Energy Management of Hybrid Electric Vehicles

Mphil/PhD project - 9 months report

Author: Dennis Dörffel

Supervisor: Dr. Suleiman Abu-Sharkh

University of Southampton

School of Engineering Sciences

1 Introduction 3
1.1 Individual Mobility Now and in Future 3
1.2 Impacts of Individual Mobility 3
1.3 Alternative Individual Mobility Solutions 4
1.3.1 The Electric Vehicle 4
1.3.2 The Hybrid Electric Vehicle 5
1.3.3 Renewable Fuels 6
1.3.4 Fuel Cells 7
1.4 Research Objectives 8
2 The Battery 10
2.1 Structure of Batteries 10
2.2 Energy and Coulomb Capacity of Batteries 11
2.3 Life and Cost of Batteries 12
2.4 Charging Batteries 13
3 Battery Equalization 16
3.1 Different methods of equalizing 17
3.1.1 Equalizing charge phase or string equalization 17
3.1.2 Current Shunting or Dissipative Equalizer 19
3.1.3 Method of Switched Reactor 21
3.1.4 Flying Capacitors Method 22
3.1.5 Other Methods 23
3.2 Neighbour or Referenced Equalization 24
3.3 Continuous or Discontinuous Equalization 26
3.4 Topology of Equalizer 30
3.5 External Interface and Control 32
3.6 Design Example 33
3.7 Conclusions 39
4 Energy Management of Hybrid Electric Vehicles 39
4.1 Concepts of Drive Train Configurations 40
4.1.1 Grade of Hybridisation 40
4.1.2 Type of Hybridisation 40
4.1.3 Special HEV concepts 42
4.2 Drivetrain Configuration for our HEV 43
4.3 Energy Management 44
5 Conclusion and further work 45

6 References 45

1 Introduction

This report gives a brief introduction into alternative and common drive trains in vehicles. It will show that electrically powered vehicles are a sensible alternative to combustion engine powered vehicles. The discussion of advantages and problems will lead to ideas, solutions and questions. Future work to answer these questions will be proposed – the objectives of our further research.

1.1 Individual Mobility Now and in Future

Individual mobility is a major requirement for most people in the developed countries. It is seen as a motor for our economy, it assures independence and freedom. Mobility and especially individual mobility has become a basic need [1].

Individual mobility increases rapidly all over the world [2]:

"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."

1.2 Impacts of Individual Mobility

Though individual mobility is such an important factor in our lives, it has started causing a number of problems concerning resources and impacts on the environment:

Individual mobility needs resources, which are expected to run short in the (near) future.

The main resources are:

- **Space:** Vehicles need space for driving, parking and disposal at the end of life.
- **Material:** Production and maintenance of vehicles consume material; only some of them are recycled.
- **Oxygen:** Combusting fuel in the engine consumes oxygen from the air.

- **Energy:** Production, driving, maintenance and recycling of a vehicle consumes energy.

Further to these resources, there are some other major impacts on the environment:

- **Noise:** “Road traffic noise is the major source of noise annoyance in the community.” [3]
- **Pollution:** Combusting fuel pollutes the air with CO_2, NO_x, CO, SO_2, VOC, particles and more. Oil leakages pollute the ground and water.
- **Waste:** The production, driving, maintenance and disposal of vehicles produce waste.
- **Danger:** The high kinetic energy (mass and velocity) of modern vehicles endangers human beings and our environment in general; costly damages to buildings, infrastructure and other vehicles can occur.

Due to rising awareness of some of these problems, alternatives are getting increasingly into focus.

1.3 Alternative Individual Mobility Solutions

Some alternatives to the common cars are more or less in the public discussion. They are:

- Electric Vehicles
- Hybrid electric vehicles
- Renewable fuel powered vehicles
- Fuel cell powered vehicles
- Human powered mobility

They are discussed below.

1.3.1 The Electric Vehicle

The electric vehicle (EV) uses electric power to propel the car. The electric motor is superior to the combustion engine in many points, such as:

- Higher efficiency – less energy consumption
- The kinetic energy can partially be “recycled” and stored in the battery with regenerative braking
- No local pollution
- More silent

- Smaller, lighter, less parts, less maintenance, higher reliability (electric motor – if compared with internal combustion engine)

The main problem is storing the electric energy. The energy storage density of batteries is about 100 times worse than the energy storage capacity of fuel. The range of a pure electric vehicle with sensible battery weight is limited to about 200 km and the recharging (refuelling) time is comparatively high (at least 30 minutes).

1.3.2 The Hybrid Electric Vehicle

The hybrid electric vehicle (HEV) combines the advantages of the electric motor with the better energy storage density of fuel. The HEV uses both, an electric motor and a fuel-powered engine. The challenge is to find the power-train configuration and energy-management that combines the advantages and cancels out the disadvantages – not vice versa.

The Toyota Prius (full size four-seater) and the Honda Insight (two-seater) 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 [4] while the VW Golf TDI 1.9 achieves only 40.4 mpg (5.8 $^{l}/_{100\ km}$) [5]. 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 [4]. Experts estimate that common internal combustion engines in cars will not be able to meet future regulations concerning tailpipe emissions and that hybridisation will be necessary.

However, hybrid electric vehicles in general have two major disadvantages:

1. <u>They still consume too much fuel.</u> The Toyota Prius achieves 58 mpg (4.1 $^{l}/_{100\ km}$) on the combined cycle [4]. Modern Diesel cars like VW Golf TDI achieve 52 mpg (4.5 $^{l}/_{100\ km}$) on the combined cycle but this is without hybrid drive train [5].
2. <u>They are expensive.</u> A comparable internal combustion engine (ICE) car costs less, because the hybrid electric vehicle requires more components. The Toyota Prius for example costs about £ 16,500 [4] and the VW Golf TDI costs about £ 13,500 [5]. It should be mentioned that Toyota currently makes no profit with each sold Prius at this price.

Experts rank hybrid electric vehicles only as a temporary solution.

1.3.3 Renewable Fuels

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 million 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 – the net CO_2 emission is zero.

The most important renewable fuels are:

- Alcohol
- Bio Diesel
- Bio Gas
- Wood

Biogas 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 could easily be distributed through the existing infrastructure. Brasil for example runs a high percentage of cars on alcohol.

Beyond renewable fuels, there are some alternative fuels, like:

- Gas (LPG or Natural Gas)
- Coal

They are already used in many applications like heating and electric power plants. They are fossil fuels and not renewable. Advantages compared to the combustion of oil in cars are not mentionable and too small for changing over to these sources.

Renewable fuels represent a reasonable alternative and overcome the problems of global warming and running short of fossil fuels. The main questions are:

- What are the costs for renewable fuels?

- What "energy-plant" area is necessary to satisfy the world energy demand in future?
- What impacts will these global energy plants have?

Renewable fuels are a reasonable solution in combination with other alternatives like hybrid electric vehicles or fuel cells.

1.3.4 Fuel Cells

The electric motor is superior to the combustion engine in many ways as explained in section 1.3.2, but the storage of electric energy for long distance rides is the main difficulty. The fuel cell is capable of directly producing electric energy from fuels like hydrogen, methanol or even 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.

The fuel cell appears to be the answer to impacts like:

- Energy consumption
- Noise
- Pollution

The theoretical efficiency of fuel cells 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 the favourite type to be used in cars. The **practical** efficiency of this fuel cell system including gas purification is about 40% [6].

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 [7]. In conclusion, the fuel cell appears to be the most reasonable solution in the far future.

The fuel cell on its own is no solution for the near future, because:

- Technology is not available to combine all promising advantages of fuel cells in one practically usable system.
- The fuel (energy) still needs to be "produced" somewhere.

However, a near-term solution for individual mobility is needed and energy-saving technology and awareness is necessary to keep the power plants for regenerative energy small.

1.4 Research Objectives

Individual mobility has become a basic need. On the other hand, impacts are growing and availability of other basic needs like clean air, low noise, space and more is reducing.

The alternatives mentioned above mainly target the problems like

- Oil dependency
- Energy consumption
- Pollution
- Noise (partial)

Combinations of different alternatives like running a hybrid electric vehicle or fuel cell car with renewable fuels can achieve reasonable improvements. But technology and infrastructure are not ready and cost will be high. Other impacts like

- Danger
- Waste
- Space
- Material

are not considered at all in this document so far. Some facts can help to find solutions:

- Most journeys are short journeys, shorter than 40 km.
- Short journeys can comfortably be undertaken with small lightweight vehicles.
- Smaller lightweight vehicles reduce all mentioned impacts.
- Small vehicles for short journeys can be battery powered until the fuel cell is competitive.
- Electric energy can be generated renewably with existing technology and distributed over the existing infrastructure.

A “narrow purpose” vehicle as mentioned can be optimized to reduce all impacts. There are five main logical obstacles to reach this scenario:

1. People increasingly want huge cars, because they make them feel saver. *Big might be saver for the individuals in the vehicle, but small cars are saver for the surrounding.*

2. Huge cars are not more expensive to produce than small light cars. *Small light cars with low impacts are cheaper to run than big heavy ones.*
3. Many people are afraid of changes. *Using well-known technology like combustion engines in vehicles is proven and "safe". People know how to drive this kind of vehicles – handling a small electric vehicle is certainly different. They will need to start off from a niche market*
4. People want the freedom to travel long distances whenever they want and they want to have a multi-purpose vehicle. At least they do not want to worry about the range. *A good energy management with driver information can help to assure peace of mind. An auxiliary power unit can assure to travel the once-a-week longer distances. Effective and efficient car rental or sharing can be implemented to provide a range of vehicles for all purposes.*
5. Mobility must be affordable. *Electric vehicles are comparatively expensive because of high battery cost and short battery life.*

We investigate in the "peace of mind energy management" for electric and hybrid electric vehicles. We try to prolong and estimate the life of the batteries to reduce cost.

Other instances may help to overcome other obstacles by

- Stopping the competition of weapons: increasing vehicle mass and size.
- Making small light cars more attractive, by charging for the real impacts for example.
- Making people, especially young people aware of the impacts and demonstrate other technologies.
- Install effective and efficient car rental or sharing and make public transport a good alternative for long distances.
- Investigate in "energy research" like energy sources, energy storage, energy distribution, energy saving.
- Make energy saving a challenge and not a burden.

2 The Battery

The battery is one of the energy storage units in HEVs and the only energy storage system in BEVs. The battery is comparable to a fuel tank, but high cost, low energy storage density and shorter life often make the battery the weakest point in an electric vehicle drive train.

2.1 Structure of Batteries

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 1V and 4V. 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.

Every cell can store a certain amount of energy, but most batteries are specified by their **coulomb capacity** in Ah instead. The energy storage capacity of the battery can be increased by increasing the capacity or by increasing the voltage. Usually larger cells will be chosen for increasing the capacity, but sometimes, the cells are connected in parallel. From the view of power electronics and electric motors, the battery should have higher voltage. Higher voltages result in smaller currents for the same power and smaller currents are easier to handle and cause smaller losses. From the view of the battery, it is easier to increase the energy content by increasing the capacity. The capacity can easily be increased by increasing the cell-size up to a certain level, while increasing the voltage always means more cells. More cells always mean more connectors and more problems with cell-imbalances.

In conclusion, this document will always call the whole pack of cells or blocks in an EV a **battery**. The way of connecting the cells or blocks is the result of an optimisation process with one uncertain variable: The effects of cell-imbalances in HEV and BEV batteries, which will be discussed in chapter 3.

2.2 Energy and Coulomb Capacity of Batteries

As mentioned above, batteries have a small energy capacity if compared with a fuel tank. The Table 2-1 compares the fuel tank with a BEV battery (lead-acid): A small conventional car is compared with two virtual electric vehicles. EV1 has the same mass for the "tank" (tank or battery) and EV2 has the same driving range then the conventional car.

	Small Car	Virtual EV1	Virtual EV2
Capacity of the tank	45 litre 405 kWh	0.11 litre* 1.0 kWh	13 litre* 120 kWh
Weight of fuel or battery	45 kg	45 kg	3,860 kg
Distance on one tank	600 km	6.0 km	600 km

Table 2-1: Comparison of a fuel tank with a battery

*EVs do not consume fuel, but their energy consumption can be measured in litres of oil-equivalent for better comparison: 1 litre of petrol generates about 9 kWh of energy. Virtual EV1 and EV2 are no real EVs because neither the short range of EV1 nor the heavy battery of EV2 make sense, but they demonstrate the energy storage capacity of batteries by trying to keep one variable constant.

The battery, used in Table 2-1 is a Hawker Genesis pure lead-tin battery [8] with a specific energy of between 22 Wh/kg and 31 Wh/kg, depending on the discharge current. Other types of batteries with a different composition like the FORTU Bat have about 200 Wh/kg [9], but even this is hardly comparable to the 9,000 Wh/kg of fuel.

The capacity of EV batteries is usually specified in Ah, because this is more precise as the following example may demonstrate:

A "12 V – battery" with a coulomb capacity C has an energy capacity of:

$$E = C \cdot \overline{V_{ter\min al}}$$

The average terminal voltage $\overline{V_{\text{terminal}}}$ is the average of the decreasing terminal voltage during the whole discharge process. The average terminal voltage of the "12 V – battery" in our 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. Unfortunately, C is a function of many parameters as well: more or less the same as mentioned above.

Hawker [8] defines a 25 °C environment for their Genesis batteries, but also provides information about the capacity as a function of temperature. The capacity of most battery types depends on the discharge current. A lead-acid battery with C_{20} = 60 Ah might only have C_5 = 50 Ah; where C_x specifies the battery capacity, when discharged with a constant current over x hours. [10] Example: C_{20} = 60 Ah means the battery can be discharged over 20 hours with a constant discharge-current of 3 A.
Unlike a fuel tank, batteries loose their capacity due to self-discharge during idle times. 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 discharges to 50% within 1.5 years at 25°C [8].

In conclusion, the amount of energy stored in batteries is not only small but also uncertain and depends on several variables. The fuel gauge of a car shows red when there are “only” about 100 km left, but this can be the **total** range of BEVs. Thus, BEVs require a high efficiency and good energy management with driver information.

2.3 Life and Cost of Batteries

Batteries are expensive items. The cost for a certain storage capacity is between £100 / kWh to £500 / kWh or higher. This means between £ 2,000 and £ 10,000 for the battery just in a small vehicle with 100 km driving range. Unlike the fuel tank, batteries might not last for the whole vehicle life and their condition will deteriorate 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 full cycles, depending on the type of battery.

Some parameters will further influence this cycle life:

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

The EOL is usually defined as 80% of the battery's rated capacity. The DOD can easily be defined as well and is usually 80%. The influence of temperature and shock on the battery life can be determined by tests.

The "treatment" is difficult to define but the influence of this complex variable is very significant, as some examples may demonstrate:

- Wrong charging of a Hawker Genesis battery may result in a life of 30 cycles instead of the usual 500 cycles. [11]
- Wrong equalization of cell imbalances in a battery string may cause 80% reduction in cycle life. [12]

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 [12]. The user of the battery (the driver of the car) is another considerable variable, but very difficult to define as well. Vehicle manuals containing extensive information about "How to treat the batteries …" might prolong their life but are not helpful for the user at all.

Some companies rent or lease the batteries in their BEV. The rental cost is between £ 50 and £ 100 per month. This is hardly acceptable for most users.

In conclusion, the battery is that component of an EV that adds the main cost to it. Battery management is necessary to assure best possible treatment and longest lifetime without interfering much with the driver. Better knowledge for predicting the battery life in EV applications and battery monitoring is useful to keep rental cost down.

2.4 Charging Batteries

The batteries in EVs are rechargeable. The charging can be compared with filling the fuel tank. Unlike this, charging can take place at home or in a parking place if a socket is available. The actual electric energy network can be used without the need for filling stations with huge fuel tanks and special equipment against fire and environmental damage. No new energy distribution system as for hydrogen has to be built. On the other hand, charging needs a charging scheme that is specialised for the size and type of battery and charging is much slower than refilling a fuel tank.

The following example demonstrates this difference:

- Filling the tank of a car takes a few minutes. That means refilling takes about 20 seconds per 100 km driving range.
- Charging from a household 3-phase socket can "refill" with about 9 kW. That means more than 2 hours per 100 km driving range for a small EV.

The charging scheme is usually provided by the battery manufacturer, but some general comments shall be made:
Batteries can be charged with a DC or pulsed current. The charging process consists of different charging phases:

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

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. The current depends on the battery capacity. VARTA recommends charging the Drymobil [10] in this phase with about $I_{charge} = 0.2C$ (0.2 times rated capacity) or $I_{charge} = C/5$ (one fifth of rated capacity) and a voltage limit of 2.35 VPC (voltage per cell). 0.2C or C/5 means charging with 20 A for a battery with C = 100 Ah capacity.

The **absorption charging** phase returns the last percentages of energy, but takes a comparatively long time for this, because the battery might be damaged, when too high currents are applied. The charge acceptance is reduced in this phase. For example, C/140 should be applied 0.6 times as long as the initial charging phase to the Drymobil [10]. Though this phase returns only a small amount of energy, it is essential for most of batteries to prolong their life.

The **float charging** maintains the battery in a fully charged state. This phase reverses all self-discharge processes and keeps it fully charged all the time when not in use.

Some types of batteries require an **equalizing charge** phase, to fully charge all cells in series. Usually this phase takes a very long time.

In some applications and for some battery types, service charging may be sensible. **Service charging** will only occur when necessary or regularly, but rarely. This is a special charging algorithm and can include cycling. Cycling means several charges and discharges. Aims can be the reduction of memory effects like in NiCd cells or reduction of passivation effects in general.

Generally, there are different methods for charging a battery:

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

Most manufacturers recommend one or more different combinations of these methods for recharging. An IVIa or CC-CV-CC-a charging algorithm means for example 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. This is followed by a constant current (CC) regime in the absorption-charging phase, which will automatically terminate (a).

In conclusion, charging of batteries is not only a comparatively slow process due to the power limitation of the mains and 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 and usually results in the need for a battery management system (BMS).

3 Battery Equalization

The battery of hybrid and pure electric vehicles consists of many electrochemical cells electrically connected in a series string. In some cases, a constant number of cells form a block and these blocks are connected in series to form the battery.
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 mean that one is fully charged first and others may not be fully charged. [13] Either the first block is being overcharged or the last lacks to be fully charged or both. This effect dramatically increases with the number of discharge-charge cycles of the battery leading to reduced performance and shorter battery life. If the blocks have different temperature, this effect becomes even worse.

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

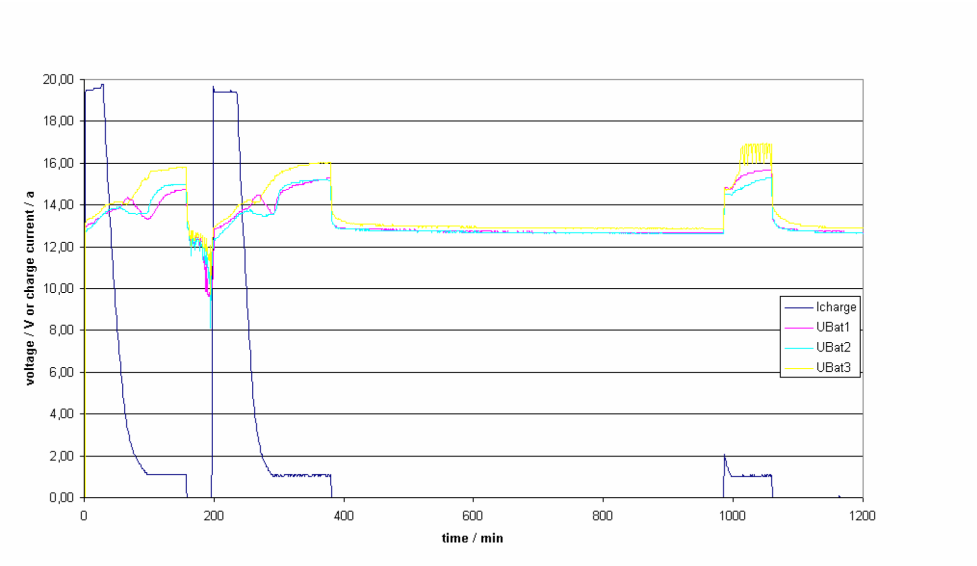

Figure 3-1: Charging of three old blocks in series without charge equalization

There are different methods for equalizing the blocks or cells in a series connection, which will be discussed in section 3.1.

Any of these methods can be combined with

- Neighbour or referenced equalization principle (section 3.2)
- Continuous or discontinuous equalization strategy (section 3.3)
- Different topologies of equalizer (section 3.4)
- External interface or without (section 3.5)

The blocks could also be connected in parallel or in a mixed way, but this is very uncommon, because the mentioned effects become even more difficult to handle. [13]

3.1 Different methods of equalizing

This section is about methods for equalizing. Different hardware circuits are necessary to implement the various methods. The following methods are used in practice:

- Applying an additional equalizing charge phase to the whole battery string - string equalization (section 3.1.1)
- Method of current shunting - dissipative equalization (section 3.1.2)
- Method of switched reactors (section 3.1.3)
- Method of flying capacitors (section 3.1.4)
- Other methods (section 3.1.5)

3.1.1 Equalizing charge phase or string equalization

This method works by applying a small current through the battery after charge completion. The current is applied for a long time (several hours) or forever and must be higher than the self-discharge rate. Alternatively, a constant voltage can be applied to the whole string.

In good natured battery-chemistries like lead-acid, NiMH or NiCd (unlike Li-Ion), fully charged cells will not be damaged, when further charged with these small amounts of energy. The full cells transform further energy into heat, while the last cells in the string will be fully charged. [13]

This string equalization is an addition after the end of the charging process (equalizing charge phase).

In the sealed lead-acid battery, for example, the small current will be taken up by the internal oxygen cycle when exceeding the gassing voltage. In unsealed lead-acid battery as another example the current will lead to some gassing, which is a normal

process in charging this type of battery: necessary to stir and mix the electrolyte in order to prevent the formation of layers of different acid concentration.
This method has only one advantage:

- No additional circuits and cables required

It has several disadvantages:

- Equalizing takes a very long time and will not reach 100% in most applications
- Difficult to adapt this method to changing battery parameters over their lifetime (e.g. self-discharge rate increases over the lifetime)
- High corrosion and aging rates because of heat generation in the cells
- No equalization during the initial charging process
- No equalization during the discharging process

No equalization during the charging/discharging process means that one single cell/block determines the behaviour and thus the recommended treatment of the whole string. Every cell/block voltage has to be measured to determine the end of discharge, preventing the weakest battery from deep discharge; also every cell/block voltage needs to be taken to control the charging process preventing the first fully charged blocks from being overcharged with high currents. This cell or block voltage measurement requires additional circuits and cables thus reducing the advantage of this method.
To avoid the additional circuits the limits need to be chosen more carefully, that means choosing a higher end of discharge voltage and choosing lower voltages in the constant voltage charging phases. However, this leads to longer charging times and getting less energy out of the battery than possible.
Equalizing over a long time needs an exact adjustment of the cell voltage. The optimal charge keeping voltage for a lead-acid cell for example is between 2.23 V and 2.27 V. Lower rates will lead to undercharge and higher rates to a faster corrosion rate and aging. “Elevating cell voltages beyond 2.3 VPC can result in more than 40% reduction in battery life.” [12]
In conclusion, this method cannot be recommended unless the application provides enough charging and equalization time and using tough, low-cost and unsealed batteries that do not deteriorate significantly when being overcharged. Expensive and

sealed batteries should apply methods that are more accurate, because the high corrosion rates of this method will reduce the battery life dramatically. The question regarding this method is whether it is better to equalize and accept higher corrosion rates or to apply the equalizing phase just sometimes or never.

3.1.2 Current Shunting or Dissipative Equalizer

The principle of dissipative equalization is to draw energy from the fullest cell or block and dissipate it in a resistor or transistor. Figure 3-2 shows the principle: A device such as a transistor dissipates energy from a single cell or block. The control circuit controls this device to keep all cells in the battery string equalized.

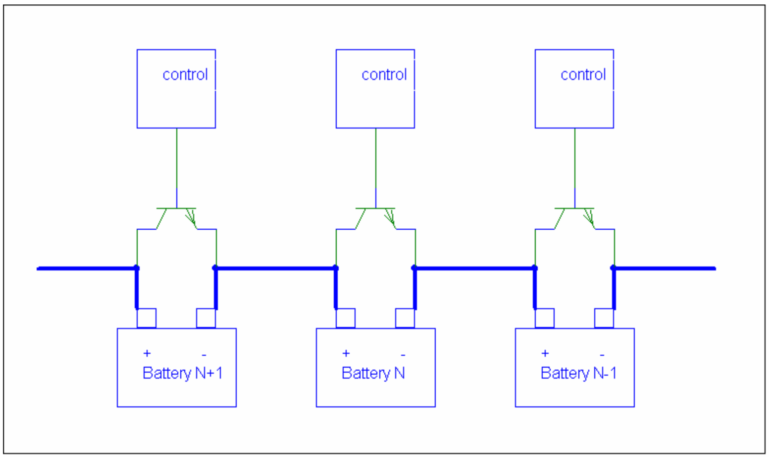

Figure 3-2: Principle of a dissipative equalizer

The advantages of this method are:

- Simple and low-cost circuit
- Long wires possible – no EMC-problems, no high frequencies
- Can be used with referenced equalization (see later)

The disadvantages are:

- Energy is dissipated into heat and therefore lost
- The equalizing current is very limited (around 500 mA for a 12 V block)
- Higher equalizing currents require big and more expensive heat sinks
- Continuous equalization is not recommended, because of high energy dissipation

This method can be combined with a very simple control circuit. Figure 3-3 shows the circuit in principle: It uses a zener-diode that measures the block voltage to control the transistor.

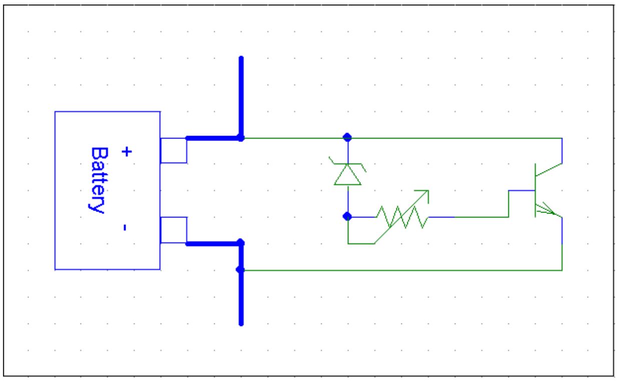

Figure 3-3: Principle of a simple dissipative equalizer

The circuit starts drawing some energy from the block at an adjustable voltage threshold near to the gassing voltage. The higher the block voltage is the higher this dissipated current will be. Figure 3-4 shows a typical relationship between block voltage and equalizer current for a 12V lead-acid battery.

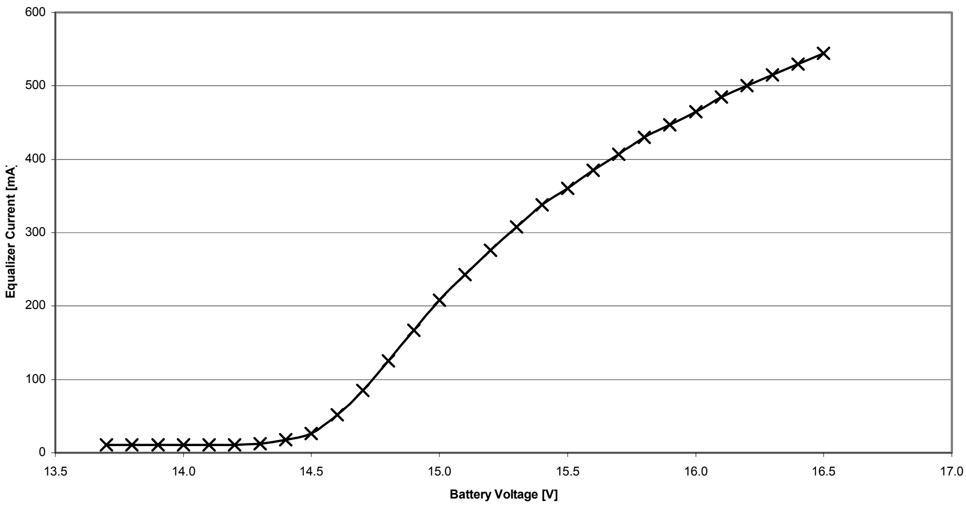

Figure 3-4: I-U diagram of a simple dissipative equalizer

Cells or blocks in the string with a higher voltage see a smaller current when charged than those with lower voltages. This causes the last blocks in the string to receive a better charge than without equalization.

This principle might work very well with constant-voltage (CV) charging. It works less well with constant-current (CC) charging and combinations, because the voltage is expected to rise quite high in some CC charging phases: much higher than the gassing voltage.

Figure 3-4 shows a simple equalizer adjusted for CC-CV-CC charging: In the last CC phase the block voltage can rise up to 16.5 V and the equalizer must be able to cope with this voltage in terms of heating power. The curve can be much steeper and thus better for equalization if applied to a CV charging method.

Unfortunately, there are no proven results with this method and the CC-CV-CC charging is the recommended one for lead-acid batteries in electric vehicle applications to quickly and fully charge the batteries. Other and more precise control strategies can be combined with this method and are subject to a later discussion.

3.1.3 Method of Switched Reactor

The main disadvantages of dissipative equalizing are the loss of energy and the comparatively low currents. The method of switched reactors transfers energy from the cells with higher voltage to the lower charged cells instead of dissipating the energy. This method works bi-directionally, usually comparing two neighbouring blocks. A Daisy Chain assures all blocks are equalized. Less energy is “lost” and there is no need for big heat sinks. The equalizing currents can be above 2 A without difficulty. Figure 3-5 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 neighboured block is charged with this small amount of stored energy.

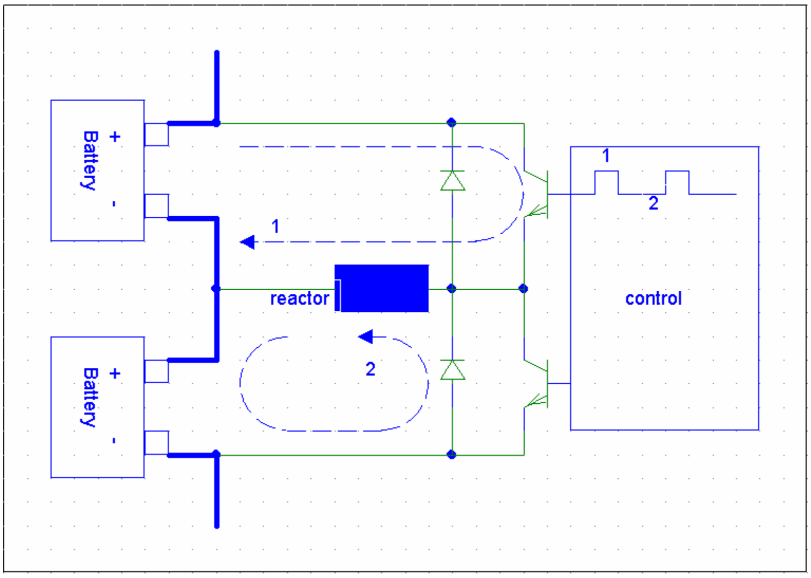

Figure 3-5: Principle of equalizing with switched reactors

The advantages of this method are

- High equalizing currents possible
- Small loss of energy
- Bi-directional equalization: full cells are discharged and low cells are charged
- Continuous equalization is possible (see section 3.3)

Disadvantages are:

- More complicated and not straight forward circuit
- Referenced equalization not easily possible (see section 3.2)
- Neighbour equalizing needs high accuracy for batteries with many cells

Again, this method can be combined with different control strategies. They will be mentioned later.

3.1.4 Flying Capacitors Method

This method is comparable to the method of switched reactors, but uses capacitors instead of reactors. Figure 3-6 shows the circuit in principle: The switches just switch back and fro with a certain frequency. The capacitor "between" two blocks will reach 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.

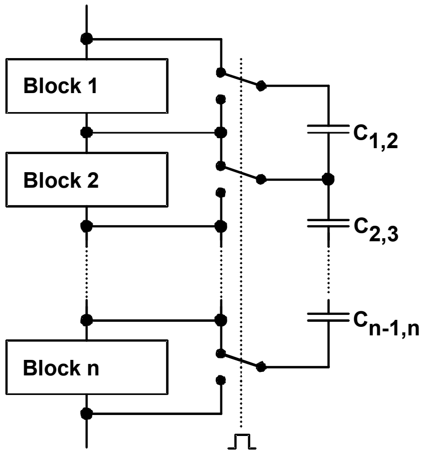

Figure 3-6: Principle of equalizing with flying capacitors

The disadvantages of the flying capacitors are:

- The need for changing switches instead of closing switches is more difficult to implement with transistors. Relays need more space, are less reliable, slow and more costly.
- Switching capacitors result in current peaks, which cause unnecessary heat in the battery. Heat means faster ageing.
- No referenced equalization easily possible
- Neighbour equalizing requires high accuracy for batteries with many cells
- Only a small amount of the energy storage capacity in the capacitor can be used for equalizing.
- The smaller the voltage differences are the smaller is the equalizing current, slowing down the equalizing process.
- This approach usually requires a centralized or partly centralized topology (see below)

The advantage is a very simple control algorithm, just switching with a certain frequency when equalizing is enabled.

3.1.5 Other Methods

The described methods work either by dissipating energy or by redistributing energy. Another possibility 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. This leads to a centralized equalizer. This method can be applied to low voltage batteries (up to 7 blocks of 12 V in series). Higher voltages need isolated solutions:

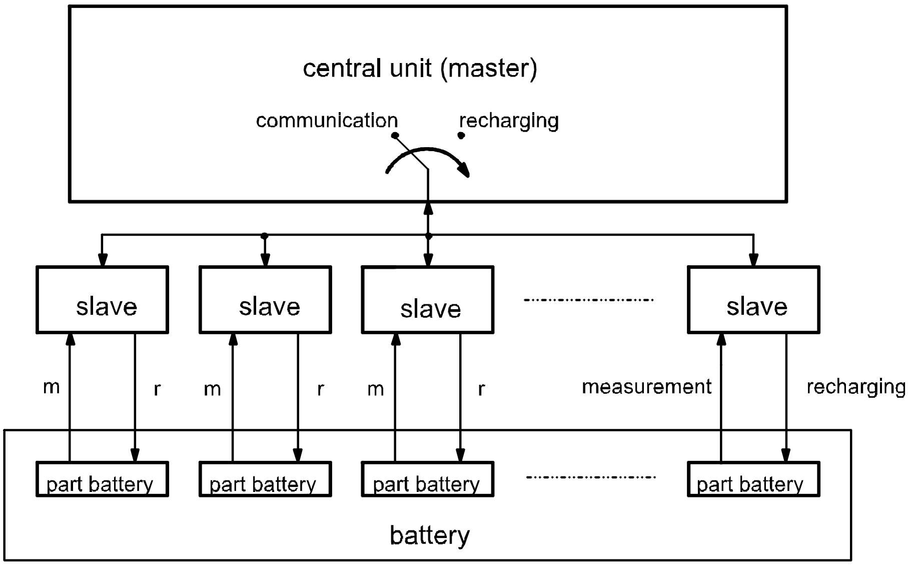

Figure 3-7: Isolated distributing equalizer circuit [14]

The shown circuit uses a bus system and high frequency transformers for communication and small equalizing power distribution. It uses a master – slave topology.
These methods are very complex but provide the most effective equalization and fast charging.

3.2 Neighbour or Referenced Equalization

Some of the mentioned methods like the switched reactor and the flying capacitor better go along with neighbour equalization. **Neighbour equalization** means that the equalizer compares the voltage of two neighbouring blocks and equalizes these two blocks. A daisy chain of the equalizer modules assures all blocks in the battery to be equalized.
The main advantages of the neighbour equalization are:

- No need for any voltage references – just the voltage difference between two blocks is decisive

- No need for temperature measurement and compensation – the charger will do this
- Block temperature can automatically be taken into account, if it can be assumed, that two neighboured blocks have a similar temperature

Of course, this strategy has some disadvantages as well – mainly in battery strings with many blocks:

- Neighbour equalization is comparatively slow and might be less effective, because energy cannot be transferred directly from one block to any other. It has to be transferred from one to the next
- Neighbour equalization will be less precise, because the errors can accumulate over the whole battery string

Figure 3-8 shows how small equalizer errors can cumulate to a huge absolute error in worst case. This effect grows with the number of blocks or cells and is dangerous, because the absolute block voltage is more important than the relative voltage if compared with a neighbouring blocks.

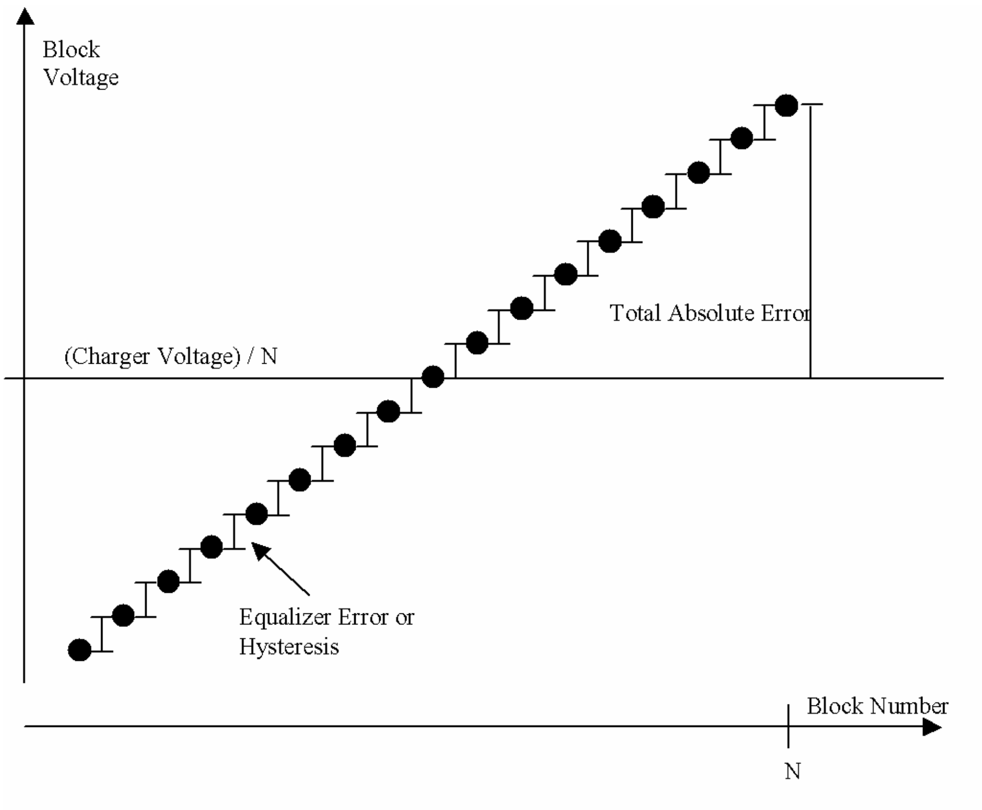

Figure 3-8: Worst-case cumulating of equalizer-errors in a battery string with 17 blocks

The **referenced equalization** can be applied to avoid this effect. This strategy uses a reference to compare the block voltage. Every block is compared with a reference. The absolute error is the same as the equalizer error or hysteresis. Compared to the neighbouring equalization, all the advantages turn into disadvantages and vice versa.

In conclusion, the reference equalization is the better solution, if high precision or many blocks are required; otherwise, the neighbour equalization is the better choice.

3.3 Continuous or Discontinuous Equalization

The question of continuous or discontinuous equalization is a part of the equalizing strategy. It can vary between no equalization, equalization as rarely as necessary or equalization as frequently as possible.

The question when to start and when to stop the equalization has two independent aspects:

1. What is the voltage difference between blocks or cells to start with equalization and what is the voltage difference to stop it again? (Voltage Hysteresis)
2. In what battery state (charge, discharge or idle) should the equalizer operate?

The bigger the hysteresis is, the greater the differences in cell voltages become. Oscillations will occur if the hysteresis is very small. Trying to keep every cell of a lead-acid battery between 2.23 V and 2.27 V in the charge holding phase for example requires a very small hysteresis. Highly accurate equalizing like this on one hand and high equalizing currents for old highly dissimilar cells on the other hand require an adjustable equalizing current. This could be controlled with a closed loop to reduce cell imbalances to a minimum. Equalization will take place continuously without any hysteresis. On the other hand, the circuit needs to be more complex and every equalization current means causes losses.

The questions to be answered are:

- How to build a simple, low-cost and reliable equalizing circuit with adjustable current and closed loop control?
- How large are the losses depending on the hysteresis and the age of the cells?
- What improvement in battery life can be expected depending on the equalizing cell voltage hysteresis?

There are three main battery states:

1. Discharging
2. Idle
3. Charging

Figure 3-9 shows a complete cycle of discharging, charging and idle of three old Hawker Genesis in series. They show huge dissimilarities in voltage while discharging, especially towards the end of discharge.

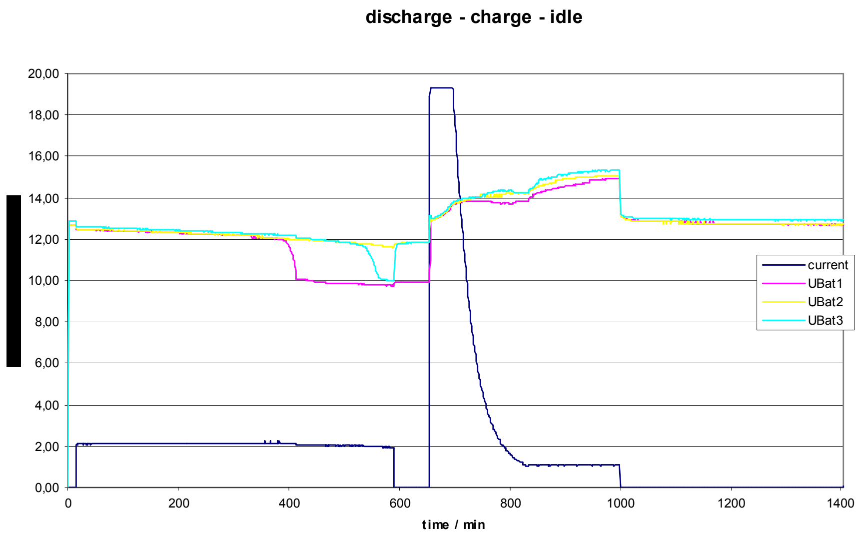

Figure 3-9: Complete cycle of a battery with three old 12V blocks

Without single block voltage observation, this would lead to deep discharges before the cut off voltage is being reached. With single block voltage observation, the worse block determines the behaviour of the whole battery. Equalizing the amount of energy between all blocks means getting a higher amount of energy from an old very dissimilar string.

On the other hand, equalization has losses and is not worth it if the blocks are very similar while discharging. The figure above shows an old string that was used without any equalization. Using equalization in the charging phase might not have allowed the blocks to become that different in first place.

The idle phase is not critical in terms of deep discharge, undercharge or overcharge. But it could be a good opportunity to equalize cells if the time in the charging or discharging periods is not sufficient to do so. This could keep the required equalizing currents smaller. However, the energy losses through equalization in this phase might be worse than all the advantages of this idea. An intelligent algorithm, enabling or disabling the equalizer depending on the behaviour in the last charging or discharging is a good but also very complex solution.

During charging the equalization helps to prevent the blocks from undercharge and overcharge while keeping the charging time as short as possible.

Comment: name?

In float charging – if appropriate – it keeps down oxidation and thus damage to the cells as discussed earlier.

Equalizing could be enabled

- During the whole charging process
- When some cells or blocks (but not all) exceed a certain voltage
- In the float charging phase

Equalization during the whole charging process seems to be not an appropriate solution, because the individual cells or blocks are meant to run free in their voltage in the constant-current phases [15]. The main reason for equalizing during the whole charging process without interruption is that it is a simpler solution without the needs for any interfaces to a charger.

Quite simple as well would be to enable equalization when one block or cell starts to be high in voltage (somewhere around the gassing voltage). However, this would also mean equalization during the last constant current charging period, where the voltage is meant to exceed the gassing limit and blocks are meant to run free [15]. Also equalization might not be possible in the float charge phase, because the voltage is meant to be quite low – probably lower than the enabling voltage. A detection, whether only some but not all cells or blocks exceed the equalization voltage could be a solution to help the cells running free in all constant-current phases.

To enable equalization in the float-charging phase as well but not during the whole charging process needs communication with the charger or a more intelligent solution (float-charging phase detection). Having no equalization in the float-charging phase at all cannot be recommended and float charging should be omitted in that case in order to avoid oxidation.

Questions to be answered are:

- Can cell/block imbalances be kept small when using equalization during charging only or is it sensible to equalize during discharging and idle periods as well?
- What equalizing currents are necessary to keep the blocks or cells equalized over their lifetime when using continuous or discontinuous equalization?

- What equalizing-losses will occur during lifetime when using continuous or discontinuous equalization?
- When should batteries better run free in their voltage without equalization?
- How to build a simple, low-cost and reliable circuit that is capable of equalizing with the necessary currents and that is disabled in all charging phases where the blocks are meant to run free in voltage?
- How to avoid the float-charging phase if no simple circuit is capable to handle this?

3.4 Topology of Equalizer

There are different possible topologies for battery equalizing systems:

- Central 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 may or may not be linked between modules to allow for communication.

The centralized solution …

- Does not need a link (e.g. a bus-system) for communication between modules
- Has to cope with high voltage drops in one housing, if applied to a battery with many blocks
- Is not easily scalable to the number of blocks in different batteries

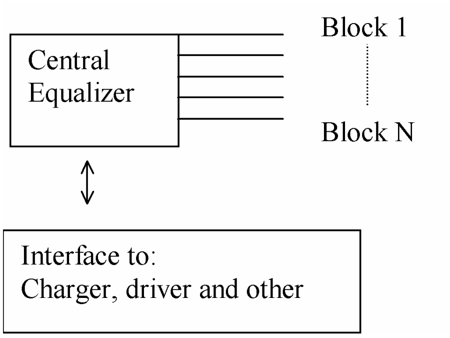

Figure 3-10: Central Equalizer with Interface

Thus, the centralized equalizer as shown in Figure 3-10 is a simple and reliable solution for batteries with a few blocks and comparatively low voltages, say up to about seven blocks with 12V. High production volumes for a certain number of blocks, like the for example the 42V system in cars, will favour this solution due to its simpler construction and system integration.

Having a battery with a higher voltage and more blocks requires the equalizer to be split into more than one centralized part, as shown in Figure 3-11. This is also true, if the battery string is split into parts and not located in one area in the vehicle. This method usually requires an isolated interface or bus system between the modules, if communication or external interface is needed. The BEMU from SKI [16] uses this topology.

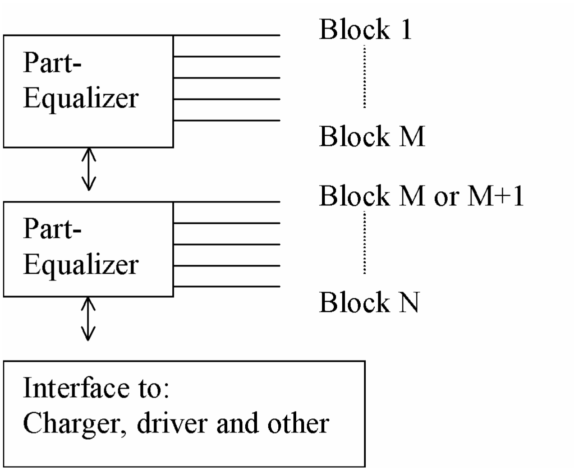

Figure 3-11: Partly centralized equalizer with interface

In some cases like the simple dissipating equalizer or the PowerCheq from PowerDesigners [12] without any communication or interface it is sensible to have a topology with one standalone module per block or between two blocks.
The main advantages are:

- Fully scalable with the number of blocks in every battery, thus reducing cost because of higher possible production volumes
- No long wires required
- Temperature gradients on long battery strings can easily be taken into account

The disadvantage is:

- If any interface or communication is required, this topology will suffer from higher complexity and thus higher cost.

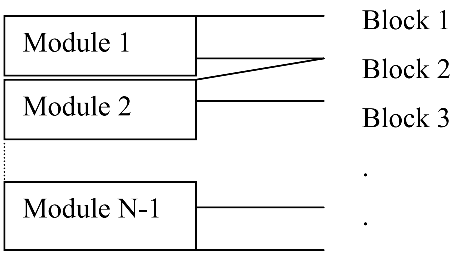

Figure 3-12: Modular equalizer without interface

Master-Slave architectures combine some advantages of the modularised and centralized topology:

- The central solution becomes scalable to the number of blocks or cells
- The modular solution receives capabilities like interface and communication

On the other hand, the master slave architecture is quite complex. It is a sensible solution if intelligent control and interfacing is required.

In conclusion, the topology of the equalizer does not influence the quality or the results of equalization. The decision on the optimal topology should be made depending on several issues like cost, number of blocks to be equalized, battery voltage, production volume, circuit design and interfacing.

3.5 External Interface and Control

External control or interface can include one or more of the following items:

- Output: charge current too high (equalization is not possible)
- Output: cell or block voltages, highest or lowest block voltage, maximum block voltage difference
- Output: cell or block temperatures, highest or lowest block temperature, maximum block temperature difference
- Input: disable, enable or override equalization
- Input: charging phase
- Input: aimed block or cell voltage as a reference for closed loop control

- Others like for programming, battery maintenance or diagnostic features

External interface and control will increase the cost of the system, but it will also offer a range of possibilities. Simple digital I/O like the enable input is quite low-cost to be implemented. Data transfer I/O, as for cell voltages and temperature will be a more expensive feature. Some topologies are better suitable for external control than others. Additionally some strategies, like equalizing only in the charge-holding phase require external control and some, like continuous equalization do not.

To determine whether any further external control is necessary or not, some questions need to be answered:

- Will the equalizer be able to equalize the batteries over their lifetime without reducing the charge current or not? Reducing charging current requires communication with the charger.
- If not – How much will battery life be decreased if charge current will not be reduced?
- Is it sensible to measure and communicate block voltages and temperatures?

3.6 Design Example

The best way of equalizing batteries depends on several parameters and issues like:

- The number of cells or blocks
- The battery type (capacity, cost, robustness, cycle-life)
- The recommended charging specifications
- The implemented charging characteristic
- The implemented thermal management
- The production volume and purpose
- The knowledge about the battery
- The likelihood of changing the type of battery over the lifetime of the vehicle

Since there is no unique algorithm available that determines the best equalizing method based on all of these circumstances, it is helpful to go through an example:

The SAM from CREE is a small battery powered electric vehicle with the following specifications:

- The traction battery consists of 14 blocks with 12 V each.
- The battery type is the Hawker Genesis G26EP with 26 Ah @ 10h discharge rate.
- The estimated cost for replacing the whole string is about £ 1,100.00 including labour.
- The lifetime is about 500 cycles (80 % DOD). End of life means 80 % of original battery capacity.
- With about 50km on one charge this would mean 25,000 km until battery reaches end of life. This gives £ 4.40 battery cost per 100 km. Little driving (5,000 km / a) means 5 years battery life and around £ 18.33 per month. Driving a lot (20,000 km / a) means 1¼ years battery life and around £ 73.33 per month.
- The Genesis is robust against deep discharges and it is comparatively robust against high voltages.
  The Genesis is very likely to be undercharged in EV applications, thus leading to high block dissimilarities, dramatically reducing lifetime and performance.
- The recommended charging of the Genesis in electric vehicle applications with the fastest possible recharge is the specially designed "Fast Charge Algorithm" as shown in Figure 3-13 on page 35.
- The SAM implements a charging algorithm that (just) meets the specifications with a maximum current of $I_{charge,max}$ = 13 A.
- There is no active thermal management in the SAM, but the whole battery is mounted in one place and in a thick aluminium casing with water-cooling. The block temperatures can be expected to be equal. The water-cooling also heats the battery in very cold environment, but without control.
- The estimated production volume is 1,000 cars/year to 5,000 cars/year, that means 14,000 battery blocks/year to 70,000 battery blocks/year. This is a medium production volume for the equalizer.
- The purpose is the public market and Hawker provides a good knowledge about the batteries. In general, knowledge about battery powered electric vehicles in a series production is very low.

- Battery systems are improving rapidly. The growing demand on traction batteries in hybrid and battery electric vehicles will make other battery compositions available at a lower cost. The change of the battery type during the lifetime of the vehicle is quite likely.

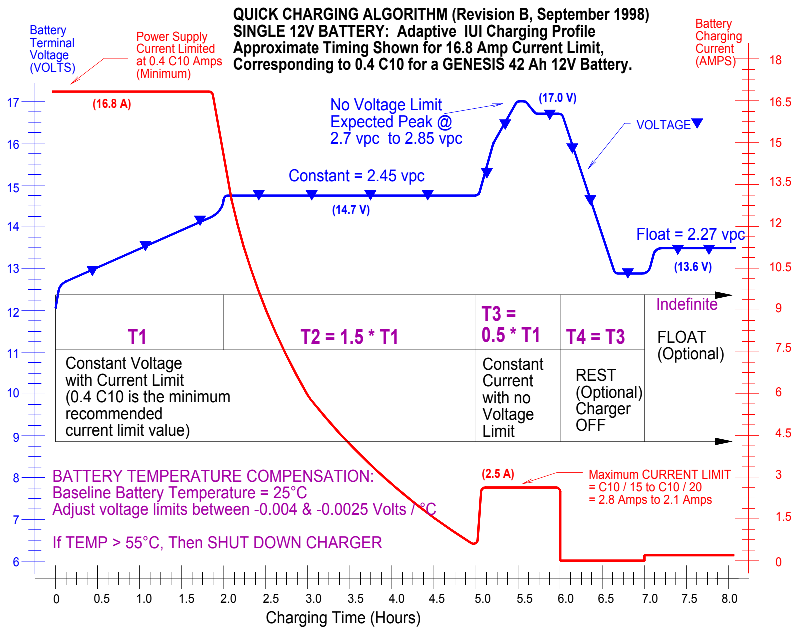

Figure 3-13: Fast charge algorithm for Hawker Genesis [8]

The fast-charge algorithm, shown in Figure 3-13 consists of three or five charging phases:

1. First constant current phase (CC1) with a minimum current of 0.4 C10. Our charger has 13 A in this phase. CC1 continues until the block terminal voltage reaches between 14.7 V and 15.0V (the figure above uses 14.7 V), when the charger switches to the next phase.
2. The second phase is a constant voltage phase (CV1) with a block voltage between 14.7 V and 15.0 V. This voltage also depends on the block temperature as shown in the figure above. Time determines the end of this phase: It should be 1.5 times as long as the CC1 phase, before the charger switches to the next phase.
3. The third phase is another constant current phase (CC2) but with lower current. The current in this phase should be between C10 / 15 and C10 / 20. For the 26Ah battery this means a current between 1.3 A and 1.74 A. In this

phase, the voltage should run free and without limitation up to an expected peak of 17.0 V, but the phase must proceed. This phase should be 0.5 times as long as the CC1 phase. Hawker recommends an additional float charge phase, if the batteries are frequently undercharged, which might easily happen in an electric vehicle.

4. Before the additional float charge phase (FLOAT) can start, the fast charge algorithm recommends a resting phase. The whole battery should rest for the same time as the duration of the CC2 phase.
5. The last phase is a float-charging phase, which should never stop until the charger is switched off for driving. This phase is a CV phase with 13.6 V per block – temperature compensation is required.

The charger can easily control the current through the battery string, but not the block voltage as discussed in this chapter. Thus, there are three points that require equalization:

1. The switching point between CC1 and CV1: Undercharge is most likely in this cyclic battery application. Thus, the latest block that reaches the CV1 voltage (between 14.7 V and 15.0 V) should determine the end of CC1 and relating to this, all further timing constants.
2. Equalizing should assure the block voltage to be between 14.7 V and 15.0 V.
3. The FLOAT phase needs equalization to prevent oxidation on one hand and undercharge on the other.

Since there are no results available that show the relationship between these needs and the battery life, it is reasonable to assume all of these three needs are essential. Due to the high number of series blocks and the high battery voltage (up to 240 V), the centralized solution seems not to be reasonable. A continuous method is not appropriate as well, because the blocks should run free in their voltage in CC1 and CC2 phase.

Unfortunately, Hawker does not specify a tolerated voltage range in the FLOAT phase, but if the cell voltage should be between 2.23 V and 2.27 V, it would mean a hysteresis of about 0.5 mV when using a solution that compares two serially connected blocks. 0.5 mV requires high precise operational amplifiers with offsetadjustment and stabilized power-supply. Another solution is comparing each block-voltage with a voltage-reference, but this requires intelligent equalizer modules. The FLOAT phase could be identified either by an intelligent equalizer module or by an isolated enable signal from the charger or management.

An equalizer that is capable of handling the FLOAT phase will certainly be able to keep all blocks between 14.7 V and 15.0 V regarding the accuracy. Small equalizing current might be insufficient, but the Genesis is not very likely to be overcharged in this application and 0.3 V provides a lot of room for smaller equalizing currents. The equalizing currents are usually chosen between 1 % and 2 % of the Ah capacity – in this case 1 % of Ah rating means $I_{equalize}$ = 260 mA. This small equalizing current is easily achievable by any kind of equalizing methods – even the dissipating equalizer.

The last design question is how to determine, when to start and when to stop equalization. The equalization should start in the CC1 phase, to lengthen this phase until every block has reached the CV1 voltage between 14.7 V and 15.0 V plus temperature compensation. Equalizing should end, when the charger starts the CC2 phase or when all blocks have reached the 15.0 V level. To determine whether all blocks have reached the 15.0 V level requires intelligent modules and higher level of communication in this application (14 blocks). It seems to be easier, using an interface to the charger or management. The charger or management should enable the equalizer with a simple isolated enable input – which is required anyway.

The intelligent equalizer with the voltage reference could easily determine, whether one block has reached the 14.7 V and start equalizing. The charger should then continue the CC1 phase until the battery voltage reaches 14 * 14.7 V (all voltages require temperature compensation). The charger keeps this voltage in the CV1 phase for the specified time. The charger disables the equalizer in the following CC2 phase, so that the cells run freely in voltage. The equalization will be enabled again in the last float-charging phase (CV2). The equalizers could be equipped with an additional output, which would tell the charger to reduce the charging current if the equaliser is not able to maintain the voltage under the 15.0V limit.

In conclusion, there are two sensible solutions:

The first solution is a daisy-chained equalizer with high precision and with enable input as shown in Figure 3-14.

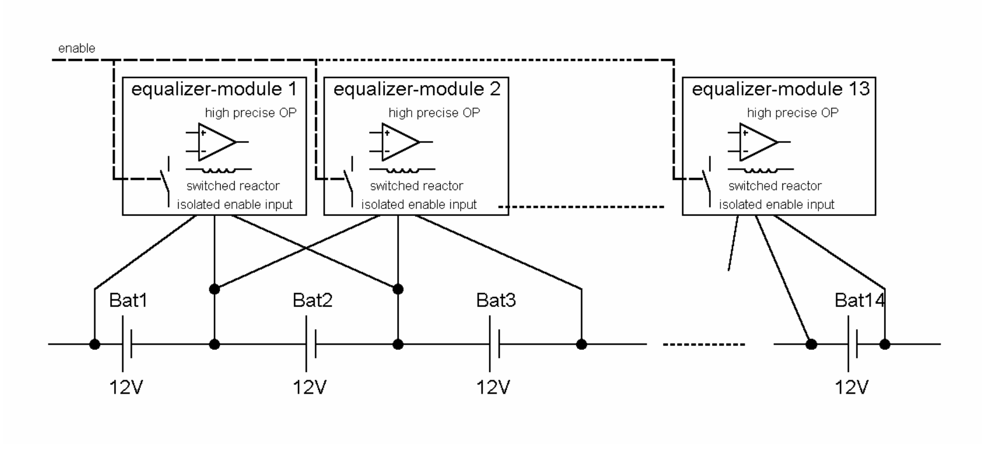

Figure 3-14: Daisy chained equalizer with high precision OP and enable

The Daisy Chained equalizer can also be packaged into one central or some part central case in order to reduce wiring. One housing for three 12 V modules (or six 6 V modules) is a very interesting solution, because it is useful for the new automotive 42 V system.

The second solution is an intelligent equalizer with voltage reference and partly centralized topology, as shown in Figure 3-15.

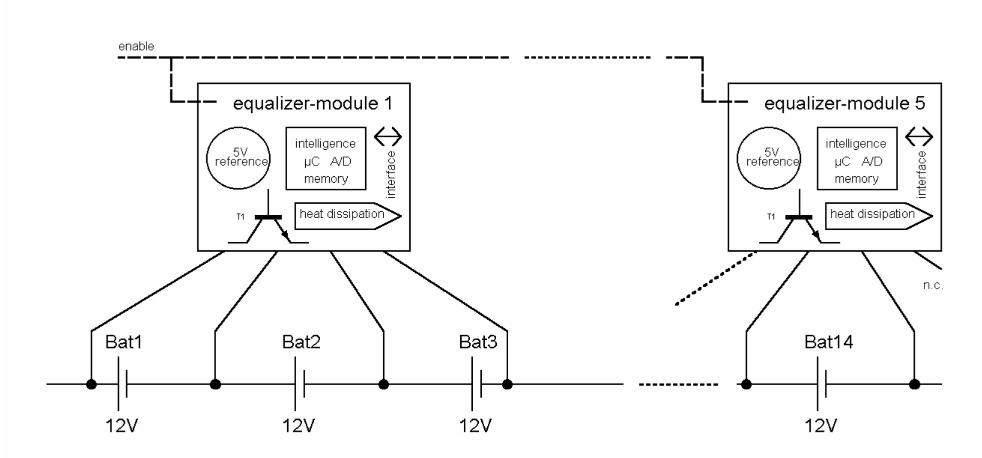

Figure 3-15: Intelligent equalizer with voltage reference and partly centralized topology

The intelligent equalizer should be equipped with an on-board temperature measurement, to avoid higher communication interfaces and a bus-system. The equalizer can be equipped with an interface for in-circuit-programming and data read-out. The data-storage capability and in-circuit-programming makes this solution better suitable for research and for vehicles in the first series production, in order to provide flexibility and acquire knowledge about equalisation.

3.7 Conclusions

The optimum equalizing method and strategy depends on several circumstances. It will vary from application to application and from battery-type to battery-type.
In cyclic applications with CC-CV-CC charging schemes, it is necessary to interrupt the equalization in the last CC phase.
The float charge needs a very precise equalization: The more blocks are involved in one string, the more precision is required.
Main questions to be answered are:

- How huge are the energy losses due to equalization?
- What equalizing currents are required?
- Can good equalizing in the first charging phases make a float charge phase and thus high-precision equalization redundant?

4 Energy Management of Hybrid Electric Vehicles

Hybrid electric vehicles are capable of reducing emissions, fuel consumption and noise. The drive train of the common internal combustion engine (ICE) car consists of

- One energy storage unit (tank)
- One energy-conversion unit (engine)
- One energy-conversion control unit (throttle)

The drive train of a hybrid electric vehicle needs at least

- Two energy storage units (tank + battery)
- Two energy-conversion units (electric motor + combustion engine)
- Two energy-conversion control units

The drive train of the hybrid electric vehicle is a complex system.
This system provides more degrees of freedom than the ICE vehicle. Optimisation is possible but challenging. The process of optimisation can be split into two categories:

1. Optimisation of the drive train configuration. This is an engineering process before selling the car to the customer.
2. Energy or drive train management. This is a process when using the car.

This project focuses on energy management, but optimising the energy management will be very abstract without choosing the drivetrain configuration first and the best energy management will be useless if the drivetrain configuration does not suit it.

Thus, we will have a look at the drivetrain configuration first and than discuss the management for the chosen system.

4.1 Concepts of Drive Train Configurations

This chapter will give a brief introduction into different HEV drive train configurations and their advantages and disadvantages. Two dimensions have been established to briefly describe the drive train configuration of a HEV:

1. Grade of hybridisation
2. Type of hybridisation

4.1.1 Grade of Hybridisation

The grade of hybridisation describes the share of power provided by the electric motor or energy provided by the electric energy storage over a driving cycle. This dimension can be communicated as a percentage number between 0% and 100%. 0% represents a common internal combustion engine (ICE) vehicle with no electric drive-motor at all. 100% represents a pure EV with no second energy storage and conversion unit. Precisely spoken, one has to specify whether this number expresses the share in energy or power.

Example: A concept with a powerful electric motor that propels the car and an ICE with the same power to generate electricity just need a small electric energy storage capacity (battery). The system could be described as a 50% grade of hybridisation in terms of power, but only 5% grade of hybridisation in terms of energy storage. The higher the grade of hybridisation, the higher is the advantage in terms of fuel consumption, noise and pollution. The disadvantages are smaller range or higher cost and higher vehicle mass due to a larger battery.

4.1.2 Type of Hybridisation

Three main types of HEV exist:

1. The series hybrid electric vehicle (SHEV) uses the electric motor to propel the car. The second energy conversion unit (an ICE for example) is used to generate electricity.
2. In the parallel hybrid electric vehicle (PHEV) both, the engine and the motor are mechanically connected to the drive shaft. Both can independently or together propel the vehicle or assist each other.
3. The power split drive system is another type. A planetary gear splits the engine power to a generator or to the wheels with variable share. Electric motor and engine are coupled with a clutch, so that the car can be propelled purely electrically.

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

Advantages of the SHEV:

- Less mechanical couplings. Simple packaging and modularisation.
- Engine operation can be smoothened or run in its optimum point.
- Engine noise and vibrations can easily be minimised.
- Engine size can be minimised to satisfy the average power needs only.

Advantages of the PHEV:

- The engine can directly propel the car. No long chain of power conversions with their losses is required.
- Motor and generator can be smaller and less expensive.

The power split 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 conversion chain is required.
- Fully automatic drive train, no change of gears.

The planetary gear drive train is a very clever but highly complex idea; it is implemented in the Toyota Prius [4].

The SHEV develops its main disadvantages if the average power requirements are high in comparison to the maximum power requirement. Fast cars, mainly made for

long highway driving for example would need the full high power for all three components: motor, generator and engine. This would be expensive and not very efficient. The SHEV type is very suitable for city and neighbourhood cars and busses.
The PHEV type is very suitable for long-range vehicles, because the engine can be chosen smaller and peak power will be provided by the electric motor. The smaller engine runs in a more efficient operating region and the motor can regenerate braking energy and use it for the next acceleration to smoothen down the engine operation. This PHEV will have slightly reduced 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 highways. The maximum speed generally defines the maximum power needs (rated, not peak power). This cannot be provided by the battery over a long range, thus the engine needs to provide the necessary power. The bigger the engine the worse the HEV achievements are. No known solution can yet achieve all requirements like high speed, good acceleration, low fuel consumption, low pollution, low noise and affordable cost!

4.1.3 Special HEV concepts

Though all combinations of hybridisation grade and HEV types are conceivable. Very useful combinations are:

- **Power assist type**. The power assist type HEV is a PHEV that mainly uses its ICE. The ICE can be smaller than normal (except for high speeds) and the motor provides assisting power for acceleration and short hills. The engine runs in a more efficient region, the operation can be smoothened for less pollution and noise and the vehicle can be propelled purely electric over very short distances and low speeds like in traffic jams. If the motor replaces the starter and the generator, this concept is called a **starter-alternator** HEV. Another name for this concept is **Mild HEV**. This could be the solution for fast, expensive, long-range highway vehicles.
- **Range Extender HEV**. This concept is originally a pure EV with all its 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 common ICE car, the range can be called unlimited.

This concept is usually a SHEV type and could be the solution for small, cheap short-range vehicles.

Another parameter that defines HEV is whether it is plugged into the mains or not. If yes, they are called **Plug in HEV**.

4.2 Drivetrain Configuration for our HEV

Most journeys are short journeys. Thus, most environmental impacts can be cut down with a solution for short journeys. A range of 40 km would be sufficient for most journeys, but pure EV with a short range make people feel unsafe. They do not know whether they reach their destination or not – people want peace of mind concerning the range. At last, people want the freedom to use their car for a longer distance from time to time as well.

Thus, our proposal is a plug in range extender SHEV.

- Most journeys will be undertaken purely electric – with highest possible efficiency and lowest possible impacts.
- Batteries can be chosen small, light and affordable.
- Engine can be small, light, cheap, durable and silent.
- Engine only runs occasionally, but if it runs, it will operate in its most efficient and less polluting region.
- Peace of mind concerning the range.
- Renewable fuels can be chosen.

To keep the engine size small, the maximum speed needs to be limited to about 70 mph or 110 km/h, which is the speed limit on a UK highway. Although the speed is limited, the acceleration will be good, because the main power will be supplied by the electric motor.

The pure electric range will be about 40 km. The APU extended range will be about 200 km. Electric motor power will be 24 kW, limited by the motor controller. Engine-generator power will be about 10 kW. Maximum continuous battery power is 12 kW.

The grade of hybridisation is about 20% concerning the energy (changeable with the fuel tank size) and about 50% concerning power (changeable with other batteries). Considering that most journeys will be purely electric, this plug in concept will achieve a “99%” hybridisation grade. 12 kW battery power will be sufficient to propel the car in cities and around neighbourhoods. The engine starts automatically to provide more power or increase range if demanded.

4.3 Energy Management

The optimisation of the energy management is a question of the goals that are to be achieved. A vehicle can be optimised to be very fast or very efficient or very comfortable and so on. The drive train configuration and the specifications and characteristic of the components play another role in the energy management. Goals, component specifications and configuration determine the energy management.

The energy management can be left to the driver, as it was the case many years ago or it can be implemented to higher levels like in some modern cars. However, the driver is a part of the system in every case and takes over some management work. Hence, the interface between vehicle, implemented management and driver needs to be specified. The goals are to reduce environmental impacts, that have been mentioned in section 1.2, while maintaining the requirements for individual mobility like range, acceleration and speed:

- Run the engine and generator as rarely as possible to improve energy efficiency.
- Run the engine-generator set near to its most efficient point.
- Run the engine only when noise and emissions play a minor role.
- Avoid switching the engine on and off to keep the cold-engine-runs as short as possible for less pollution.
- Assure the battery to stay within all their limits like voltage maximum, voltage minimum, current maximum, temperature maximum and minimum without sudden declines in performance.
- Provide the driver with information and advice that helps him playing the role that he wants to play (but encourages him to drive efficiently – as a challenge).

5 Conclusion and future work

Some work has been done on battery equalization as a part of prolonging their life. Some of the mentioned questions can be answered by implementing a microchip-controlled equalizer with some recording facility into an electric or into a hybrid electric vehicle.

The main work will be the drive train configuration and the energy management for a small delivery van – a hybrid electric Ford Fiesta:

1. The drive train needs to be configured in detail.
2. Components need to be tested for our purposes (efficiency).
3. Goals for the energy management need to be described in detail.
4. The management methods need to be chosen and described.
5. Driver information and advice need to be specified.
6. Implementation of all mentioned aspects into a vehicle.

6 References

1. Maslow, *Maslow's Pyramid of Needs*.
2. A. Schafer and D. Victor, *The future mobility of the world population.* ISI Citation Database, Pergamon-Elsevier, 2000. **ISSN: 0965-8564**.
3. D. Thompson, *N3. The drive-by test*, in *Automotive Engineering II*. 2002. p. 10.
4. Toyota, *Prius - Environment*. 2002.
5. VW, *VW Golf 1.9 TDI*. 2002.
6. H. Kleine and U. Stimming, *Brennstoffzellen: Funktion, Typen, Systeme (Fuel-Cells: function, types, systems)*, in *TAE-Seminar* 2001: Esslingen (Germany). p. 11 - 15.
7. Spiegel, *Brennstoff-Delle: Wie fahren wir in Zukunft?*, in *Spiegel-Online*. 2002.
8. K. Jana, *Genesis Application Manual*. 2000, Hawker Energy.
9. FORTU, *FORTU Bat*. 2001.
10. VARTA, *Bordnetzbuch (On-board Power Supply) Batterieratgeber fuer das Bordnetz und den Elektrobootsantrieb in Segelbooten, Motoryachten und Wohnmobilen*. 1998, Hannover: VARTA. 59.
11. K. Jana, *Electric Vehicle Application Handbook For Genesis Sealed-Lead Batteries*. 1998, Hawker Energy.
12. N. H. Kutkut, *Prolong the life of series battery strings with individual battery equalizers*, in *electric & hybrid vehicle technology international*. 2000. p. 116 - 121.
13. H. Wenzl, *Batterietechnik (Optimierung der Anwendung - Betriebsfuehrung - Systemintegration)*

Technology of Batteries (Optimization of Application - Usage - Integration) + additions from Seminar at TAE (21.05.2001). Kontakt & Studium. Vol. Bd. 582. 1999, Renningen-Malmsheim: expert verlag. 253.
14. B. Hauck and J. Altmeier, *Test and Evaluation of the Battery Management System with the Two Wire Bus*. 2001: Kaiserslautern. p. 7.
15. K. Jana, *Charging pure lead-tin batteries*. 1999, Hawker Energy.
16. S. Khuwatsamrit, *Battery Management System*. 2001, SKI.