 ºC. The test procedure is programmed in the Digatron battery tester PC. The program is shown in appendix A.

3.3 Determination of Battery Parameters

Modeling batteries helps understanding, simulating and predicting the behaviour of them in the application. One of the simplest models using an equivalent electrical circuit approach is shown in Figure 3-3.

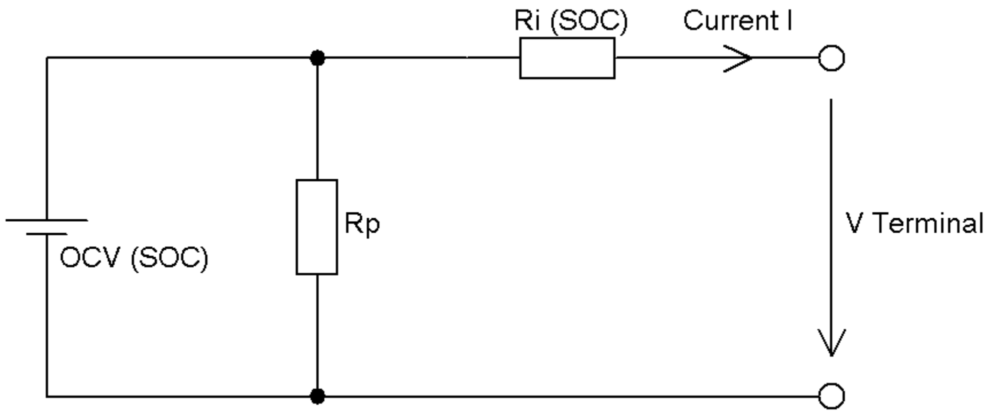

Figure 3-3: The Simple Battery Model

The battery is modeled with its open circuit voltage OCV, the over-voltage resistance or internal resistance R_i, and the self-discharge resistor R_p. OCV and R_i are functions of the state of charge (SOC) of the battery. The dependencies are investigated in the following subsections.

3.3.1 Determination of Open Circuit Voltage

The open circuit voltage OCV is determined in dependency of the state of charge (SOC) of the battery. This allows prediction of behaviour or determination of SOC during operation. The usual determination of OCV in dependency of SOC is a time consuming process: The battery is charged and discharged; the SOC is determined through counting Ah. The Current is stopped at specific SOC and the OCV is measured directly at the battery terminals ($V_{Terminal}$) after waiting several hours. The long time for waiting is required for reaching steady state voltage at the terminals. The Battery is cycled before running the test to assure constant behaviour. Several tests are undertaken and several cells are tested for determining the OCV in order to obtain statistical values like repeatability, distribution, uncertainty and mean value. The temperature is controlled and tests are repeated with different temperatures in order to obtain the temperature behaviour of the battery.

The test is simplified significantly in order to save time: After cycling the battery once, the behaviour is found to be constant to a satisfactory level. One full cycle is applied as described in section 3.2. The Battery voltage is been plotted against SOC as shown in Figure 3-4.

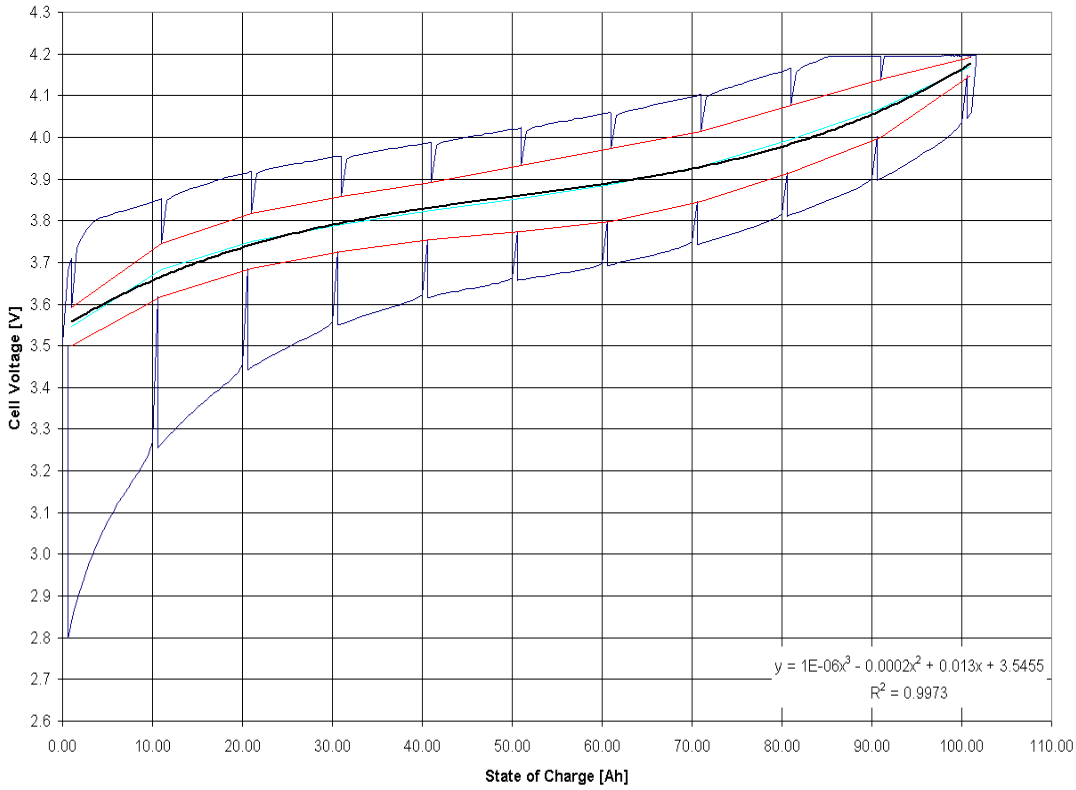

Figure 3-4: Cell Voltage Against SOC during Charging and Discharging with 33 A

The blue graph shows the terminal voltage of the cell. It forms a hysteresis due to the higher voltage during charging and the lower voltage during discharging. Every 10Ah the current was stopped for 1 minute and the voltage approached but did not reach the OCV. All these points lay on the red curves. The OCV must be between these red curves. The turquoise curve is the mathematical mean between these red curves and this is assumed to be the OCV of the tested cell. It is useful to obtain a mathematical model of the OCV. The black curve can be found by using a polynomial regression. It follows the shown equation and approaches the turquoise curve very well with an R-squared value of $R^2 = 0.9973$.

The OCV is a model parameter and this should be constant regardless what current is applied to the battery. The analysis is applied to the 100 A test data in order to validate this method of determining the OCV. Figure 3-5 shows the result.

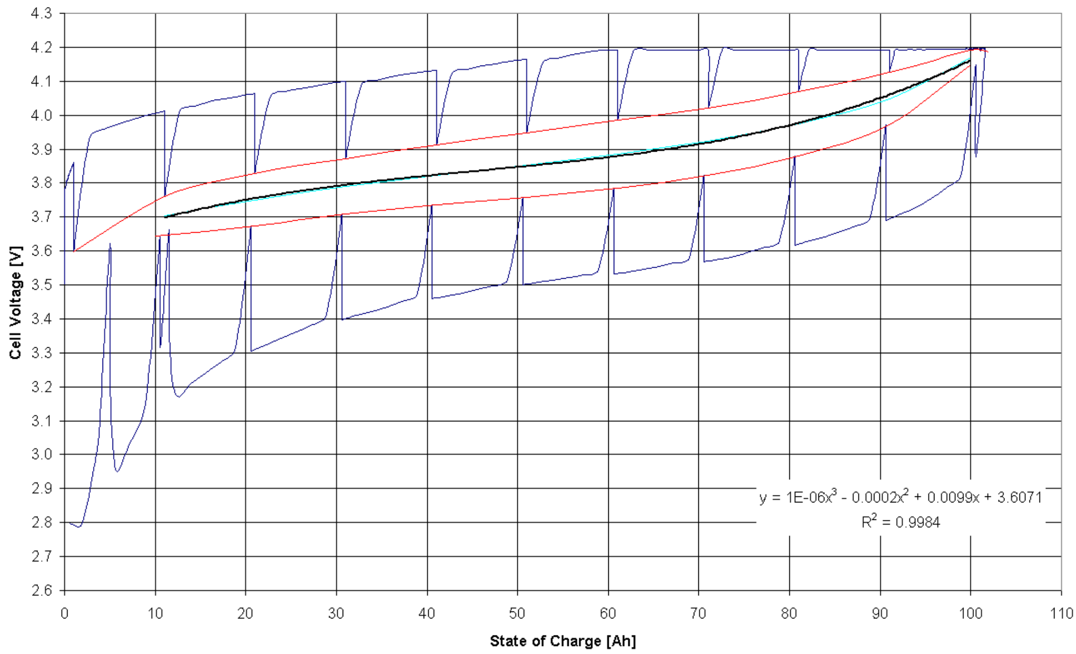

Figure 3-5: Cell Voltage Against SOC during Charging and Discharging with 100 A

Unfortunately the battery tester stepped out twice close to the end of the discharging period, because of too high resistance in the connecting cables. This explains the voltage step at SOC of 5 Ah and the second voltage rise at SOC of 11 Ah. In consequence of this, these values are not taken into account when calculating the OCV curve (black).

Figure 3-6 shows both OCV graphs obtained from the 33 A and the 100 A test in one figure.

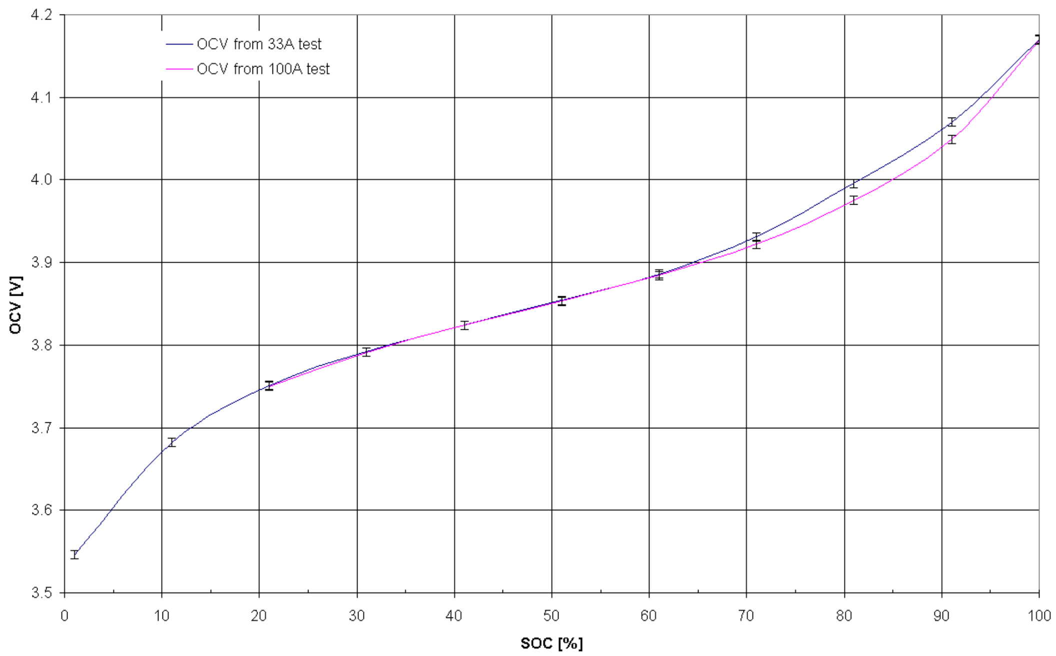

Figure 3-6: Comparison of OCV Test Results

The error bars in Figure 3-6 represent the ± 5mV error in the voltage measurement of the Digatron. The two tests match within the error bars for SOCs between 20% and 60%. They differ slightly for SOCs between 70% and 90%. This can either be explained by the uncertainties of the proposed method for determining the OCV or by temperature dependence of the OCV, because temperature was not constant during tests. The maximum error is ± 10 mV or an equivalent of ± 1.5 % SOC. This is in the range of most battery management systems with 10 bit A/D converter. It can be stated that the proposed method for determining the OCV is valid.

Though temperature differs about 10 K between the 33 A test and the 100 A test, the OCV is almost the same. This suggests that the OCV has no strong dependence on temperature. Further tests, especially at lower temperatures, need to be undertaken in order to confirm this assumption.

3.3.2 Determination of Internal Resistance

The internal resistance helps predicting the behaviour of the cell voltage when applying a charging current or a load to the battery. Determination of the internal resistance requires similar considerations as mentioned in 3.3.1. The internal resistance during charging is different from that during discharging. Additionally the current can not be applied for several hours to ensure steady state of the terminal voltage, because applied current changes the SOC. Current should be applied without interruption in order to minimize errors due to this, but this would require additional cycling of the cell and time is not sufficient for that. The same set of data that have been acquired during the test procedure described in 3.2 (the test was stopped for one minute every 10 Ah) is therefore used. The following equation is used for calculating the internal resistance based on the simple battery model shown in Figure 3-3:

$$R_i = \frac{OCV - V_{Ter\min al}}{I}$$

Equation 3-1: Calculation of the Internal Resistance in the Simple Battery Model

This equation is valid for charging and discharging. OCV is obtained from the method described in subsection 3.3.1. Terminal voltage $V_{Terminal}$ and current I are measured just before switching the current off for one minute, because the terminal voltage has reached steady state at this point most likely. Figure 3-7 shows the results of this analysis for the 33 A test.

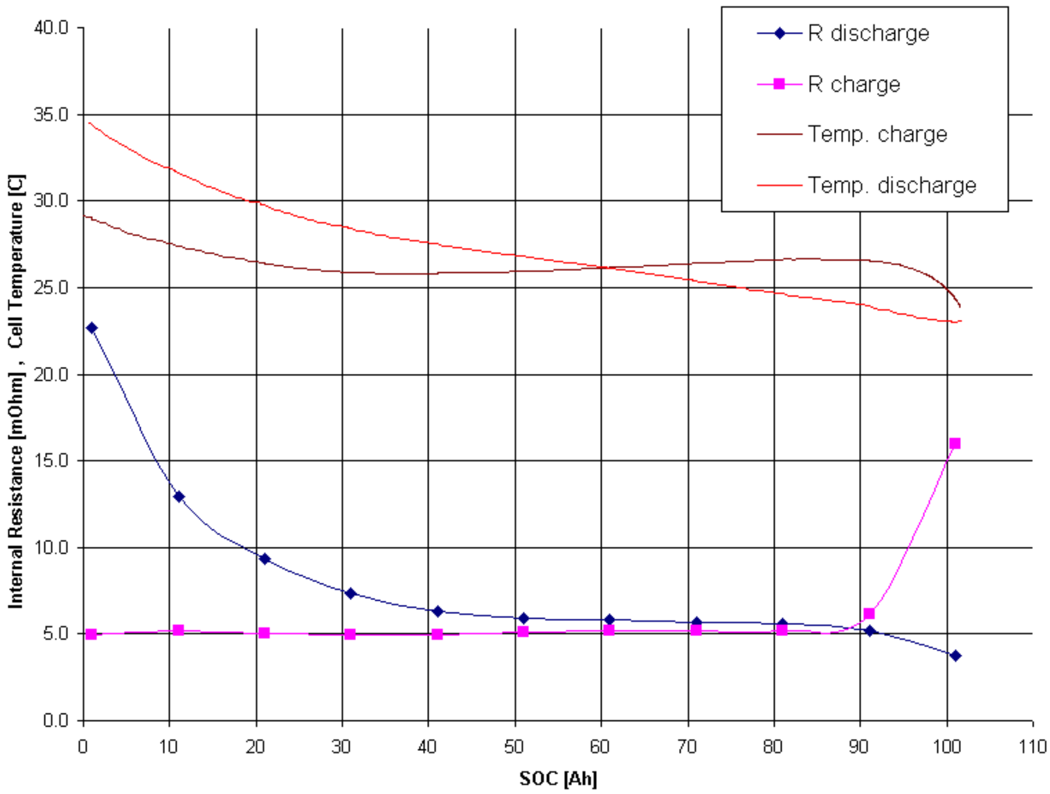

Figure 3-7: Internal Resistance and Temperature of the Battery During Charging and Discharging with 33 A

The 100 A discharge and charge procedure has been accounted for validating the results obtained from the 33 A test.

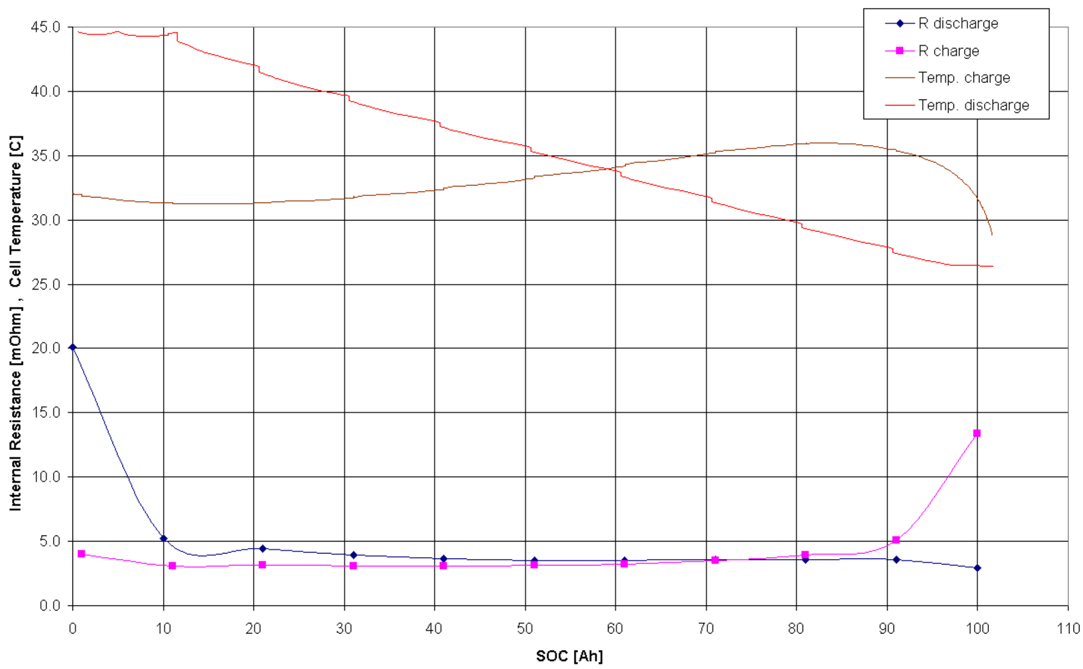

Figure 3-8: Internal Resistance and Temperature of the Battery During Charging and Discharging with 100 A

The temperature is measured between two cells on the outside case as shown in Figure 3-1. This causes delay of temperature measurements, because the plastic case is not conducting temperature very well. The heat is produced inside the cell and it takes significant time till the outside case temperature follows. The red graph in Figure 3-8 shows a step in the rising temperature during the one-minute pauses due to this delay and it is suggested to measure the temperature on one of the terminals instead.

The internal resistance obtained from the proposed test method behaves similar in both cases. The charging resistance is flat and rises till the end of the charging. The discharging resistance rises till the end of discharge. One major difference is that the resistances obtained from the 100 A test as shown in Figure 3-8 are about 20 % smaller than the ones obtained from the 33 A test as shown in Figure 3-7. Another difference is that the internal discharging resistance obtained from the 100 A test behaves flat between 20 % SOC and 90 % SOC, whilst for the 33 A test it starts rising from 50 % SOC on downwards.

It is suggested that these differences are due to different cell temperatures during the tests. Figure 3-7 and Figure 3-8 show the behaviour of the cell temperature: it is higher during the 100 A test. The cell temperature has an effect on the internal resistance of batteries. Usually the internal resistance decreases with higher temperature because chemical processes in the battery are accelerated. Li-Ion battery test data obtained from other manufacturers show similar behaviour, but less remarkable. The internal resistance of the high-energy Li-Ion battery LEV95P from GS increases about 5% at 0 ^{0}C if compared with 45 ^{0}C. The change of resistance in the ThunderSky battery is much higher. It has to be considered that the simple model is not accurate enough to explain the battery behaviour. Another analysis of test data and a more complex model is suggested in subsection 3.3.4.

3.3.3 Characterization of the Battery

Internal resistance and SOC do characterize the battery already, but these parameters are not very suitable for choosing the battery size and the number of cells. Power capability during charging and discharging and voltage swung are more suitable. These figures are derived from OCV and internal resistance. The alternative approach for determining the complex model parameters in subsection 3.3.4 may be more accurate, but has not been used so far, because the model needs to be validated first. This will be part of future work. The simple model is well known and reasonably accurate for choosing battery size and cell numbers.

The power capability of one cell during discharge is vital to know for estimating the required cell size and number in order to obtain certain vehicle drivability. The maximum output power is depending on the SOC. It is calculated based on the internal resistance R_i and the OCV obtained from the 100 A test.

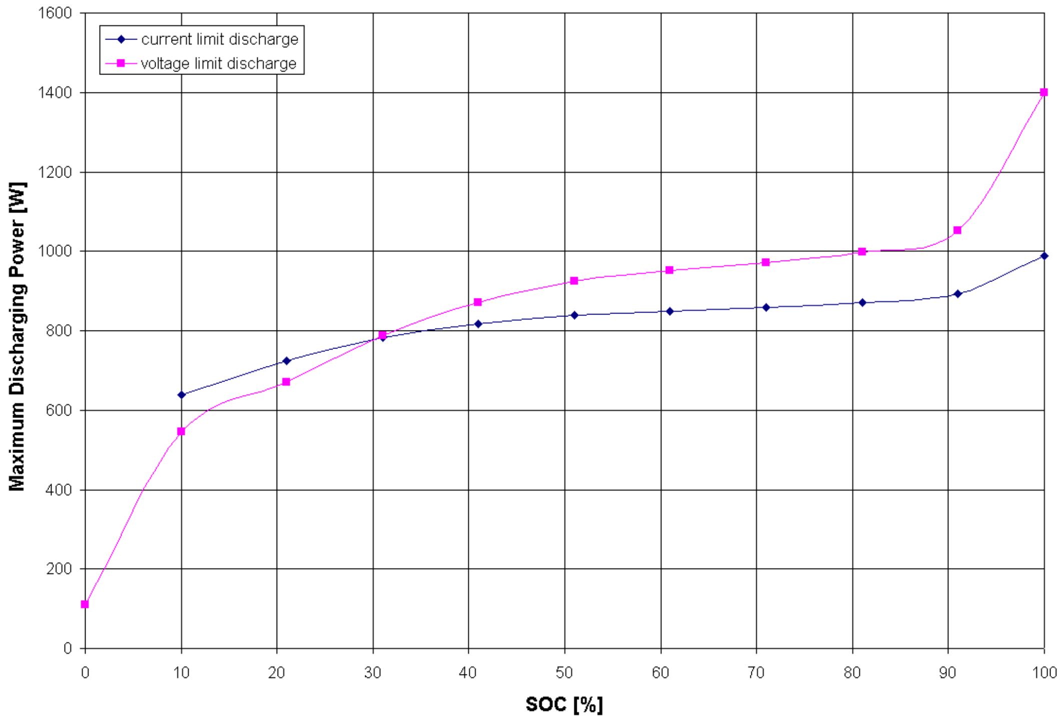

Figure 3-9: Maximum Discharge Power as a Function of SOC

The maximum output power of a battery or a cell is limited by the maximum output current I_{max} and the minimum terminal voltage V_{min}, whichever comes first. The manufacturer of the Li-Ion cell recommends a maximum discharge current I_{max} = 300 A and a minimum cell terminal voltage V_{min} = 2.6 V. The red graph in Figure 3-9 shows the maximum output power due to terminal voltage limitation. It is based on the following equation:

$$P_{\max} = V_{\min} \cdot \frac{OCV(SOC) - V_{\min}}{R_i(SOC)}$$

The blue graph shows the maximum output power due to current limitation. It is based on the following equation:

$$P_{\max} = \left| I_{\max} \right| \cdot (OCV(SOC) - \left| I_{\max} \right| \cdot R_i(SOC))$$

The maximum allowed output power has to stay below both.

The maximum charging power determines the effectiveness of regenerative braking and is essential for designing the generator strategy. It has been obtained in an equivalent way as the maximum discharge power.

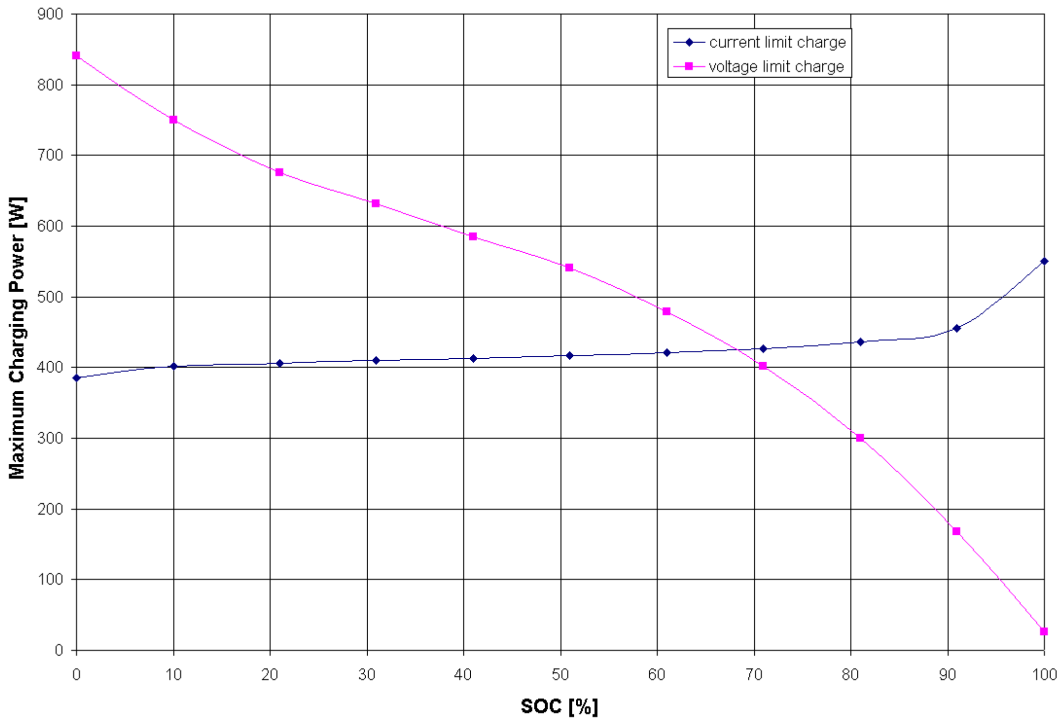

Figure 3-10: Maximum Charging Power as a Function of SOC

Figure 3-10 shows the two graphs representing the current limit of I_{max} = 100 A for charging and the terminal voltage limit of V_{max} = 4.25 V, both recommended by the manufacturer. The red graph, showing the power limitation due to the maximum cell voltage is based on the following equation:

$$P_{\max} = V_{\max} \cdot \frac{V_{\max} - OCV(SOC)}{R_i(SOC)}$$

The blue graph shows the current limitation based on the following equation:

$$P_{\max} = |I_{\max}| \cdot (OCV(SOC) + |I_{\max}| \cdot R_i(SOC))$$

The maximum allowed input power has to stay below both graphs.

The maximum voltage swung between charging and discharging with maximum power is interesting in order to match the number of cells to the motor and motor controller. It essential to know this for choosing the components that operate on battery voltage like the motor controller or DC/DC converters.

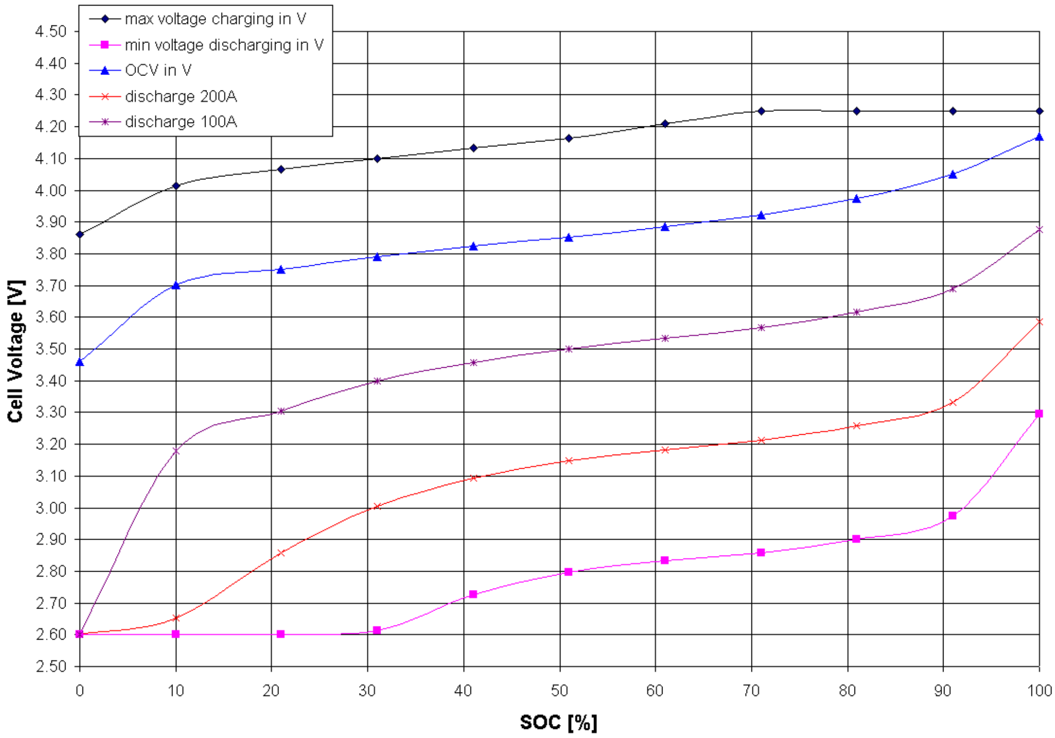

Figure 3-11: Maximum Voltage Swung of One Cell

Figure 3-11 shows the maximum voltage swung of the 100 Ah Li-Ion cells from ThunderSky. Maximum voltage, minimum voltage and OCV have been plotted as functions of the SOC. The values are calculated based on the internal resistance and OCV obtained from the 100 A test. The minimum voltage is the basis for choosing the number of cells in series connection in order to provide sufficient voltage to the controller and motor under full power. The total voltage swung can be obtained by multiplying the cell voltage swung with the number of cells in series connection. The maximum voltage is essential for designing the electronics that operate on battery voltage.

3.3.4 Improved Battery Model Based on the Dynamic Behaviour

The previous subsections were based on the simple model shown in Figure 3-3. This simple model assumes static operation of the battery. It is sufficient for range prediction, power calculations and specification of DC voltage range. The electric vehicle is not a static charge or discharge application. The dynamic behaviour needs to be studied in order to determine battery management speed requirements, calculate SOC without using Ah-counting and test model parameters without waiting for static terminal voltage behaviour. Additionally the more comprehensive model helps understanding the battery behaviour and helps linking it to its chemistry models.

The battery test described in 3.2 proposes a pause during the charging and the discharging every 10 Ah for one minute. Measurements are taken every second during this pause. These measurements allow the study of the dynamic behaviour of the battery. Figure 3-12 shows the rise in cell voltage during the pause form discharging with 100 A at a SOC of 71%.

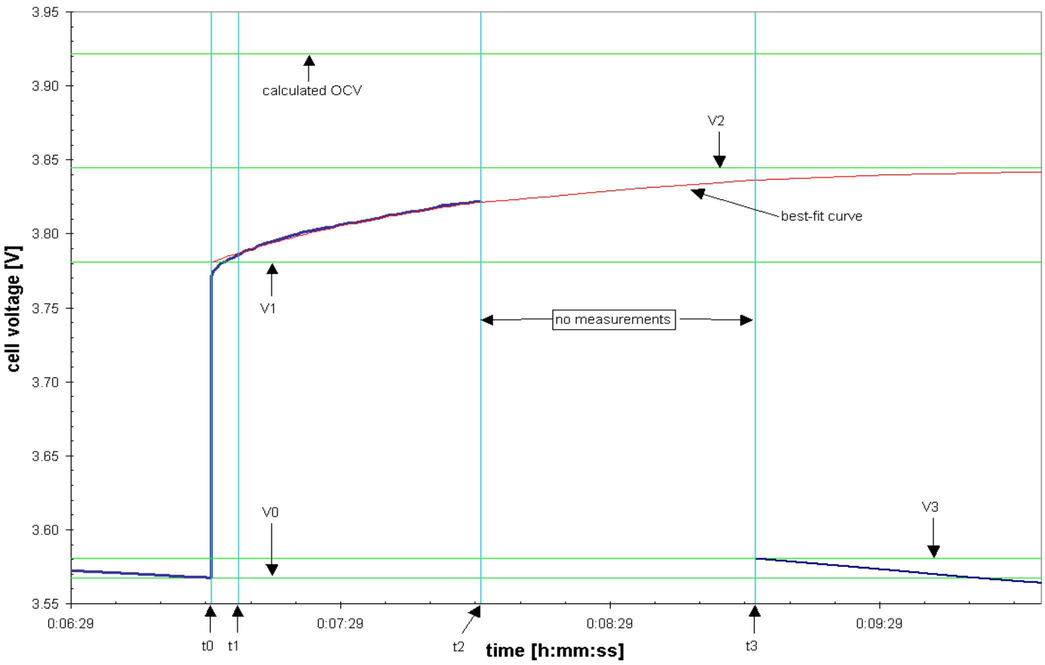

Figure 3-12: Behaviour of the Cell Voltage when the 100A Discharging Current is Paused at 71% SOC

From the left to the right, the cell voltage (blue curve) decreases with decreasing SOC during discharge before t_0. At t_0, the current is switched off and the cell voltage "jumps" up from the voltage V_0 to the level close to V_1. The battery tester takes measurements of the rising voltage between t0 and t2 with a sampling time of $^1/_s$. The shape of this voltage rise is approximated with an exponential best-fit curve shown in red. Five seconds between t_0 and t_1 are not taken into account, because of a much shorter time-constant in this region. The red best-fit curve seems to approach the level V_2 within a few minutes. The discharging current is re-applied somewhere between t_2 and t_3 where no measurements are taken. The exact behaviour of the test-equipment and the battery during this time is unknown and the dynamic response of the battery when reapplying the current cannot be studied. The cell-voltage reaches level V_3 at t_3. This level is higher than the voltage V_0 at t_0 before the pause. The cell voltage continues decreasing with decreasing SOC after t_3.

The simple model in Figure 3-3 cannot explain this behaviour at all. According to the simple model, the voltage should jump from V_0 to OCV immediately after stopping the current. Figure 3-13 shows the proposal for an improved equivalent circuit model that takes the dynamic behaviour into account.

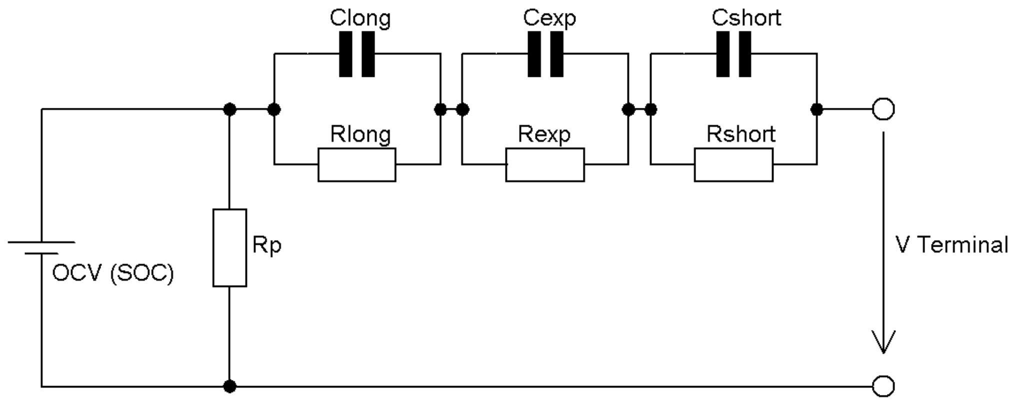

Figure 3-13: Improved Equivalent Circuit Model

The resistance R_{short} models the voltage jump from V_0 to V_1. The capacitor C_{short} in parallel to it models the behaviour between t_0 and t_1, where the voltage rise has a shorter response time than it could be approached with the exponential curve fit. The RC-network with Rexp and Cexp models the exponential rise of cell voltage that is approximated by the red curve in Figure 3-12. Though voltage seems to approach level V_2 in Figure 3-12, the voltage in fact reaches OCV if waited for long enough. This behaviour is modeled with R_{long} and C_{long}. The time constant $R_{short} \cdot C_{short}$ is in the order of seconds or less, the time constant $R_{exp} \cdot C_{exp}$ is in the order of minutes and the time constant of $R_{long} \cdot C_{long}$ is in the order of hours. A similar model has been suggested for lead-acid batteries [21].

3.3.5 Experimental Determination of Model Parameters

The test procedure and set of data for determining the model parameters of the improved equivalent circuit model is described earlier. These measurement data are now analysed in the following way:

The exponential rise curve of the battery voltage after stopping the current is extracted and MS Excel is used to find the best exponential curve fit between t1 and t2 for several SOC and charging as well as discharging. The voltage V_2 is chosen in a way that this curve fit reveals the best possible correlation with the test data. Correlations between $0.9902 \le R^2 \le 0.9996$ are achieved. A constant time t1 - t0 = 5 s was chosen for all SOC and charging as well as discharging in order to assure complete discharge of C_{short}.

Averaging V2-charge and V2-discharge recalculates the OCV, because this value is closer to the SOC than the values used in 3.3.1 for SOC determination. The values obtained from the first method are compared with the values obtained from this method. Both methods reveal similar results within the measurement accuracy as shown in Figure 3-14.

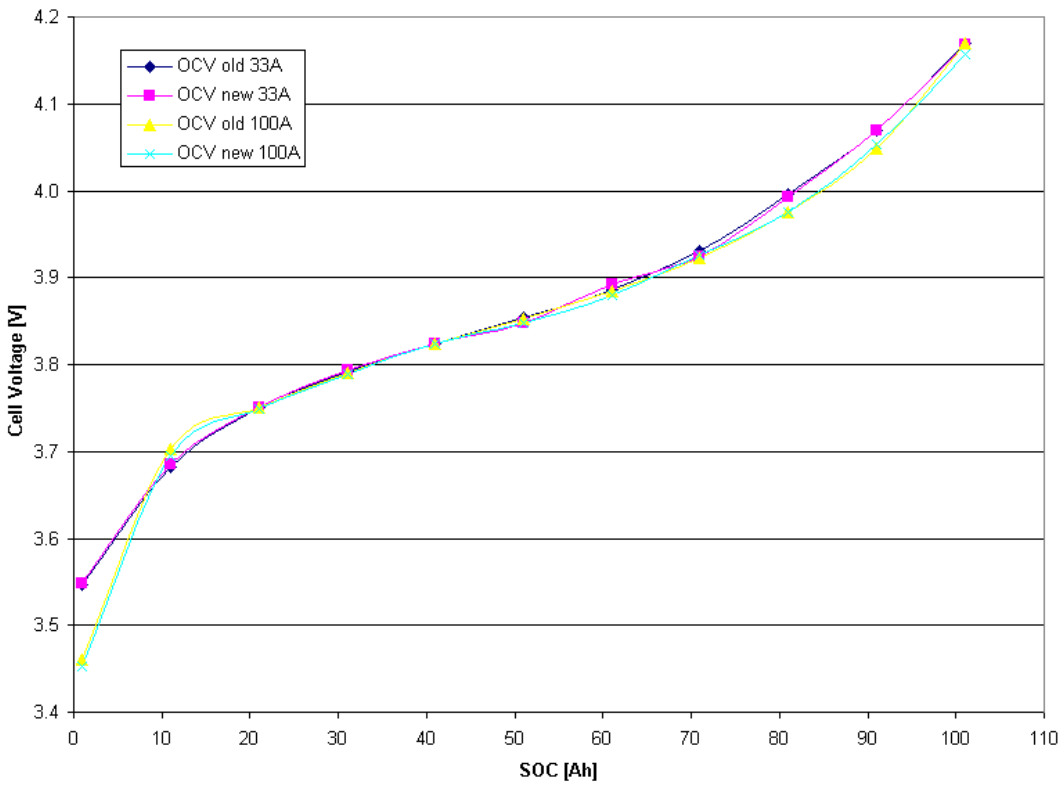

Figure 3-14: Comparison of OCV Obtained from Different Methods of Determination

Figure 3-15 shows the OCV and the slow voltage drops during charging and discharging at different currents. The voltage rise or drop between SOC and V_2 is independent on the discharge current. It also remains almost a constant value of 68 mV between 11% SOC and 91% SOC.

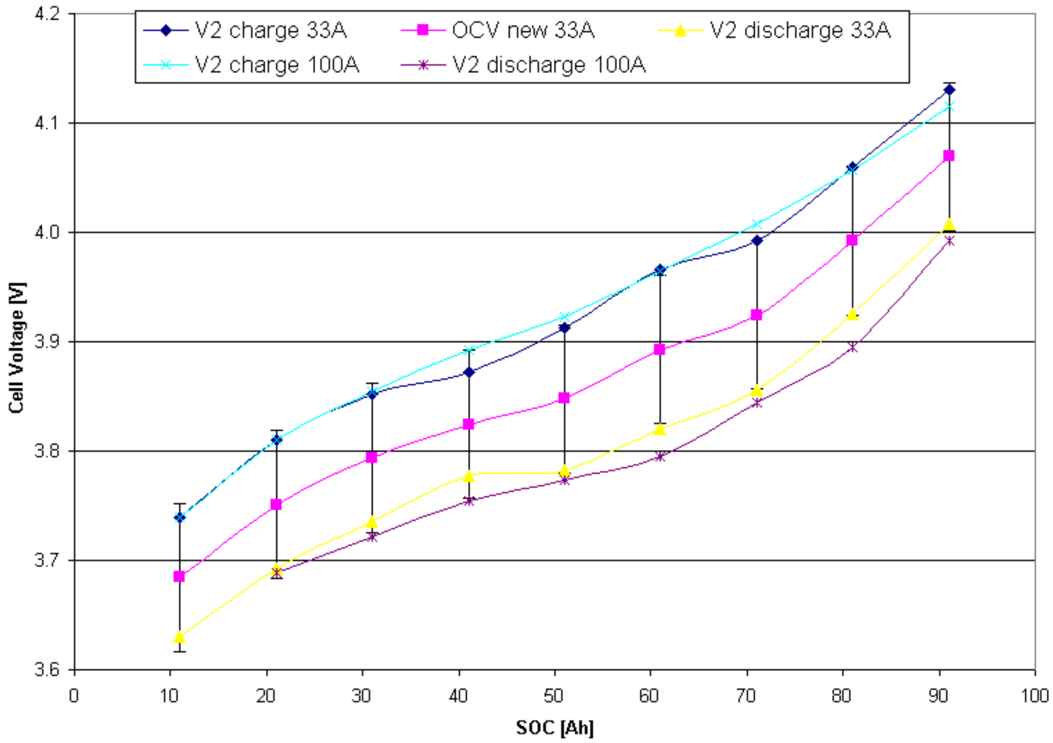

Figure 3-15: Constant Voltage Rise or Drop with Long Time-Constant

This constant voltage drop is in contrast to the improved model in Figure 3-13. The resistor R_{long} employed by the improved battery model would result in a voltage drop that is proportional to the current. A Zener-diode with V_{zener} = 68 mV models the actual behaviour much better than the resistor R_{long}. The proposed equivalent circuit model is shown in Figure 3-16. The proposed Zener-voltage has a variance of 0.14 mV among the test data between SOC 21% and SOC 91%. The R-C network in parallel to the Zener-diode is required in order to model the slow discharge. The model is valid for discharging only. The Zener-diode needs to be turned around for charging.

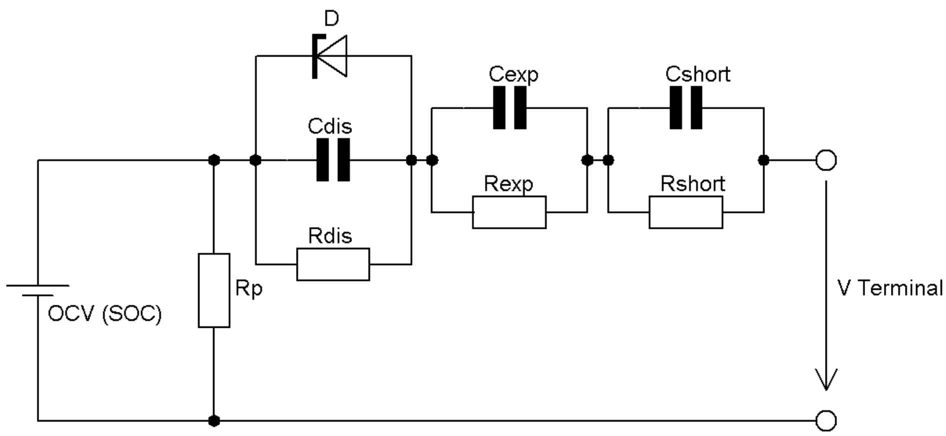

Figure 3-16: Proposed Equivalent Circuit Model

The other voltage drops V_2-V_1 and V_1-V_0 are proportional to the current. This suggests calculating the resistance. Figure 3-17 shows the resistances for the modified battery model. The thin lines are obtained from the 100 A test whereas the thick lines in the same color are obtained from the equivalent 33A test. Both of these lines should be more or less coincident.

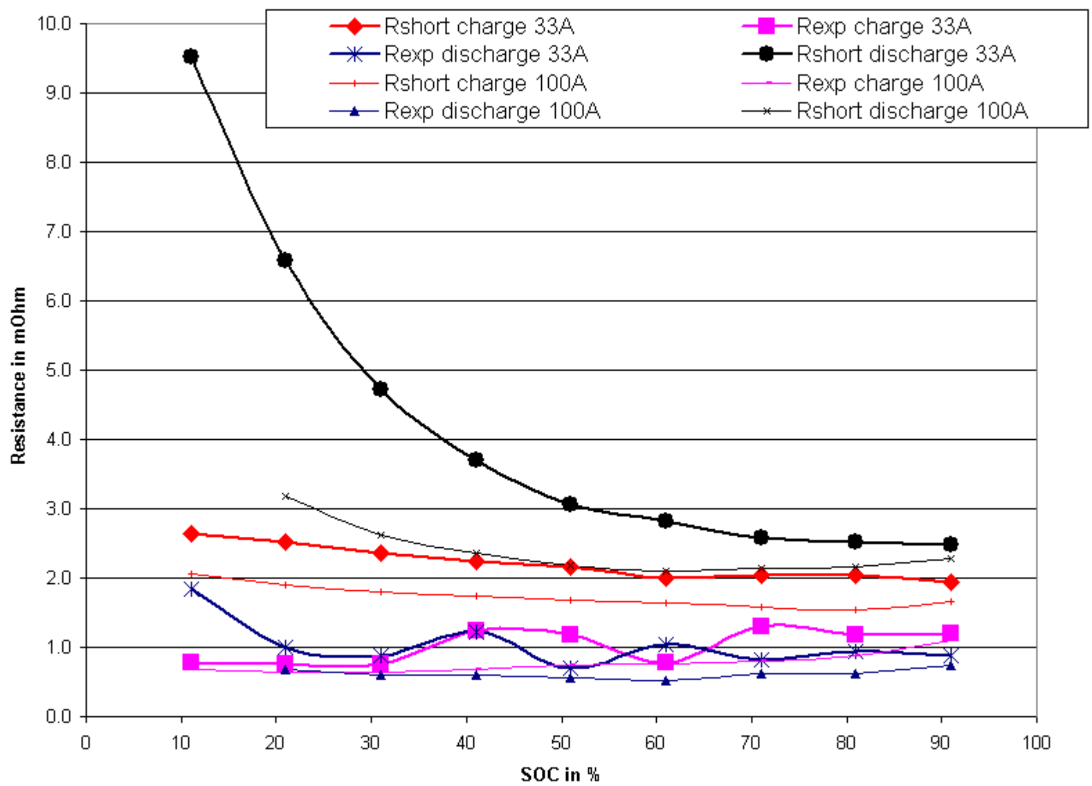

Figure 3-17: Resistances of the Modified Battery Model

Reasonable coincidence can be found for the medium fast RC-combination with R_{exp}. These values show no significant difference or trend between charging, discharging, high current, low current and even SOC though the temperature was not constant during the tests. They can be modeled with a fix resistor that is independent on SOC, temperature, current and direction of current-flow.

The calculated mean value is R_{exp} = 0.869 mΩ with a variance of 0.077 mΩ.

Unlike R_{exp} the R_{short} resistance is not coincident between the test with 33 A and 100 A. Further tests and analysis are required in order to determine whether this is a result of different temperature during tests. More testing is required as well for:

- Studying the dynamic behaviour not only after stopping the current but also after applying the current. This is essential for validating or enhancing the model.
- Studying the temperature dependency of parameters in order to make the model useful in all environmental circumstances.
- Studying the behaviour of parameters over the lifetime of the battery in dependency of cycles, age and usage. This is the basis for end of life prediction.
- Linking the equivalent circuit battery model to the chemistry models in order to predict battery performance before mass-producing the battery. This helps optimizing the chemistry for a given application.
- Statistically sound parameter value determination including variation between cells.
- Determination of self-discharge rates and their variance in order to specify cell-equalization requirements.

4. Proposal for a Hybrid Electric Vehicle Drivetrain

All hybrid electric vehicles (HEV) comprise at least two different power converters – an electric motor and a fuel converter. Apart from this fact, which is the only common thing about all HEVs, there are innumerable options. Size, type and configuration of energy source, energy storage, power distribution and power conversion can be varied. This high number of degrees of freedom makes it difficult to find "the right choice". Additionally this choice determines the path for future developments and could lead either to technological leadership in the market or into a dead-end.

This chapter deals with finding and investigating a drive train based on the considerations in the review chapter 2. The first section in this chapter summarizes and categorizes different HEV drive train options. The second section describes the variables with their main dependencies and proposes a drivetrain configuration. The third section specifies an "optimal vehicle" based on what has been stated in the second section. Section four deals with the simulation of the drivetrain that is proposed in section three. Section five describes the configuration of the test-vehicle based on off-the-shelve products and the last section summarizes this chapter.

4.1 HEV Drivetrains

This section gives a brief introduction into different HEV drive train configurations and their advantages and disadvantages. Two dimensions are established to briefly describe the drive train configuration of a HEV: [24]

- The grade of hybridization
- The type of hybridization

The **grade of hybridization** is measured in two different ways:

1. The ratio of implemented electric propulsion power to the power of the secondary energy converter.
2. The stored electrical energy.

It would make no sense to focus on the ratio between the stored electrical energy and the energy stored in the fuel, because the stored electrical energy will always be a small fraction of it. It is suggested to calculate the theoretical pure electric range of the vehicle instead. The higher the grade of hybridization, the higher is the advantage in terms of fuel economy, noise and pollution. The disadvantages are higher purchase cost and higher vehicle mass due to a larger battery and/or more powerful electric motors.

Two main **types of hybridization** exist:
The **series hybrid electric vehicle (SHEV)** uses the electric motor to propel the car. The fuel converter (an internal combustion engine - ICE - for example) is used to generate electricity. In the **parallel hybrid electric vehicle (PHEV)** both - the engine and the electric motor - can independently propel the vehicle or assist each other. The

SHEV and the PHEV can be combined in different ways - called mixed types. The power split HEV and the combined HEV are well known implementations of this mixed type. A planetary gear splits the engine power to a generator or to the wheels with variable share in the power split drive system. Electric motor and engine are coupled with a clutch, so that the car can be propelled purely electric. The combined HEV uses a clutch to connect or disconnect the engine to the gearbox. The engine is permanently connected to a generator and the electric motor is permanently connected to the gearbox. This arrangement allows operating either in parallel HEV mode or series HEV mode.

The advantages and disadvantages of the different types depend on the application, the grade of hybridization and the implemented energy management. It is difficult to judge them, but the following list gives a brief idea.

Advantages of the SHEV: [25]

- Less mechanical couplings. Simple packaging and modularization.
- Engine operation can be smoothened or run in its optimum point.
- Engine noise and vibrations can be minimized.
- Engine size can be minimized just to satisfy the average power requirements.
- Fuel cells can replace the engine-generator module.

Advantages of the PHEV: [25]

- The engine can directly propel the car. No long power-conversion chain is required.
- The propulsion motor can be small and less expensive. A separate high-power generator is not required.

The planetary gear drive combines some of the advantages of the SHEV and the PHEV. The main advantages of the planetary gear drive system are:

- The engine does not need to follow the vehicle speed (very smooth operation).
- The engine can directly propel the car. No long power-conversion chain is required.
- Fully automatic drive train, no change of gears.

The **power split drive train** with planetary gears is a very clever but highly complex system; it is implemented in the Toyota Prius [13].

The **combined HEV** combines some advantages of the parallel and the series HEV. Compared with the series HEV the advantages are:

- A smaller electric propulsion motor than in the series HEV can be implemented.
- The generator can be chosen smaller.
- The efficiency on long-distance and motorway driving is increased

But the cost advantages of the smaller electric motors in the combined HEV will be offset by the requirement of an automated clutch and a more complex management. Noise isolation becomes less effective and the place for the engine is predetermined. Fuel cells cannot easily replace the engine-generator.

The SHEV disadvantages increase with the average power requirement getting closer to the maximum power need. Cars that are made for fast motorway driving or heavy vans and trucks that travel on their maximum speed for a long time require the full power capability for all three components: motor, generator and engine. This is expensive and not very efficient. The SHEV type is very suitable for city and neighborhood cars and busses: Fuel consumption, exhaust-emissions and noise are very low.

The PHEV type is very suitable for long-range vehicles. Peak power is provided by the assistance of an electric motor and the engine can be chosen smaller than in a conventional drivetrain. A smaller engine operates in more efficient regions. The motor can regenerate braking energy that is stored in the battery for the next acceleration to smoothen down the engine operation. This PHEV will have reduced emissions and slightly smaller fuel consumption.
The main problem for all HEV is maximum vehicle speed, because the drive train must be able to maintain this speed for a long time on motorways. The maximum speed generally defines the maximum power needs (rated, not peak power). The battery cannot provide this over a long range, thus the engine needs to provide the necessary power. The bigger the engine is the worse the HEV achievements are. There is no known solution yet that achieves all desires like high speed, good acceleration, low fuel consumption, low pollution, low noise and affordable cost!

Though all combinations of hybridization grade and HEV types are conceivable. Very common combinations are: [24]
The **power assist HEV** is a PHEV that uses its ICE mainly. The ICE is smaller than in a comparable conventional car (except for high speeds) and the electric motor provides assisting power for acceleration and short hills. The engine runs in a more efficient region, the operation is smoothened for less pollution and noise and some vehicles can be propelled purely electric over very short distances and at low speeds like in traffic jams. The power assist HEV has a comparatively low grade of hybridization. It requires a high power battery rather than a high energy one. If the motor replaces the starter and the generator, this concept is called a **starter-alternator** HEV. Industry is going to introduce a higher car voltage system with 42 V instead of 14 V in order to electrify and add several components for higher comfort, higher safety, lower fuel-consumption and lower emissions. The 42 V system is capable of powering the starter alternator as well, this would help to reduce the complexity and cost of a second voltage system within HEVs. This concept is called **Mild HEV**. The power assist type HEV is a good solution for long-range motorway vehicles. The **Range Extender HEV** has its origins in pure EVs with all their advantages. An auxiliary power unit (APU) is used to extend the range. The APU produces the average power, needed to propel the vehicle – or less. If the range is comparable to a conventional ICE car and the refueling as fast as well, the range can be called unlimited. This concept is usually a SHEV type and is a good solution for small and light vehicles that are intended for shorter trips mainly. It offers advantages over the PHEVs in all applications with low maximum speeds and urban traffic conditions like for city buses and taxis.

Another parameter that defines HEV is whether it is plugged into the mains for recharging. If so, they are called **Plug-in HEV.** Plug-in HEVs achieve potentially better fuel-economy and less pollution than HEV that are not recharged from the mains electricity supply. Though this is actually dependant on the mixture of electricity power generation it should be clear that the energy of the future would always come across electricity – like for example the sustainable generation of hydrogen for fuel-cell vehicles. See section 2.1.1 for more information.

Renault is testing their Kangoo with range extender drivetrain, Toyota is implementing its power-split hybrid with planetary gear drive into different chassis (Prius was the first) and Fiat introduced a combined hybrid Multipla Ibrida. But apart from those, most manufacturers shifted their focus to the power assist or mild HEV after some unsuccessful attempts like the Audi Duo – a parallel hybrid with a massive lead-acid battery. The new approach of introducing HEVs is through a mild HEV in the high-performance market. Some very fast cars for example use engines that are powerful enough to propel the car at 300 km/h, but the car is electronically limited to 250 km/h for safety reasons. The oversized engine is required to enable very good acceleration up to 250 km/h and smooth driving. Industry is working on starter-alternator versions of these high-performance cars in order to reduce ICE size for better fuel-economy and fewer emissions. They claim to introduce this new technology in expensive cars first and then make it available in standard cars once it is established in mass production. This is the usual way of introducing new technology to the mass markets, but in this case there are three general obstacles:

1. **No market:** Small cars in mass markets do not require high performance and speeds up to 250 km/h and they are usually not used for long-distance driving as well. These small cars are needed for short journeys and the daily way to work or for shopping – traffic jams and red traffic lights are more likely than driving with 250 km/h on motorways. The advantages of the power-assist HEV become extremely small in this application and do not justify higher purchase price.
2. **Small advantages:** The main disadvantages of cars with conventional drive train like local pollution in cities, noise and fuel consumption originate from the mass-market cars driving in urban areas and not from a few high-performance cars driving on motorways. Once the power assist is introduced to the small cars, the advantages are very small in urban traffic.
3. **Long time before market introduction:** The introduction of the mild HEV type in high-performance cars may be quite soon, but another couple of years are required for the introduction in the cheap car markets and it will take additional 9 years before appearance on roads is dominated by mild HEVs. Unfortunately 15 to 20 years are far too much in relation to the small advantages of mild HEVs.

Finding the "optimal" configuration is highly dependant on the circumstances that are taken into account. Considering the circumstances mentioned in the review chapter and based on the technological pros and cons mentioned in this section the following statements can be made:

The focus should not be put on the high-performance vehicles but on the small cars of the mass market instead, because their impacts to the environment are higher. Thinking more globally, it should be mentioned, that long-distances could be traveled conveniently in a much more efficient and effective way than in cars. Trains offer much higher energy-economy and – if organized properly – traveling can be more comfortable and can be planed better. Urban and short-distance driving on the other hand will be dominated by individual traffic except from high agglomeration areas where effective public transport can be implemented. Other solutions are likely to decrease quality of life. The series HEV promises more advantages for the mass market of small and cheap cars than the parallel HEV. Its introduction can be fairly soon, because the drive train is not very complex and most components like electric motors and combustion engines are well studied. Main issues are the purchase cost and the reliability of the battery. Thinking more ahead reveals that the series hybrid electric vehicle is a step towards the introduction of fuel cells, because the engine-generator can simply be replaced by a fuel cell, which is not the case for PHEVs. Though there are some investigations for implementing the fuel cell without a battery, the first introduction of fuel cells for propulsion in cars will very likely be in cooperation with a battery. The battery stores regenerated energy during braking and provides peak power – just like in a series HEV. In other words, the first fuel-cell vehicles will be series HEVs.

4.2 Design Template for the proposed Drivetrain

Based on the discussion in the previous section 4.1, the proposed drivetrain investigated in this and the following sections is a series HEV with plug-in facility targeted at low cost mass-market vehicles. The fuel converter provides sufficient power to propel the car over distances similar to those of conventional cars. The battery is chosen as small as possible in order to minimise weight and cost. The battery has sufficient energy and power to propel the car purely electric for 90% of all undertaken journeys by cars in this market (50 miles in urban traffic conditions) [26]. The engine runs as rarely as possible – only if additional power or more range is required. A management system determines when to stop or start the engine automatically trying to minimise the impacts. The engine is not connected to the gearbox like in combined HEVs in order to minimise complexity, enable efficient noise and vibration insulation and open the way for alternative fuel-converters like Stirling-engines or fuel cells.
This section deals with defining general drive train characteristics in such a way that the main disadvantages of the proposed HEV type are minimised without sacrificing the advantages.

The main issues of this type of HEVs are:

- A high number of components are required (engine, generator, electric propulsion motor, big battery and charger). This can lead to high cost and high vehicle mass. High vehicle mass increases tyre noise and energy consumption. Higher energy consumption either decreases pure electric range or requires an even bigger battery.
- There are many power-converters in a series chain like engine - generator - power control unit - battery - motor control unit - electric propulsion motor - gears. This reduces overall drive train efficiency and can lead to poor fuel economy – even worse than in a conventional car.

The conclusion is that main potential problems are **high purchase cost**, **high vehicle mass** and **poor efficiency**.

The optimisation process requires a definition of cost-functions. But there are many parameters that need to be taken into account and many variables that can be adjusted. Most of them depend on uncertain development of circumstances in the future or non-countable “values” like for example customer expectations. A closer look at the main problems helps simplifying the optimisation process:

The poor efficiency problem is a result of the long energy-conversion chain. The battery should be chosen big enough to satisfy the energy and power requirements for most of the journeys. The engine – generator – power control unit is rarely used. The efficiency of these components becomes a small issue and they can be optimised for low weight and low cost. The effective energy conversion chain is that of a pure electric vehicle and that is the most efficient way of vehicle propulsion. Regenerative braking helps to maximise the overall efficiency. Some components lay within the conversion chain twice: once during acceleration and propulsion and once during regenerative braking. These components are: battery, motor control unit and electric propulsion motor. They should be very energy efficient in order to maximise the pure electric range for a given battery size. This helps to keep the battery as small as possible. The battery is the most crucial component of the drive train. It adds major cost and mass to the vehicle. The choice and management of the battery are therefore the main focus of this work.

The drive train configuration is chosen already and this reduces the variables to a manageable number. The following discussion mentions all variables, starting with the most crucial components. Main relationships are determined and most influencing variables are highlighted.

Battery: Chemistry, Energy content, power capability, voltage / cell number, type of temperature control and battery-technology can be chosen. Li-Ion is the proposed battery chemistry. The Li-Ion technology promises the best potential in terms of size, weight and energy efficiency. The cycle life is very good and there is some potential for low-cost in mass-production and the calendar life is improving. In order to provide sufficient pure-electric range, the high-energy type is chosen rather than the high-power type. The number of cells in series defines the battery voltage. A high number of Li-Ion cells require an expensive battery management system for monitoring voltage and temperature of all of them. Low battery voltage means high currents for same power and high currents increase cost and weight for cables, connectors and power electronics – a common limit for commercially available components is around 300A continuous. The battery voltage must match the motor voltage and the availability of products has to be taken into account. The type of temperature control can be natural cooling with lowest complexity and weight, forced air cooling/heating or water cooling/heating with highest effectiveness but also weight and complexity. The decision about cooling/heating is made later after testing the battery and investigations of in-vehicle behaviour. The energy content and the power capability of the battery are not independent – the higher the energy content is, the higher the power capability is and battery size, cost and mass increase. **The energy content/power capability is the most influential variable.**

Electric propulsion motor: Type, continuous power, maximum power/torque, torque/speed characteristic, current/voltage characteristic and type of cooling are the variables. The type of motor should be as efficient as possible, small and lightweight for a given power. Permanent magnet motors generally require variable gear ratios unless field weakening is used which would require inset magnet rotor design. Induction motors do not require variable gear ratios but they provide worse power to weight ratios. Other types like switched reluctance motors are investigated for keeping the cost down. Higher torque is preferable against higher speed, because high motor speed requires a two-stage reduction gearbox, thus increasing noise and cost. High torque motors with high efficiency on the other hand increase motor cost, size and weight. The torque/speed characteristics are preferably similar to a constant power curve. This combines good hill-climbing ability with high speeds downhill and matches the expectations of drivers. The current/voltage characteristics must match the battery voltage and current capability. Aspects about the type of cooling are similar to the ones mentioned in the previous paragraph. Electric motors provide over-torque capability, which means the maximum power is several times higher than the continuous power. Higher torque can be applied for a certain time until the motor reaches a high temperature. This time is usually sufficient for acceleration and short hills. Continuous motor power and maximum power are not independent – motors with high continuous power will provide higher maximum power. The maximum power/torque is a function of the time the torque is applied. The cooling system and the thermal behaviour influence the power ratings. **The choice of motor type for efficiency, size, weight and cost and the choice of continuous power rating for maximum speed are the most influencing variables.**

Motor controller unit (power-electronics): The motor controller adds substantial cost to the system. It is optimised for the chosen motor in terms of continuous output current and maximum output voltage. The main influencing variable is the maximum peak output current, because this defines the cost of the power electronics for a given maximum voltage. The overload capability of the motor usually exceeds the short time rating of the power electronic. The maximum output current needs to be defined in order to provide sufficient torque for acceleration and hill climbing, but lowest possible cost. The design and type of cooling are vital issues, because they define the power de-rating over time behaviour and this should match the motor de-rating characteristic. The efficiency should be good. **The peak output current is the main influencing variable.**

Gearbox: Gear ratios and type of gears are the variables. Choice of number and value of gear ratios is essential for optimising driveability, gradeability and maximum speed. Ratios must match the motor, the mass of the vehicle and the desired vehicle speed. Manual transmission is an option but not desirable because of the different behaviour of the HEV drive train when compared to a conventional vehicle – drivers would need to be retrained. Automatic transmission is not a good option because of poor efficiency. An automated manual transmission is a conventional gearbox with a clutch. It is operated automatically using a control circuit and actuators for the gears and the clutch. It provides better efficiency than the automatic gearbox but less smooth driving. It is more complex than the manual gearbox. A continuous variable transmission (CVT) has the highest potential: good efficiency, low noise, smooth driving, low weight and low complexity/cost. A gear with one fixed gear ratio only matches to induction motors or permanent magnet motors with field weakening.

These combinations are in competition with permanent magnet motors combined with a CVT. A clutch is not required at all if the electric motor has low inertia or if it is electronically synchronized. **Gear ratios or maximum/minimum gear ratio for CVTs are the main influencing variables.**

Engine or fuel-converter: Type, power and type of cooling are the variables. Different types of fuel-converter can be implemented: four-stroke, two-stroke, steam turbine, Stirling-motor or fuel-cell running on gasoline, gas, diesel, hydrogen or other renewable fuels. All concepts need to be reviewed – even the two-stroke – because the engine can be operated and optimised for a single operation point, but this is not part of this study. The engine rarely runs and the choice of other HEV system components is almost independent on the choice of fuel-converter type. The type of cooling is an issue: air-cooled engines can be isolated against noise and vibrations very effectively, but the system size increases. The isolation of water-cooled engines requires less space, but is slightly less effective due to water hoses that need to be connected to the radiator. Water-cooled engines can be easier preheated for lower emissions during the first minutes after starting and motor temperature can be controlled. Water-cooling is likely to be chosen for small vehicles, because space is an issue. Continuous power for operation needs to be determined to satisfy the average power requirement of the vehicle. The point of operation needs to be defined, because the point of maximum power is usually not the point with maximum efficiency or acceptable life expectancy. **The main influencing variable is the engine power in a chosen operating point or region.**

Generator: Type, power, rpm/torque, voltage/current and type of cooling are the variables. The engine and the battery requirements already determine some variables like power and voltage/current. The type of cooling is not an issue, because this motor will not enter overload operation and will always operate at speeds with sufficient natural cooling if forced cooling is not required by the type of motor anyway. The rpm/torque characteristic can be chosen within certain limits. Higher rpm instead of higher torque is preferable, because this is likely to decrease the generator size and weight. The ratio between engine speed and generator speed should not exceed certain values, because it cannot be dealt with using a single stage transmission. **The engine is not supposed to run very often and thus, the type of generator should be chosen to be cheap, small and lightweight rather than for very high efficiency.**

Table 4-1 summarises the main adjustable variables:

Component	Variable	Dependencies	Remarks
Battery	Energy content and power capability	Cost, driveability, weight	Sufficient power and energy for urban driving
Electric motor	Type	Cost, size, weight	Not part of this study
Electric motor	Continuous power	Maximum vehicle speed and air drag	
Power electronics	Maximum output power or current	Driveability, size, cost and weight	
Power electronics	Design and type of cooling	Size, mass and power de-rating	De-rating should match motor de-rating
Gearbox	Type	Cost, size, weight, driveability	What motor type?
Gearbox	Gear ratios or CVT characteristics	Vehicle mass, continuous and maximum motor torque, maximum speed	
Fuel converter	Continuous power	Maximum vehicle speed and air drag	Operational region

Table 4-1: Main Variables and Dependencies for Drivetrain Components

This table shows the main variables and - in addition to what has been discussed so far – the main dependencies that are effected by these variables or do effect the variables depending on were the optimisation process starts. The vehicle mass is the main factor that determines the energy content of the battery, because the desired pure electric range has been defined previously (about 50 miles in urban traffic). Other properties like rolling-resistance, air drag and efficiency of the drive train play a role as well but are not subject of optimisation. In addition to the energy requirement the battery needs to provide sufficient power in urban traffic in order to prevent starting the engine. Most dependencies are – unfortunately – not straightforward. The vehicle mass for example determines the required energy content of the battery. This energy content defines the battery mass, which again influences the vehicle mass. Mathematical equations for solving this problem do not exist and are extremely difficult to obtain especially for all factors about prizes. The following process has been employed in order to cope with these circumstances:

All parameters are estimated in a first approach, based on simple dependencies and calculations. A simulation tests these estimations in a second step. Tuning would be necessary in a third step in case of insufficient results.

4.3 First Approach to an "Optimal" Configuration

This section describes the process of determining the parameters of the proposed drivetrain based on the discussion in section 4.2. The vehicle mass plays a major role. Though lighter cars could be developed it has been decided to base calculations on a small conventional car that is actually available on the mass market in order to assure comparability. Maximum speed is another issue that determines electric motor size and fuel-converter size and thus cost and weight. The maximum speed has been design for 70 mph, the speed limit in U.K.

The paper "Performance Evaluation of a Low Cost Series Hybrid Electric Vehicle", presented on the Electric Vehicle Symposium 2002 in Korea describes this process in more detail. Please refer to appendix B. This paper still considers the implementation of an automated manual transmission though a CVT would enhance the concept. Further studies on the behaviour and the applicability of a CVT in this drive train will be undertaken. The simulation results presented in the paper were only preliminary and basic. Section 4.4 describes further simulations that have been undertaken. The paper introduces the idea of the "Peace-of-Mind" drivetrain. The concept provides peace of mind regarding environmental impacts comparable to pure electric vehicles. But also peace of mind to the customer assuring he buys a versatile and cost effective product and peace of mind to the driver that the vehicle takes him to his desired destination without worries about running flat on the battery.

4.4 Simulation of Peace-of-Mind Drivetrain

One of the main disadvantages of series HEV is the increased number of components and the long power conversion chain. This can lead to high cost, high mass and poor energy efficiency. The focus of this simulation is the energy efficiency of the proposed drivetrain under different driving conditions. Cost and mass are kept low by choosing components as small as possible. It has been shown earlier that the mass can be kept as low as in a comparable vehicle with ICE. Simulations have to prove whether driveability is sufficient: it must be similar to comparable vehicles with conventional drivetrain.

4.4.1 Description of the Simulation Package

The simulation work is carried out using ADVISOR 2002. The National Renewable Energy Laboratory (NREL) has developed and still maintains ADVISOR for simulating vehicle drivetrains. ADVISOR is based on Matlab and uses a backward-facing simulation method: The calculations do not start with the driver demands and end up with the vehicle behaviour – it is the other way round: calculations starts with the vehicle behaviour that are predefined through a programmable driving-cycle. This method is easier to implement, because well-defined driving cycles exist, but modeling driver behaviour is not an easy task.

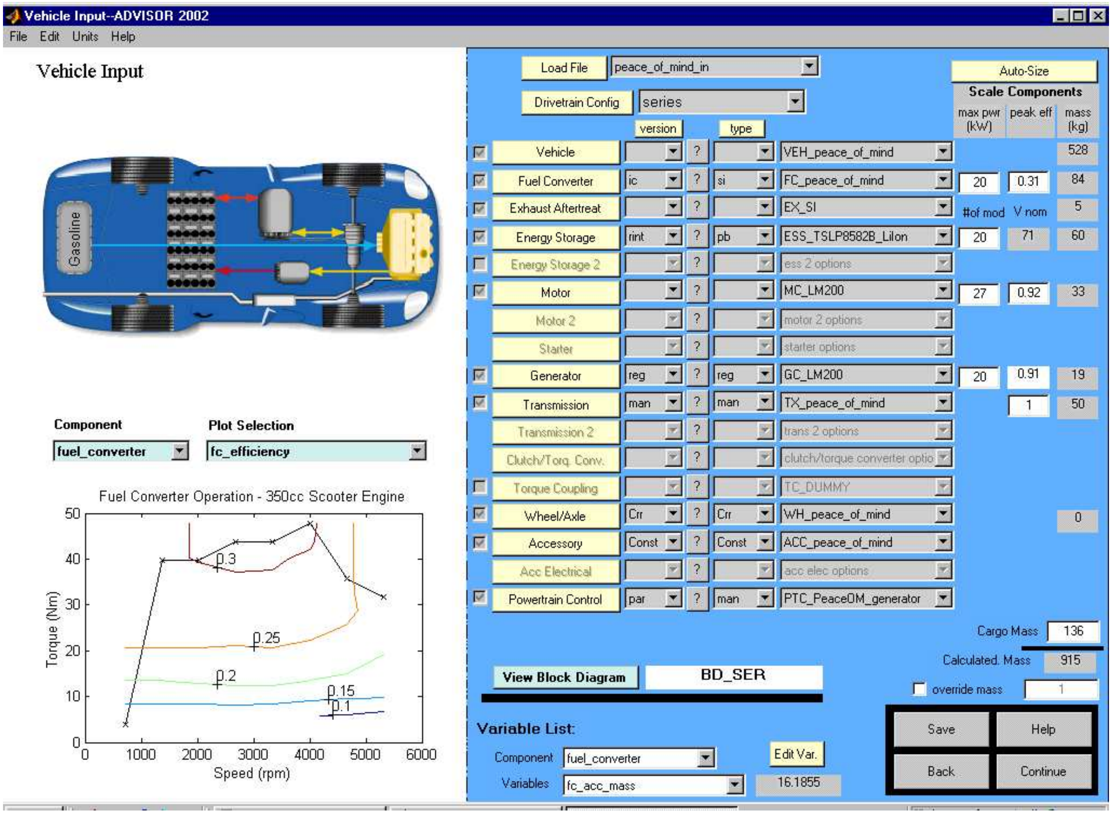

Figure 4-1: First Page of ADVISOR 2002

Figure 4-1 shows the first page of ADVISOR 2002. The vehicle configuration is defined on this page; this includes the drivetrain configuration (series HEV, parallel HEV, etc.) and definition of components. Components can be chosen from lists and scaled with a scaling factor for optimization processes. A cargo mass can be added or the total mass can be overridden. Certain variables can be chosen, viewed and edited. An auto-size function can help optimizing the size of components. The top of the left side of the page visualizes the drivetrain configuration and the bottom shows a graph of a component that can be chosen. The vehicle configuration can be saved. Components can be defined in Matlab M-files and added to the lists of components. Refer to subsection 4.4.2 for further information on component models.

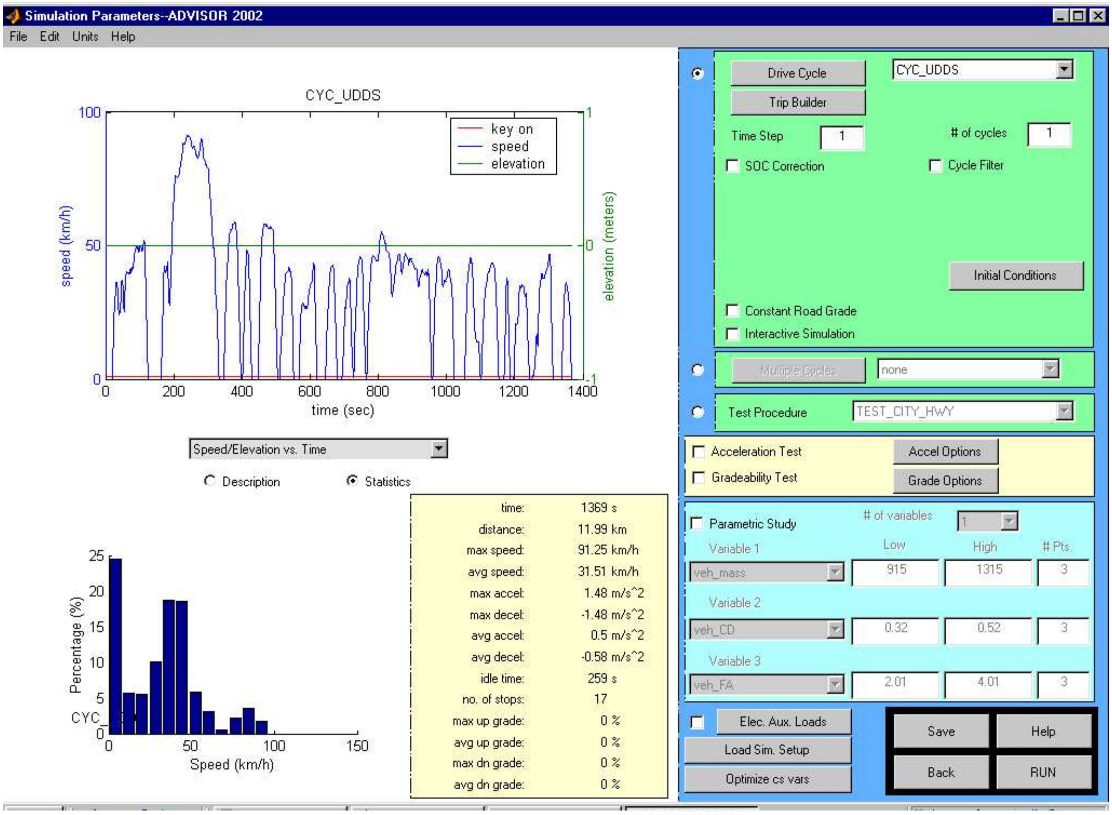

Figure 4-2: Second Page of ADVISOR 2002

The second page of ADVISOR 2002 defines the driving cycle, or to be more abstract the vehicle behaviour. The vehicle behaviour is the start for all calculations in ADVISOR 2002. Driving cycles can be chosen from a list, existing cycles can be modified or new cycles can be defined in M-files. Trips out of up to eight different cycles can be defined and the number of cycle repetitions can be chosen. Battery state of charge correction can be switched on or off. This feature is essential for hybrid electric vehicle, because it makes a difference whether the battery is fully charged or almost empty. Initial conditions like battery SOC and temperature of components can be defined and interactive simulation can be enabled or disabled. The road gradient is defined in the driving cycle M-file, but can be overridden in this window. Multiple different cycles with same initial conditions can be run and complex test procedures can be chosen, defined and stored. Additional tests can be selected for determining gradeability and acceleration performance. Parametric studies can be launched with up to three variables. A tool for optimizing the control strategy of the drivetrain management can be launched and electrical auxiliary loads can be defined and enabled or disabled. The driving cycle and some statistics about it are visualized on the left side of this window. After completing this page, the simulation is defined and can be started.

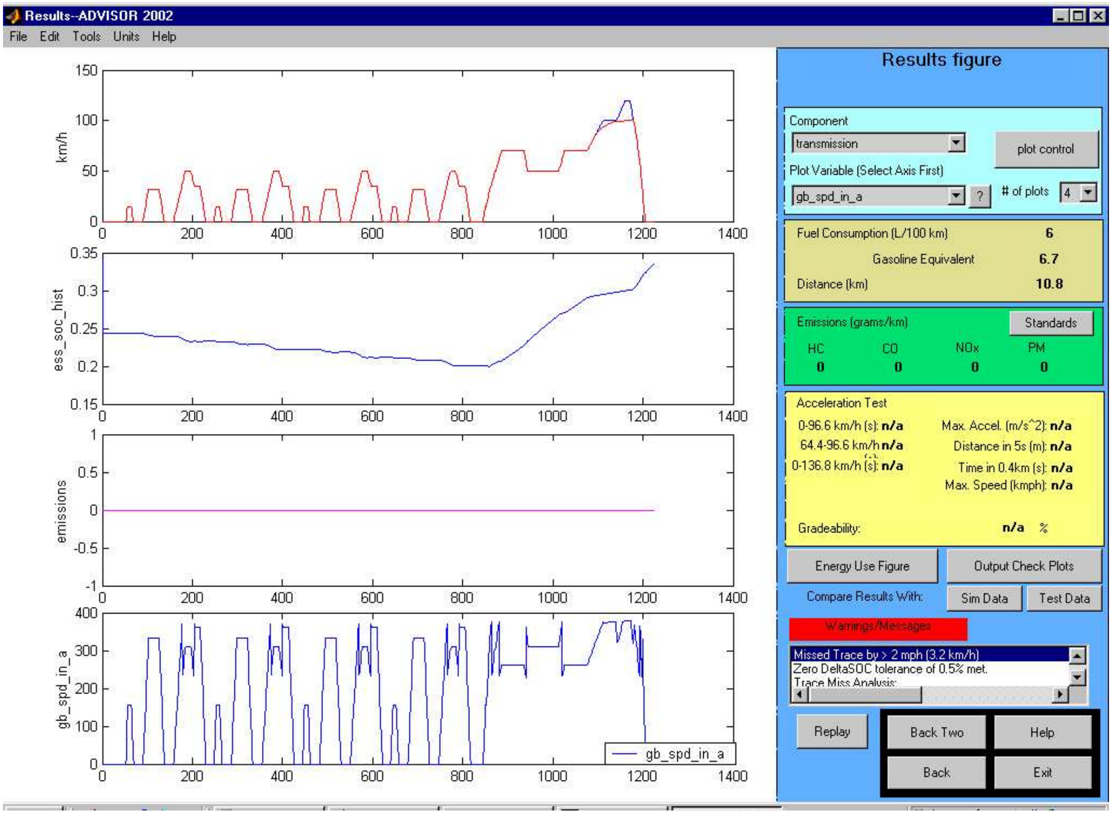

Figure 4-3: ADVISOR Page with Main Simulation Results

Figure 4-3 shows the window with the main simulation results obtained from ADVISOR 2002. The number and content of the graphs on the left can be chosen. Emissions, fuel consumption and results from additional acceleration and gradeability tests are shown on the right. Results can be compared with test data. The top graph on the left shows the driving cycle and how the actual vehicle was able to follow this demand. Energy use figures in tables and bar charts can be viewed and several output check plots can be obtained. Some of these features are shown in the simulation results of the proposed drivetrain in the following section.

Though many features are implemented in ADVISOR, some results need to be questioned and seem to show wrong figures like the gasoline equivalent in HEV mode without SOC correction, but this is dealt with later. It has to be mentioned that simulations take a very long time and complex simulations tend to be difficult to inspect. The components are chosen carefully before running simulations in order to avoid excessive parametric studies.

4.4.2 Simulation Model for the Proposed Drivetrain

This subsection briefly describes the component models in general and specifically for the Peace-of-Mind vehicle (PoM). The model files can be found in appendix C. Most components are defined by specifying their efficiency maps and their limitations like current, voltage, speed or torque limitations. The vehicle model is based on the vehicle mass and the air-drag. The power-requirement at the wheels for this vehicle is calculated in order to follow the driving-cycle. The wheel/axle and transmission losses are added to this power requirement. The wheel/axle model specifies losses based on the coefficient of rolling resistance plus axle losses. Wheel slip force coefficients, wheel radius and inertias plus the fraction of regenerative braking are specified in this file as well. The PoM model for the wheel/axle is based on an existing ADVISOR model.

The gearbox is modeled by defining the number of gears and the gear ratios. The gear shifting is defined in the powertrain control file. Gearbox losses are specified in an existing VW gearbox file. The drivetrain configuration specifies the component that provides the gearbox input power. The electric propulsion motor has to provide this power in the series HEV. The efficiency map of the motor determines the power required from the battery and / or from the fuel converter. The motor file models the motor / controller combination. It is based on the efficiency map, the maximum torque over speed map, the overtorque factor, the maximum controller current and the minimum controller voltage. A thermal model can be implemented. The motor controller combination for the PoM drivetrain is modeled based on scaled test data from the Lynch LMC64 motor and an average controller efficiency of 90 %.

The powertrain control specifies the operation of the vehicle. It determines whether power comes from the fuel converter or from the battery. It also specifies other powertrain control behaviour like gearbox, clutch and engine control. A simple thermostatic control strategy is implemented for the PoM drivetrain. The fuel-converter is switched on and off at certain SOC values. ADVISOR calculates the most efficient point of operation and the engine/generator runs in that point during simulation. The control strategy in the PoM is in fact much more sophisticated. It is described in chapter 5, but this simple model helps determining performance and energy-consumption as a basis for finding the suitable control strategy. The gear shifting can be specified in different ways. Down- and upshift are specified depending on the vehicle speed for the PoM.

The fuel converter is modeled with an efficiency map, speed and torque limits. A thermal model can be implemented for calculating exhaust gas temperature as a basis for predicting exhaust emissions. The PoM engine model is a scaled version of an existing ADVISOR file for a small gasoline engine. The generator that is connected to the engine is modeled through its efficiency map, maximum current, minimum voltage, continuous torque over speed map and the overtorque factor. ADVISOR assumes the generator running at the same speed as the engine. A transmission ratio is modeled by scaling the speed/torque characteristic of one of the two components. The PoM generator model is based on a scaled version of the Lynch LMC64 test data.

The battery can be modeled in different ways. For the PoM, it is modeled by defining OCV and internal resistance over temperature and SOC. The data are taken from an existing SAFT Li-Ion battery file and are scaled up to the ThunderSky 100 Ah size. It must be assumed that the SAFT battery performs different than the ThunderSky. The ThunderSky model will be implemented as soon as the test data described in chapter 3 are complete.

The exhaust of the fuel converter can be modeled in order to simulate exhaust emissions. A predefined model for a gasoline engine is used for the PoM drivetrain, but the emissions are not in the focus of this work so far. Knowledge about emission becomes essential when specifying the hybrid drivetrain control in the future work, because frequent start-stops of a cold engine result in poor emissions.

The accessory is modeled by drawing a constant electrical power from the power bus or by drawing a constant mechanical power from the engine or by a constant torque load on the engine or by combinations. A 60 W constant electrical load has been assumed for the PoM drivetrain. ADVISOR takes losses during charging of the batteries NOT into account. They have to be considered when analyzing the results.

Though some component models do not reflect the actual configuration, they are all based on available products and simulation results do show the potential of this drivetrain technology. The actual components need to be modeled in future work in order to compare simulation results with real-driving results.

Two vehicles are defined for simulating the PoM drivetrain: a pure electric version of the proposed drivetrain and the hybrid version, because ADVISOR 2002 has problems deriving the fuel-consumption of HEVs in pure electric mode. The definitions for these vehicles can be found in appendix C. The ThunderSky Li-Ion battery has two current limits: 300 A during discharging and 100 A during charging. ADVISOR cannot take battery current limits into account directly. A maximum controller current can be defined, but this does not distinguish between discharging and charging (regenerative braking). The HEV mode makes it even more difficult, because the controller input current does not equal the battery current ($I_{controller} = I_{battery} + I_{generator}$). This is dealt with in the following way:

- The motor controller current is set to 300 A in EV mode, because this equals to the battery current. The definition of the motor file in EV mode is manipulated in order to limit the generating torque in a way that the peak recharging current into the battery is 100 A maximum.
- The generator power together with the battery power in HEV mode is sufficient to provide full power to the motor. The motor torque can be set to the actual ratings in driving mode. The regeneration torque is set to small values, because an intelligent generator control strategy cannot easily be implemented in the simulation if possible at all.

Both workarounds produce errors, but the results regarding energy efficiency and pure electric range are trustful, because the effects of the mentioned workarounds have been tested in simulation and the results were not affected significantly. The results for driveability need to be confirmed by comparison with the performance of the test-vehicle.

4.4.3 Simulation Results for the Proposed Drivetrain

The simulation at this stage of the work focuses on verifying the proposed drivetrain as a sensible concept. It does not aim to optimise the drivetrain or to quantify parameter influences – this will be part of future work.

The main issues of the proposed drivetrain are energy efficiency, driveability, pure electric range, vehicle cost and vehicle mass. Cost is not part of the simulation, but cost issues are permanently taken into account by keeping components as cost-effective as possible. Mass figures are estimated based on existing products and they need to be confirmed later. This sub-section investigates in energy efficiency, driveability and pure electric range by simulation. Assessment is performed through comparison with existing products. The simulation work is carried out using ADVISOR 2002, described in 4.4.1.

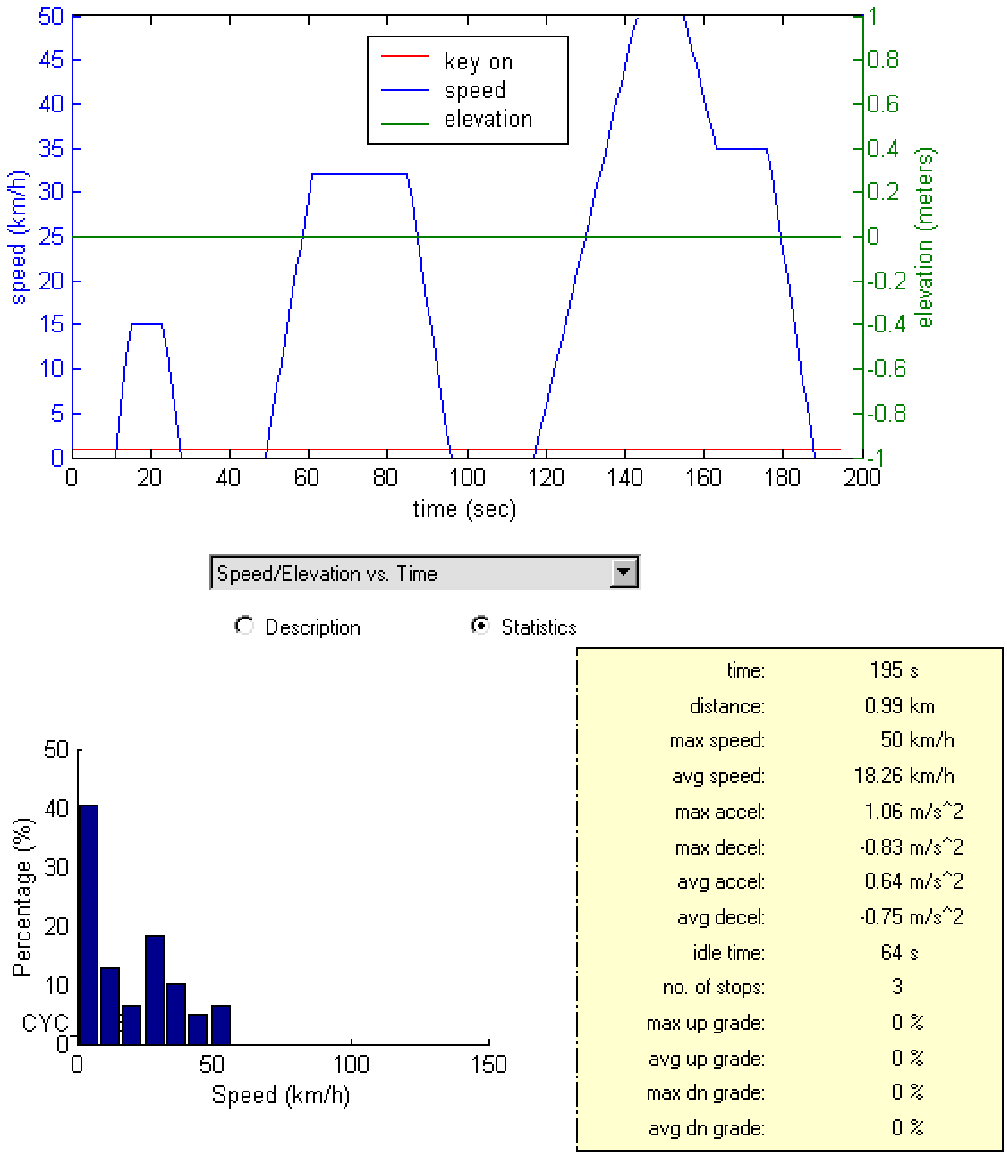

Figure 4-4: The European Urban ECE Driving Cycle

The first test is undertaken using the ECE driving cycle, also called MVEG. This driving cycle is the official driving cycle for assessing fuel-consumption and emissions in the European Union. Figure 4-4 shows this driving cycle together with some statistics. The vehicle achieves a consumption of 1.1 $^{l}/_{100km}$ (260 mpg British or 214 mpg US) fuel equivalent and manages to drive 90 km in pure electric mode. The acceleration and maximum speed is sufficient to follow the cycle definition even at a low state of battery charge of 10%. The simulation is undertaken at 20 ^{0}C and the battery needs to be preheated in cold conditions in order to achieve this performance.

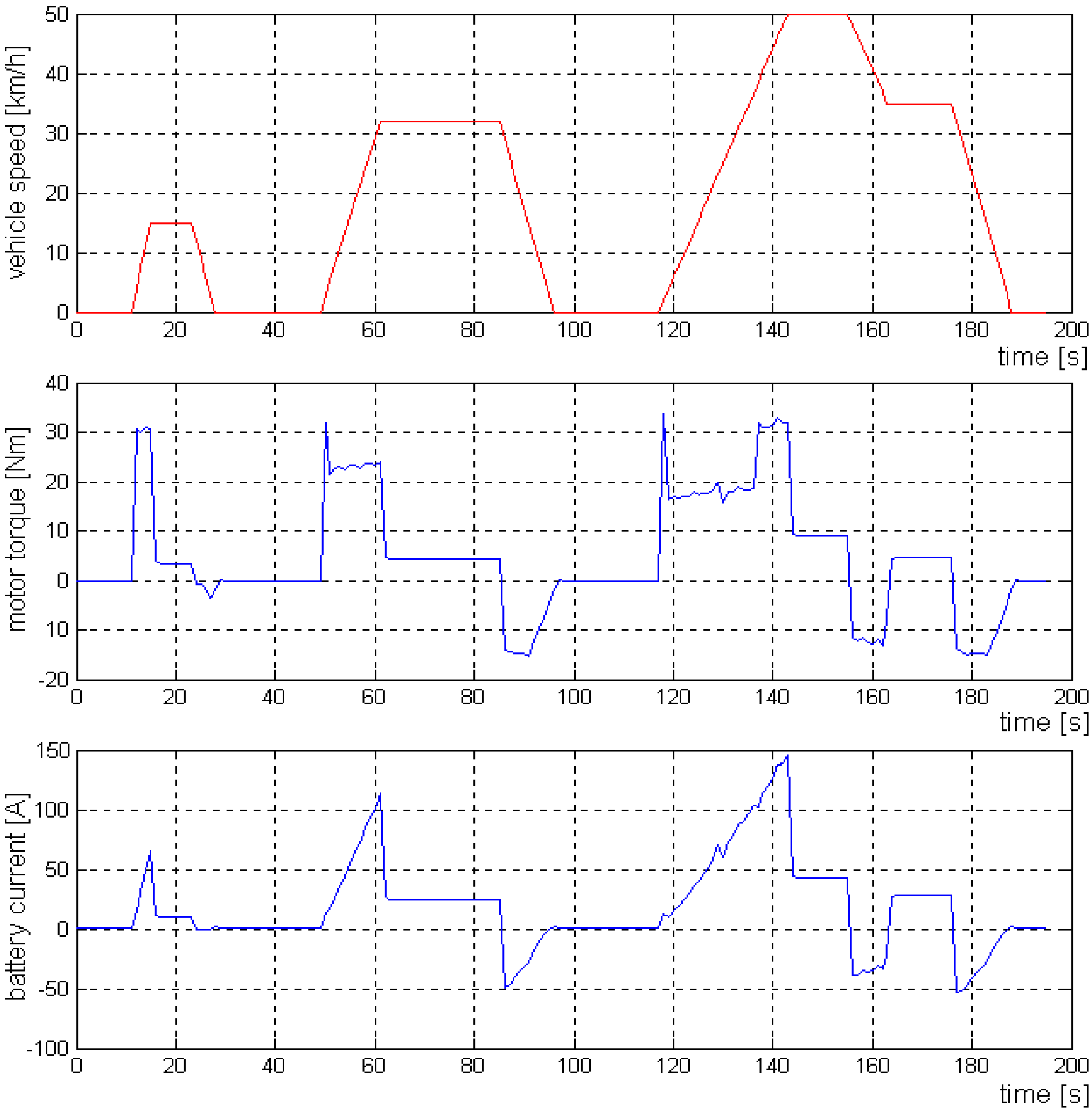

Figure 4-5: The Simulation Results for the ECE Test Cycle in Pure Electric Mode

Figure 4-5 shows the simulation results for the ECE test cycle in pure electric mode. It reveals that motor torque stays well below the continuous rating between 35 Nm and 65 Nm depending on motor speed. The battery current stays below 300 A during acceleration and below 100 A (above -100 A in the figure) during regenerative braking.

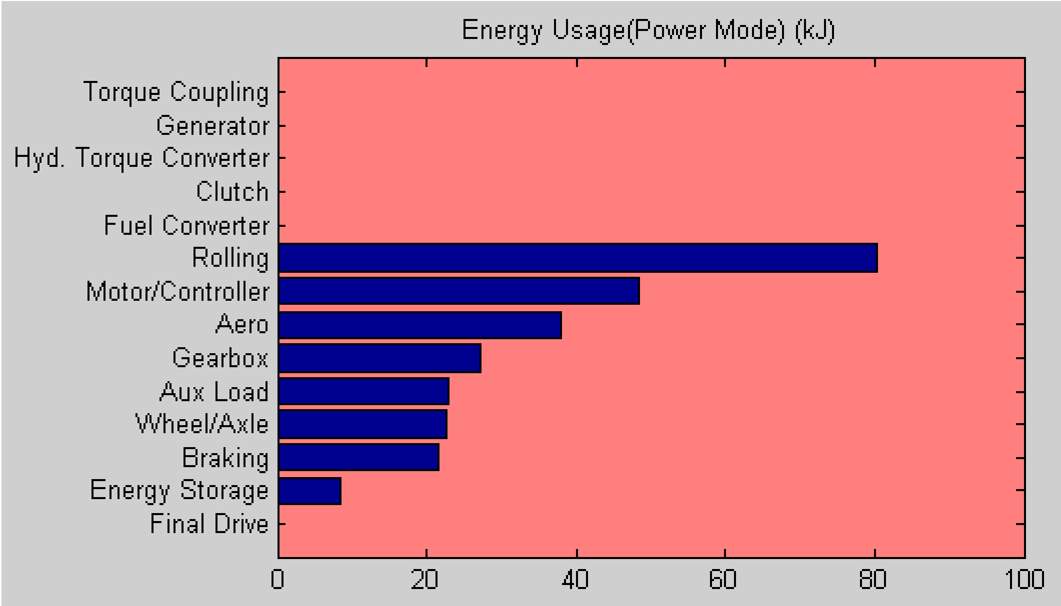

Figure 4-6: Loss-Plot in Pure Electric Mode in ECE Driving Cycle

The engine in conventional vehicles provides power for accelerating the vehicle, for climbing up hills and for overcoming the losses at certain speeds. The energy for accelerating the vehicle is stored as energy for linear movement of a mass m at a certain speed v: $E = {}^{1}/_{2}\, mv^2$. This stored energy is dissipated in the form of heat in the brakes during deceleration. The efficiency of the engine has to be taken into account in order to calculate the total energy used for a certain distance.
The proposed drivetrain can regenerate some of the stored energy by recharging the batteries during braking. Ideally the battery just needs to provide the unavoidable losses in bearings, on tires and due to air drag. Brakes are still required in practice in order to provide emergency braking, braking when the battery is fully charged or for stopping the vehicle, because the regenerative braking always requires some movement of the car. The battery is limited in recharging power as described in subsection 3.3.3 – the ThunderSky can be recharged with up to 100 A. The loss-plot in Figure 4-6 shows that losses due to braking are comparatively small. 100 A recharging current are sufficient for deceleration in most situations in urban traffic. The loss plot also reveals that the rolling resistance of the tires causes the highest losses in urban traffic. This underlines that the vehicle mass plays a major role and should be kept as small as possible. The motor/controller combination adds substantial losses as well though it is very efficient already. This supports the earlier statement that the motor/controller selection is vital for the concept: both should be very efficient. The losses due to the 60 W auxiliaries are also mentionable, because 60 W is a comparatively small power for auxiliaries. They would have no mentionable effect in conventional powertrains with inefficient combustion engines but it plays a significant role in the proposed drivetrain powered from batteries. The implementations of several auxiliaries like power steering, seat heating or climate-control for example need to be well considered and the driver should be made aware of the energy consumption. Future development of auxiliaries like ABS and management systems for example will also need to focus on energy-efficiency.

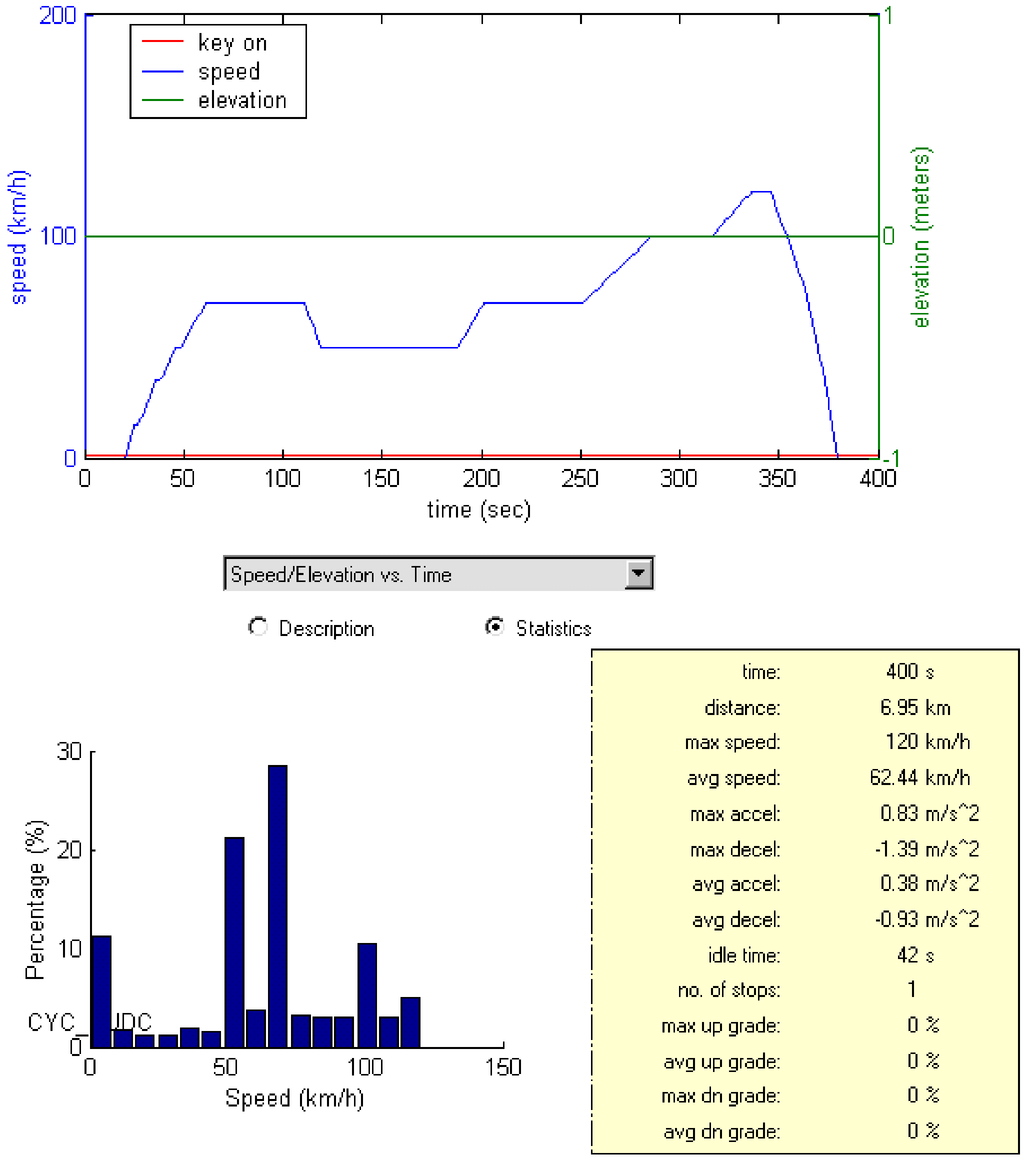

Figure 4-7: The European Extra Urban Driving Cycle EUDC

The next simulation was undertaken using the European EUDC extra urban driving cycle, shown in Figure 4-7.

The energy consumption is 1.4 $^{l}/_{100km}$ (200 mpg British or 170 mpg US) of fuel equivalent and the pure electric range is 60 km.

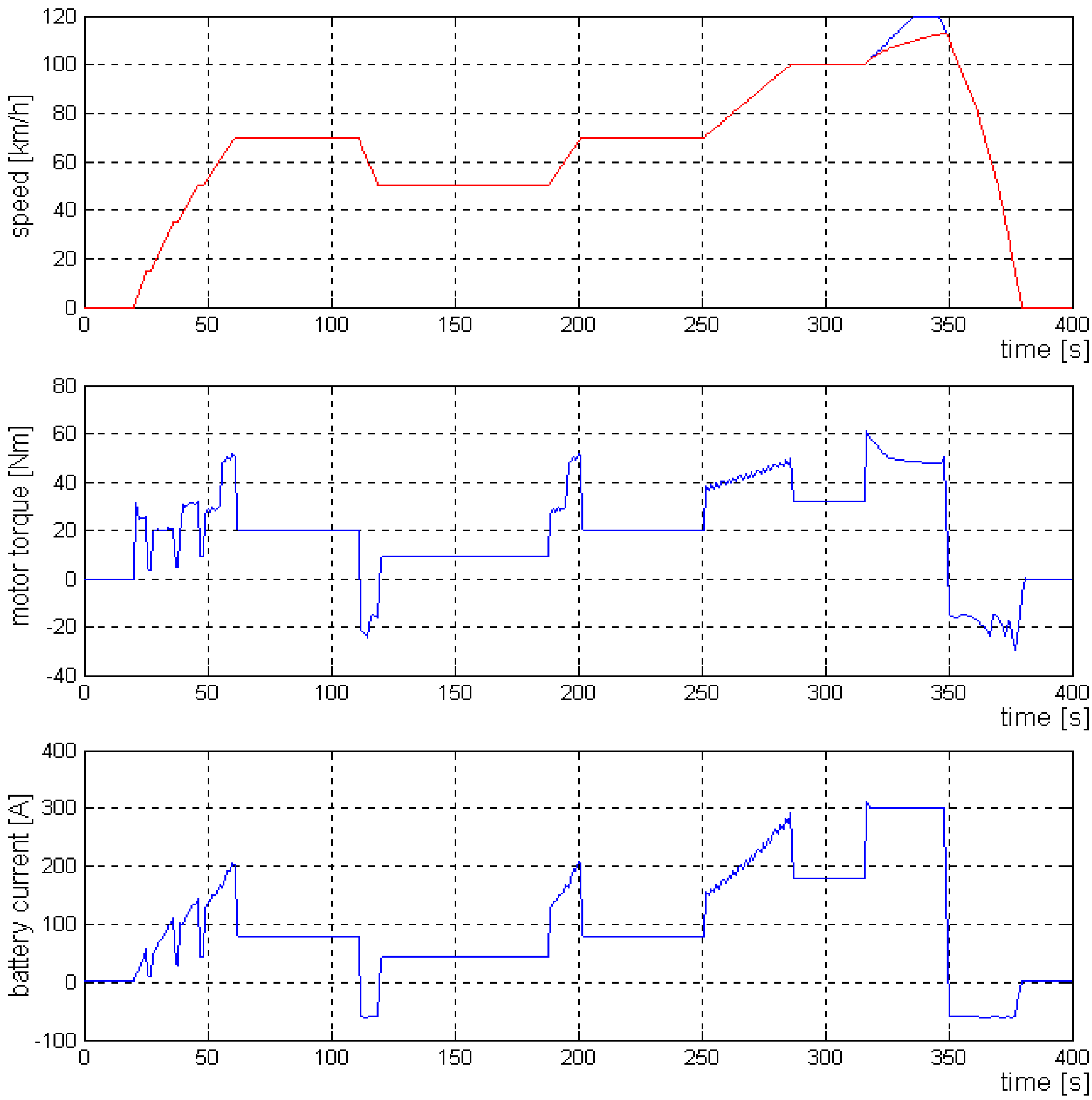

Figure 4-8: The Simulation Results for the EUDC Test Cycle in Pure Electric Mode

Figure 4-8 reveals that the acceleration is not sufficient for following the test cycle above 100 km/h. The blue curve in the top diagram of Figure 4-8 shows the desired speed for the driving cycle and the red curve shows the achieved simulated speed. The top speed of 120 km/h can be achieved, but the acceleration in fourth gear is not sufficient. The motor torque is not the limiting factor as the diagram in the middle of Figure 4-8 shows. The battery current is shown in the bottom diagram. The limit of 300 A battery current is the bottleneck in this case. A current of about 400 A at full SOC would be sufficient to follow the cycle. This current is available once the engine/generator is turned on and the required motor torque of about 65 Nm reaches the continuous rating of the motor. The battery current limit of 100 A during regenerative braking is sufficient for deceleration as shown in the bottom diagram.

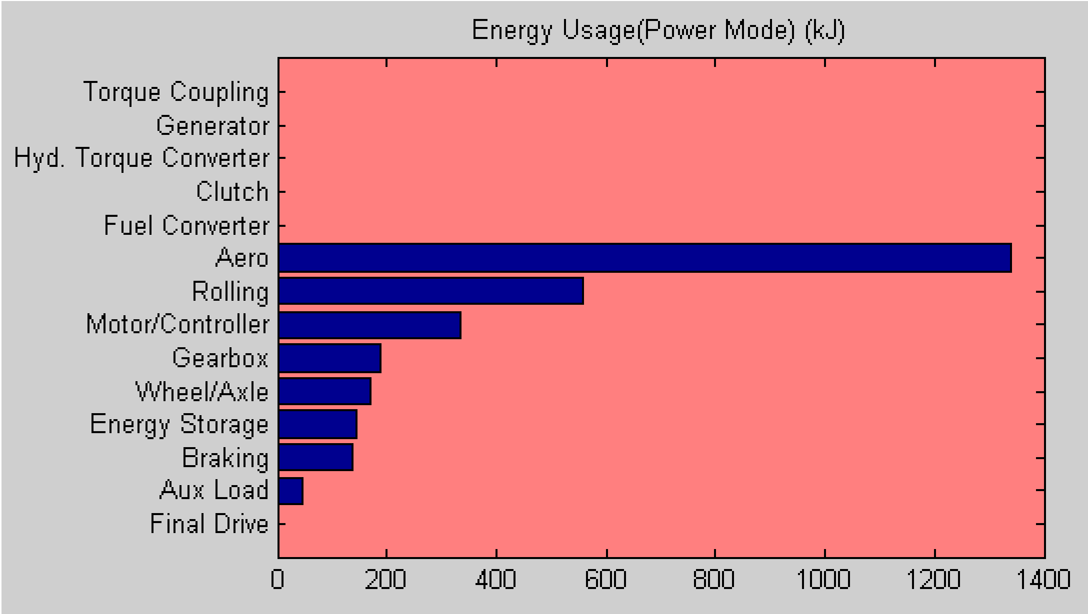

Figure 4-9: Loss-Plot in Pure Electric Mode in EUDC Driving Cycle

The loss plot in Figure 4-9 is added for comparisons with the ECE loss plot in Figure 4-6. The absolute energy usage values depend on the driven distances. They are not the same in the ECE and the EUDC test-cycles, but the relations between the component losses are comparable. It is revealed that the air drag plays a major role when driving in extra urban conditions.

All following simulations are undertaken in HEV mode. The intelligent drivetrain management that is proposed in chapter 5 is not implemented in the simulation. Simulations are using a simple control strategy instead: The engine is switched on if the battery SOC is lower than a certain adjustable value and it is switched off if another adjustable value is exceeded. The values for simulating energy consumptions are set in a way that the SOC stays between 70% and 75%. Simulations of acceleration and speed performance are based on settings assuring that the engine is switched on continuously.

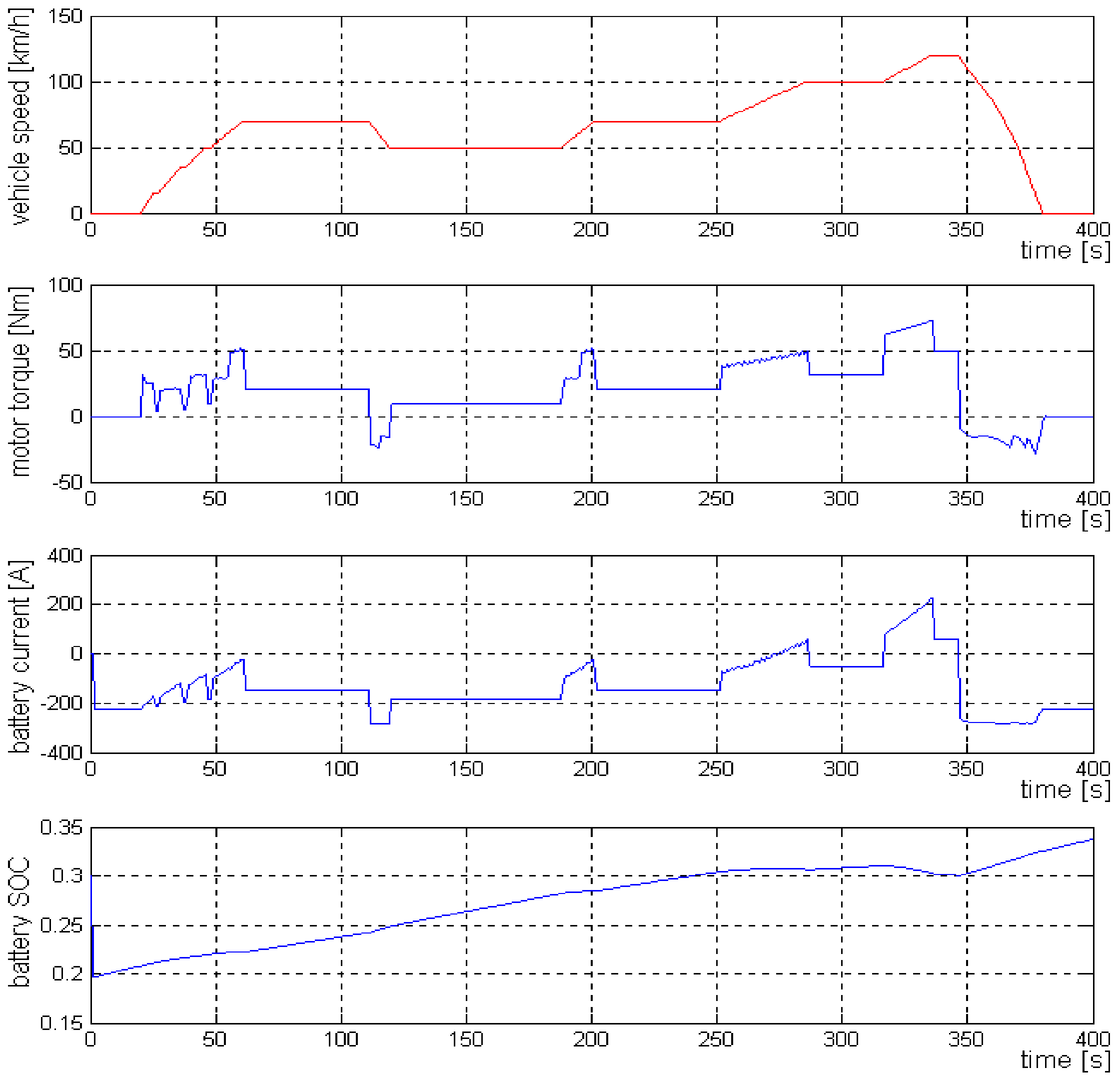

Figure 4-10: The Simulation Results for the EUDC Test Cycle in Hybrid Mode

The vehicle achieves a fuel consumption of 4.5 $^{l}/_{100km}$ over a distance of 209 km in the EUDC test cycle with the engine switched on continuously. The simulation ran through 30 EUDC test cycles to obtain this result. Figure 4-10 shows the behaviour during the first cycle.

The vehicle is able to follow the cycle in terms of acceleration and top speed. The motor torque reaches its continuous rating of 63 Nm during acceleration in fourth gear above 100 km/h. The battery current reaches 200 A maximum. The over-torque capability of the motor and the battery current have free reserves for faster acceleration than demanded in the EUDC cycle or for additional gradients.

The engine/generator power is sufficient to increase the SOC of the battery during the EUDC cycle as shown in the bottom diagram in Figure 4-10. The simulation cannot limit the battery charging current and this exceeds the limit of -100 A as shown in the third diagram. The control strategy that is proposed in chapter 5 reduces the engine power to prevent this happening.

Aggressive driving or continuous high speeds on motorways are the worse cases for this type of drive train. The fuel consumption is 5.7 $^{1}/_{100\text{km}}$ in a simulation with constant 70 mph. The engine/generator power is sufficient to propel the vehicle over more than 700 km.

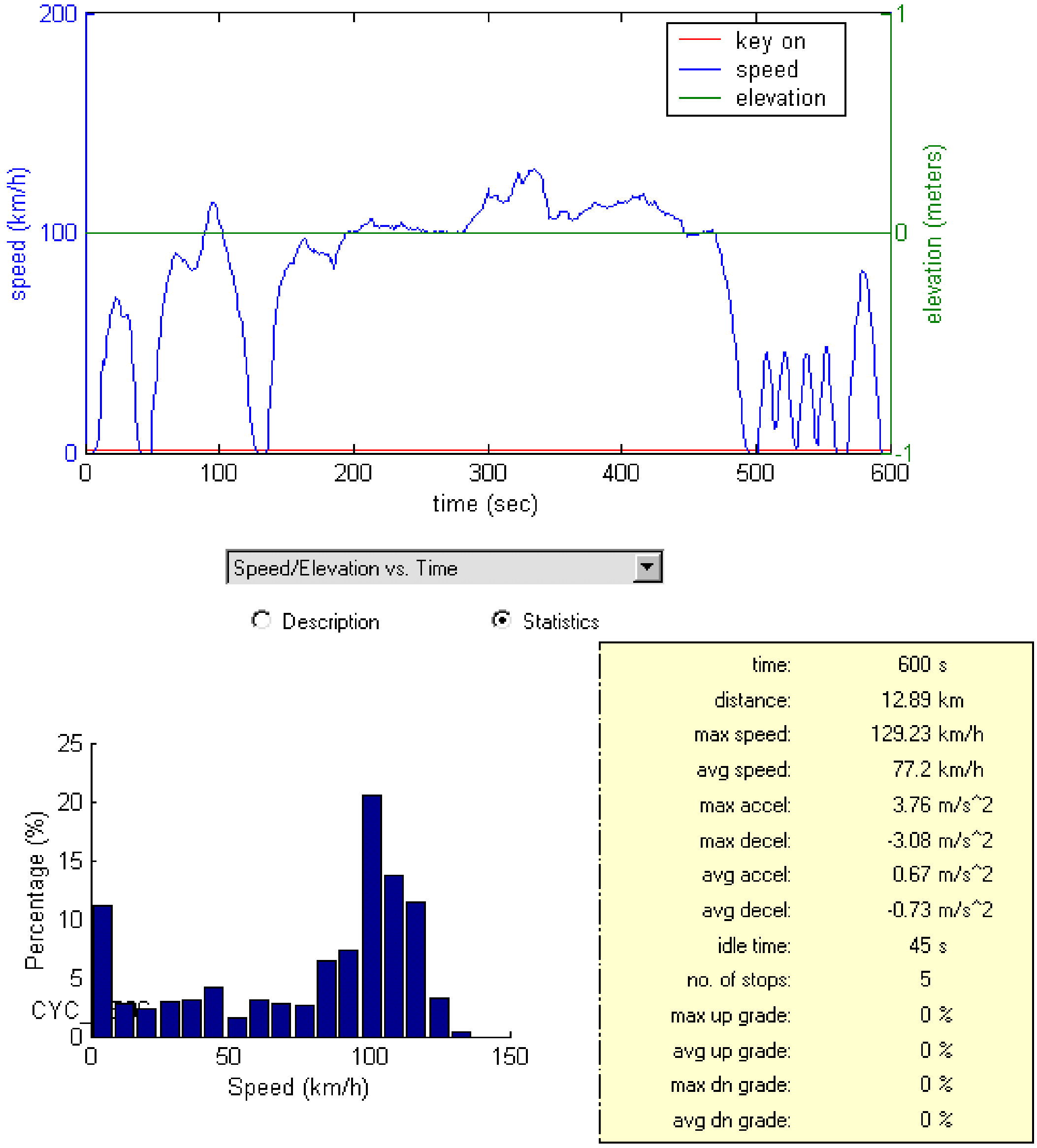

Figure 4-11: The Agressive US06 Driving Cycle

The worse fuel consumption of 6.6 $^{1}/_{100\text{km}}$ occurs when simulating the aggressive US06 driving cycle, shown in Figure 4-11. This driving cycle is useful for assessing the driveability in terms of acceleration.

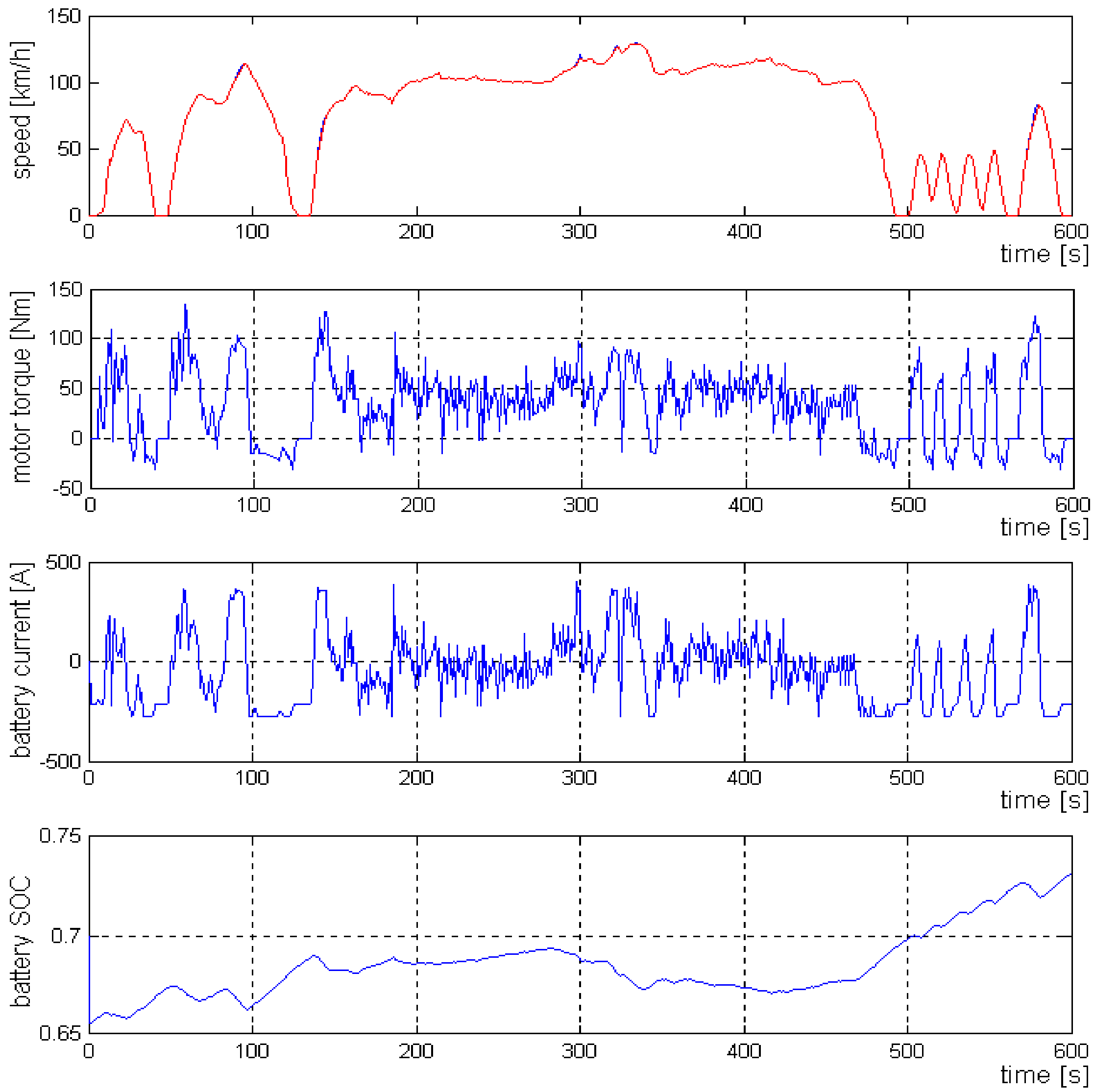

Figure 4-12: Simulation Results for the US06 Driving Cycle

The second and the third diagram in Figure 4-12 show the severe changes in motor torque and battery current as a result of the aggressive driving style.

The vehicle manages to follow the driving cycle very well as shown in the top diagram in Figure 4-12 except some minor speed differences shown in the plot in Figure 4-13. These trace shortfalls are due to both: battery current limitation and peak motor torque limitation.

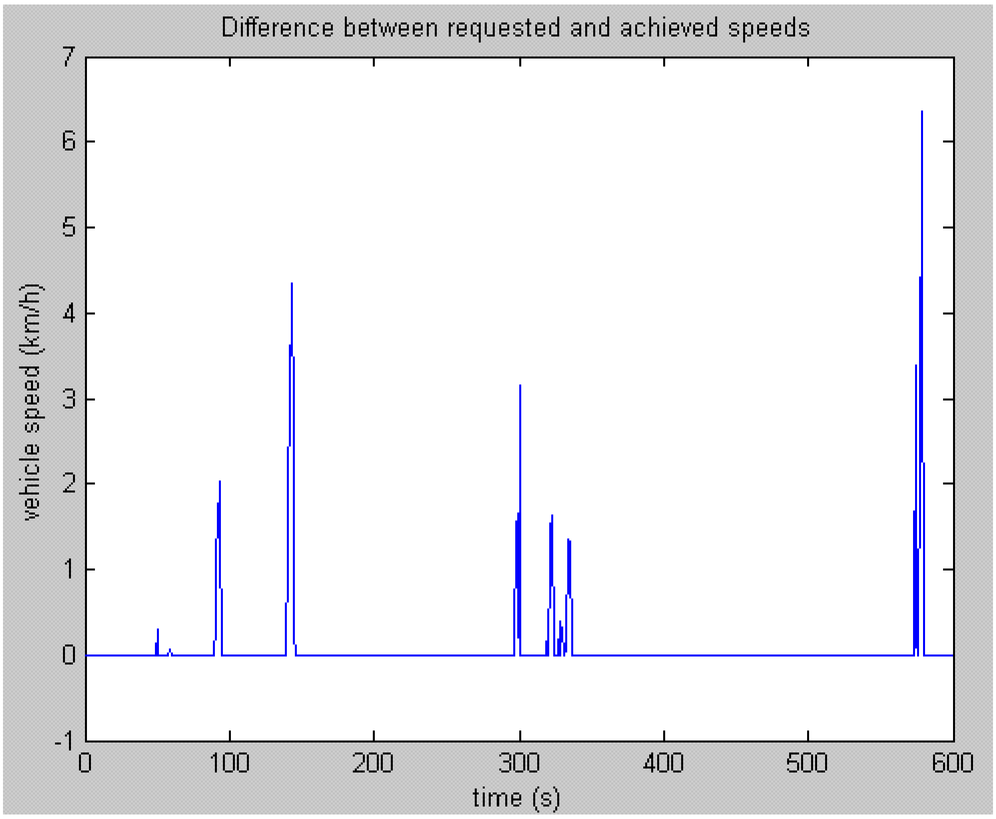

Figure 4-13: Trace Shortfalls During US06 Driving Cycle

The maximum acceleration and the gradeability in different driving cycles are simulated as well. The vehicle has to follow the driving cycle for passing the gradeability test. All results are summarized and compared with other vehicles in Table 4-2.

	PoM EV	PoM HEV	Toyota Prius	Opel Corsa Eco
Fuel cons. ECE	1.2 $^{l}/_{100km}$	3.3 $^{l}/_{100km}$	5.9 $^{l}/_{100km}$	6.5 $^{l}/_{100km}$
Fuel cons. EUDC	1.6 $^{l}/_{100km}$	4.5 $^{l}/_{100km}$	4.4 $^{l}/_{100km}$	4.0 $^{l}/_{100km}$
Fuel cons. 70 mph	2.2 $^{l}/_{100km}$	5.7 $^{l}/_{100km}$	4.5 $^{l}/_{100km}$	?
Fuel cons US06	-	6.6 $^{l}/_{100km}$	6.7 $^{l}/_{100km}$	?
Range ECE	90 km	-	-	-
Range EUDC	60 km	-	-	-
Acc. 0 – 100 km/h	36.4 s	15.8 s	15.8 s	18.5 s
Acc. 0 – 50 km/h	7.3 s	4.3 s	5.7 s	?
Max. acceleration	3.9 $^{m}/_{s}{}^{2}$	4.1 $^{m}/_{s}{}^{2}$	3.5 $^{m}/_{s}{}^{2}$	?
Grade. ECE	8 %	15 %	12 %	?
Grade. EUDC	-	3 %	7 %	?
Grade. 70 mph	(1.1 %)	2.1 %	6.5%	?
Max. speed	100 $^{km}/_{h}$	128 $^{km}/_{h}$	163 $^{km}/_{h}$	157 $^{km}/_{h}$

Table 4-2: Simulation Results for the Proposed Drivetrain (PoM) in Comparison with Other Vehicles

The PoM could achieve a top speed of 120 $^{km}/_{h}$ in pure electric mode, but acceleration and hill climbing ability are insufficient in fourth gear. It is suggested to remain within third gear in pure electric mode and this limits the top speed to 100 $^{km}/_{h}$. The fuel-consumption figures for the Peace-of-Mind vehicle in pure electric mode are measured in liters of fuel equivalent according to the relation in Equation 2-1. A charger efficiency of 90 % is already taken into account. The figures for the Peace-of-Mind vehicle in hybrid mode are based on purely fuel-powered operation. Real-life operation will be a mixture of purely electric and purely fuel-powered operation.

All values for the Corsa Eco are obtained from Opel - not from simulation - and some values are not available. The Corsa Eco is chosen for comparison because it is a car with conventional drivetrain that is cost-effective with good versatility and lowest fuel-consumption in the market of gasoline cars. Diesel cars are not compared because they do not comprise particle filters in small cars and emissions are poor. Direct fuel injection cars like the VW Polo FSI are not compared because of their high purchase price and higher performance. The Smart is not compared because of its lower versatility in terms of space. The Toyota Prius is compared because it is one of the first cars with hybrid electric drivetrain that has been introduced to the market. A simulation model for the Prius is available in ADVISOR and all measures are obtained from simulation.

All simulation results need to be questioned in general. The test-vehicle will be simulated and results will be compared with the real-driving performance, range and energy efficiency. This allows drawing conclusions whether the simulation results are trustful or not.

4.5 Configuration of the Test-Vehicle

The proposed drivetrain is going to be implemented in a test-vehicle in order to evaluate the simulation results and discover practical performance of the drivetrain. The chassis and the drivetrain components for this test-vehicle are off-the-shelve products in order to reduce time for development. This means that components cannot be chosen in an optimal way. Availability and purchase cost issues for single quantity have a higher priority than the optimal component choice. Nevertheless, the test-vehicle acts as an entry-point for a practical optimization process and real-driving results still can be compared with simulation results. This section explains the choice of components and describes the component specifications of the test-vehicle. The drive-train design process has to start with the actual vehicle chassis and its parameters. It will not follow the process described in section 4.2 and 4.3. The following paragraphs outlines the design process:

<u>Vehicle chassis:</u> The vehicle chassis is a Ford Fiesta MkII Van that was made available cheaply through the main sponsor of the project. The original vehicle mass of the Ford Fiesta Van is 920 kg according to the Ford dealer in Southampton. The actual vehicle is different from this: 1.0l engine, tank, exhaust system, clutch are taken out and are replaced with smaller engine, smaller tank, small exhaust system, battery, electric motor, generator, power-electronics, heater and vacuum pump for the brakes. The vehicle weight is measured on a weighbridge after taking out the conventional propulsion components: it weighs 760 kg including Lynch LMC64

propulsion motor (will be used as generator later) and Li-Ion batteries. The weight for engine (60 kg), propulsion motor (22 kg) exhaust system (10 kg) and fuel tank including fuel (30 kg) have to be added. The curb weight will be about 882 kg for the complete HEV – less than the original vehicle. The test-vehicle has to carry up to two persons (additional 200 kg). **A vehicle mass of 1082 kg is taken into account for all the following calculations.** The air-drag coefficient, the frontal area and the rolling resistance coefficient are estimated by comparison with other vehicles with available data: $c_w = 0.36$, $A_F = 2.0\ m^2$ and rrc = 0.9%.

Propulsion motor: The propulsion motor cannot be chosen, because it is included in the purchase of the Fiesta. It is a Lynch Supermotor. This motor basically consists of two Lynch LMC64 mechanically and electrically coupled. The Lynch motors are brushed DC motors with permanent magnets and pancake-design. They provide very good efficiency of about 90% over a wide operational region and offer very good power to weight ratio of about $1^{kW}/_{kg}$. The main disadvantage is the limited speed range and the constant torque over speed characteristic. The specifications of the Supermotor are:

$P_{mot,cont} = 21.2$ kW	$m_{mot} = 21.2$ kg
$V_{mot,max} = 60$V	$n_{mot,max} = 3900$ rpm
$I_{mot,cont} = 400$ A	$T_{mot,cont} = 52$ Nm

Battery: The chosen battery is a Li-Ion battery as discussed earlier. ThunderSky from China was the only manufacturer who was able to supply a suitable battery for an affordable price. Their range of Li-Ion batteries at the date of purchase reached from 10 Ah cells over 50 Ah and a 100 Ah to 200 Ah cells. Each cell provides about 3.6 V. A cell number of 18 in series connection is chosen in order not to exceed the speed limit of the Lynch motor. The 100 Ah cell is chosen, because the 50 Ah cell does not provide enough power and the 200 Ah cell is too heavy and expensive. The battery (18 cells of 100 Ah) weighs about 55 kg, provides up to 19 kW and has energy content of about 6.5 kWh. 19 kW are sufficient to propel the vehicle in urban traffic and 6.5 kWh are sufficient to run the vehicle purely electric for at least 30 miles in urban traffic. Both measures are estimated in the same way as proposed in 4.3.

Engine/Generator: About 11 kW of average power are required to propel the car at motorway speeds (70 mph). A 250 cc scooter engine is chosen in order to fulfill this requirement. The scooter engine is a comparatively modern, water-cooled 4-stroke engine. It is small, lightweight and is cheaply available as second-hand. It produces up to 15 kW and 12 kW to 13 kW lay in an acceptable efficiency region. The generator is a Lynch LMC64 DC motor. It is chosen because it is available for free, it is small, powerful and lightweight and it can produce the required 11 kW from the 13 kW engine power with an efficiency of around 90 %.

Gearbox: The original gearbox of the Ford Fiesta is used until a CVT is available. The gear-ratios are fixed and cannot be chosen, the ratios of the 4 forward gears are obtained through measurements on the vehicle:

First gear	14.5 : 1
Second gear	8.0 : 1
Third gear	5.5 : 1
Fourth gear	4.0 : 1

The rolling circumference of the wheel is 1660 mm. The only adjustable parameter is the ratio of the belt-drive between the electric motor and the gearbox. The following paragraph deals with determining this ratio. Unlike in section 4.3 where the gear ratios could be chosen they cannot be optimized for all driving situations in this case. The optimal ratio is calculated for all different driving situations using the equations from section 4.3. A summary of this result is:

- Continuous hill climbing of 20% gradient in first gear requires a ratio 0.84 : 1 or higher
- Urban driving up to 40 mph in second gear requires 0.76 : 1
- Rural driving up to 60 mph in third gear requires 0.74 : 1
- Motorway driving up to 70 mph in fourth gear requires 0.85 : 1 or smaller

A ratio of 0.8 is chosen, because smaller ratios can easily overheat the propulsion motor in fourth gear. Higher values are not necessary because the gradeability is not in the focus of tests and top-speed can be reached with 0.8 as well – it is even more suitable for testing the driveability on motorways under less optimal conditions.

4.6 Summary – Proposal of Vehicle Drivetrain

The comparison of the proposed vehicle drivetrain (Peace of Mind – PoM) with on-the-road vehicles in Table 4-2 shows that the fuel consumption is much better in pure electric mode – up to 5.9 times in urban traffic - if compared with the conventional drivetrain in an Opel (Vauxhall) Corsa Eco. The Toyota Prius is better than the Corsa in urban traffic, but still worse than the PoM in hybrid mode and much worse than the PoM in electric mode. The Prius is worse than the Corsa in extra urban traffic, better than PoM in hybrid mode, but much worse than the PoM in electric mode. This is the sort of advantages we can expect from mild hybrids. Considering that the proposed drivetrain is mainly designed for short journeys in pure electric mode it promises much higher advantages in terms of fuel economy – especially in urban traffic.

The driveability of the proposed drivetrain in terms of acceleration is very good in hybrid mode if compared with the Toyota Prius or Corsa Eco – especially in urban traffic. In pure electric mode it is acceptable for urban driving and almost sufficient for extra urban driving. The main issue is acceleration on hills at higher speeds. The pure electric range is sufficient for most of the journeys undertaken in a small vehicle. The energy management of this drivetrain is a key issue: it has to run the engine as rarely as possible to keep the outstanding fuel-economy of the pure electric mode. But it has to run the engine if driveability or longer range is required. Further simulations are required in order to obtain the knowledge for drivetrain management decisions. Simulation results need to be compared with real-driving results and a better understanding of component cost is required in order to develop a template for the PoM drivetrain.

5. Drivetrain Management Requirements

Section 4.4 shows that the proposed drivetrain has significant advantages in terms of fuel consumption if the vehicle runs purely electric. The drivability on the other hand is better in hybrid mode. This and some other trade offs need to be managed in order to optimize the system during operation. Optimization goals, tradeoffs and management strategies are identified in section 5.1. Input and output variables that are required to perceive these strategies are defined in the second section of this chapter.

5.1 The Energy Management Goals, Trade-offs and Strategies

The global goal of the energy management system is the reduction of environmental impacts but also providing drivability. This is the main trade-off, because drivability of this drivetrain in terms of acceleration, gradeability and speed is very good if the engine/generator is switched on while impacts like local exhaust pollution, noise and energy consumption are increased. The optimal management between this tradeoff is of course a question of driver demands. The driver is part of the energy management and deserves control of and information about the drivetrain. This section identifies specific management goals and tradeoffs. The effects of driver demands are studied.

The loss-plot in Figure 5-1 reveals that the engine/generator set adds the main losses to the vehicle system. Running the engine continuously is the worst case in terms of fuel consumption, noise and local pollution.

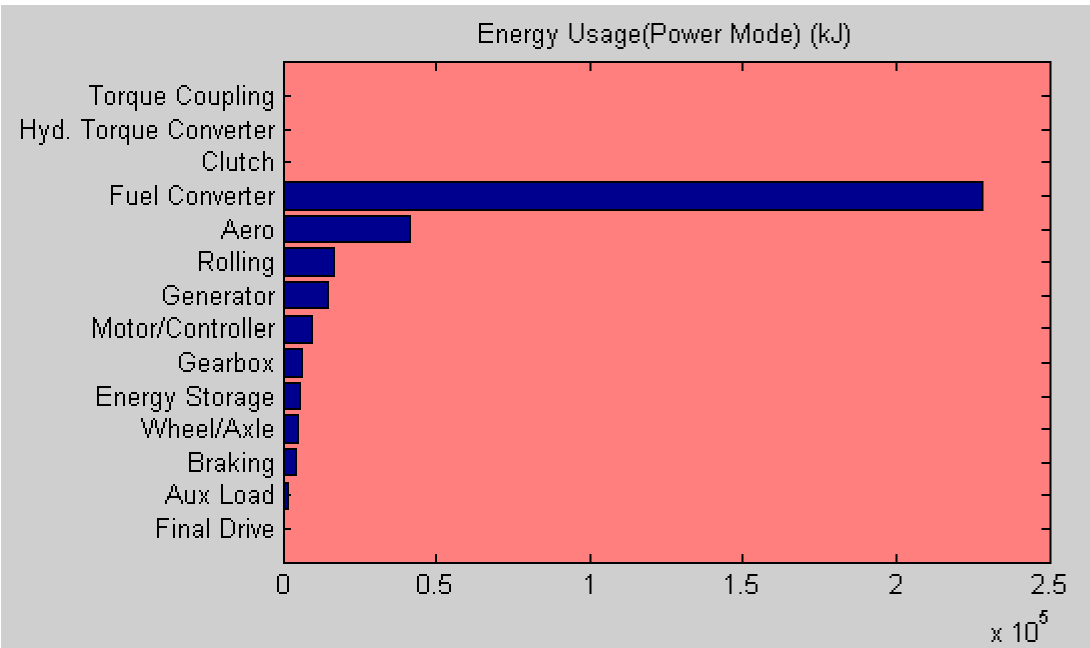

Figure 5-1: Loss Plot During Hybrid Mode in EUDC Test Cycle

The engine generator should run as rarely as possible. Three reasons exist for starting the engine:

1. The battery cannot provide enough energy for the desired remaining range.
2. The battery cannot provide sufficient power.
3. The vehicle is not recharged from the mains.

The following paragraphs explain this in more detail:

1.) The engine needs to be started if the remaining range is higher than the battery can provide with its actual SOC. If the engine needs to be started at all, it should be started outside urban areas and preferably at higher vehicle speeds. This reduces local exhaust pollution in urban areas and noise impacts outside and inside the vehicle are kept low. Higher vehicle speeds require higher propulsion power. The generator produces power for the propulsion and only small amounts need to be stored in the battery. This increases the efficiency. The battery cannot be recharged with full generator power and the undesirable case of vehicle stops where the engine needs to run in less efficient low-power operation is minimized. The engine should run as short as possible – just sufficient to reach the desired destination plus some safety. On the other hand, the performance and energy efficiency of the battery decreases with lower state of charge: Figure 3-8 in subsection 3.3.2 shows that the internal resistance of the battery increases rapidly below 10 % SOC and maximum discharge power decreases rapidly below 30 % SOC due to the lower cell voltage limitation as shown in Figure 3-9. Operation in the region of 10 % SOC and lower should be avoided at all and operation below 30 % is undesirable if high power requirements are likely.
It is likely that the engine provides more power than the journey requires on average. This happens if the journey is long but with low average speed. In this case the battery is recharged and the generator needs to be stopped or idled to prevent overcharging. Frequent start and stops of the engine are undesirable, because this implies poor exhaust emissions and engine efficiency. It also decreases the lifetime of the engine. Another option is idling the engine or running it in low power regions. This is undesirable, because it also leads to poor efficiency. The maximum battery recharging power decreases rapidly above 70 % SOC due to the higher battery cell voltage limitation as shown in Figure 3-10 in subsection 3.3.3. The engine needs to run in a less efficient low-power operation region. Additionally less energy can be regenerated due to the lower recharging capability of the battery. The engine/generator should not recharge the battery to more than 70 % SOC.

2.) It is required in certain circumstances to start the engine for assisting the battery with additional power. Simulations have shown that battery power is sufficient for urban driving and almost sufficient for extra-urban driving. It is insufficient for accelerations and hill climbing at high speeds. The driver in fact needs to judge what is sufficient to him and what is not. Table 5-1 suggests a strategy that takes different driving styles into account.

Driving style	Strategy	Kick down	Influence of SOC
Very relaxed	Engine remains off even on motorways.	-	SOC, range and road-type determine the start of the engine. Power is disregarded.
Relaxed	Same as above, but engine starts if speed cannot be maintained due to gradients.	Engine kicks in above a certain speed for better acceleration.	Shifts to “Flexible” if engine needs to provide energy for range.
Flexible	Engine starts on motorways and certain highways.	Same as above but starts at a lower certain speed.	Required range encourages starts on highways.
Performance	Engine starts on motorways and all highways.	Same as above	Engine is switched off on highways below certain speeds if SOC is sufficient.
Aggressive	Engine remains on all the time.	-	Engine idles at high SOC.

Table 5-1: Management Strategy and Preferred Driving Style

The engine should not be started and stopped frequently in order to minimize cold engine runs.

3.) The management is simplified if the vehicle is not recharged from the mains: The engine is switched on if battery SOC requires charging. This should happen preferably outside urban areas. The driving styles “Very relaxed” and “Relaxed” mentioned in Table 5-1 would not be necessary, because it does not make sense to deplete the battery SOC.

Some further aspects require management:

- Battery Management: The battery needs to be managed. It needs to stay within all their limits like cell-voltage maximum, cell-voltage minimum, discharging current maximum, charging current maximum, temperature maximum and minimum without sudden declines in performance. The charging process needs to be controlled depending on the highest cell-voltage. The discharging power needs to be reduced if a cell-voltage reaches its minimum or if the maximum current is reached or if maximum temperature is reached. The regeneration power and/or engine power need to be reduced if a cell-voltage reaches its maximum or if the maximum current is reached or if the maximum temperature is reached. Temperature may be controlled actively and cells require equalization. The battery state of health determines its power capabilities, efficiency and maximum energy content. This influences the management decisions about switching the engine on of off.
- Fuel-converter Management: The engine needs to run in its most efficient point for a given power requirement. A control of the engine and the power controller for the generator is necessary in order to achieve this in different driving conditions and for different SOC of the battery.

- Propulsion motor management: The propulsion motor needs management in order to make use of its over-torque capability for accelerations and short hills without damaging it.

The driver requires information that helps him making decisions. Like remaining recharging time, battery SOC, battery state of health (SOH), fuel consumption and total energy consumption for example.
The driving style significantly influences the impacts on the environment. The driver must be provided with feedback about his demands. The "Aggressive" strategy provides the best possible drivability but the highest impacts. The driver would always chose this mode if he had absolutely no feedback about his driving. Actual energy consumption and estimated energy consumption for the journey are possible ways of feedback. The estimated consumption for example could be compared with best possible consumption in a "Relaxed" mode.
A major problem is not to overload the driver with difficult, complicated or too many information. This could distract him from the traffic. Also some drivers may want to have more information and others may like no information. The design of the driver information system is difficult. Toyota has implemented a small color LCD screen in the middle of the dashboard in their HEV "Prius". The driver can watch the log of the fuel-consumption over five minutes in the past and instantly test the impacts of his driving style. Average fuel consumption and actual fuel consumption are displayed. One star is displayed for a certain amount of energy that has been recharged through regenerative braking. This encourages the driver to accelerate and brake smoothly rather than aggressively. The driver is encouraged for low-impact driving like in a game without ruling him. Another page on this display visualizes the actual work of the powertrain. The main information like speed, fuel-gage etc. is still in front of the driver. The displays in the Toyota Prius are a good example for an effective driver information system. It has been reported that drivers started having competitions about regenerative braking stars.

5.2 Input and Output Variables of the Energy Management

This chapter identifies all input and output variables that are required in order to perceive the strategies explained in section 5.1.

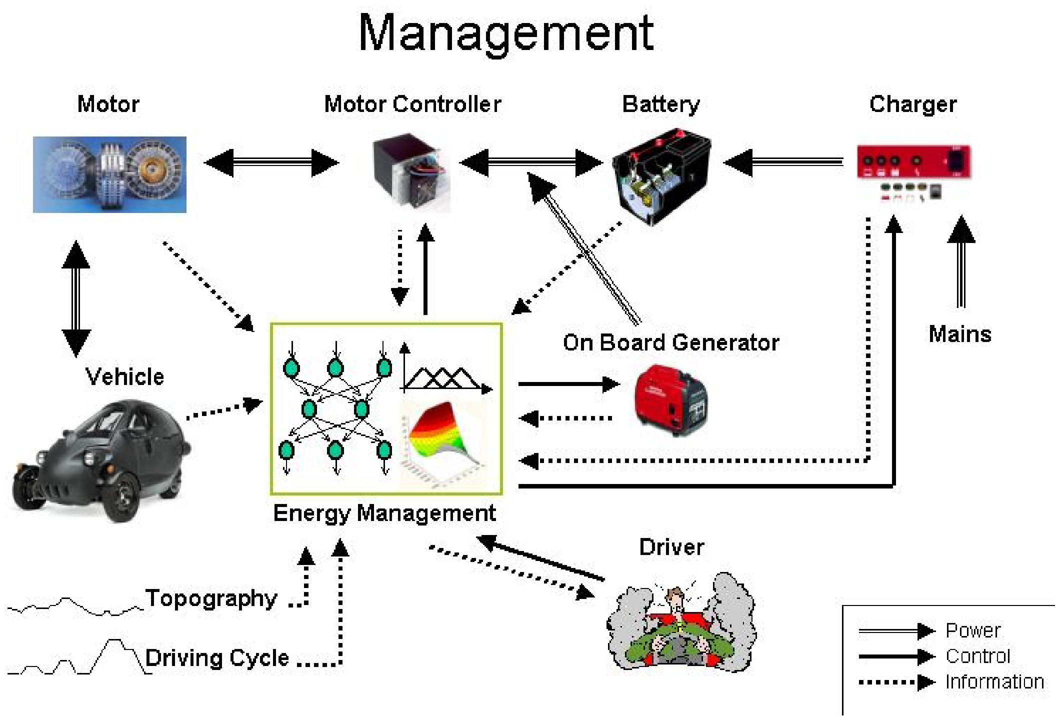

Figure 5-2: Visualisation of the Energy Flow and Management

Figure 5-2 visualizes the energy flow and the flow of information in the proposed drivetrain. The energy management is visualized in a centralized way in order to keep the figure simple. The topology is not defined yet. It is likely that the management responsibilities are distributed among several components. The following paragraphs identify the input and output variables and describe them in depth. Descriptions are as concrete as possible at this stage of the work and they are kept abstract but precise were available knowledge is not sufficient yet.

The acceleration pedal and the brake pedal are the conventional control instruments for the **driver**. Further instruments need to be implemented in order to give the driver a better control over the drivetrain behaviour: start of the engine can be overridden in case the driver wants immediate full power and stop of the engine can be overridden if the driver desires silence. The driver can enter his preferred strategy: between "very relaxed" and "aggressive" as defined in section 5.1. The output to the driver is subject to the design of an appropriate driver information system. The driver can enter his desired destination and once he has done so – for example through speech-recognition – the system can work out the best route and the **topography** of this way. The **driving cycle** can be estimated depending on the streets to be driven on, the traffic information and the preferred driving style. The energy management system calculates the estimated power requirements on the route and the estimated total

energy consumption. This helps the system to determine if or when to start the engine and how to maintain the battery SOC.
The vehicle needs to provide information about the speed and the position for calculating the energy consumption and the remaining distance. These values help determining if and when to start the engine.
The **motor and motor-controller** provide information about motor speed or voltage, motor torque or current and motor temperature. This helps exploiting the full capabilities of the motor including over-torque capabilities without damaging it. The control variables are direction of rotation, drive / regeneration mode, desired torque.
The following inputs are measured at the **battery**: cell voltages, temperatures and battery current. Battery state of charge (SOC), state of health (SOH) and actual input/output power capabilities are calculated. The charger and the motor controller are controlled with regards to the battery parameters and states. Cell equalization and an active battery temperature control can be required under certain circumstances.
The **generator** provides feedback whether it has been successfully started. Measurement of output power or current is not essential. Engine speed needs to be measured and controlled, because it could exceed the limits in case of sudden drop of output current. Start/stop and power demand are controlled through the energy management system.
The **charger** provides information whether it has been plugged into the mains and about the charge current. The charge current is almost equal to the battery current, which is already measured, but the charger current reaches much lower values and it is sensible to measure it separately from the battery current for higher precision. The charger output power is controlled from the energy management.

Component	Input variable	Output variable	Remarks
Driver	Acceleration pedal Brake pedal Engine off/on/auto Strategy Desired destination	Several information	Output visualization requires proper design
IT	Topography Driving cycle Traffic information		Driving cycle derived from street information and traffic information
Vehicle	Vehicle speed Vehicle position		
Motor/controller combination	Speed or voltage Torque or current Temperature	Direction Drive/regen. mode Desired torque	
Battery	Cell voltages Cell temperatures Battery current	Cooling/heating Equalization	SOC, SOH and actual power capability are calculated
Engine/generator	Operation feedback	Start/stop Power demand	
Charger	Mains connection Charger current	Output power, current or voltage	

Table 5-2: Input and Output Variables to the Energy Management

5.3 Summary – Drivetrain Management Requirements

The basic management requirements are defined, but further work can to be done in order to answer the following questions:

1.) Is it more efficient to run the engine in its operating point of maximum efficiency and switch it on and off several times in order not to overcharge the battery or is it more efficient to run it in less efficient lower power regions but continuously? What about noise and pollution in these different strategies?
2.) When should the engine be idling and when should it be switched off instead?
3.) How can the engine be controlled in order to cope with sudden decline in power requirements? This could happen if the driver quickly releases the acceleration pedal. The engine needs to be throttled down quickly in order not to charge the battery with excessive currents and to prevent the engine from exceeding its speed limit.
4.) How does the preferred strategy effect the energy consumption and other impacts?
5.) How to estimate the driving cycle and the required energy for a journey depending on strategy, topography, street-information and traffic information? How important is which kind of information?
6.) How can the drivetrain operation be determined based on the information mentioned in 5.)? This needs to be specified in more detail.
7.) Under what circumstances is battery cell equalization essential and how powerful does it need to be?
8.) Under what circumstances is an active temperature-control of the battery essential?

The different strategies mentioned in Table 5-1 need to be concretized and described more precisely. The management topology needs to be defined. Possible management objects within the energy management could be:

- Battery management
- Fuel-converter management
- Propulsion motor management
- Information management
- Drivetrain management

The distribution of management tasks and the communication between these objects need to be specified. The technical requirements of control tasks like resolution and speed need to be determined.

6. Description of the Hardware

This chapter describes the design of the hardware in the research vehicle. The research vehicle is a converted Ford Fiesta MkII, the drivetrain that is implemented is described in chapter 4.5. The actual state of implementation and future scope of work are discussed in the following sections. The design is based on some general criteria:

- Cost effectiveness
- Time effectiveness
- Adaptability and Capability for Development
- Accessibility for ease of monitoring and maintenance
- Reliability and Safety

Cost effectiveness and **time effectiveness** are essential criteria in this project due to limited budget and man-hours. The estimated cost for the research vehicle is under £10,000 in total. The project has to be finished within one PhD project (three years) by one man. This includes time for catching up with state of the art, theoretical work, practical work, developing public relations and writing thesis. It is supported by undergraduate students within their final projects and technicians in a workshop at an additional cost.
The following is the strategy that is adopted:

- Neglect certain design criteria like beauty and vehicle functionality.
- Use off-the-shelve products where possible.
- Start with a simple design that can be extended and developed further at a later stage. This avoids purchasing expensive products that are not necessary. The equipment just meets the requirements.
- Adopt a modular design with modules that may be useful for future projects. This may increase purchase cost and time for development, but it is more efficient in the long term.
- Keep a record of expenses or time for different tasks. This contributes to the project management and supports decisions for and in future projects.
- Write down the design ideas, their implementation and their success or failure. This increases the value of the work.

The developed hard- and software have two main functions: Providing and storing information about the drivetrain behaviour and managing the drivetrain (energy management). Research questions and management requirements are uncertain in the actual state of the project. Modularity is the strategy adopted in order to make the hardware **adaptable** to other management requirements. It makes it **capable of development** for future research investigations.

Components and information (measurement points, interfaces) must be easily **accessible**. Changing components may be necessary and research may require some unexpected measurement or control.

Reliability and **safety** are not the main criteria in this research vehicle. The car does not need to last for 100,000 miles. But it should provide reliable data. Brake-downs during tests can make data non-usable. Considering safety criteria is essential to run the car on public roads.

6.1 Electrical Architecture in the Research Vehicle

The vehicle is a standard Ford Fiesta MkII that has been converted to a pure electric vehicle by Lynch Motor Company. The original 12V electrical system remained in the vehicle and the new electrical system is added in overlay architecture.

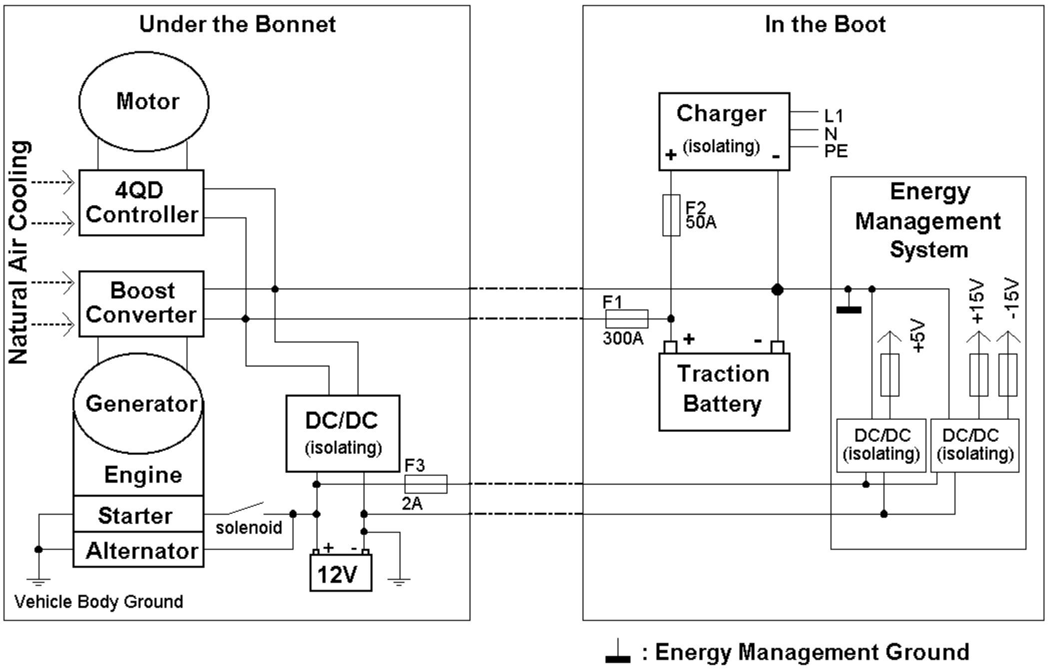

Figure 6-1: Electrical Systems in the HEV

Figure 6-1 shows these two electrical systems. The original 12 V battery is recharged from the traction battery through a DC/DC converter. This DC/DC converter is switched off when the vehicle is parked to reduce energy losses through overcharging and losses in the DC/DC converter. The turnkey switches the converter on and off. The DC/DC converter charges with small currents (5 A) if compared with a conventional alternator (60 A). This can cause deep discharging of the 12 V battery if the car is not operated for several days. This is very likely to happen especially if the battery is old (high self-discharge and high overcharge losses) and the car is used in short-distance driving only. The DC/DC converter should additionally switch on if the 12 V battery voltage is low and the traction battery has sufficient state of charge.

The 12V battery minus is connected to the vehicle body in the conventional electrical system. However, the traction battery has a much higher voltage: up to 77 V in this case. The high-voltage system is isolated from the vehicle body in order to reduce the risk of electrical shock, short-circuits in the high-voltage system and leakage currents. This requires an isolating DC/DC converters and additional cables for the traction battery ground.

The energy management system requires three different voltages: +15 V, –15 V and +5 V. The ground (0 V) for this system must be connected to the traction battery minus as a reference for measuring voltages (potentials) in this system. The voltages could be generated from the traction battery through simple non-isolating step-down converters with common ground. This would reduce cost in production vehicles. For this prototype it was easier and cheaper to generate these voltages from the 12V system using isolating DC/DC converters.

All uncontrolled electrical power sources – the two batteries – have been fused according to the designed current in that circuit to prevent risk of fire. The motor (in regeneration mode) and the generator act as electrical power sources and the controlling circuits (four quadrant controller and boost converter) must incorporate current limiting features. They must be located close to the motor and the generator to reduce any risk of short-circuits between the generating device and the controlling device, because current is not limited or fused in this connection.

The engine is a standard scooter engine. It comprises a 12V starter and an alternator without additional cost for this prototype. They are connected to the 12V vehicle system without any fuse like in a standard scooter or car. The alternator recharges the battery when the engine runs. Production cost would come down, if the alternator is not implemented and the 12V battery is recharged only through the DC/DC converter. Further cost reduction is possible if the engine is started through the generator without an additional starter motor. If the engine is started from the generator that is connected to the high voltage system, the 12V vehicle system does not need to provide the high starting power. The 12V battery becomes redundant. This would reduce cost and weight. It needs to be investigated, what peak power and continuous power is necessary within the 12V system for specifying the DC/DC converter.

The proposed drivetrain requires high currents of up to 600 A peak or 400 A continuous. Number of connections and cable length between the high current components (motor, generator, power electronics, fuses and battery) are reduced to a minimum in order to reduce losses. Analysis of the share of these losses should be undertaken. A better design of components with bus bars can reduce the number of connections and the losses.

Figure 6-1 shows that some components of the drivetrain are placed under the bonnet and some are placed in the boot of the car. This requires comparatively long high current cables. These cables increase cost, weight and losses. Motor, generator, engine and power electronics are noisy, produce exhaust or require cooling. They are located under the bonnet. The battery does not easily fit under the bonnet together with these components. The Energy management and the charger should be located close to the battery because of several connections in the prototype state. They must be easily accessible and not exposed to humid, hot or vibrating conditions.

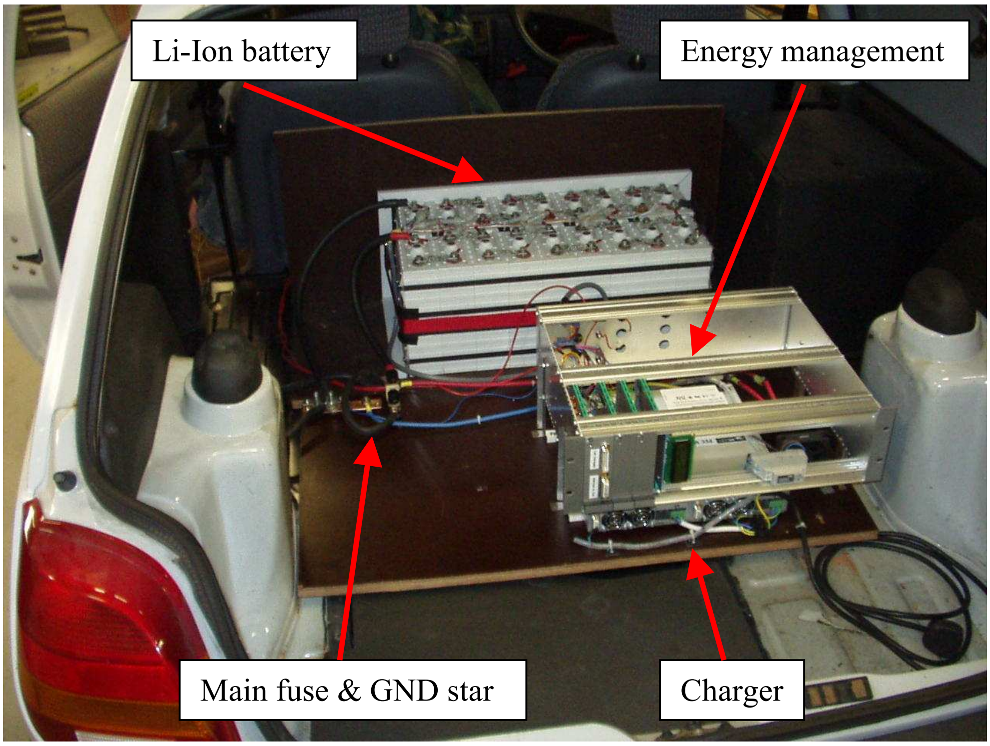

Figure 6-2: The Boot of the Research Vehicle

Figure 6-2 shows that battery, energy management, fuse and charger are placed in the boot of the vehicle. They are easily accessible, protected against humidity, heat, cold, and shock and they are close to each other in this place. The charger and management system would be small and sealed in production vehicles and could be placed elsewhere. The battery would fit under the bottom of the vehicle like a spare wheel. All shown components would vanish completely out of sight; the cargo space would be comparable to any modern car with conventional drivetrain.

Still it is likely that the battery would be located remote from the motor and generator because of space and better weight distribution. Long high current cables with all their potential problems (cost, weight, losses, inductance and EMI) will be required like in the research vehicle. That means, the research vehicle design and its problems are comparable to the potential production vehicle design. Alternative vehicle designs should be considered in case of severe problems.

6.2 Hardware Structure of the Energy Management System

The energy management is centralized and located in the boot of the car as discussed before. The centralization makes changes and adaptations easier, because all data come together in one processor. Only the software for one microprocessor needs to be changed.

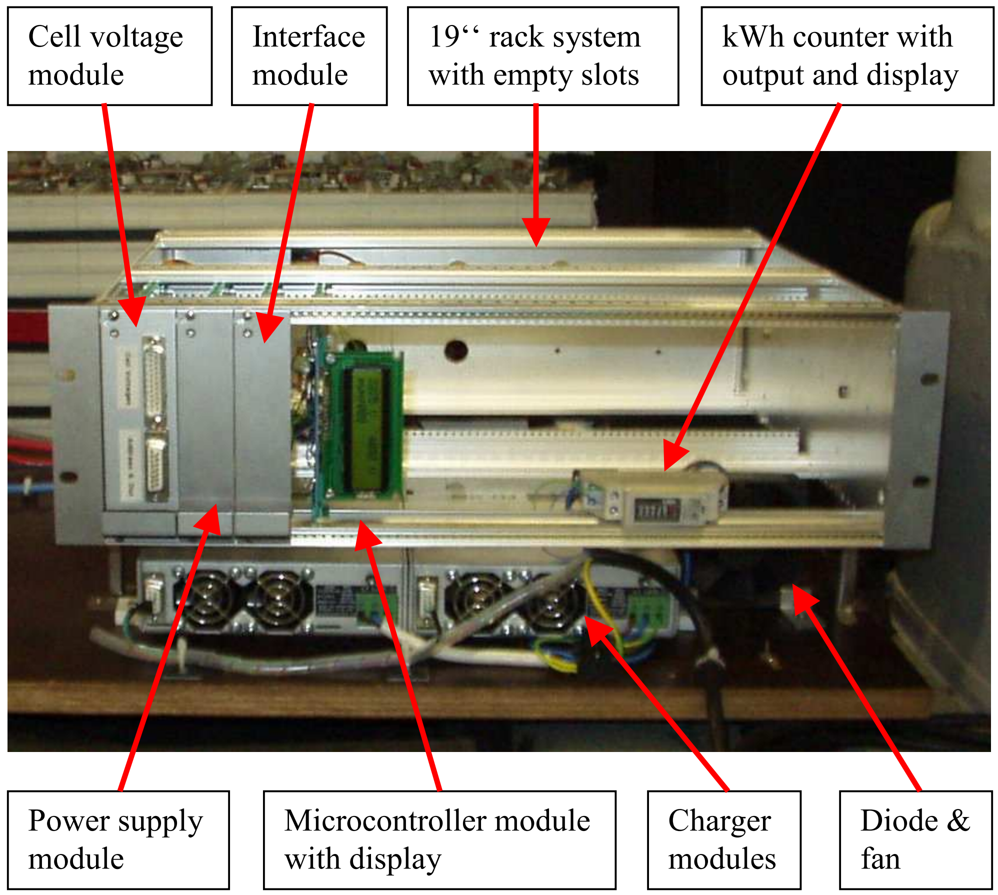

Figure 6-3: Energy Management and Charger in the Boot of the Vehicle

Figure 6-3 shows the energy management and the charger in the boot of the vehicle. All components except the battery are mounted on a wooden plate and can be taken out in one unit with a few simple connections. The battery is mounted on a separate wooden plate. The energy management sits in a 19’’ rack system. This rack is mounted on top of the charger modules and the charger diode with its fan. An energy counter is mounted in the rack system. Modules containing prototype board in Euro format slide into 32 way or 64 way connectors in the middle of the rack. These connectors are gold plated to withstand vibrations and increase reliability. Connectors, switches and displays can be mounted in the front of the modules. The width of the front can be chosen according to the requirements and modules can contain more than one board. The rack is open on top and bottom. Closures, dust covers and EMC-kits are available and can be implemented later if necessary.

Figure 6-3 shows the front of the four modules that are implemented so far. There is plenty of space for further modules this gives room for further development of the system.

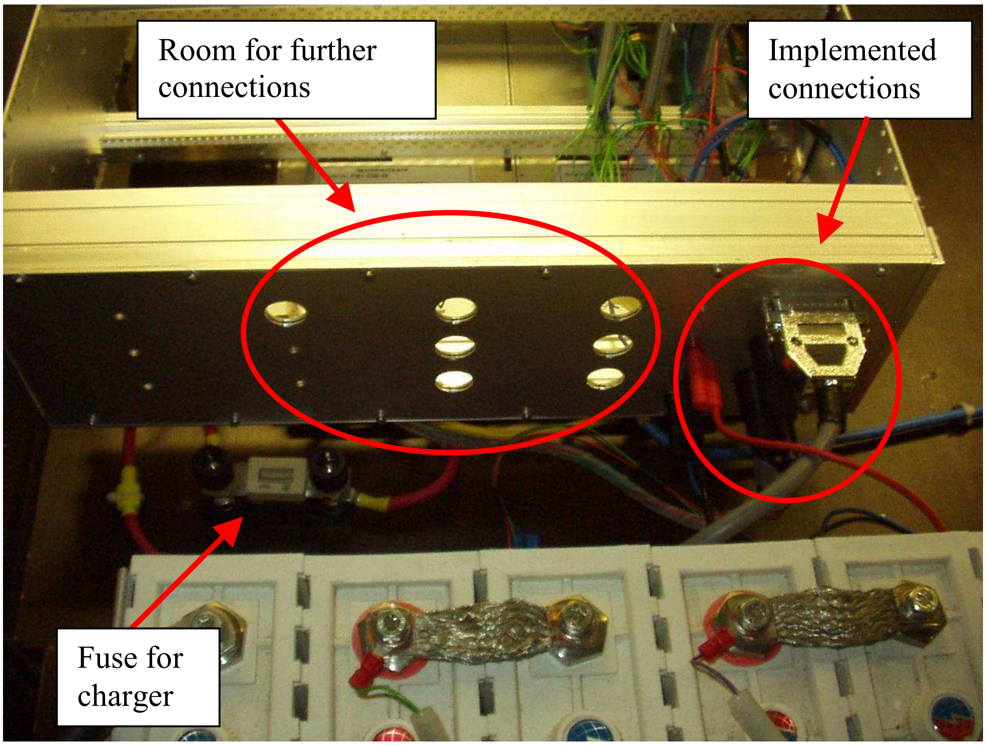

Figure 6-4: Connectors in the Back of the Energy Management

Figure 6-4 shows the connectors in the back of the rack. Several holes for further connectors are already drilled. The connectors allow fast and easy disconnection of the energy management rack or the whole wooden plate. The module connectors inside the rack and the connectors at the back are wired. The module connectors with their 32 or 64 ways are available for wire-wrap technology or for soldering. Cables are soldered to the pins of the connectors and protected with small heat-shrink in the prototype. It is recommended to invest in wire-wrap technology instead. The connections are more reliable, require no soldering skills and are much faster to make.

The 19’’ rack system offers modular design. Many options, kits and system are available. It is expensive but most of it can be reused in future projects.

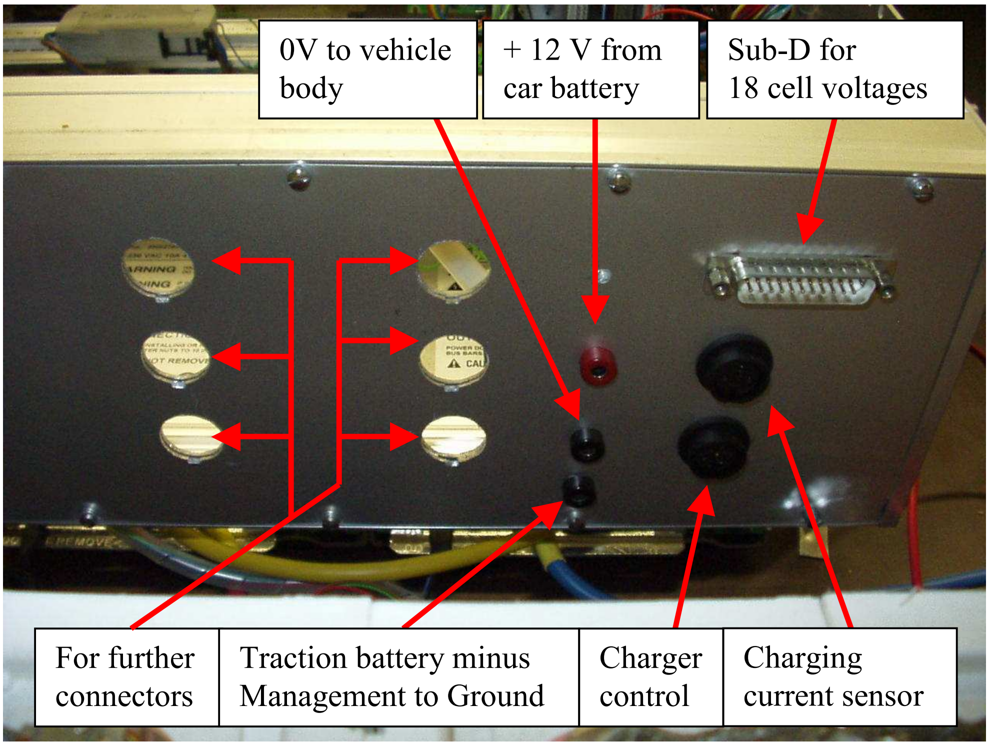

Figure 6-5: Connectors at the Back of the Energy Management in Detail

Figure 6-5 shows the back of the rack with the connectors in detail. Three single plugs are used for the 12V power supply and the battery ground. One Sub-D connector connects all eighteen battery cells to the management for the cell voltage observation. One connector with three pins connects the LEM current sensor for the charging current and one connector with 7 pins connects the charger and the kWh-counter with the energy management. Further holes are prepared for connecting current sensors, temperature sensors and for controlling motor, engine, generator and fans when necessary. Cost effective connectors are chosen that do not require expensive tools. All connectors use a lock mechanism.

Sub-D connector types are chosen for high pin-numbers, because of their low price. They are secured with screws. Amphenol CO91B DIN connectors are chosen for up to 9 pins per connector wherever possible because of their low price. They are secured with a bayonet. Round connectors like those are easier to mount, because just a hole needs to be drilled and no shape needs to be punched. This saves time and money.

Figure 6-3 shows the charger module and four implemented modules in the 19'' rack:

- The power supply module
- The cell-voltage observation module
- The micro-controller module
- The interface module

They are described in the following sections.

6.3 The Power Supply

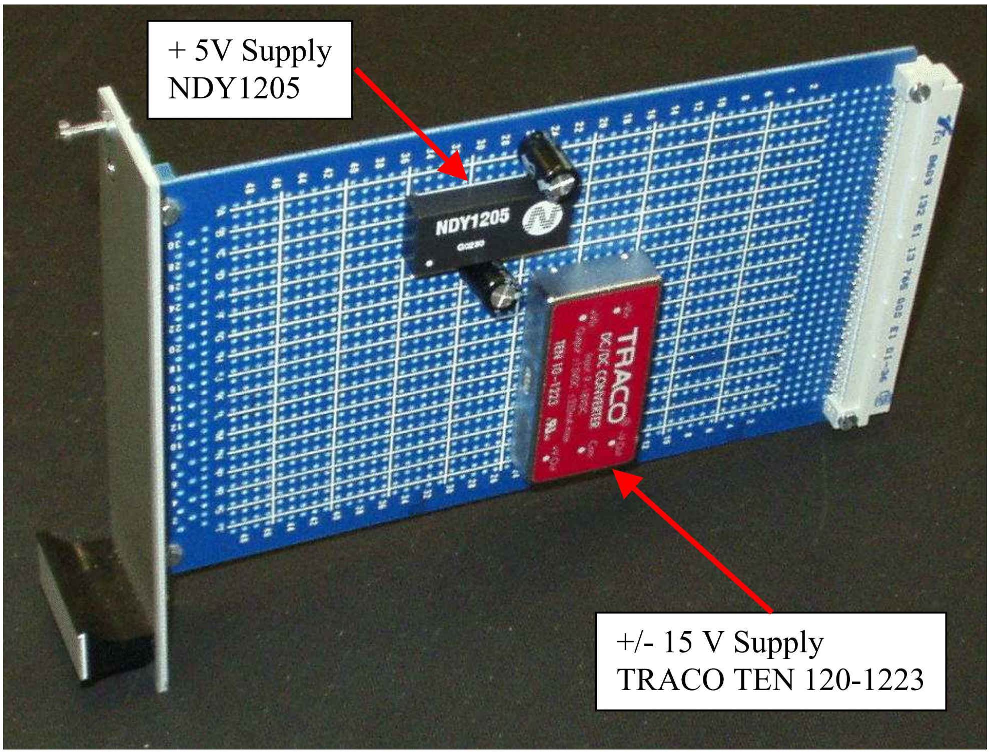

Figure 6-6: The Power Supply Module

Figure 6-6 shows a picture of the central power supply module with two DC/DC converters. The power supply for the energy management is fed from the vehicle 12 V system. It needs to be isolated as mentioned in 6.1. Isolating DC/DC converter in HF-switching technology are expensive and cost are not linear to their output power. One central power supply module is cheaper than smaller power supplies for each module.

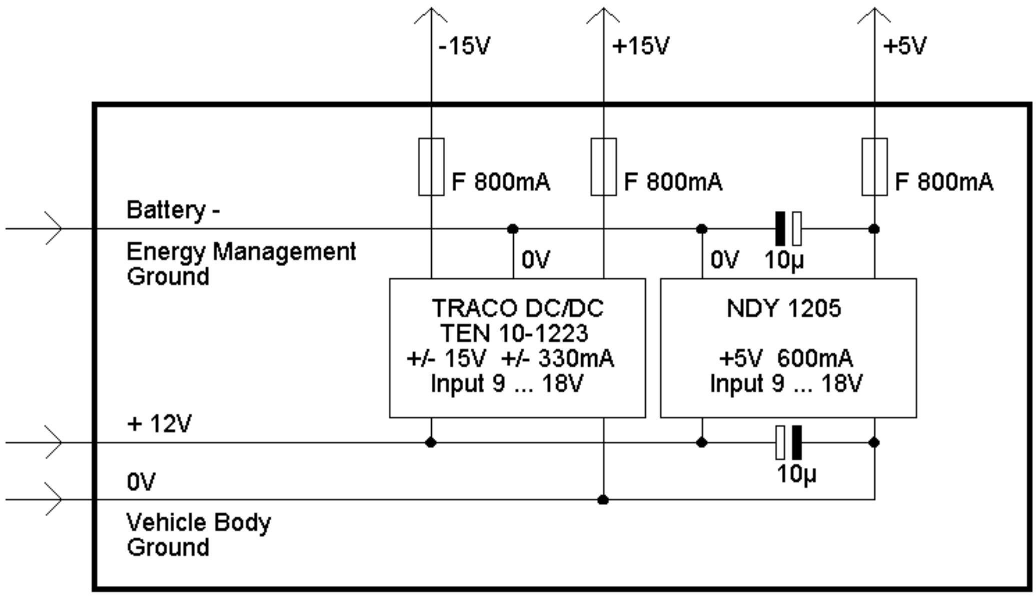

Figure 6-7: The Power Supply Module Circuit

Figure 6-7 shows the circuit of the power supply. Three voltages are required for most of the electronics: ± 15V for operational amplifiers, instrumentation amplifiers and LEM current sensors and + 5V for microprocessors and other electronic devices. If other voltages are required like + 12V or a high precision voltage reference for A/D converters they can be obtained from these three voltage by using simple voltage regulators with common ground.

The required current is estimated in order to determine the power specification for the DC/DC converter: 200 mA are required for four LEM according to the datasheet plus 24 mA for the cell voltage measurement module (measured). A DC/DC converter (TRACO TEN 10-1223) with ± 15V and ± 330 mA (10 W) is chosen to provide headroom of about 100 mA for future developments. The current required for the micro controller (Technosoft IMMC240 DSP card) is 110 mA at + 5 V. The NDY 1205 with + 5 V and 600 mA is chosen, because it is the isolating DC/DC converter with smallest available power and acceptable price. Both DC/DC converters provide a wide input voltage range in order to cope with the voltage range of the 12 V car systems. It can between +9 V and +14.4 V. The input voltage range of the NDY and the TRACO is 9V … 18V. The DC/DC converters comprise current limit and over temperature protection. In addition all voltage outputs are fused with fast (F) 800 mA fuses. This helps finding faults.

The ground and supply wires are connected to common points on the 32 way module connector in order to minimize EMI problems. Suitable bus bars need to implemented in the rack system for ease of connection to these supply voltages.

6.4 The Charger

The proposed HEV drivetrain requires recharging of batteries from the mains power supply. The manufacturer of the implemented Li-Ion battery recommends a certain charging algorithm, but in order to make the hardware versatile, it was assumed, that other batteries require different algorithms. Usually the following data are required to control the charging process:

- Time
- Battery temperature
- Battery or cell voltages
- Charging current

Some algorithms require taking into account the accumulated or differentiated measures of some of these data like ${}^{dV}/_{dt}$ or charged Ah in proportion to discharged Ah. Charging of Li-Ion batteries requires great care in order to prolong the battery life and to prevent risk of fire due to overheating or overvoltage and build up of lithium metal. The voltages of all eighteen cells need to be monitored separately. The charger therefore needs to be significantly 'intelligent' and several values like battery temperature or cell voltages are required for the energy management not only during charging but also whilst driving and regenerative braking.

The intelligence for the energy management during driving and for charging is merged and centralized in only one but more powerful micro controller in order to keep the system simple and adaptable to changes. The power electronics for charging is a separate module. It consists of an AC/DC converter that is controlled from the central energy management.

This section describes the AC/DC converter hardware. The following criteria have been considered when searching for suitable products in the market:

- Output voltage between 46.8 V and 76.5 V
- Output current up to 30 A continuous
- Output voltage safely controllable through simple interface
- High efficiency
- Small and lightweight design
- Preferably off-the-shelve product
- Affordable
- Rugged design

No product meets these criteria. The solution is connecting two VICOR PFC Mini with 48V 30A in series. The PFC Mini is a 1.5 kW controllable AC-DC power supplies in lightweight and efficient HF-switching technology. The efficiency typically exceeds 80 %.

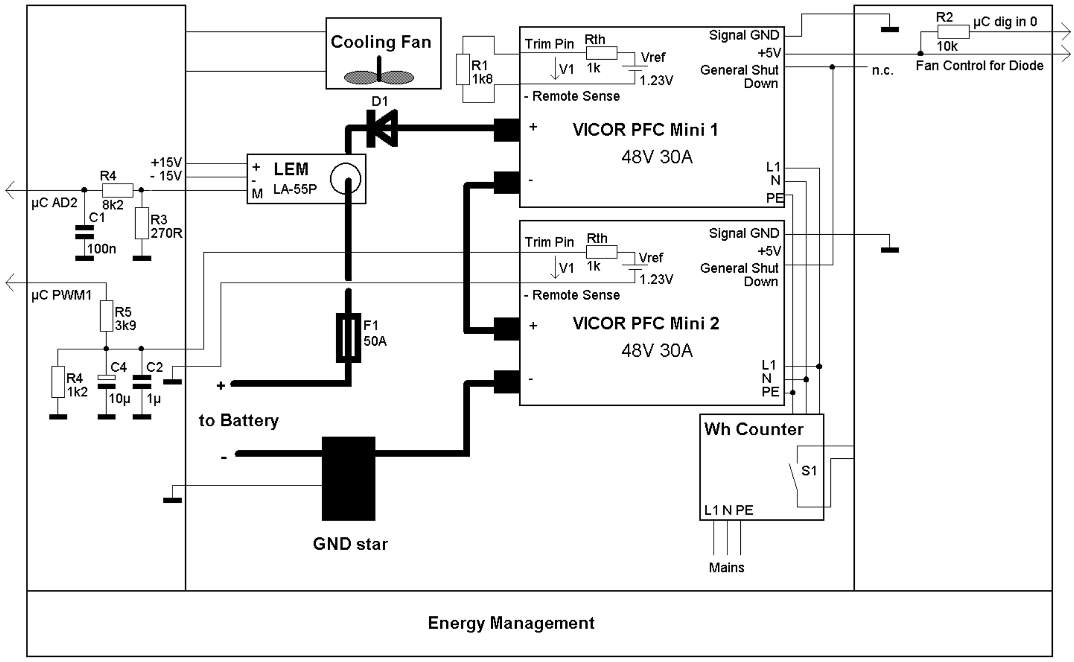

Figure 6-8: The Charger Circuit Diagram

Figure 6-8 shows the series connection of these two VICOR modules. The diode D1 adds losses but is necessary to prevent overvoltage on one of the PFC Minis. The battery voltage is not equally divided between the two modules and it is likely that the full battery voltage is applied to one of them only – especially during switching on and off. This would damage the output stage. The diode D1 prevents this. It is cooled with a fan that is controlled from the energy management.

Both PFCs provide a +5 V voltage supply output if connected to the mains. One of them is used to indicate to the energy management whether the charger is plugged in the mains or not. The fan for the diode is controlled directly with this signal without going through the micro controller and software. The general shut down inputs are connected to the energy management but they are not used so far.

An energy counter (SWHM 12 from ZSG) is connected between the mains and the charger. The electrical energy consumption of the car can be measured either directly by reading the display or by connecting the counter to the energy management through its opto-isolated interface.

The output of the charger is fused with a 50A fuse before it is connected to the battery. A LEM LA-55P senses the charging current for the energy management. The manufacturer of the PFC Minis (VICOR) suggests a certain circuit for connecting two of them in series and controlling the total output voltage. The suggested circuit helps sharing the power between the two modules equally to assure a similar lifetime. This circuit has been tested and does not work for battery charging: The proposed circuit requires a certain load. This load is not sufficient when powering up the charger and also towards the end of the charging algorithm. The PFC Mini 1 is set to a fixed output voltage and PFC Mini 2 is controlled from the energy management instead.

The “Trim Pin” and the “– Remote Sense” pin of the PFC Minis control the output voltages. V1 is the voltage between these two pins called “input pins” in the following paragraphs. Figure 6-8 shows the equivalent internal circuit of the charger modules. V_1 equals to V_{ref} if no resistor or voltage supply is connected to the input pins. The output of each PFC is the nominal voltage (48V) in this case. X % increase or decrease of V_1 leads to X % increase or decrease respectively in the output. The PFC Minis can be controlled with either a resistor or a voltage supply connected to the input pins. A resistor R_1 is used to set PFC Mini 1 to a fixed output voltage. The following equations apply:

$$V_{out1} = 48V \cdot \frac{R_1}{R_{th} + R_1}$$

$$R_1 = \frac{R_{th} \cdot V_{out}}{48V - V_{out}}$$

The output voltage of PFC Mini 1 should be set to half of the average battery voltage during charging. This shares the power equally between the two PFCs. The average battery voltage during charging is about 4.0 V per cell or 72.0 V for the whole battery pack of 18 cells.

$$\mathbf{V_{out1} = 36\ V \text{ and } R_1 = 3\ k\Omega}$$

The PFC Mini 2 is controlled with a voltage. A PWM output of the micro controller in the energy management is connected to a combination of a voltage divider and a RC - low-pass filter to the input pins of PFC Mini 2 as shown in Figure 6-8. The micro controller control-voltage is between:

$$V_{PWM,min} = 0V \leq V_{PWM} \leq 5V = V_{PWM,max}$$

This controls the output voltage of PFC Mini 2 between its desired maximum and minimum output voltage:

$$V_{out2,min} \leq V_{out2} \leq V_{out2,max}$$

The total output voltage of the charger can be controlled between:

$$V_{out,min} = V_{out1} + V_{out2,min} \leq V_{out} = V_{out1} + V_{out2} \leq V_{out1} + V_{out2,max} = V_{out,max}$$

The battery voltage can reach values between:

$$V_{bat,min} = 46.8\ V \leq V_{bat} \leq 76.5\ V = V_{bat,max}$$

With V_{out1} = 36 V the PFC Mini 2 must at least be controllable between

$$V_{out2,min} = 10.8V \leq V_{out2} \leq 40.5V = V_{out2,max}$$

Taking into account the voltage drop over the charging diode D1, the 50A fuse and the wiring (2V) as well as 10% error (4V), the PFC Mini should at least be controllable between:

$$V_{out2,min} = 10.8V \leq V_{out2} \leq 46.5V = V_{out2,max}$$

$V_{out2,min}$ is not crucial because battery reaches $V_{bat,min}$ during discharging but not during charging. The controllable range of V_{out2} should not be too wide because this would decrease the resolution of the control. Resistors in Figure 6-8 are chosen:

$$\mathbf{R4 = 390\ \Omega \text{ and } R5 = 1.2\ k\Omega}$$

The total output voltage of the charger with these values is:

$$\mathbf{V_{out,min} = 48V \leq V_{out} \leq 84V = V_{out,max}}$$

6.5 Cell-Voltage Observation

The Li-Ion battery requires single cell-voltage observation for safety reasons. Either a distributed bus-system or a central data acquisition is possible. See 2.5.2 for more information. The battery voltage is comparatively small in the proposed drivetrain. The eighteen cell voltages are measured centrally because less development time is needed if compared with the bus-system. Figure 6-9 shows this central cell voltage measurement module that slides into the 19'' rack of the energy management system. This module selects the cell voltage that is to be measured with one A/D converter input of the micro controller in accordance to the address given by the micro controller.

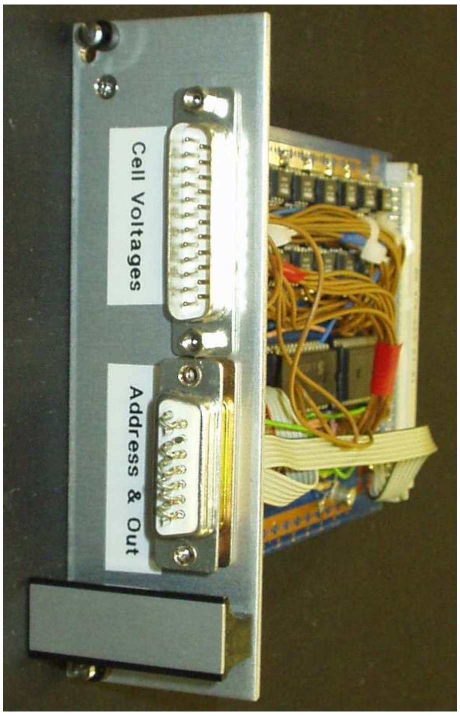

Figure 6-9: Central Cell Voltage Measurement Module

A multiplexer (MUX) is required in order to measure the 18 cell voltages with only one A/D converter input of the micro controller. Instrumentation amplifiers (INA) are required to measure the potential difference across the battery cell with the non-differential A/D converter input. Two options have been reviewed:

1. MUX first and one INA afterwards. This requires multiplexing 18 differential inputs with voltages of up to 77V. Only one standard INA afterwards is required. Supertex offers high voltage MUX and analog switches with up to 8 channels differential. Three of them are required and need to be addressed with a brake before make logic to measure 18 cell voltages.
2. 18 INAs first and one MUX afterwards. This requires 18 high voltage INAs and two 16-channel single-ended MUXs. The high-voltage INA117P is suitable for this job. It has a common mode input voltage range of ± 200V. The two 16-channel single ended MUX need to be connected for measuring 18 voltages.

Though the 18 INA117P are quite expensive, the second solution is chosen. For 18 cells it was cheaper and less time consuming, because no brake-before-make circuit needs to be designed. It is found, that cell-voltage observation is significantly cheaper for up to 16 Li-Ion cells in series: Solution one or solution two can be chosen. Solution two does not require expensive high-voltage INAs and solution one only needs a simple control-logic and cheap MUX. Solution one is probably preferable. Solution two is preferable above 16 cells due to cost reasons. The bus-system is recommended for high-volume production and batteries with more than 16 cells or prototype with more than 32 cells. Higher development time and cost pay off with less wiring complexity and higher modularization. Battery voltages exceeding 200 V make isolated bus-systems essential because the INA 117P is not capable of voltages higher than 200 V.

Figure 6-10 shows the circuit of this cell voltage measurement module in principle. Not all 18 paths are shown for simplifying the figure, but the working principle and all the features can be seen.

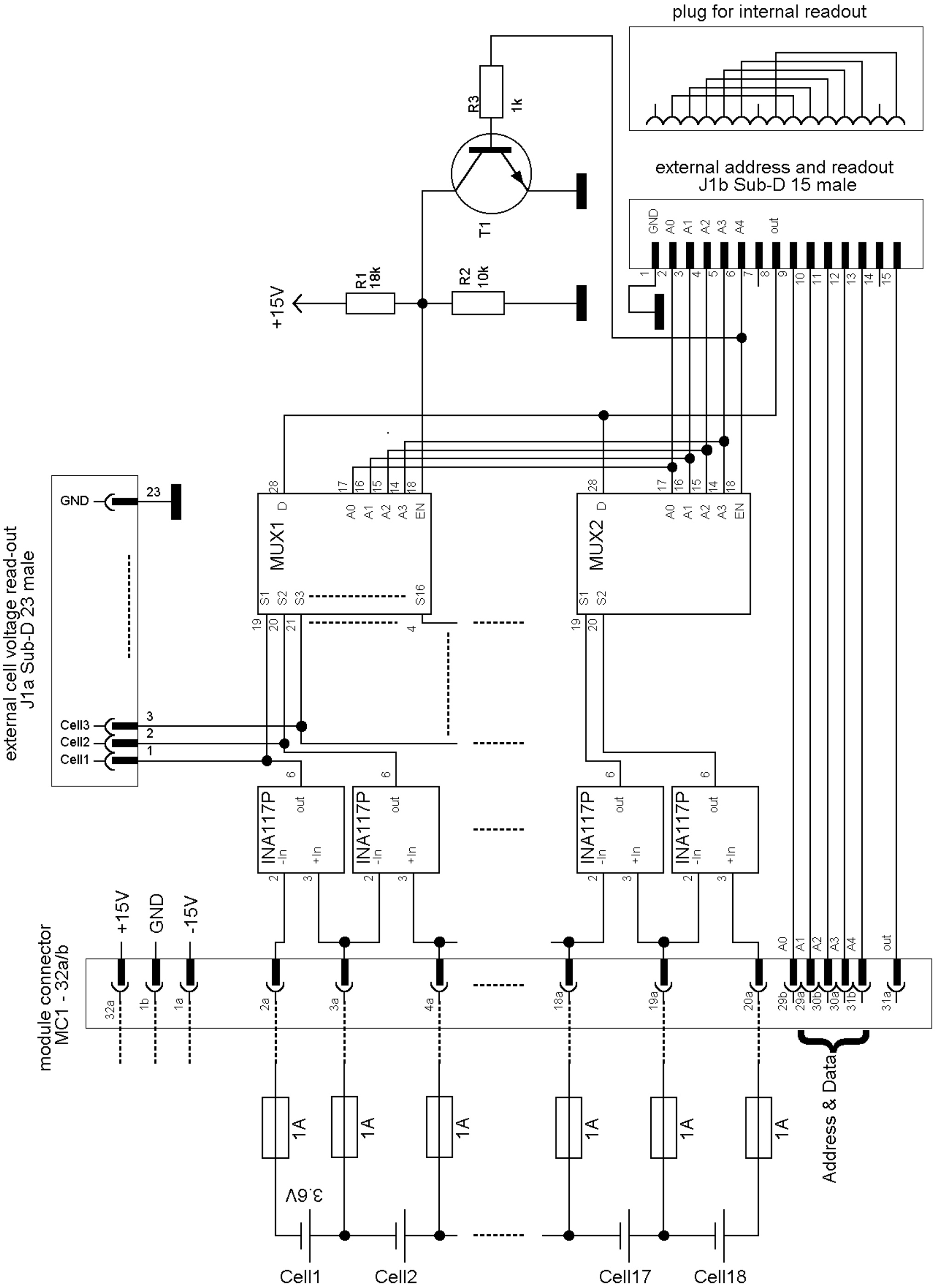

Figure 6-10: Circuit of Cell Observation Module in Principle

The circuit is described starting from the bottom (left):
19 wires are connected to the 18 battery cells with fuses (1A, fast) close to the battery to prevent fire in the cables. All these cables end in one connector that is connected to

the energy management as shown in Figure 6-5. This eases disconnection of the energy management. This connection is not shown in Figure 6-10 for simplifying reasons. Figure 6-10 shows the module connector (MC1) within the energy management. This connects the power supply for the cell voltage measurement module, the battery cell voltages, the addresses from the micro controller module for selecting the cell and its single ended cell voltage to be measured from the A/D converter in the micro controller.

The 18 cell voltages are fed into 18 INA117P. They provide 18 single ended cell voltages that have the same magnitude (multiplication factor of one) as their respective battery cell, but can be measured against the management ground (battery minus). These single ended outputs are connected to a plug (J1a) for external cell voltage read-out. A data recorder for example can be connected to this Sub-D plug that is shown in Figure 6-9 and labeled with "CELL VOLTAGES". These analog signals reach values between 0V in case of disconnection from the battery and + 4.25V in case of a fully charged battery cell. They are connected to two 16 channel single ended MUX (TEMIC DG 406DJ). A four-bit address (A0 … A3) selects one of the 16 channels of each MUX and a fifth bit selects MUX 1 or MUX 2. The transistor inverts the fifth bit so that MUX 1 is enabled when MUX 2 is disabled and vice versa. The resistors R1, R2 and R3 are chosen in a way that only one MUX is enabled at a time, even during fast switching transients. Using two MUX and this switching transistor extends the channels from 16 to 32. Only 18 are used in this circuit. The five-bit address and the analog MUX output are connected to another external Sub-D plug as shown in figure Figure 6-9. An external control or data acquisition circuit, for example a DSP-card in a PC can be connected to this interface. In case no external control is required, a short-circuiting plug as shown in Figure 6-10 is plugged in for connecting address and readout to the micro controller in the energy management.

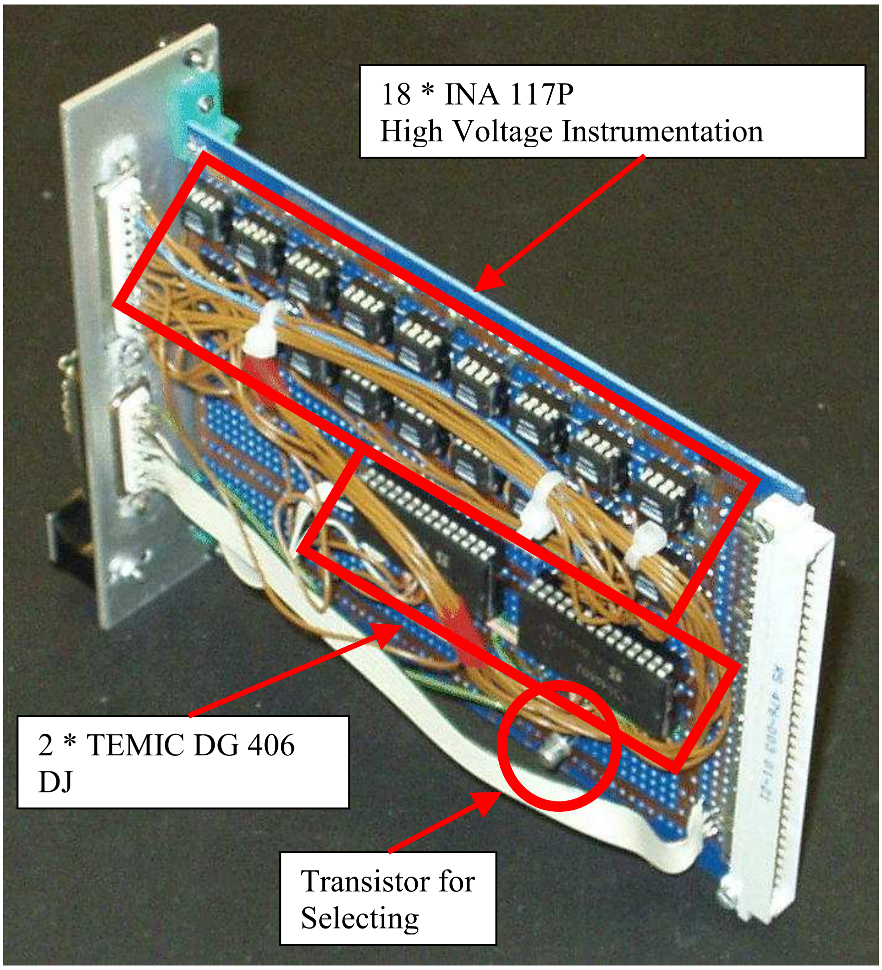

Figure 6-11: Layout of the Cell Voltage Acquisition Module

Figure 6-11 shows the front of the layout of the cell voltage acquisition module. The INA117P require a +15V, -15V and ground power supply as well as two tantalum capacitors, connected to ground each. Several pins need to be connected to ground. The MUX has a wide supply voltage range, but can be connected to +15V, -15V and ground as well. A special prototype board is used for faster development and more reliable and EMC conforming operation. The board features connection to the DIN 41612 connectors that is the standard in the 19’’ rack system. Main advantage is the three copper stripes for voltage supplies and a special design for integrated circuit prototype design.

Figure 6-12 shows the back of this PCB with the power supply stripes, the tantalum capacitors and several cable connections.

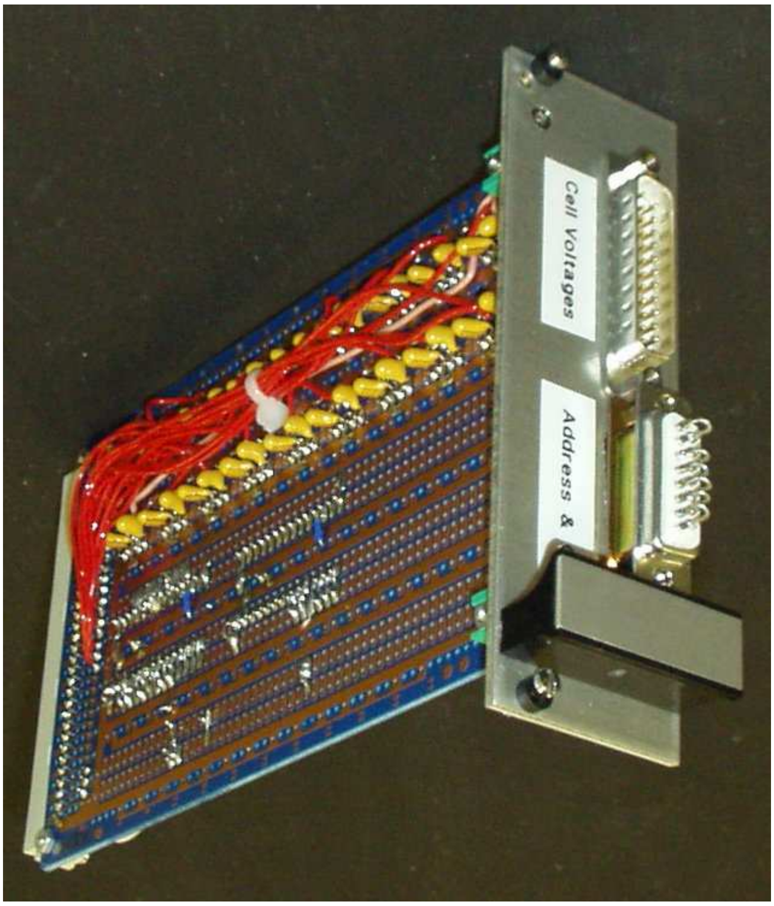

Figure 6-12: Back of Cell Voltage Acquisition Module

Soldering such a circuit without a PCB layout is very time consuming and requires great care. Designing a layout overcomes these problems. The time for soldering comes down but the time for development goes up. Total time is higher and the designed PCB is difficult to change later on. Integrated Circuits should be soldered directly without using sockets for higher reliability in series production, but this is not an issue in a prototype. Failure of integrated circuits is far more likely and sockets help repairing or changing the module. The connecting cables that can be seen in Figure 6-11 and Figure 6-12 can easily melt and short-circuit when being soldered. This circuit is tested after soldering and can be sprayed with PCB-layout plastic spray for conserving the state of functionality, but this makes any changes more difficult. The use of more expensive heat resistant cables with Teflon is recommended instead. This saves time during soldering and makes the circuit more reliable without prohibiting changes later on.

6.6 The Micro-controller Module

The energy management requires a powerful micro controller with many A/D converter inputs and PWM outputs. The micro controller is a module on its own within this energy management in order to keep the system modular. Another micro controller board can be designed and plugged in without changing other modules of the energy management. An interface to a powerful PC-based data acquisition and control system can be designed and substitute the micro controller.

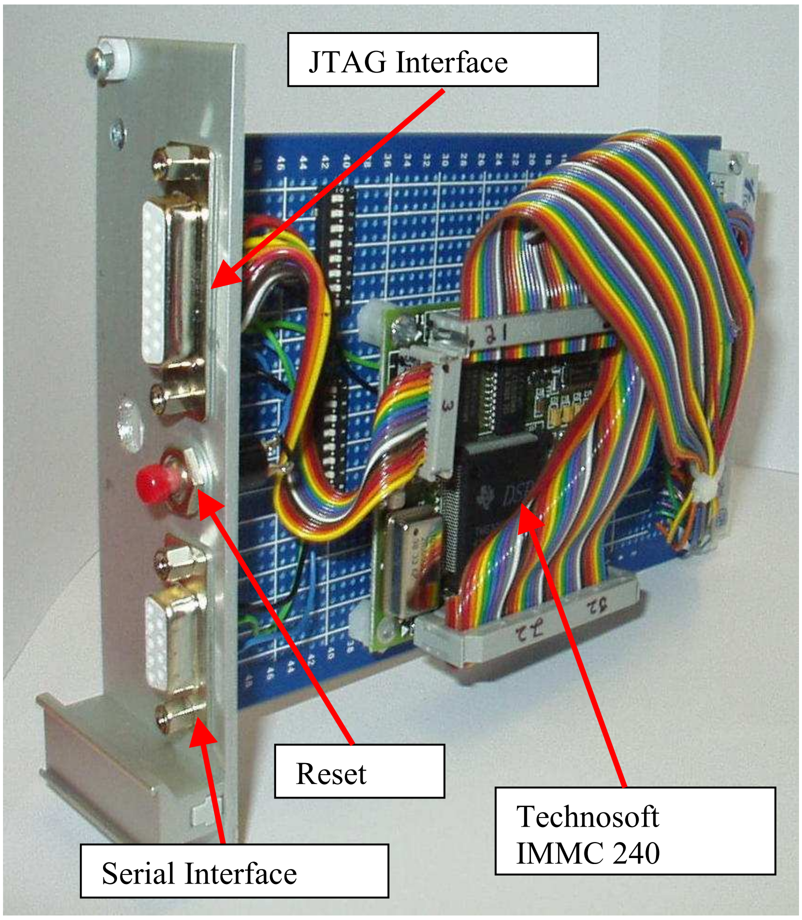

Figure 6-13: The Micro Controller Module with DSP Board

Figure 6-13 shows the micro controller module with the powerful Technosoft IMMC 240 digital signal processor (DSP) board. Other DSP or micro controller can be chosen, but the IMMC 240 is already available. The IMMC 243 would be more suitable because of its implemented CAN bus, but the CAN bus can be added on the interface module later (see 6.7) or the IMMC 243 can be plugged into the socket on the micro controller module and replace the IMMC 240 if necessary.

The RS-232 serial interface connector in the front of the module is implemented for communication and in-circuit-programming. The reset switch is necessary in case of reprogramming the controller or after stepping out.

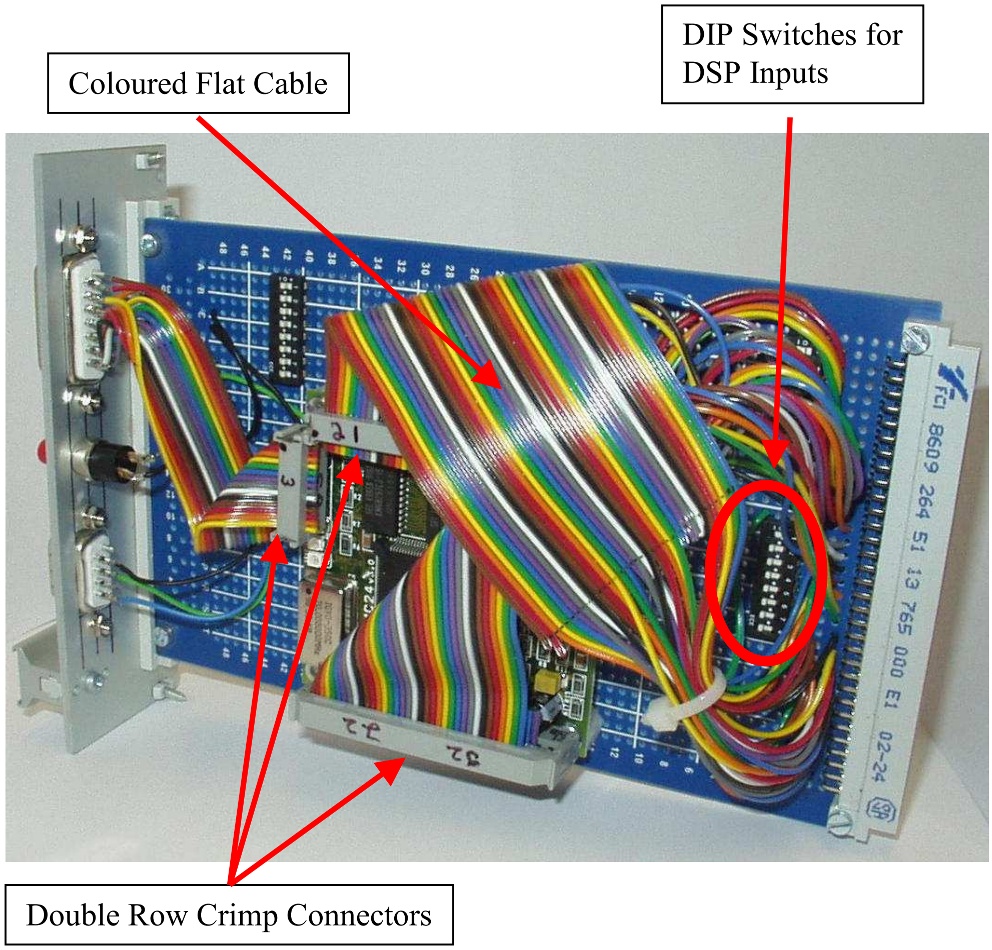

Figure 6-14: Design of the Micro Controller Board

The JTAG interface allows using a special emulator and specific programs provided by Texas Instruments. The IMMC 240 board with its Texas Instruments DSP provides:

- 6 PWM outputs
- 16 A/D converter inputs
- 16 digital I/O

Most of these I/O will not be used from the beginning but may be used later. Unused input pins must be connected to analog ground. DIP switches are implemented to connect or disconnect all inputs to analog ground in order to keep the system adaptable. Figure 6-14 shows the design of the micro controller board with these DIP switches. The IMMC board is not soldered into the board. It is just mounted instead and coloured flat cable with double row crimp connectors connect the IMMC board connectors with the JTAG interface, the DIP switches and the module connector. This helps changing the IMMC board in case of failure or in case the IMMC 243 with CAN bus is required. Flat cables with crimp connectors are the fastest way of reliably connecting the double row connectors of the IMMC board and the colours help to identify the signal paths.

The IMMC 240 is an expensive DSP. The first functions are implemented with a cheap PIC controller card as shown in Figure 6-15. It can slot into the energy management rack instead of the IMMC 240. The PIC is easier to program and the system can be tested without damaging the expensive DSP. Once the system works properly and/or the PIC is not powerful enough anymore, it can easily be substituted by the DSP module again.

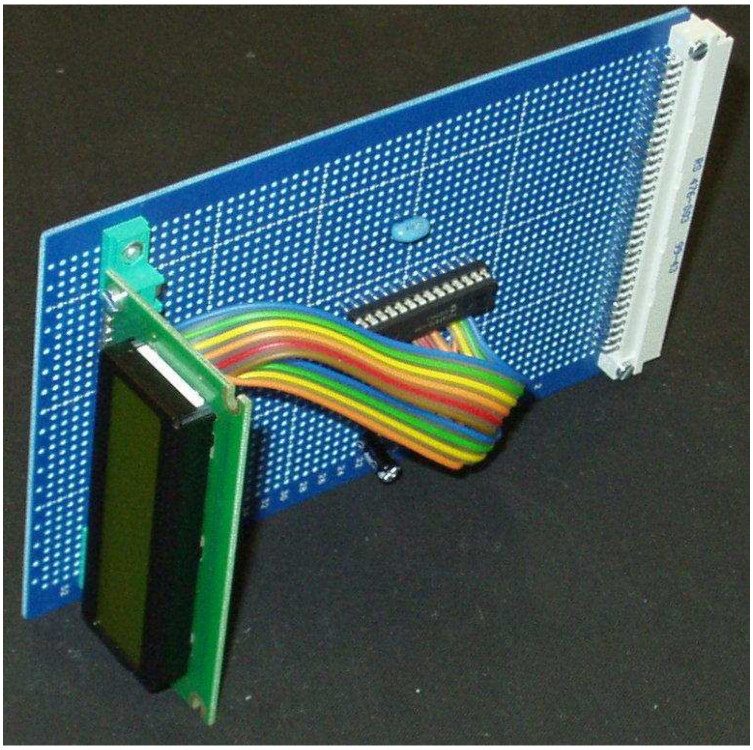

Figure 6-15: The Preliminary PIC Controller Card

6.7 The Interface Module

Most micro controllers make use of similar interfaces like

- A/D converter with 0V … 5V input range
- Digital I/O with 0V / 5V signal
- Communication interfaces without line driver

The interface module, shown in Figure 6-16 interfaces all signals from and to the micro controller cards. It converts all signals to one and the same standard, which is compatible with most micro controllers. Different micro controller modules or a PC based control can easily be exchanged thanks to this extra interface module. Other circuitries that do not suit to any of the other modules in the energy management system are implemented on this module as well, like for example the fan control for the charger-diode. Figure 6-16 shows that only a few circuits are implemented so far. Circuits can easily be implemented when needed thanks to plenty of room for development and use of a special prototype board. This board is used for the cell voltage acquisition module as well. See 6.5 for description. Most circuits on this board are for:

- Interfacing the LEM current sensors to the micro controller A/D converter
- Interfacing the micro controller PWM outputs to controlled modules like charger or motor controller
- Increasing fan out of digital controller outputs
- Isolating inputs or outputs

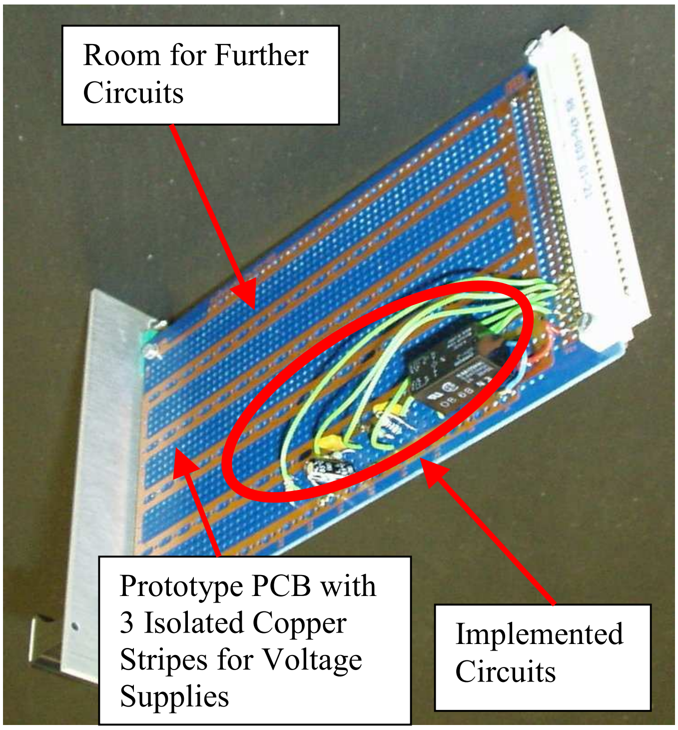

Figure 6-16: The Interface Module

7. Real-Driving Results

Real-driving results are not yet available for the proposed hybrid electric drivetrain, because the vehicle is still in its first stage of conversion:

- The electric motor is a small 11 kW Lynch motor. It will be replaced with a double Lynch motor with 21 kW. The small motor limits the continuous torque to non-satisfactory levels and this results in poor acceleration – especially on hills. The peak torque can be high but energy efficiency suffers in the over-torque region. This leads to high currents but still poor acceleration and gradeability. Frequent changing of gears is required in order to achieve acceptable gradeability, acceleration and speeds.
- The motor controller is a single quadrant standard Curtis with 400A (two minutes) and 200A (one hour) continuous rating. The double motor requires more power. A more powerful motor controller is required as well for good acceleration and short hills.
- The engine-generator is not implemented yet and this results in poor drivability in some conditions and lack of power on motorways.
- Regenerative braking is not implemented. It promises to return about one third of the propulsion energy during urban driving and a better battery performance.
- The battery and drivetrain management is not finished. Driving needs to be careful in order not to damage the battery.

Though the vehicle is still in this first stage, some impressions of driving results can be mentioned:

- The total electrical energy consumption has been measured using a kWh counter attached to the charger: 334.0 miles have been driven so far and 96.4 kWh have been recharged in order to manage this distance. This is an equivalent of 17.9 $^{kWh}/_{100km}$ or 140 mpg (british). Considering that regenerative braking is not yet implemented and that the car has been used in very poor circumstances like one trip of 5 km per week and recharging between all trips, this is a very good result. Available electric vehicles of this size like the Peugeot 106 require 20 $^{kWh}/_{100km}$. The better efficiency can be accredited to the lower battery weight.
- The Curtis controller controls the output voltage (speed of the motor) rather than the motor torque (current). The Curtis limits the acceleration by using a defined ramp in order to keep the currents low. This means the driver has no control over the acceleration – it is predefined in the controller! This gives the driver an impression of being slow. The acceleration pedal should control the current.
- The changing of gear ratios is required frequently – otherwise poor acceleration has to be accepted. The right time for changing the gear is difficult to determine by the driver because the motor is silent and the optimal strategy is different if compared with conventional vehicle technology. The time required for shifting is quite high – this will become worse with the double motor with its higher inertia. An automated gearbox or a CVT is required to enhance the drivability.

- The brushed motor is not noisy, but it can be heard quite well. This is good because changing gears would be more difficult without any noise, but a CVT or automated gearbox does not require this feed-back. Different mounting for better noise insulation can make this drivetrain completely silent. The vacuum pump for assisting the brakes should be isolated better as well.
- The voltage at the motor controller is measured and it tends to drop down a lot. The motor cannot reach its full speed. It has to be investigated whether this voltage drop is a result of internal resistance of the battery, of contact resistances or of cable resistance. The battery voltage should be chosen higher in order to exploit the full motor capabilities.
- The battery voltage tends to drop much more if the vehicle is left in the cold over night without recharging. This leads to worse performance. Research is required in order to understand the main reason for this behaviour: is it due to low temperature or is it because of the time between last charging and driving? Would regenerative braking (charging with high currents) improve the performance? Battery heating, charging management or more battery cells in series may be required in order to cope with this disadvantage.
- The concept and the vehicle have been exhibited to the public in order to receive an impression of their attitudes. Feedback is generally positive and several people mention they would buy a car like this even if the purchase price were slightly higher. A few would prefer a higher top speed of about 80 mph.

All mentioned aspects should be investigated and improvements made. The achievements of single steps should be monitored and compared with theoretical expectations.

8. Future Work

Potential for future work on the proposed drivetrain concept has been determined in all previous chapters. This chapter gives a brief summary before methods and committed work within this project are identified.

Tidal wave and geothermal heat power generation need to be included in the energy considerations before making a final comment on the necessity for energy efficient technologies. Technological developments on all involved areas need to be tracked, because changes can have significant effects on the proposed drivetrain.

All future drivetrains and especially the proposed hybrid electric drivetrain are dependent on batteries. The following potential for future research can be identified:

- Equalizing of Li-Ion batteries is essential. The proposed method using small equalizing currents is very cost-effective. It needs to be verified by implementation and long-term tests. The required equalizing current in dependency on the battery capacity needs to be obtained. Too small currents may not be sufficient and too high currents can cause immediate terminal voltage drop or high system cost. The battery model parameters R_p for self-discharge rates and R_{dis} in Figure 3-16 need to be found. R_p helps determining the minimum required equalizing current and R_{dis} the maximum allowed current without immediate voltage drop.
- The battery cost plays a major role in order to provide competitive running cost if compared with conventional drivetrains. Behaviour of battery performance over lifetime needs to be studied in dependency on certain circumstances. This knowledge helps predicting the lifetime and cost of a battery and finding the optimal size of the battery in order to assure a certain vehicle behaviour and reliability after a given mileage.
- The battery behaviour in dependency on the temperature needs to be determined. This knowledge is essential either for finding the limitations of the proposed drivetrain regarding weather conditions or for specifying the requirements of a temperature management for the battery.

Validating and improving the battery model in subsection 3.3.5 and adding the temperature dependency to it could deal with all mentioned aspects of research on the battery.

Price dependencies of components (especially motor, power electronics and battery) need to be better understood in order to take the cost factor more into account when proposing the drivetrain in chapter 4. The type of motor / gearbox combination and their performances, efficiencies and cost is a specialty. This knowledge is available and needs to be put together. The first approach to an optimal configuration in section 4.3 needs to be extended to a full template including limitations and performance studies based on a better understanding of dependencies. Taking less into account available products but more possible products and price dependency information. The development of the template has to follow the way introduced in 4.2. More simulation is required in order to determine the suitable energy management and for completing the template. It is essential to verify the simulation results by comparing them with test-data. Modeling of actual components of the test-vehicle need to be undertaken and data logging in the vehicle need to be implemented.

A suitable structure for the energy management needs to be specified in accordance to automotive standards and based on practical issues like control speed, modularity, safety, reliability, user-friendliness and cost. In addition to some very specific questions mentioned in 5.3. The distribution of management tasks and the communication between these objects need to be specified.

Several components and the design require investigations in order to reduce cost for production vehicles. Starter, alternator, generator and 12 V system requirements have some potential for reducing cost, but it is not part of this work. This work focuses on the structure and the requirements for the battery management and the energy management systems. A suitable cost-effective BMS needs to be described based on the requirements in hybrid electric vehicles and the behaviour of the battery. Both can be obtained from the prototype and the battery testing and modeling. Further functions and systems need to be implemented in the energy management in the prototype for gathering the knowledge required for designing the systems:

- Control of the electric propulsion motor
- Implementation and control of regenerative braking
- Battery cell equalization
- Implementation and control of the fuel converter
- Implementation of SOC calculation
- Design of a suitable data logging system
- Design of a driver interface

Though this breadth in investigations was necessary so far in order to gain the required background knowledge, it clearly needs to be concentrated now. Most engineering and design tasks related to the proposed drivetrain require more background knowledge on the battery. The battery model and the changes of model parameters will be in the focus of the future research work.

It is tried to obtain information on practical implementations in parallel in order to identify unconsidered issues. Some engineering tasks are carried out in cooperation with and based on the knowledge of this research work:

The University of Berlin is designing a suitable four quadrant motor controller. The requirements and interface are specified in order to ease control of the motor and implementation of regenerative braking. The battery management system is developed in cooperation with a Scottish company. This will also comprise the battery cell equalization, SOC calculation, design of a suitable data logging system and a basic driver interface using a PALM digital personal assistant. The work on the implementation and control of the fuel converter has been started as a third year students project at the University of Southampton.

The future research will be carried out based on a field-test:

Some electric vehicles in Britain and Germany will be equipped with Li-Ion batteries. The implemented battery management system (BMS) will store statistical data on the use of the batteries. A portable device and software will be developed. This device can change the software in the BMS for updates, it can read and store the statistical data and determine the actual battery model parameters during driving. This device will be send back and fro to different selected test-candidates. All test-vehicles are different so that the battery use will vary. The data from this field-test will be analysed by statistical techniques in order to obtain information on changes of battery parameters in dependency of its usage. Analytical techniques will help to validate the battery model. But first some more battery testing is required in order to minimize the more difficult in-vehicle analysis. A basic understanding of the chemistry needs to be obtained in order to validate the electrical circuit model.

9. Conclusions

A new series hybrid electric drivetrain concept has been specified, called Peace-of-Mind. It is based on the review of actual vehicle design considerations, energy considerations and technology considerations including battery issues. It promises

- Noticeable contribution to lower CO_2 emissions and less energy consumption.
- Improvements for local air quality in urban areas.
- Some improvements in other environmental impacts like noise or emissions.
- Fuel / energy supply within the existing infrastructure.
- Fuel-flexibility - that means the drivetrain can easily be adapted to other fuels without a complete new design.
- Ease of technology changes and improvements - that means new technologies (fuel cell) can be implemented without major redesigns.
- Near-term market introduction through employing mainly available technology.
- Affordability and desirability.

It may meet all the requirements defined in the research question. Simulation results indicate the viability of this concept, but they need to be validated. The exploration of practical issues like the drivetrain management requirements and running the test vehicle suggest that the battery is a key issue to this and other future drivetrain concepts. A quick battery test and a new battery model for a modern lithium-ion battery are proposed. The quicker test helps determining the battery behaviour with fewer resources. The new battery model is better suitable for specifying management requirements and predicting battery behaviour in hybrid electric drivetrains. It forms the basis for in-vehicle testing of battery parameters. In-vehicle testing will be part of the future work for obtaining information about the changes of battery parameters over their lifetime. The new battery model can be related to the electro-chemical models for closing the existing gap between application issues and production knowledge.

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Appendix A: Battery Test Program

Appendix B: Publication

Appendix C: Matlab Model Files for ADVISOR