CHALMERS
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Implementation of power electronic energy storage unit designed for Chalmers ECO-marathon hybrid car

Master's thesis in Electric Power Engineering

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Abstract

The general scope of this master thesis work is to design, construct and evaluate the electric storage unit and parts of the electric drive train for the series hybrid car Smarter. Smarter was designed by master students at Chalmers, and would be participating in the Shell ECO marathon competition in 2009.

A supercapacitor (LIC) was designed and constructed by combining individual Lithium-Ion supercapacitor cells. The LIC was evaluated and compared to a commercially available supercapacitor (Maxwell EDLC), to decide which one to use in the SMARTER car. Two power electronic converters, along with converter control methods, were evaluated with regards to design and performance. This thesis work also covered the installment of the chosen equipment in the vehicle, therefore installment issues such as cabling and connection points also needed to be considered.

Both supercapacitors that were tested were found to fulfill performance requirements, but with the LIC a significant reduction in weight was achieved, mainly due to its acrylic glass housing. Both converters were found to be suitable, one being better in one aspect, the other better in another, so both were prepared to be installed in the car and both were actually used during the race runs.

Unfortunately due to mechanical issues SMARTER was not able to complete any of the three race runs it was supposed to. Therefore it is difficult to draw any detailed conclusions about the performance of the electrical storage and power converter design, but the design and the entire hybrid drive train was operational and functioned as intended.

Acknowledgements

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1 Introduction

1.1 Background

This master thesis work was carried out as part of the Chalmers's contribution to the Shell Eco Marathon competition (SEM) 2009 (see further information in chapter 1.4). The vehicle, SMARTER (see further information in chapter 1.5), which was the focus of this thesis, was to participate in the urban concept class, with the goal to run a track as energy efficiently as possible. Since this required the vehicle to be of hybrid technology, there was a need to construct an electrical energy storage unit and some power electronics for propulsion. That is the scope of this thesis work.

1.2 Goal

The main goal of this master thesis is to produce a supercapacitor energy storage that was significantly lighter than those supercapacitors that were available on the consumer market. There was a supercapacitor purchased for this project, the Maxwell BMOD0140-E048 BOOSTCAP Ultracapacitor Module, an Electrolyte Dual Layer Capacitor (EDLC), which would later be evaluated against the own produced supercapacitor, based on both performance and weight. The EDLC has a weight of 13.5kg and since that would add a lot of extra weight to SMARTER, the project would benefit a lot if this weight were decreased. This is done by combining Lithium Ion Capacitor (LIC) cells, to achieve needed voltage and energy levels to propel the vehicle, and construct a housing for them.
Also the problem with the design of energy efficient power electronics for the propulsion needed to be addressed.

1.3 Design Constraints

The energy storage had to be a supercapacitor instead of conventional batteries because the SEM regulations declared that batteries were forbidden. Also the total electrical energy must be able to be measured before and after every race.
The main idea of the SEM is to run a vehicle as energy efficiently as possible and therefore the main focus for the propulsion's power electronics was energy efficiency. It would be needed to have a converter for which the voltage (speed) and the current (torque) could be controlled. Since as much energy efficiency as possible was desired some kind of regenerative breaking also had to be implemented. This also makes the total weight of the vehicle an important factor that has to be addressed in every decision.

1.4 Shell Eco Marathon

Shell Eco-Marathon is a competition that's been arranged every year by Shell since 1985. The participants design and build their own vehicles in order to run as energy efficient as possible around a track. There are two main categories, the prototype and the urban concept. The prototype vehicles are futuristic and streamlined where the primary design consideration is reducing

drag and maximizing efficiency. The urban concept vehicles are more like the conventional 4-wheel cars that roam the streets of today.

The track is run seven laps and then the vehicle's fuel consumption is measured and recalculated into kilometres per litre petrol. The vehicle with the most kilometres per litre is the winner, not the one that finished first like in a conventional race.

1.5 SMARTER

SMARTER is a hybrid vehicle developed at Chalmers in order to take part in the Shell Eco Marathon Urban Concept competition. The vehicle is constructed with a carbon fibre composite unibody, which with its low weight, and constructional stability reduces the potential weight of the car itself substantially. The SMARTER vehicle can be seen in Figure 1.

Figure 1 The SMARTER vehicle

The total weight of the vehicle with all components mounted is only *74kg*. The hybrid propulsion model that was chosen was the series hybrid model, in which there is an internal combustion engine that powers a generator, which in turn powers an electrical storage unit that powers an electric motor which causes the propulsion of the vehicle. The series hybrid solution is further explained in chapter Hybrid Systems.

The SMARTER vehicle is propelled by two electric motors, one for each of the back wheels, which draw their power from the supercapacitor energy storage. The supercapacitor is charged by two generators that are driven with a small gasoline powered internal combustion engine. The engine is a *35cc* naturally aspirated air-cooled four-stroke engine. [1]

2 Theory

This chapter explains how the electrical components and systems that make up the SMARTER hybrid vehicle work and what they do.

2.1 Hybrid Systems

A hybrid vehicle is a vehicle that is propelled both by an electric machine (EM) and an internal combustion engine (ICE). Using an EM for propulsion has many advantages, where the main one is the possibility to generate energy when the vehicle brakes. There are mainly two ways this can be utilized, either as a parallel hybrid, see Figure 2, or as a series hybrid, see Figure 3.
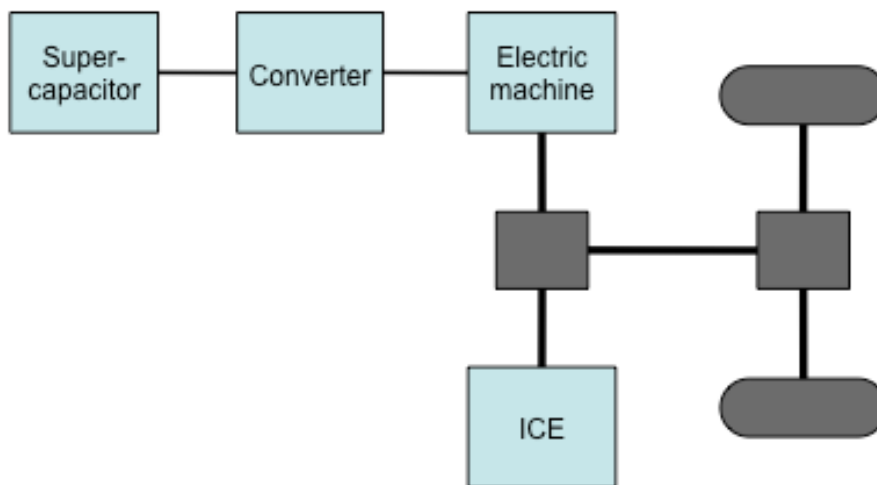
Figure 2 Parallel hybrid layout.

In the parallel hybrid system the ICE, when operating, propels both the vehicle's wheels and an EM that will operate as a generator and charge the vehicle's electric energy storage. When the energy storage is adequately charged the ICE will be turned off and the EM will work as propellant for the wheels.
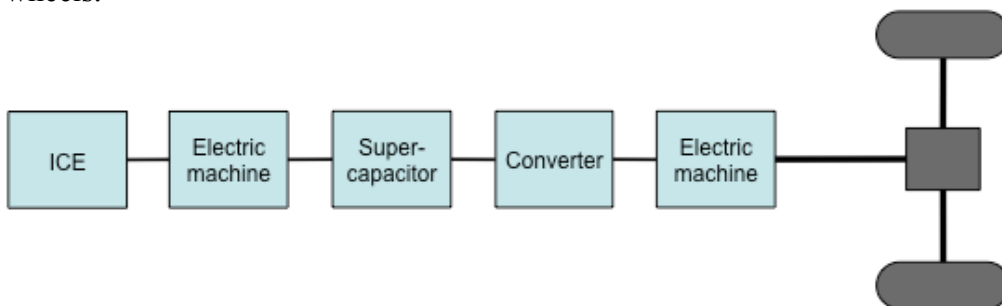
Figure 3 Series hybrid layout.

In the series hybrid system the ICE is connected to an EM, working as a generator, which charges the energy storage. The energy storage in turn puts power to another EM, working as a motor, which propels the vehicle's wheels.

2.2 Supercapacitors

A supercapacitor is an electrochemical capacitor. It differs from a regular electrostatic capacitor where the capacitance solely depends on the surface area of the electrodes see Figure 4.
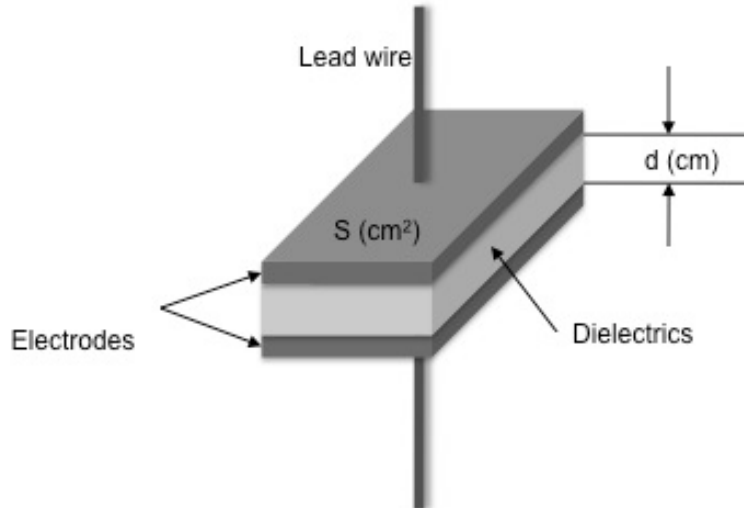
Figure 4 Electrostatic capacitor

In a supercapacitor the capacitance is dependent of the chemical and structural properties of the electrodes and the electrolyte. When put under charge the barriers between the two electrodes and the electrolyte get induced with ions and holes see Figure 5.
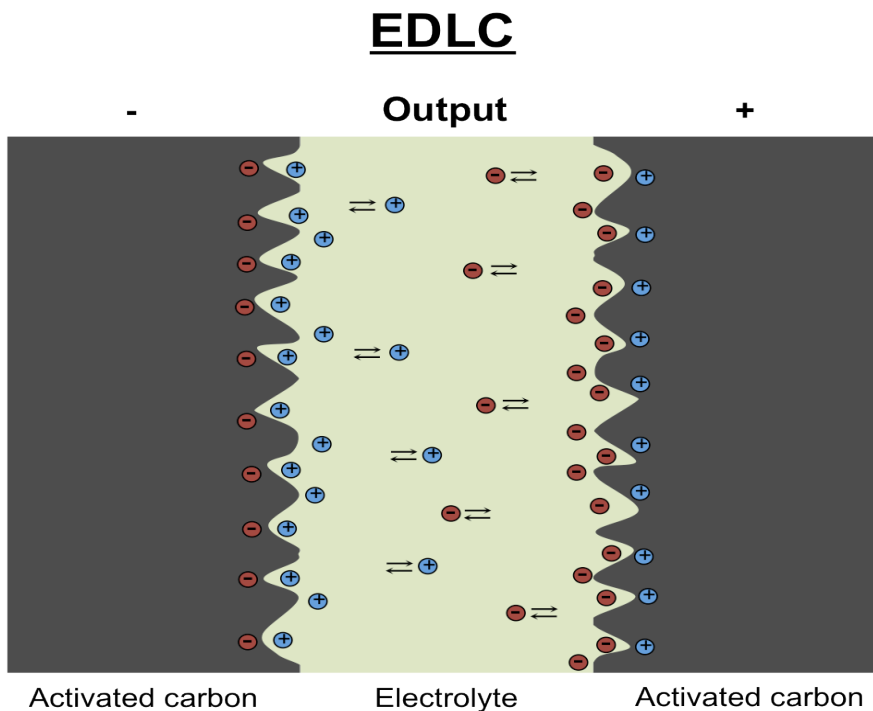
Figure 5 Structure and function of an ideal double-layer capacitor (EDLC). Applying a voltage to the capacitor at both electrodes a double-layer will be formed separating the ions in the electrolyte in a mirror charge distribution of opposite polarity

4

The name for the most common used supercapacitor today, the Electrical Dual Layer Capacitor (EDLC), comes from the two barriers between the two electrodes and the electrolyte. The EDLC uses activated carbon as electrodes that is a common material with good electrical properties.

There are also other types of supercapacitors where various types of semiconductor material are used for making one of the electrodes. One of those is the lithium ion supercapacitor. The advantage by using doped lithium ion material as one of the electrodes is that it's possible to get an even higher capacitance then from an EDLC given they both have the same size and weight. How this works is explained in chapter 2.2.3. This is the main reason a new supercapacitor energy storage unit was built. This is achieved by series coupling of a number of lithium ion capacitors since they have a very high energy density compared to the more conventional EDLC. The high energy density implies it is possible to construct a lighter supercapacitor with the same electrical properties.

2.2.1 Background

This chapter will elaborate on the supercapacitor in general and the thoughts behind the design choices made for this thesis. As stated in the background chapter 1.3, the SEM regulations did not allow any electric power storage other than a supercapacitor. The reason for this rule is mostly due to that the energy stored in a supercapacitor is much easier to calculate than the energy stored in a battery. This energy is calculated with Formula (1).

$$W_{stored} = \frac{1}{2}CV^2 \tag{1}$$

Where W is the stored energy in joules, C is the capacitance in farad and V is the voltage in volts.

2.2.2 The EDLC, Maxwell module

For this project there was already purchased a supercapacitor, the Maxwell BMOD0140-E048 BOOSTCAP Ultracapacitor Module. This supercapacitor is an EDLC and the specifications can be seen in Table 1.

Measurement Items	BMOD0140-E048
Operating Temp. Range	40°C ~ +65°C
Rated Voltage Max	48.6V
Rated Voltage Min	0V
Capacitance	140F
DC-IR	11mΩ
ESR	9mΩ
Energy Density (Weight)	3.40wh/kg
Cell Dimension	416x190x160 mm
Cell Weight	13500 g

Table 1 Specifications for the Maxwell ELDC

2.2.3 Lithium Ion Capacitors

The capacitors that will be used to create the electric power storage are the 2200F lithium ion capacitor (LIC) from JM Energy (JME). These have about 4 times higher energy density than conventional EDLC and more than 2 times higher power density than conventional batteries. A comparison of the energy and power density for the most common types of power storages can be seen in Figure 6.
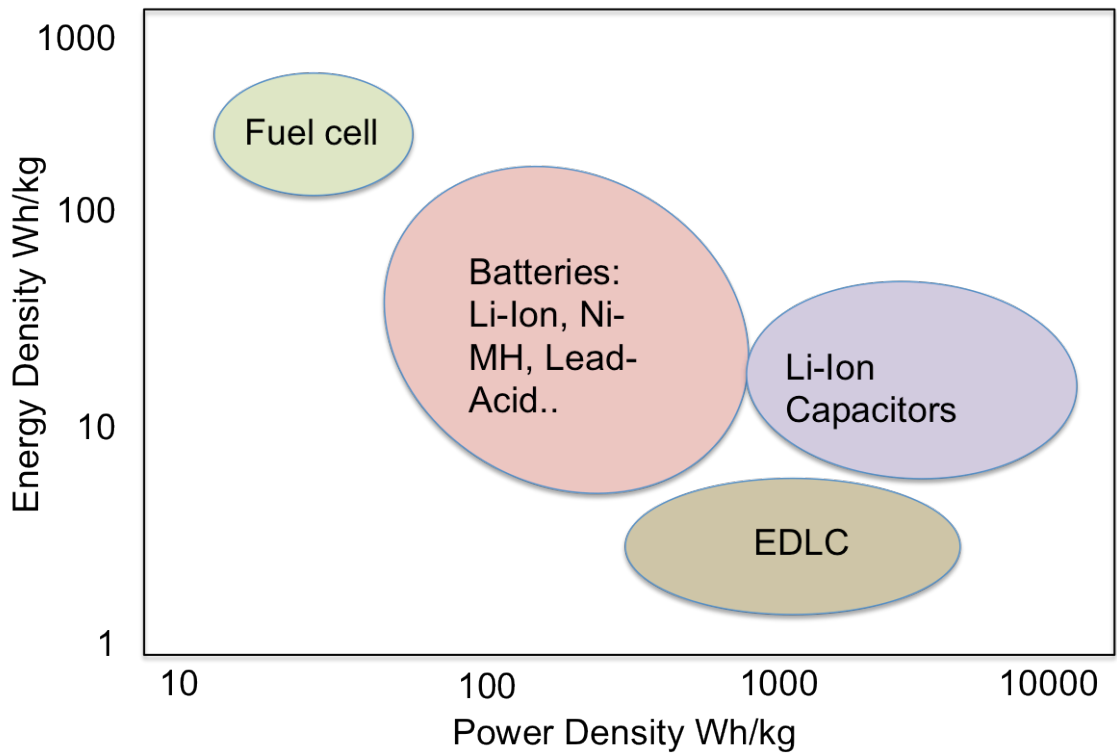
Figure 6 Power and energy density for different energy storage

Instead of having anodes and cathodes made of activated carbon as a conventional EDLC has, the capacitors from JME have a lithium ion doped carbon anode. This makes the capacitance in the anode much higher than the capacitance in the cathode. Formula (2) & (3) shows that this makes it possible to have a total capacitance twice as high as in an EDLC given the same size and weight.

Li-Ion Capacitor
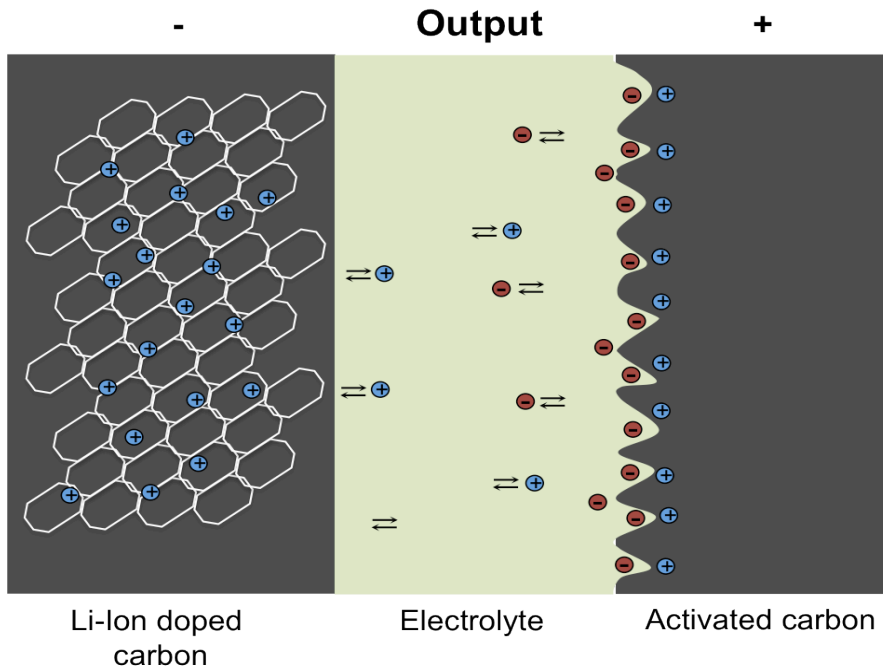
Figure 7 The main differences between EDLC and Lithium Ion Capacitors

Figure 8 Simplified circuit schematics of a capacitor.

Figure 8 gives the capacitance in a capacitor cell, C_{cell}, as follows.

$$\frac{1}{C_{cell}} = \frac{1}{C_{anode}} + \frac{1}{C_{cathode}} \tag{1}$$

For the EDLC where the anode capacitance, C_{anode}, equals the cathode capacitance, $C_{cathode}$, the total capacitance, C_{EDLC}, will be half the anode or cathode capacitance.

$$C_{anode} = C_{cathode} = C \rightarrow C_{EDLC} = \frac{C}{2} \tag{2}$$

However, in the LIC the cathode capacitance is much greater than the anode capacitance therefore the total capacitance, C_{LIC}, will equal the cathode capacitance.

$$C_{anode} \gg C_{cathode} \rightarrow C_{LIC} = C_{cathode} \tag{3}$$

The max cell voltage in the LIC is also higher than the one in EDLC, which is because of the low potential in the anode, the cell voltage is almost the same as the potential in the cathode. This combined with the higher capacitance makes the energy density almost 4 times higher in an LIC than in an EDLC, which means that you can store four times more energy in a LIC compared to an EDLC of the same size. This in turn means that the energy storage can be made much lighter if an LIC is used rather than if an EDLC was to be used.

LIC specifications for a singular cell can be seen in Table 2.

Measurement Items	LIC, 2000F, one cell
Operating Temp. Range	$20^{\circ}C \sim +70^{\circ}C$
Rated Voltage Max	3.8V
Rated Voltage Min	2.2V
Capacitance	2200F±200F
DC-IR	2.3±0.3mΩ
ESR	1.4±0.3mΩ
Energy Density (Weight)	14wh/kg
Cell Dimension	138x106x9 mm
Cell Weight	208±4 g

Table 2 LIC specifications for singular cell

2.2.4 Measuring performance

To establish the performance of supercapacitors one need to decide the internal resistance and the capacitance of the supercapacitors. One way to do this is to measure voltage and current while charging and discharging the devices. The internal resistance is then calculated using the Formula (5)

$$R = \frac{\Delta V}{I} \tag{5}$$

The capacitance is calculated using the Formula (6)

$$C = \frac{I \cdot \Delta t}{\Delta V} \tag{6}$$

Using a higher current provides better accuracy to the internal resistance calculations, since higher currents will result in more resistive losses in the capacitor. These are then easier to measure accurately.

2.2.5 Balancing combined supercapacitor cells

The capacitance and resistance in a supercapacitor depend on its exact composition down to a molecular level. Therefore when combining several supercapacitor cells there will be differences in stored energy in each individual cell due to the capacitance and resistance of each cell. Also for every load cycle this difference will diverge and the overall performance of this combined supercap will depend on how well the individual cells are balanced. This is even more so important when lithium-ion supercapacitors are used since they may be permanently damaged if they are over or undercharged. Therefore it is important to have a method for balancing the individual cells. There are two ways to balance supercapacitor cells, referred to as method 1 and method 2 and further described below.

Method 1 is a method in which the excess charge is burnt off through a simple resistance, as seen in Figure 9. The separate cell voltages are compared and the lowest measured voltage will be the set voltage level that all cells should have. To balance the other cells to that set voltage, resistors are connected to the high voltage cells for a time that is calculated to bring the cell voltage down to the set voltage with that specific resistor. The implementation of method 1 is easier than of method 2.
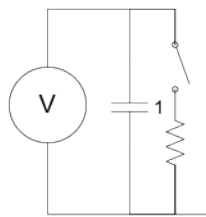
Figure 9 Balancing circuit schematic for one cell

Method 2 is to pair the cells so that the one with the highest voltage is paired to the one with the lowest voltage, and in doing so the voltage in between the two is balanced. This is then repeated iteratively until all cells are balanced. In comparison, this second method is more energy efficient: the only losses that will occur is due to the internal resistance in the connected cells and the resistance from the cabling. The details on the method that was used are explained in chapter 4.1.2.

2.3 Converters

Since the supercapacitor is an unregulatable energy source there is also a need for some kind of regulator to be able to control the power to the electric motor. For this a converter that would allow adequate control of the power was needed. There are two main types of DC-DC converters to choose from. One is the step-down (buck) converter and the other is the step-up (boost) converter.

2.3.1 Step-Down (Buck) Converter

As the name implies, the step-down converter produces a lower output voltage than the dc input voltage and a simplified schematic of the circuit can be seen in Figure 10.
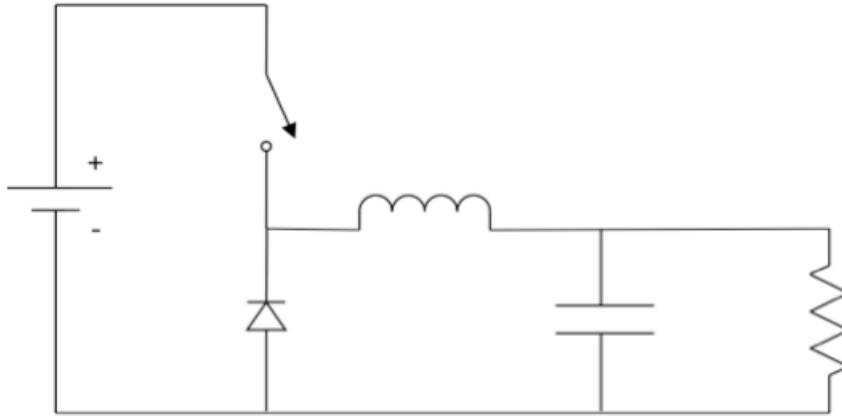
Figure 10 Buck Converter schematic circuit

Since equilibrium of energy must be maintained this means it will produce a higher current on the output than the input. The transformation happens when the switch opens and closes during set intervals. During the on state the input voltage will charge the inductor with energy and this energy will then be used during the off state of the switch.

2.3.2 Step-Up (Boost) Converter

The Step-up converter can in some way be seen as the inverse of the Step-down converter. It produces a higher output voltage than the input and therefore also a lower current on the output than the input. A simplified circuit schematic can be seen in Figure 11.
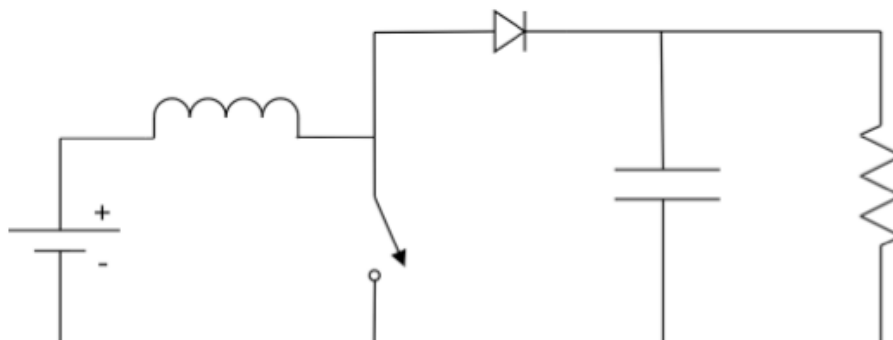
Figure 11 Boost converter schematic circuit

During the on state of the switch a higher current will pass trough the inductor and charge it with energy. When the switch then opens this higher energy will produce a higher voltage on the output than the input.

2.3.3 Modified converter

A regular converter, in this case a buck converter, shown in Figure 12 is not an optimal solution for our needs due to the losses in the freewheeling diode In the circuit there will be a voltage drop over the diode when the switch is turned off.
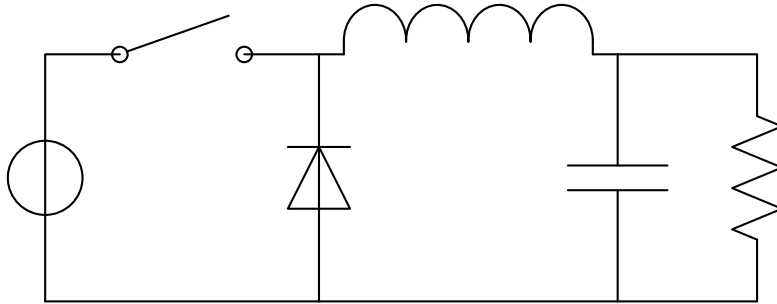
Figure 12 Simplified circuit schematic of a regular buck converter.

The losses in the diode can be calculated with Formula (7).

$$P_{diode} = V_{diode} \cdot (1 - D) \cdot I_{load} \qquad (7)$$

With a standard silicon diode, a duty cycle, D, of *0.5* and a load current, I_{load}, at *20A* the losses in the diode, P_{diode}, will be *7W* when V_{diode} is *0.7V*. This is roughly more than *1%* of the whole cars energy consumption and this is unacceptable in our converter. Instead the diode was replaced with a switch. A simplified circuit schematic is shown in Figure 13.
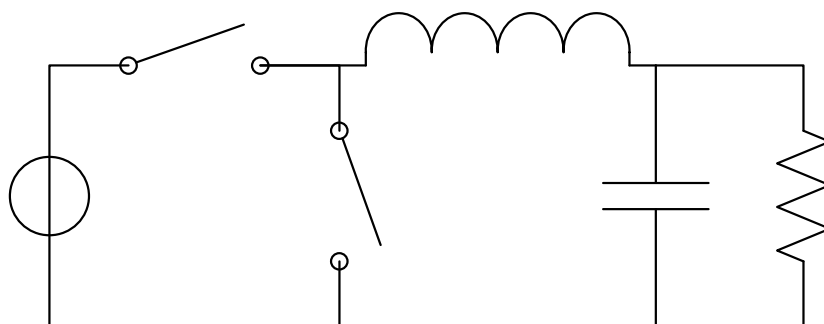
Figure 13 Simplified schematic circuit of a modified buck converter.

The losses in a MOSFET transistor is much smaller than in a diode during conduction although another switch will mean more switching losses. These losses were believed to become smaller since there would be no need to have a very high switching frequency.

2.3.4 Converter control

To control a converter so that it delivers the desired output voltage when the input voltage and the output load may fluctuate there are mainly two different approaches to choose from, pulse-width modulation (PWM) or bang-bang control (also known as on-off control). A switch-mode dc-dc converter control the average output voltage by controlling the on and off durations (t_{on} and t_{off}) of the switch. The first way to do this is by switching with a constant frequency and then adjust the duration while the switch is closed. This method is called pulse-width modulation (PWM) switching.

The other way to control the output voltage is by having a fixed on duration and change the switch frequency. This method is called bang-bang control or on-off controller. A bang-bang control is more prone to cause ripples in the output voltage than a PWM control and these ripples are hard to filter out due to the variations in the switching frequency.

3 Design Decisions

3.1 Hybrid systems

One drawback with the series hybrid system is that it requires more energy transformation steps until the energy from the fuel reaches the wheels that propel the vehicle. There is also a problem with high currents as there is a need for high torques during acceleration, which causes high losses. These drawbacks may in somewhat be compensated by the fact that the ICE can always operate in its optimized rpm range.

The parallel hybrid system on the other hand requires a more complex transmission than the series hybrid system in order to function properly, since the mechanical linkage in the parallel transmission needs to disconnect the ICE from the electric motor and the wheels when the ICE is turned off. There is also the drawback that the ICE on the parallel hybrid can't always operate in its optimized rpm range and this will affect the fuel consumption. This may somewhat be compensated by the lesser energy transformation steps and the non-existing high torque currents.

The project decided to design the vehicle as a series hybrid and the main reason for doing so was that it is mechanically easier to realize this than the parallel hybrid, which has the need for a more advanced mechanical coupling between the internal combustion engine, ICE, and the generator.

3.2 Energy storage – supercapacitor

3.2.1 Design of combined cell supercapacitor

The lithium ion supercapacitor would be constructed of 12 or 13 cells in order to be as near as possible to the maximum allowed voltage for the Shell Eco-Marathon race. The maximum allowed voltage is *48V* and since the maximum voltage on each cell is *3.8V* the maximum voltage, when they are connected in series, on the supercapacitor will be *45.6V* or *49.4V* depending on if 12 or 13 cells were chosen. Each cell has a capacitance of *2200F* and that gives a total capacitance for the 12 or 13 cells connected in series of approximated *180F* or *170F*. The number of cells will also determine the stored energy in the supercapacitor according to the Formula (1) in chapter 2.2.1. This gives a stored energy of W_{12}=*190.6 kJ* and W_{13}=*206.5 kJ* for 12 and 13 cells. So by choosing 13 instead of 12 cells there will be more stored energy but most importantly the capacitor will be able to operate on a higher voltage, which will lead to lower losses. This is due to a higher voltage will lead to a lower current and the I^2R-losses will be lower. Although a higher number of cells will lead to a higher weight but since each cell weights *208g* this is not of significant importance when it comes to choosing 12 or 13 cells. It was therefore decided to go with 13 cells. The specifications for the combined 13 LIC cells can be seen in Table 3.

Measurement Items	LIC, 2000F * 13cells
Operating Temp. Range	$20^oC \sim +70^oC$
Rated Voltage Max	49.4V
Rated Voltage Min	28.6V
Capacitance	169.2F±15.4F
DC-IR	29.9±3.9mΩ
ESR	18.2±3.9mΩ
Energy Density (Weight)	8.23wh/kg
Cell Dimension	416x190x160 mm
Cell Weight	4600 g

Table 3 LIC specifications for combined 13 cells

3.2.2 Theoretical comparison

A theoretical comparison between the LIC singular cell, LIC 13 cell and the Maxwell module is shown in the specification table below.

Measurement Items	LIC, 2000F * 13cells	BMOD0140-E048
Operating Temp. Range	$20^oC \sim +70^oC$	$40^oC \sim +65^oC$
Rated Voltage Max	49.4V	48.6V
Rated Voltage Min	28.6V	0V
Capacitance	169.2F±15.4F	140F
DC-IR	29.9±3.9mΩ	11mΩ
ESR	18.2±3.9mΩ	9mΩ
Energy Density (Weight)	8.23wh/kg	3.40wh/kg
Cell Dimension	416x190x160 mm	416x190x160 mm
Cell Weight	4600 g	13500 g

Table 4 Specifications of used supercapacitors

In order to understand how the characteristics in comparison Table 4 affects the performance of the chosen supercap in the SEM competition a comparison about each characteristics follow.

- Operating Temp. Range: Since the supercap will be situated in the same compartment as the ICE the operating temperature will be fairly high. Therefore there is an advantage for the LIC since it has a higher maximum operating temperature.
- Rated voltage Max: The difference is slight but higher voltage is desirable since one can achieve higher output power at lower currents. Since the maximum rated voltage on both the supercaps is higher than the 48V maximum allowed voltage according to the SEM rules the choice between them is equal.
- Rated voltage Min: The difference between the supercaps is fairly great and the Maxwell's performance might seem better, but one does not want to go that low, since that would require very high currents in order to achieve the same output power

- Capacitance: Higher capacitance means more energy stored in the supercapacitor. This is a desirable feature and as can be seen above the LIC is substantially better than the Maxwell.
- DC-IR: The difference in internal resistance affects the time the supercaps will take to discharge assuming they both are connected to equal loads and the same output power. The LIC will discharge more quickly than the Maxwell due to its higher internal resistance but although the difference is high the internal resistance on both are fairly low compared to the load they will operate, therefore this difference between the two supercapacitors is not too important.
- ESR: The equivalent series resistance affects how much of the current ripples, to which the supercap is exposed, that will be transformed into heat in the supercap. Although there is an advantage for the Maxwell supercap both of them have a very low ESR rating.
- Energy density: Energy density is a characteristic that is highly desirable. Since the LIC has nearly 2,5 times higher energy density than the Maxwell supercap there is a great advantage with the LIC.
- Cell Weight: As described earlier, a lower weight is very important to the overall performance of Smarter, and LIC is almost 3 times lighter than Maxwell.

In the cases where there is an advantage for the Maxwell EDLC, that advantage is only a slight one. However, in the cases where the LIC theoretically will perform better, the advantage is a great one. One can for example point out the weight factor where the LIC weighs nearly a third of the Maxwell EDLC. Based on this comparison, the design decision will be to continue work with the LIC.

3.2.3 Balancing method

While driving the vehicle the supercapacitor will discharge when the ICE is off and recharge once the ICE is turned on. These charging cycles will eventually lead to unbalanced cells. With method 1 it is not possible to balance cells during driving, since the burning off the excess charge would counteract charging. With method 2 it is possible to perform balancing while driving, however in order to do so extra apparatus must be installed in the vehicle and therefore add to its weight. Based on drive profile simulations made by other master thesis students within the SMARTER project it was assumed that balancing during the race would not be absolutely necessary, and therefore both methods could still be considered.
It was then decided that method 1, burning off excess charge, would be used. The extra losses this method would cause were considered negligible compared to the method being easier to implement than method 2.

3.3 Converter design

Since the SEM regulations state that the output voltage cannot exceed *48V* and since the maximum output voltage of the chosen energy storage unit was *49V* (as stated in chapter 2.1), choosing a step-up converter would mean that the

full potential of the energy storage unit could not be utilized. Hence, the wiser choice is a step-down converter, which would allow the output of the storage unit to be converted down to set limits.

The converter is also chosen to be a 2-quadrant dc-dc converter. Since there is no need to drive backwards with the car it may even be preferable with a 2-quadrant converter. There's less components and easier to design. The regulations in the Shell Eco-marathon say that the converter can be powered with an external battery source; therefore the power that is needed for powering the converter itself and the losses in those components can be ignored.

It was not in the scope for this thesis to also build a converter, however, a design choice had to be made. Given that a step-down converter was considered the best alternative to meet the requirements, there were two converters available, already procured for other use in the SMARTER project. One was the Maxon motor control 4-Q-DC Servo amplifier ADS 50/10, and the other was a 2-quadrant dc-dc converter built by Björn Lindgren at OSO Konsult. These two converters will here on be called the Maxon and the 2-Q converter. Existing data and tests that were carried out did not provide enough information to decide which of these converters that would be the better choice. Instead the vehicle was prepared to use both these converters so that both could be used during the competition in Germany and possibly re-evaluated after that.

3.3.1 The Maxon converter

The Maxon converter is a four-quadrant buck converter with PWM control. The gate drive is powered by the input so no external power source is needed. According to the specifications in Table 5 the Maxon converters maximum output current is *20A*, but our tests show that the maximum output current is *17A*.

Max. output voltage	45V
Max. output current	20A
Continuous output current	10A
Efficiency	95%
Switching frequency	50kHz
Built in output inductance	75μH

Table 5 Maxon converter specifications [2]

According to another master thesis project working in parallel with us on the SMARTER project a current of *20A* or more would be needed in order to produce sufficient acceleration of the vehicle. To use the Maxon converter two traction motors had to be used, one for each back wheel, and one converter per traction motor.

3.3.2 The 2-Q converter

The 2-Q converter was a modified buck converter with two groups each consisting of 6 MOSFET transistors in parallel. The upper group acted as switch from input to output and the lower group was used instead of a diode. Unfortunately there were no specifications of the 2-Q converter but according to the constructor, Björn Lindgren, it should easily manage to deliver *50kW* at *50V*. Considering this no tests of the maximum output current were performed. The gate drive was also powered by a separate power source, which meant that those losses could be disregarded. The 2-Q converter can be seen in Figure 14.
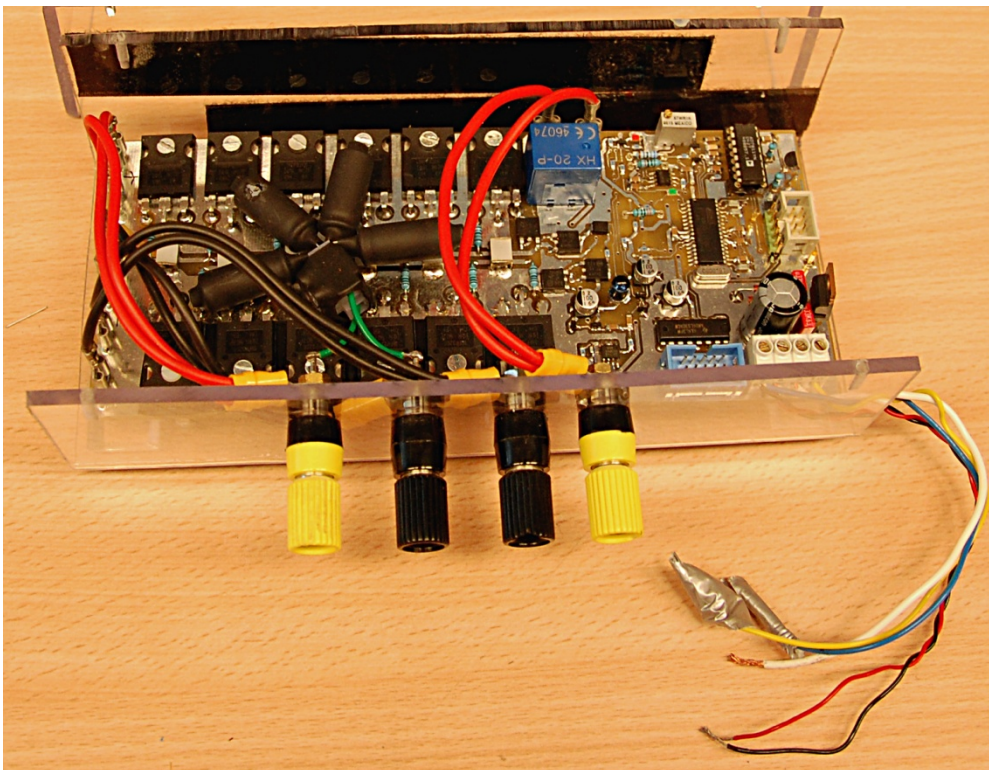

Figure 14 The 2-Q converter

3.4 Converter Control

Since, according to chapter 2.3.4, a bang-bang controller is more prone to ripples, a PWM control would most likely be the better choice but since programming the converter with a optimized PWM control would be a major task overshooting the scope of this thesis the more easier implemented bang-bang control where chosen instead.

3.5 Cable dimensioning

When choosing cables for any electric installation in a moving vehicle there is a need to decide between low-loss cables, which usually are thicker and therefore heavier, or thinner cables, which although their weight is reduced they usually have higher resistance and therefore causes higher electrical losses. In order to make the most optimized decision there is the need to know how long cables there must be and how high currents they will have to conduct.

Based on the vehicle's dimension its possible to make an assumption on how long the cables need to be. When the length of the cables are known, ohms law and the assumption of the power used to propel the vehicle will give an estimate of how big the electrical losses will be, depending on the thickness of the cable. The thickness of the cable and its estimated length will give how much weight the electrical cabling adds to the vehicle. Between these two estimations it is possible to make a decision of which cable will give the lowest energy losses.

4 Construction

4.1 Supercapacitors

To be able to install the combined supercapacitor cells in the vehicle some kind of housing had to be constructed. The supercapacitor also had to be subjected to some component and performance testing and there was also a need for a balancing apparatus. The methods for these tests and materials for the components are explained in the following chapters.

4.1.1 Construction of the housing

Since the Maxwell capacitor was supposed to act as backup in the Eco-marathon race both supercapacitors had to have the same mounting frame. So the bottom plate on the supercapacitor housing was made to match the dimensions as the one from Maxwell. The same power connector was also put on the two capacitors; this made it easy to switch between the two. According to the Eco-marathon rules there had to be one transparent side of each box that contains electronics, so the inspectors could see the inside. If this also applied to the supercapacitor housing was unclear. The Maxwell capacitor and others that are factory made would not be concerned by this rule, but a self-made housing probably would be. This was something that wasn't investigated further, because the idea of a transparent box was quite appealing. It has several advantages against an aluminium box, the acrylic glass doesn't conduct electricity, it's less than half the weight of aluminium and a prototype capacitor is something you would like to see what is inside. The weight issue was of great importance in Eco-marathon. The weight reduction with acrylic glass was very high even though that the material needed to be slightly thicker for stability reasons.

First all the pieces for the housing were constructed in Solid Works CAD-program to see that they all would fit together but also so different layouts could be tried. Images of the final CAD-drawing can be seen in Figure 15.
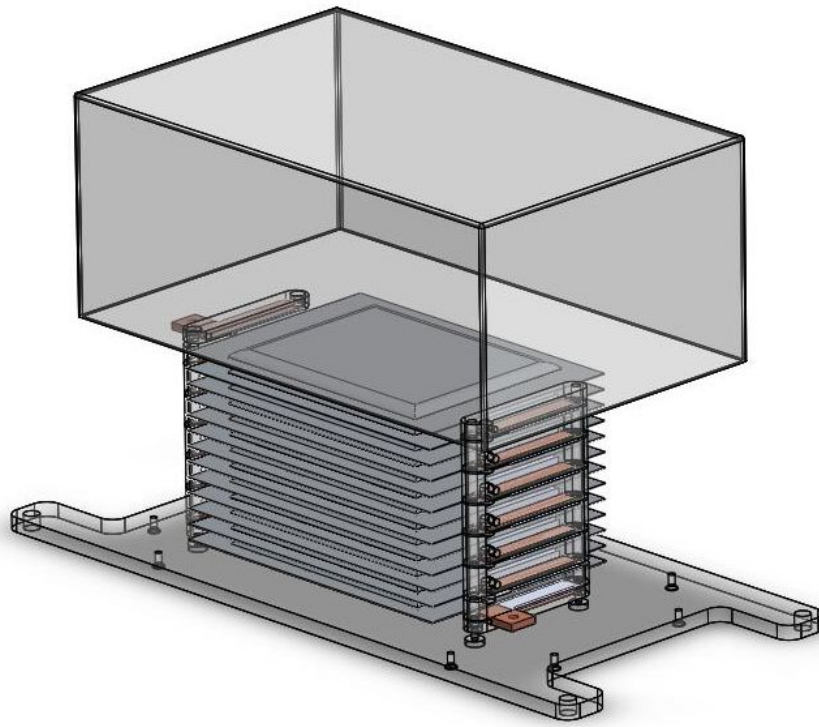
Figure 15 CAD drawing of the LIC

Since the cells contain a large amount of energy and that energy can discharge very rapidly some considerations about the design were to make it sheltered against short-circuits caused by metal tools. In every connection point of the cells small copper plates were made, that were connected to cables in order to be able to get the potential at each cell and charge or discharge them individually. These connection points were used to monitor the individual cells during our testing and also when the cells needed to be balanced in between the tests.

In Figure 16 the setup, with copper plate connections and cables, used for balancing the LIC can be seen.
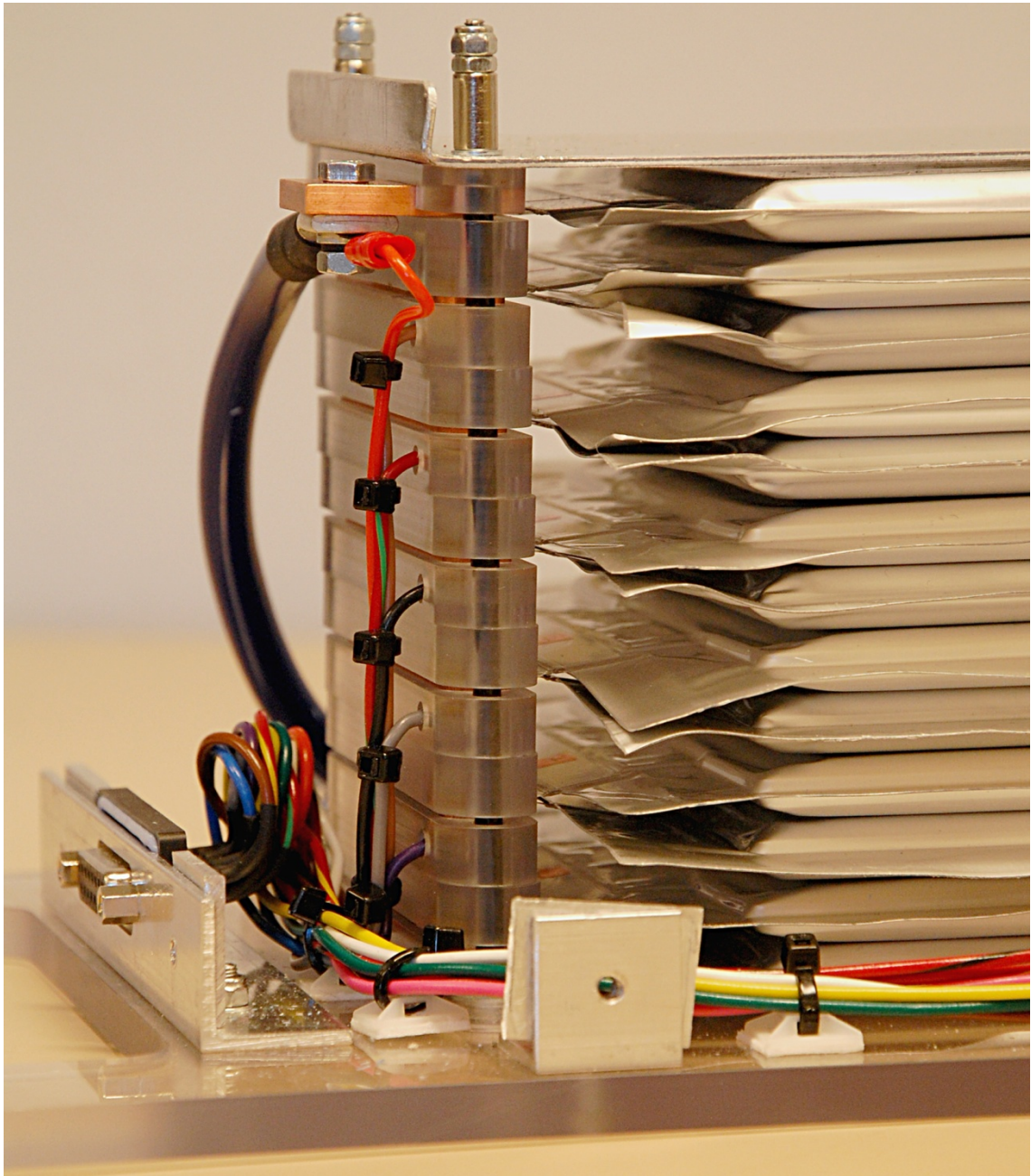
Figure 16 Close up of the LIC cell connections

4.1.2 Balancing the combined supercapacitor cells

With the assumption that there would be no need to balance the capacitor pack during the race, the method in which excess charge is burnt away, method 1 was chosen.

In order to perform the balancing, an external balancing board was built. The setup for this board consisted of resistances, a Beckhoff PLC system with analogue input terminals (EL3102) that measure potential and can act as a switch because of an inbuilt relay, and interconnecting $0.56mm^2$ cables, which can be seen in Figure 17.
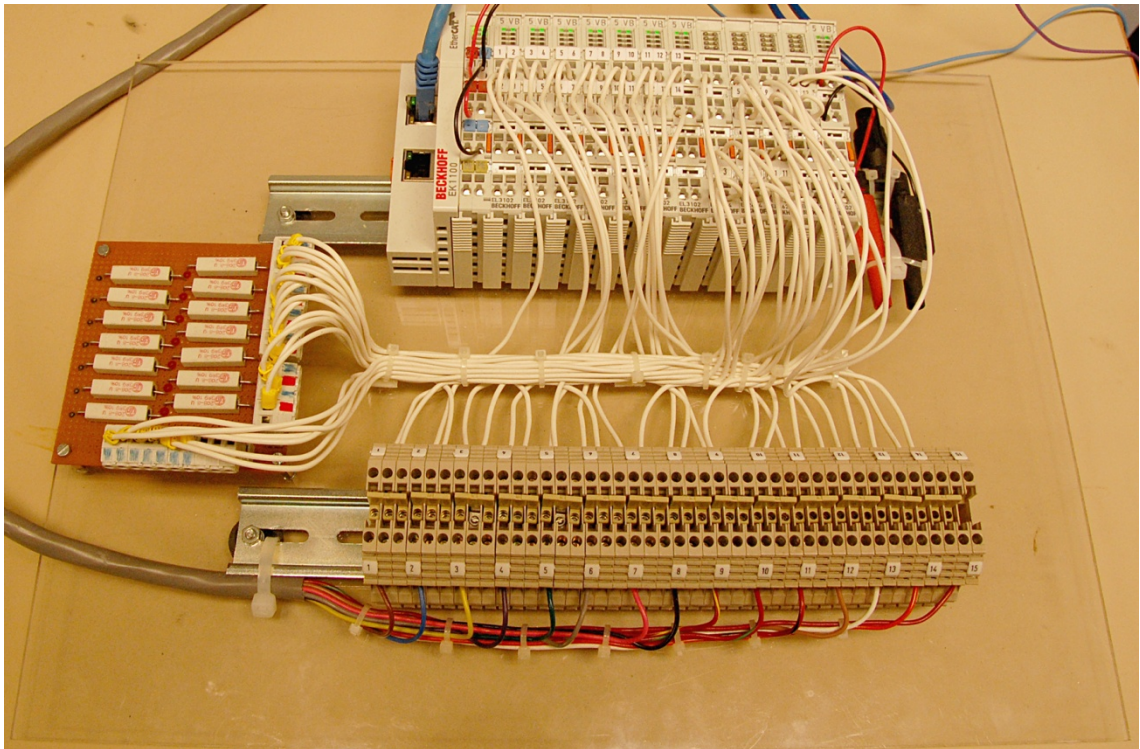
Figure 17 The balancing board.

This balancing board was then connected to the capacitor pack via a d-sub chassis connector and *0.56mm²* cables (the same type of cable used in the balancing board) at every connection point between the cells. (The connecting points were seen in Figure 16.)

When choosing cables for the balancing board, and the connection between it and the supercapacitor pack, the time needed for the dissipation of excess energy had to be considered. It was desirable that the balancing process would take at most approximately *10 minutes* since it might be necessary to balance the supercapacitor pack on short notice during the race days. The most suitable, dimension wise, was the *0.56mm²* cable. The maximum current for power transmission in these cables were *1.5A*, which gives a theoretical maximum resistance of *R=1.5A*3.8V=5.7Ω*. The resistance and the current will affect the time to dissipate a given voltage. The time for discharging a capacitor through a resistor is given by Formula (8).

$$V_c = V_0 e^{-t/RC} \hspace{3cm} (8)$$

By assuming that the balancing dissipation will be in the magnitude of *20-30 mV* this gives a balancing time in the order of *1-1.5 minutes*, which is well acceptable. With this in mind and leaving room for additional resistances in the cabling, the resistors that were chosen for the balancing board had the resistance of *3.9Ω*.

This balancing circuit setup was then used to both monitor the cell voltages and to drain the overvoltage in the cells during balancing. A schematic of the balancing circuit can be seen in Figure 18.
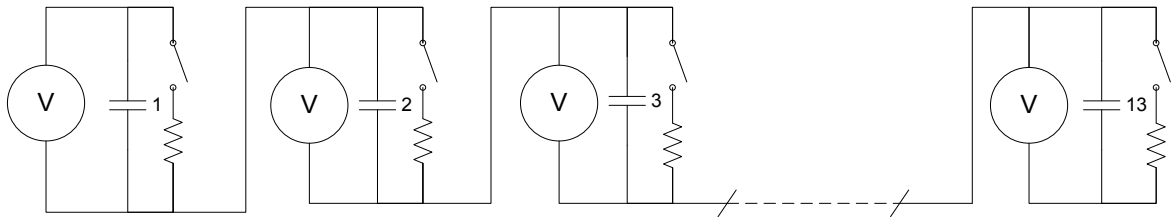
Figure 18 Balancing circuit schematic with the analogue measurement terminals (V and relays), capacitors and the resistances.

The analogue terminals are connected in series, and each capacitor cell is connected in parallel to the voltage inputs of the Beckhoff terminals. The terminals can measure *+/-10V*, and each terminal has it's own relay. The relay parts of the terminals are connected in series with one resistor. The measurements are transformed to bits and sent via an Ethernet cable to Twincat, a monitor program that can be run on a standard PC.

First, a program that could transform the bits back to voltage and present the value on the screen was written. After confirming that the presented voltage was correct, the calculations for the burning times and the relay control needed to be implemented in the control program. This was done by first finding the lowest voltage and then calculating the time it would take for each of the capacitors to reach that value by burning energy through the resistances. A timer then controlled the relays for one of each until the correct amount of energy was consumed. The Twincat balancing program can be seen in Figure 19.
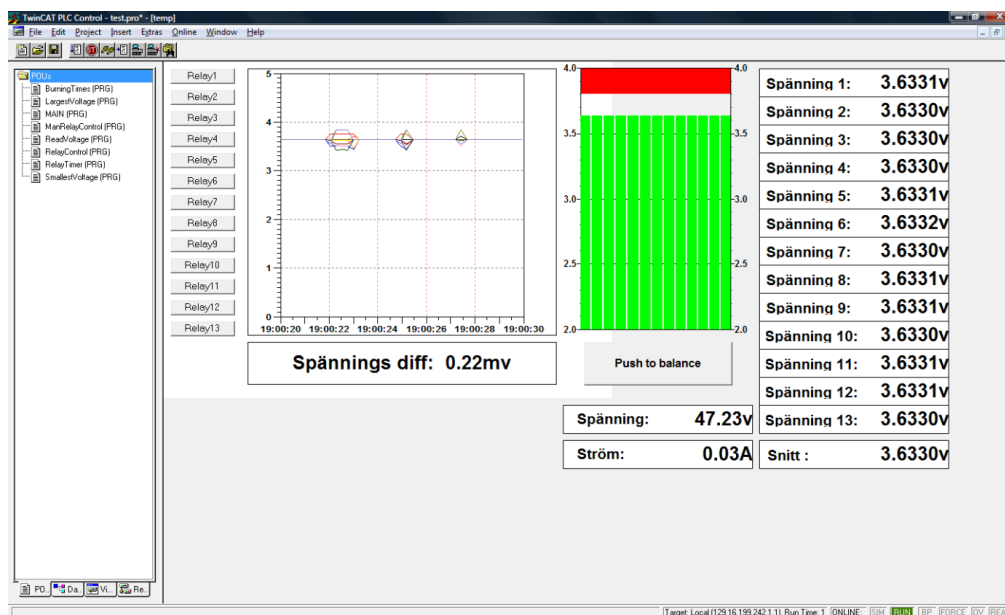
Figure 19 Screen dump of the Twincat program for cell balancing

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4.1.2.1 Balancing results

To test the setup small EDLC supercapacitors of *10 F* and *2.5 V* were used. The EDLC type was chosen since this type of supercapacitors does not suffer the risk of breakdown if they would be completely drained due to a programming error. The tests showed that the program and setup worked, but due to difference in the theoretical calculations and the real conditions and also external conditions like temperature, the calculated times did not correspond to the real times. So to have an exactly balanced capacitor pack the program needed to iterate a couple of times until the capacitors had the same voltage. Measurements also showed that the resistors of *3.9Ω* were in fact *4.2Ω* and when adding the cable resistance there were a total resistance of *4.4Ω*. This was of course implemented in the program, but made no noticeable improvement in number of times the balancing needed to be iterated.

This had now resulted in a working balancing board, which was able to balance the capacitors to a *ΔV* under *1mV*. That is probably much better than the accuracy of the measurement itself. The Beckhoff terminals were then calibrated so they all presented the exact same value. This was done by using a programmable precision DC voltage calibrator, Model 2701A from Valhalla Scientific Inc, sending exactly *3.00000V* in to each terminal. The value presented on the computer fluctuated some, but it was possible to calibrate them to an accuracy of *1mV*. The specification of the Beckhoff analogue terminals says that the error is *+/-30mV*, even though our results indicate that the error was *+/-1mV*. The measuring error needed no further investigations, to establish its accuracy, since it was not relevant to the needs to have accuracy below the *+/-30mV* specified by Beckhoff.

5 Evaluation

5.1 *Testing of the supercapacitor*

Three different tests were carried out to verify the functionality and characteristics of the supercapacitor. The first was a simple component test where the supercap was connected to a power supply and a load resistor and then cycled by charging and discharging between two set voltage levels. This test was to assure that unbalancing of the supercapacitors cells would not escalade to uncontrollable proportions, see chapter 5.1.1. Since the first test was performed under ideal conditions with controlled currents and voltages there was a need to investigate how the supercapacitor would behave when it was subjected to more realistic currents and voltages. This was done by connecting the supercapacitor to the SMARTER test bench (which was also developed as a master thesis project within the SMARTER project) with an ICE and a generator as power supply, see chapter 5.1.2. The third test was performed, by cycling with high currents; in order to get measurements from where the supercapacitors real resistance and capacitance can be calculated, see chapter 5.1.3.

5.1.1 Component testing during ideal conditions

5.1.1.1 Method

The first tests of the Supercapacitor were to establish if the cells would unbalance themselves after 5 charge/discharge cycles. The cycles were defined as charging/discharging between a maximum of *48V* and a minimum of *38V*, as these levels were assumed to be the most race-like conditions. The test setup consisted of a power supply for charging the supercapacitor and a resistor through which the supercapacitor was discharged.

If the voltage in each cell was to exceed the *2.2V– 3.8V* limits from the JME specifications the cells could deteriorate. In order to reduce the risk of that happening the first tests were conducted using a current limiter on the power supply. There was also a current limiting resistor in series with the power supply. Conceptual schematics of the measurement setup can be seen in Figure 20.
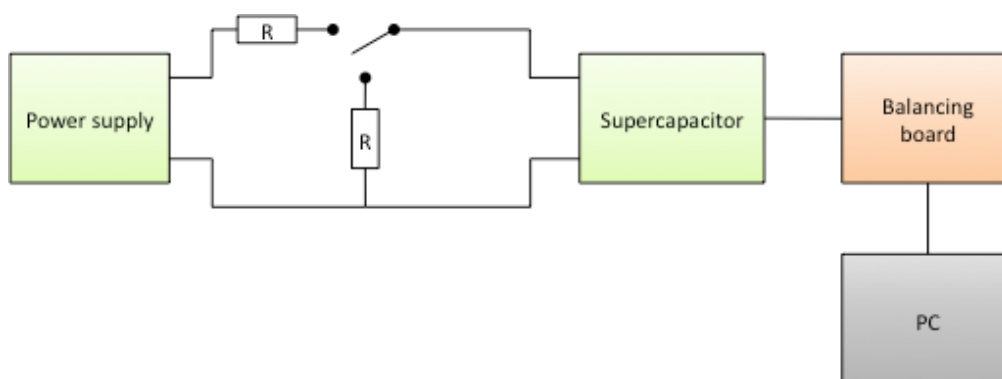

Figure 20 Conceptual schematics of the measurement setup

5.1.1.2   Test results

During the first test of the components everything was as expected; charging and discharging did in fact work, and measurement data could be collected. There was no unexplainable voltage drops in the supercapacitor cells. There were some initial concerns about heat building up in the supercapacitor cells that were placed in the middle of the capacitor pack. This heat would then cause the resistance in these cells to become higher, which would lead to that these cells would become unbalanced. The measurements showed that the cells were evenly balanced even after 10 charging and discharging cycles. This test was a strong indicator that it would be enough to run the balancing sequence between the races on site in Germany. The results of one cycle of charging and discharging of the LIC can be seen in Figure 21.
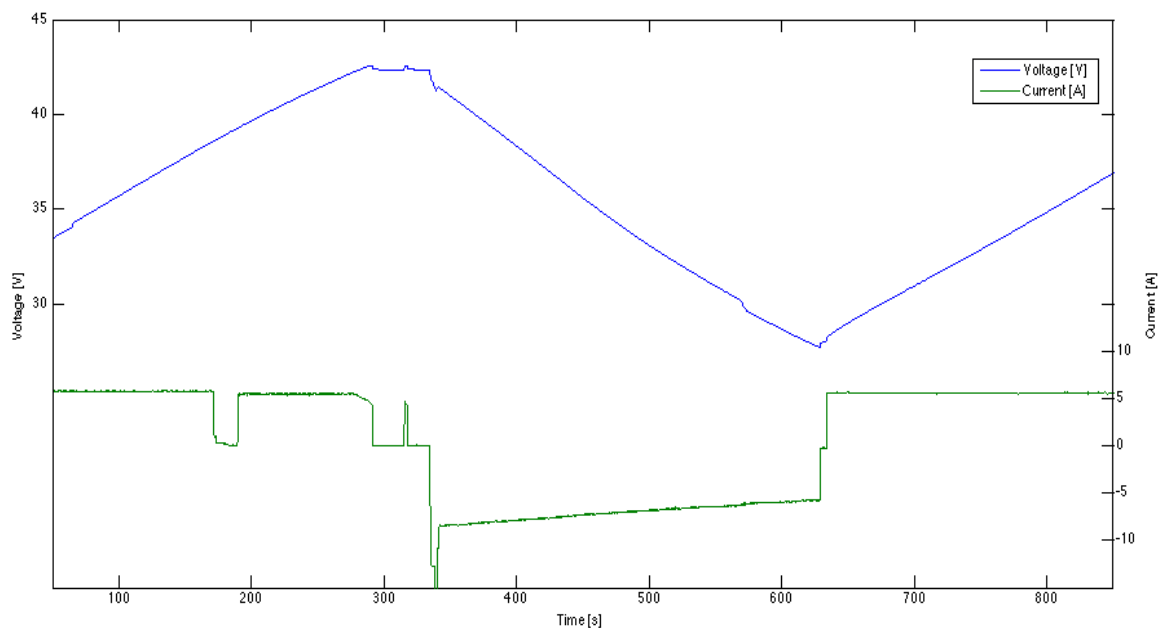
Figure 21 One cycle of charging the LIC with a DC current source and discharging over a resistor

The LIC performs as expected when charged with a controlled DC current. There is no explanation to what caused the drop in current just before the *200s* mark. The leading guess is that it had something to do with the measurement apparatus. This since there would be a change in the voltage otherwise.

5.1.2 Simulated system testing during race like conditions

5.1.2.1   Method

Since the earlier tests were performed, with satisfactory results, under ideal conditions the question of how the combined supercapacitor cells would react when they were submitted to more realistic currents and voltages needed to be investigated. The next step was to test the supercapacitor in the SMARTER test bench, using an ICE as power supply. A DC-DC converter was connected between the supercapacitor and the load resistor, so that the current would not decrease as the voltage in the supercapacitor dropped. The voltages and the current to the supercapacitor were then measured through the balancing board.

This can be viewed as a sanity check of the characteristics deduced from previous testing. Conceptual schematics of the SMARTER test bench setup can be seen in Figure 22.
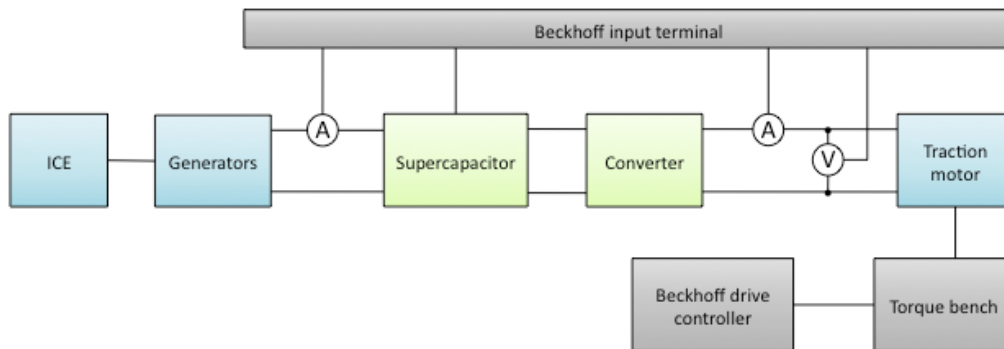

Figure 22 Conceptual schematics of the SMARTER test bench setup

5.1.2.2 Results

If there would be some reaction to the more realistic currents and voltages when the LIC was tested in the SMARTER test bench the assumption was that this reaction would manifest itself as increased heat in the supercapacitor cells or in an escalated unbalancing. The supercapacitor cells were monitored during the test and it was noted that the voltage levels were stable and there was no increased heat. From the test it was deduced that the LIC would perform satisfyingly at the Shell Eco Marathon. The result of charging and discharging the LIC with the SMARTER test bench can be seen in Figure 23.
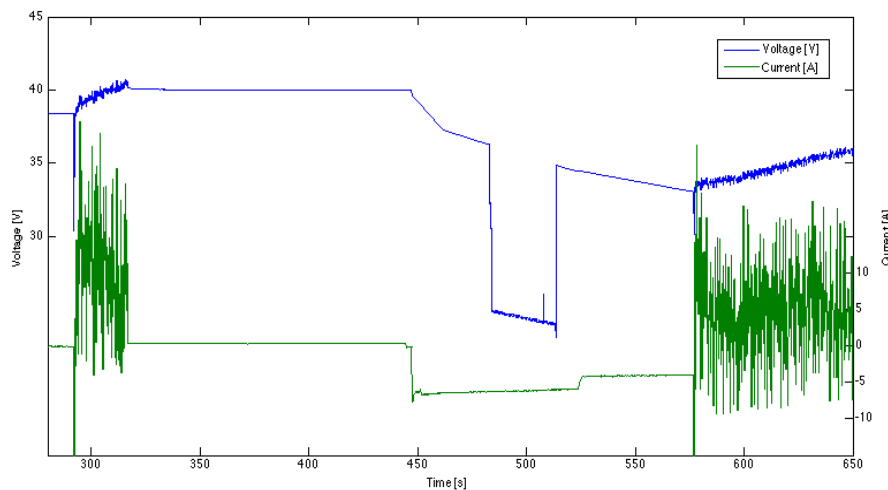

Figure 23 Charging and discharging of the LIC with the SMARTER test bench

The LIC performs very well even if the current from the generators were very noisy. The voltage drop around the *500s* mark is a bit peculiar and the leading guess about where it comes from is that it was some misconnection with the measurement apparatus.

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5.1.3 Characteristics measurements

5.1.3.1 Method

For an accurate measurement of the supercapacitors characteristic an industrial approved test bench was needed. This was found at Volvo Technologies situated at Chalmers Teknikpark. To establish the capacitance and the internal resistance in the supercapacitor the voltage was cycled between *28.6V - 49.4V* which is the rated voltage operating interval as defined by the product specifications, see Table 2 in chapter 2.2.3.

The capacitance is given by Formula (6) in chapter 2.2.4. The capacitance calculation will be more accurate if the measurement is carried out for a longer time, i.e. lower current. If the discharge time is very short any measurement errors will have a greater influence on the capacitance calculations. By setting the current to *20A* the discharge time would be approximately 3 minutes, which was considered reasonable. This is also the maximum current allowed in the Eco-marathon race. The resistance is calculated by using Formula (5) in chapter 2.2.4. With a higher current there will be more resistive losses in the capacitor, which will give higher accuracy. A current of *100A* was used in order to get a higher accuracy in the calculations of the inner resistance. The measurement setup can be seen in Figure 24.
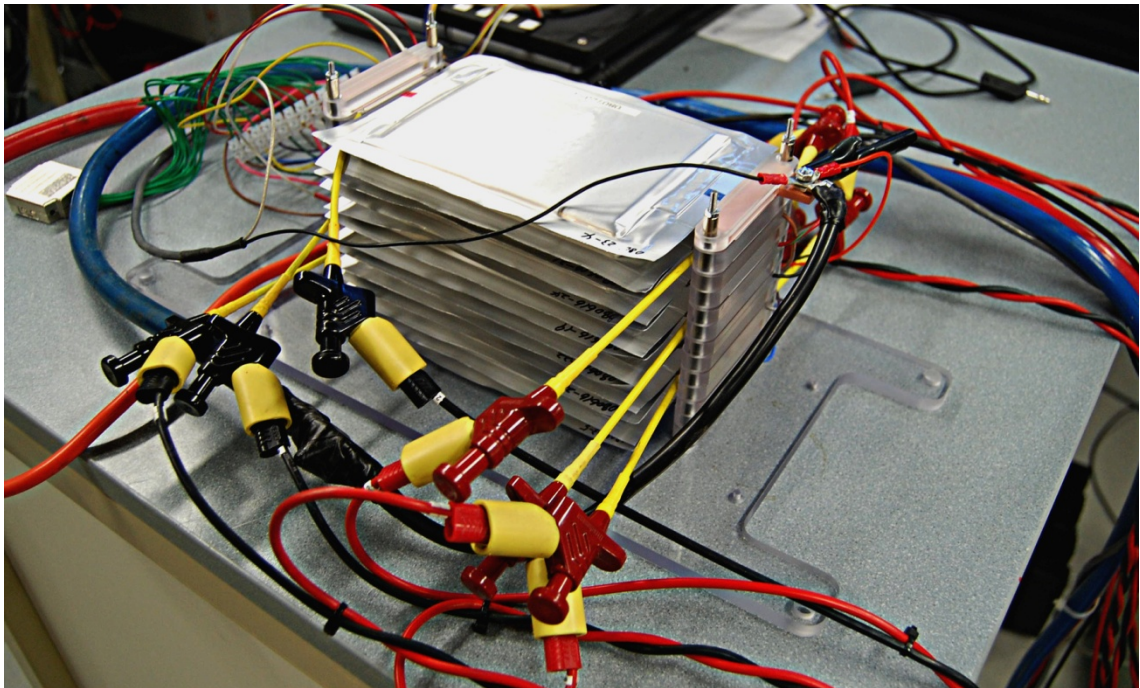

Figure 24 The characteristic measurement setup

There was also a need to investigate if there was any significant self-discharge in the supercap. For instance this could result in a rapid decrease in the voltage or that it would unbalance itself if it were left unplugged for a prolonged period. After the race in Germany the supercap was left unplugged

for five weeks. The voltage and balancing status was checked weekly and as expected no differences could be noticed.

5.1.3.2 Results (Characteristics measurements)

A graph of the characteristics measurements from the test bench at Volvo Technologies can be seen in Figure 25 Capacitance measurement and Figure 26 Resistance measurement below. With a control program the supercapacitor was discharged to *28.6V* with a current of *-20A*. Then the supercapacitor was charged to *49.4V* with a current of *+20A*. This procedure was then cycled 3 times. The resulting voltage and current characteristics can be seen in the figure below.
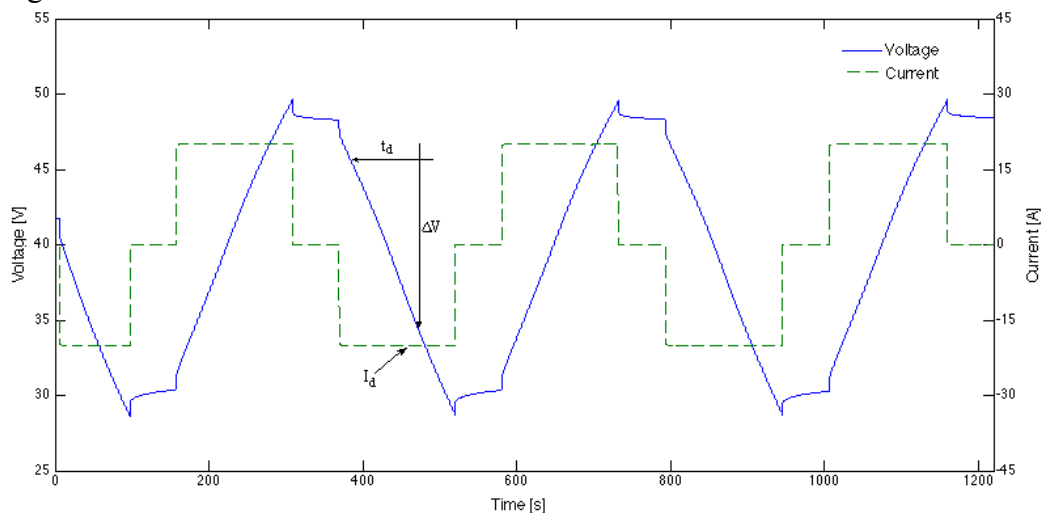
Figure 25 Capacitance measurement

From these measurements ΔV, t_d and I_d were deduced. Using the Formula (6) in chapter 2.2.4 this gives the capacitance, which can be seen in Table 6. The same procedure where then used when getting measurements for the resistance calculations. With the difference that a current of *100A* where used and the charge/discharge cycle where repeated 10 times. The resulting voltages and currents characteristics can be seen in Figure 26.
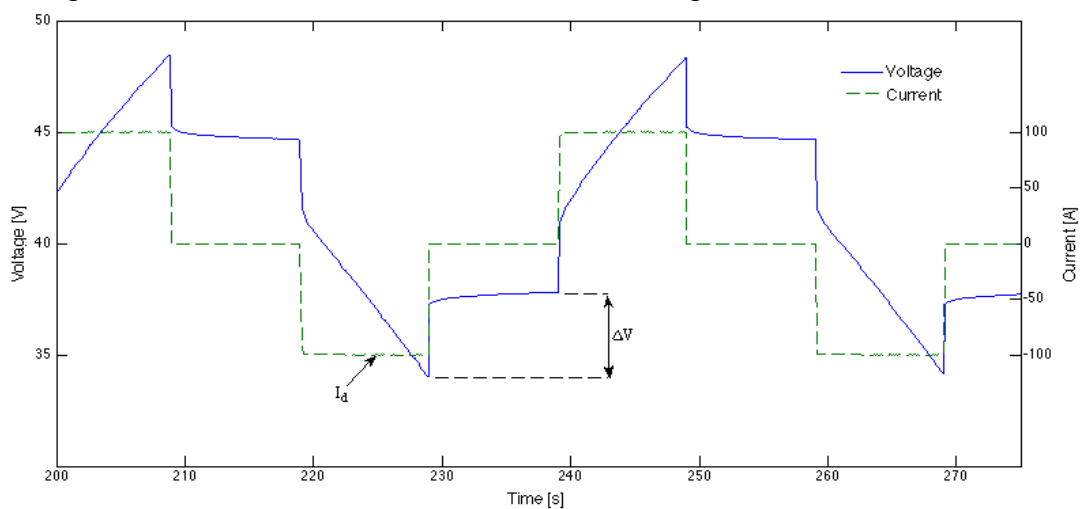

Figure 26 Resistance measurement

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Usage of Formula (5) in the chapter 2.2.4 then gives the internal resistance of supercapacitor, which can be seen in Table 6 below.

| Measurement Items	LIC 13 cells	BMOD0140-E048
Capacitance	169.4F	154.4F
DC-IR	39.5mΩ	14.3mΩ
Energy Density (Weight)	8.30wh/kg	3.75wh/kg

Table 6 The measured data for the two supercapacitors

As can be seen in reality the supercapacitors have higher resistance and capacitance than the specifications from Table 4 in chapter 3.2.2.

5.2 Testing (energy and efficiency) of the converter

5.2.1 Method

To test the efficiency of the 2-Q and the Maxon converters, the torque control for SMARTER's test bench was connected to one of SMARTER's electrical traction motors and functioned as a mechanical load. The torque control was used with one torque setting to simulate driving at constant speed test 1, and then a higher torque setting to simulate acceleration with the SMARTER vehicle, test 2. These tests were done with equal throttle gain to both converters. The test was then conducted by increasing the delivered power in six steps. During the test both the input and output power was measured from the converters with a Fluke Norma, see chapter 5.3.2. The setup of the test can be seen in Figure 27.
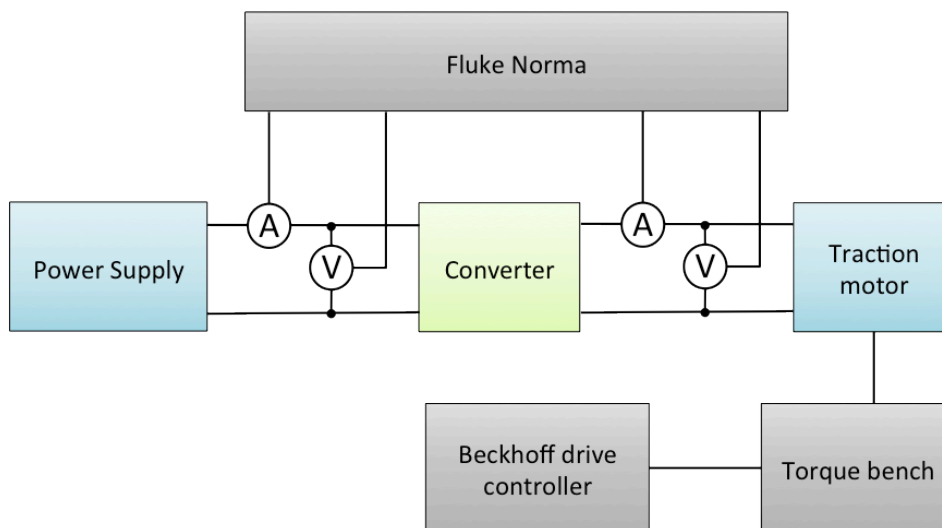
Figure 27 Conceptual schematics of the efficiency test setup

5.2.2 Results

Table 7 shows the results from these tests and when analysing them it is know that in the race SMARTER will use approximately *130W* and looking at the measurements the 2-Q converter will have an efficiency of *98%* at this scenario, while the Maxon converter have an efficiency of 9*2%.* In test 2 the test bench torque control is set with twice as much torque to simulate acceleration. The efficiency in this scenario is *94%* for the 2-Q converter and *84%* for the Maxon converter. But even though the difference in efficiency is larger when accelerating it is at constant speed that the most gain in energy lays, because of the design of the racetrack there will be no need for acceleration other than in the start of the race and the pit stop. So the efficiency gain in building a more optimized converter compared to a stock product for SMARTER is approximately *98%* contra *92%.*

2-Q test1

P_in	P_out	Efficiency
41,4	40,9	98,8%
60,7	60,3	99,3%
81,2	79,3	97,7%
100,5	99,2	98,7%
130,8	128,3	98,1%
276,4	275,8	99,8%

Maxon test1

P_in	P_out	Efficiency
44,3	29,5	66,6%
74,8	60,5	80,9%
94	80,7	85,8%
111,6	100	89,6%
140,8	129,8	92,2%
222,4	214,5	96,4%

2-Q test2

P_in	P_out	Efficiency
30,6	30,1	98,4%
41,2	39,9	96,8%
61,5	59,9	97,4%
87,4	80,2	91,8%
105,5	97,7	92,6%
138,5	130,3	94,1%
320,1	313,1	97,8%

Maxon test2

P_in	P_out	Efficiency
58,6	30	51,2%
69,5	40,4	58,1%
89,8	60,5	67,4%
108,4	80,8	74,5%
126,1	99,2	78,7%
155,2	130	83,8%
317	300	94,6%

Table 7 Efficiency test of the Maxon and the 2-Q converters

It was noticed during these tests that the motor got considerably warmer when the 2-Q converter was used compared to the Maxon converter. This was believed to be caused by the bang-bang control that causes more output ripple in the current than the PWM control. This could be investigated by performing efficiency test over the converter and the motor combined. Unfortunately here was not enough time to test this in this project.

5.3 Apparatus used for evaluation

5.3.1 Beckhoff TwinCAT – PLC and motion control on the PC

The Beckhoff PLC is a modular PLC system controlled by a standard PC. This gives the stability and efficiency of a PLC system but also the mobility and flexibility of a self constructed system. [3]

5.3.2 Fluke Norma High Precision Power Analyzer

Based on a patented, high-bandwidth architecture, the instruments deliver high-precision measurements of single or three-phase current and voltage, harmonics analysis, Fast Fourier Transformation (FFT) analysis, as well as calculations of power and other derived values. [4]

5.3.3 Valhalla Model 2701C GPIB Programmable Precision DC Voltage Calibrators

Valhalla Scientific's 2701C Programmable Precision DC voltage Calibrator utilizes innovative technology to deliver ultra-precision, ultra-stable DC Voltage from *100nV* to *1200V*. Designed to meet the most critical calibration laboratory requirements, the 2701C is at home on the production line or in the field. This lightweight, rugged, line powered instrument requires only 15 seconds warm-up. [5]

6 Discussion

6.1 Supercapacitors

One large improvement as a result of the design choices made within the scope of this thesis, affecting the overall performance of the vehicle, was the housing that was designed for the LIC supercapacitor. This made the LIC in total about three times lighter than the Maxwell EDLC, contributing about 4,6kg to SMARTER's total weight of about *74 kg* as opposed to the Maxwell EDLC, which would have added about an extra *9 kg* to that total weight. However, the acrylic glass housing is not as stable and robust as an aluminium housing, which is generally used in commercial products. It would therefore not be advisable to use acrylic glass housing if there was more focus on a robust and strong construction. But given the application for which the housing was designed, which was more or less a one off prototype, where a low weight was of high importance, the choice of acrylic glass housing was correct and served its purpose well. A visual comparison between the Maxwell EDLC and the LIC can be seen in Figure 28.
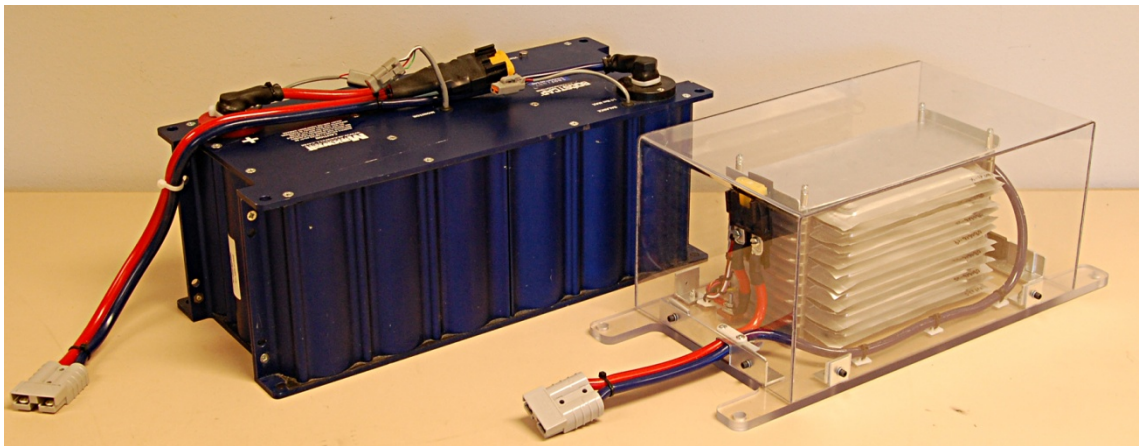
Figure 28 Visual comparison between the Maxwell EDLC on the left and the LIC including housing on the right

As for the balancing program, it could be further develop in order to automate the balancing process further. As it was, each balancing iteration needed to be started manually after assessing the measure difference between individual cells, something that could easily have been done automatically given a few rules and criteria written into the program. However, with the wrong set of criteria, an automated process might also have led to an endless balancing loop resulting in all energy being burnt off, or the balancing iterations being incomplete and still needing manual assessment in order to get a properly balanced cell pack. Therefore it is probably wise to carefully consider the need for an automated process, if one wishes to design one. If the number of iterations normally needed to achieve balance in the cell pack is low, then using an automated process is probably just not needed.

Also worth noting are the test results from chapter 5.1.3.2 (table 6) in which it can be seen that DC-IR is measured to *39.5mΩ* as compared to the specified *29.9±3.9mΩ* found in chapter 3.2.1. This means that I^2R losses are greater

than expected. They are, however, not as great as to affect the conclusion that the LIC was the right choice, considering that the weight reduction as compared to the EDLC was substantial.

6.2 Converter

Both converters performed without any mishaps but more data is needed to decide which setup would perform better. The Maxon setup with two converters in parallel added weight but also split the current in two which lowered the I^2R losses, the 2-Q setup on the other hand had a more efficient converter and delivered more power which shortened the acceleration phase, where the highest I^2R losses were. Equipping the 2-Q converter with a PWM control and investigating if it got the power needed to drive two traction motors in parallel would be advisable in order to boost performance a bit more.

There is also much weight to be lost by building the electrical components instead of buying stock products, this since stock products often tend to have unnecessary structural protection which add weight and also unnecessary functions that add components.

6.3 In the field complications

As described earlier, it was assumed that balancing the supercapacitor cells would not be needed during the races, and given the test results in chapter 5.1.2.2 it was also concluded that there would be no need to balance the supercapacitors even between the races.

Even so, balancing was done in between races mainly in order to retrieve data that would confirm the assumption that there really was no need to balance the cells throughout the race. During balancing however, some difficulties were experienced, albeit not due to voltage differences between cells. Instead it was found that the balancing board started to unbalance the supercapacitor. In order to conclude what caused this behaviour, some possible root errors theories about what might have changed were tested. The only possible variable was thought to be the capacitance of the supercapacitor pack. One theory was that it varied in capacitance due to the cooler outside air at the race site in Germany as opposed to the heated indoor laboratory at Chalmers, but when the settings in the balancing program was adjusted it was found the capacitance needed to be set down to 1*800F*/cell in order to work as intended. According to the specifications for the capacitors, this value required an ambient temperature of -*20 degrees Celsius*. Therefore, the only reasonable conclusion, at that time, was that the capacitors had deteriorated, although with no reasonable explanation.

This phenomenon experienced during the race was investigated further once back at Chalmers. The capacitance measurements were repeated, but the results were positive in that they showed no deterioration in the supercapacitors at all. They proved to be in excellent condition, and so the theory of deteriorated capacitors was concluded to be wrong.

One other theory was that there was something wrong with the laptop, which was used for all the tests on site in Germany. In order to check this, a timer was added to the program and by comparing it with an external clock it was found that there was a time difference between program time and real time. The timer in the balancing program was therefore calibrated and after calibrating everything worked as expected again. No cause was found for this, but it is believed that the problem was that windows vista had changed how it prioritizes the use of the processor cores.

7 Conclusion

This master thesis work resulted in an energy storage unit and electric drive train for use in the SMARTER car, Chalmers contribution for Shells ECO Marathon competition.

The energy storage unit was made out of lithium ion capacitor cells (LIC) and acrylic housing instead of EDLC encapsulated in an aluminium housing. The LIC was capable of storing more energy and weighing only *34%* of the previous stock model. This resulted in a *12%* weight decrease for the SMARTER vehicle, which was a significant achievement.

The electric drive system constructed by this work consisted of the converter used for controlling the traction motor of the car. There were two different setups examined and unfortunately not enough data was gathered to make any conclusion to which one would give the best performance. This was mainly due to some mechanical errors in the construction of the car, which prevented it from completing any of the three races during the competition. Although the tests performed in the lab indicates that the 2-Q setup would perform better than the Maxon setup. The 2-Q setup delivers more power and has higher efficiency but more tests and maybe some small alterations need to be made to get even better performance. During the tests the traction motor got a bit warmer when powering it with the 2-Q converter compared to when using the Maxon converter. This indicates there are higher I^2R losses in the motor and how much higher they are could be investigated. It would also be advisable to look into if a PWM control for the 2-Q converter would eliminate these losses.

References

All photos and figures used in this master thesis is taken or made by the authors Henrik Andersson and Peter Kellerman.

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[2] http://www.maxonmotor.ch/medias/sys_master/8796918546462/ADS-E-50-5-166143-11-EN-281-283.pdf 2015-05-10

[3] http://www.beckhoff.com/english.asp?twincat/default.htm
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