Joonas Sainio

Battery Management System Design and Implementation in Electric Raceabout - Electric Sportscar

Helsinki Metropolia University of Applied Sciences

Automotive and Transport Engineering

Automotive Electrics Engineering

Bachelor´s Thesis

14th May 2013

Abstract

Author(s) Title Number of Pages Date	Joonas Sainio Battery Management System Design and Implementation in Electric RaceAbout -Electric Sportscar 69 pages + 6 appendices 14th May 2013
Degree	Bachelor of Engineering
Degree Programme	Automotive and Transport Engineering
Specialisation option	Automotive Electronics Engineering
Instructor(s)	Sami Ruotsalainen, Senior Lecturer

The purpose of this Bachelor´s study was to design and implement a new user-configurable battery management system into Electric Raceabout – electric sports car. This new improved system design would replace the old battery management system in the vehicle.

The thesis begins by characterizing a professional battery management system and representing the benefits of the new system. Following the objectives of professional battery management systems, the new battery management system was designed and implemented. The thesis represents the modular system design part by part and explains the system configuration methods.

After introducing the system design the thesis represents the main ideas behind the BMS-control algorithms. These ideas include for example the use of the IR -compensation method for calculating the open circuit voltage of the cell and I^2t -based current limit calculation for the battery.

One of the main objectives was to have a user-configurable system which would allow rapid changes in the system when needed. This would enable the full testing capability of the battery management system in different kind of driving purposes such as racing track or just a normal city driving. Furthermore, the new system was designed to be able to supervise the current at least 100 times faster compared to the old system in order to react in-real time to over current errors. In addition, the modular system design and the real-time computing capability were preferred in order to bring more freedom and safety to the system functionality. With the new system, the system parameters would be very easy to configure with new code snippets and this would give the ability for the user to test new ideas and improve the system even further.

According to the reliability tests on the dynamometer the results were reliable which enables further development of the system.

Keywords	Electric Raceabout, E-RA, electric car, battery management system, bms, battery

Abstrakti

Tekijä(t) Otsikko Sivumäärä Aika	Joonas Sainio Akunhallintajärjestelmän suunnittelu ja toteutus Electric RaceAbout sähköurheiluautoon 69 sivua + 6 liitettä 14.5.2013
Tutkinto	Insinööri (AMK)
Koulutusohjelma	Auto- ja kuljetustekniikka
Suuntautumisvaihtoehto	Autosähkötekniikka
Ohjaaja(t)	Lehtori Sami Ruotsalainen

Tämä insinöörityö käsittää uuden, käyttäjälle konfiguroitavissa olevan akkujenhallintajärjestelmän (BMS) suunnittelun sekä toteutuksen Electric RaceAbout -urheilusähköautoon. Järjestelmän valmistuttua se tulee korvaamaan auton vanhan akkujenhallintajärjestelmän.

Työ alkaa akkujenhallintajärjestelmän toimintojen kartoituksella sekä uuden järjestelmän parannettujen ominaisuuksien esittelemisellä. Tämä luo pohjan käytännön toteutukselle. Tämän lisäksi työssä käydään läpi järjestelmän modulaarinen rakenne osa kerrallaan ja kuvataan laitteiden konfigurointimetodit.

Järjestelmän esittelemisen jälkeen työ keskittyy ideoihin, joihin BMS-järjestelmän ohjelmointi perustui. Näistä ideoista esitellään esimerkiksi IR -kompensointiin perustuva lähdejännitteen laskeminen sekä I^2t -perusteinen dynaaminen virranrajoitus algoritmi.

Yksi järjestelmän päätavoitteista oli rakentaa käyttäjälle konfiguroitavissa oleva systeemi, joka mahdollistaisi nopeat muutokset tarvittaessa. Tämä mahdollistaa erilaisten asetusten testaamisen erilaisissa olosuhteissa kuten rata-ajossa tai normaalilla kaupunkisyklillä. Tämän lisäksi uusi järjestelmä kykenee mittaamaan akuston virtaa 100 kertaa nopeammin kuin aikaisemmin, mikä parantaa kykyä reagoida mahdollisiin ylivirtatilanteisiin.

Modulaarinen systeemirakenne ja reaaliaikainen laskenta paransivat yhdessä systeemin turvallisuutta. Uuden systeemin ansiosta järjestelmää on helppo päivittää koodimuutoksilla, ja tämä antaa mahdollisuuden testata uusia ideoita ja kehittää järjestelmää yhä paremmaksi.

Järjestelmää testattiin vanhan BMS-järjestelmän kanssa rinnakkain, ja testien perusteella sitä voidaan pitää luotettavana. Tämä antaa pohjan järjestelmän jatkokehitykselle.

Avainsanat	Electric Raceabout, E-RA, sähköauto, akkujenhallintajärjestelmä, bms, akku

Preface

Almost three years ago I became a member of Electric RaceAbout team and for me that was the first touch of e -mobility. With the Electric RaceAbout team I got the first experience of alternative, future mobility and step by step I learned a lot of important skills. In summer 2012 I got also a great chance to carry out my internship at Porsche Engineering GmbH in the e -mobility sector. From these two great experiences I got a lot of energy to keep on researching and learning about the e-mobility for this graduate study. After these experiences I can really say that I have much more free electrons in my veins than gasoline molecules.

First I would like to thank my supervisor Sami Ruotsalainen, chief engineer of Electric RaceAbout, for all the professional support I´ve got through the project and the study. The rest of the team has proved professional team working skills when building and improving the car. I wish we all could work together also in future. Thank you for the moments of late nights when building the car and also of great trips we had in Europe.

Next I would like to thank my language supervisor Jonita Martelius for giving me valuable notes and guiding me through the technical writing along this thesis.

Then respectfully, I would like to thank Henry Ford Foundation for personal financial support during this study.

Special thanks to my beloved Riikka and my family, who supported me during my whole studies and understood that Electric RaceAbout took a lot of time from my private life.

Joonas Sainio,
Helsinki Metropolia University of Applied Sciences, 2013.

LIST OF ABBREVIATIONS

AC	Alternative Current
BMS	Battery Management System
CAN	Controller Area Network
CCCV	Constant Current Constant Voltage
DOD	Depth Of Discharge
EMC	Electromagnetic Compatibility
ERA	Electric RaceAbout
FPGA	Field Programmable Gate Array
HV -box	High Voltage Distribution Box
I/O	Input/Output
IVT	I, V, T (Current, Voltage, Temperature)
Li-Ion	Lithium Ion
PDO	Process Data Object
PLEX	Program Logic Extension
PMSM	Permanent Magnet Synchronous Motor
RF	Radio Frequency
SDO	Service Data Object
SPI	Serial Peripheral Interface
SOA	Safe Operating Area
SOC	State Of Charge
SOH	State Of Health
143s2p	143 in Series and 2 in Parallel

Contents

Appendices

1 Introduction

A battery management system (BMS) has a very vital role in electric vehicles. Its design is very challenging because firstly, the modelling of the battery behaviour is very complicated and secondly, the system has to supervise the battery parameters such as current, voltage and temperature (IVT) in real-time conditions. The BMS -system has to protect the battery according to the measured battery parameters and unfortunately very often it has only indirect control over the load. This makes the system control even more complex. The system should also be able to analyse the state of the battery through the battery´s life although many of the battery parameters are changing as functions of multiple factors such as time and temperature. Before delving more the BMS -system design, the introduction part of this thesis explains the general need of the battery management system in electric vehicles. Furthermore, the Electric Race-About project is introduced from the technical point of view in order to give a good overview of the vehicle for which the new BMS -system was designed and implemented during the study. The last part of this chapter covers the structure of this thesis.

1.1 Purpose of Battery Management System

These days Lithium -ion based batteries have taken over the electric car battery markets. Because of the nature of Lithium -ion batteries, they need careful supervision especially when they are used as large battery packs as portable energy source in different kind of electric vehicles. This duty in respect of care and supervision is carried out with a battery management system (BMS). Usually this system is provided by the vendor selling the batteries. So far, this was also the case for Electric RaceAbout - electric sportscar (ERA).

Without a reliable battery management system the battery can get out of so called safe operating area (SOA) which is bounded by individual cell voltage, battery current and temperature limits specific to the battery chemistry. Getting out of the SOA can cause serious damages through thermal runaway of the battery or at least shorten remarkable the life of the battery. The SOA limits for a specific battery chemistry are defined by the BMS designer according to the battery data sheets provided by the battery manufacturer. These limits can vary in different applications. For example in motorsport the battery has to be used near to its limits. Correspondingly in a normal city car the SOA limits are defined much more strictly in order to keep the battery away from its extreme limits. This improves the safety in the system. By setting even stricter SOA limits the battery life can be also made longer. However, as a draw back this may reduce the performance of the battery.

With a user-configurable BMS -system it is easier to develop the system further with new code snippets in order to control and analyse the state of the battery even better. This is something that was not possible with the old battery management system in Electric RaceAbout. The user was not able to fully configure the system, thus any changes in the system needed help from the manufacturer. This was one of the reasons to design and implement a new user-configurable system into Electric RaceAbout. Other reasons for the new system design are explained in Chapter 1.3 where the benefits of the new system are represented.

There is also a dark side to the freedom of configuring the BMS -system. The user must understand the nature of the battery used in the vehicle. Without proper configuration parameters the BMS -system is not able to keep the battery in its safe operating area. This means that the BMS -system cannot manage the battery properly with wrong parameter values. As the designer is responsible for the code parameters, one should also understand the effect of the changed parameters in the system. A good start for searching the right values for the battery parameters in order to keep the battery inside the SOA is to explore the data sheets of the battery provided by the manufacturer. In the case of Electric RaceAbout the recommended values for the battery limits can be found in Appendix C.

1.2 Electric RaceAbout -Electric Sportscar

Electric RaceAbout is an electric sportscar built by Metropolia University of Applied Sciences in cooperation with Lappeenranta University of Technology and Lahti Design Institute. All the 80 cooperation partners can be found on the official website of Electric RaceAbout (www.raceabout.fi/era). In order to illustrate ERA more intuitively, a cross-section view of the vehicle is shown in Figure 1.

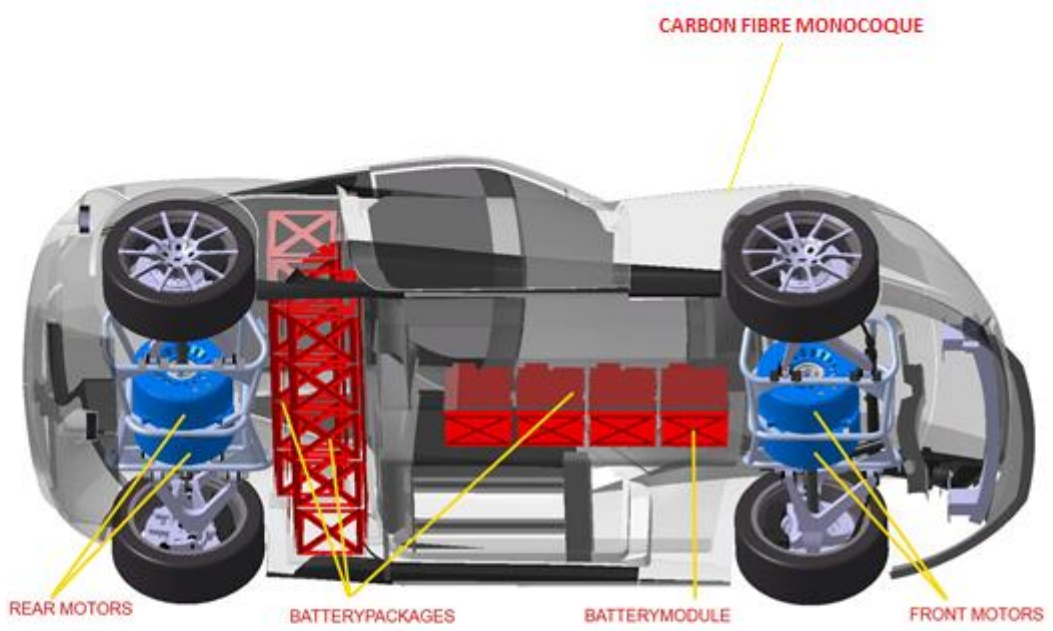


Figure 1. A cross-section view of the component layout in Electric RaceAbout.

As shown in Figure 1, Electric RaceAbout is built around a carbon fibre monocoque which weights 150kg. There are four permanent magnet synchronous motors (PMSM), one for each wheel. Two motors are installed back to back on both axles and they drive the wheels through direct drive shafts. There are no transmission or reduction gears which means that the motor spins at the same angular velocity than the wheel does. The maximum wheel speed is about 2400 rpm which means that the top-speed is about 260km/h. This has been performed with Nokian Hakkapeliitta 7s 225/40R18 tyres on frozen lake Ukonjärvi in Lapland. The battery pack stores 33 kWh energy when fully charged. This means roughly a 200km range for constant speed of 100km/h. This has been demonstrated both on the dynamometer and on oval test track at Chrysler Proving Grounds in Michigan 2010.

The motors of Electric RaceAbout are controlled with AC inverters by Semikron GmbH / Vidsedo Oy. The 12V -system is implemented by Intelligent Wiring System (IWS). Intelligent Wiring System is a decentralized node system which enables to reduce weight of the wiring system between the low voltage battery and the actuators. The system provides also the ground wiring because the body of the Electric RaceAbout is not used as a part of the electrical loop as in metal body vehicles. The 12V -system is based on state machines and CAN -messages between the nodes which control the actuators such as fans and head lights.

Electric RaceAbout can be charged in the overnight charging mode in 3-10 hours from empty to full charge depending on the number of chargers being used. The battery type is Lithium-Titanate which means that it can be also fast charged with 10C current. The battery manufacturer reports that Lithium-Titanate chemistry is perhaps the safest Lithium based chemistry in the world. This report is shown in Appendix C.

The battery is supervised by the battery management system (BMS) of which the design and implementation are described in the present study. The battery pack includes 24 slave cards which are reporting cell voltages and temperatures to the master unit of the BMS -system. This unit analyses and calculates the state of the battery. Additionally it reports battery information to the user and rest of the system devices in the vehicle. More detailed information is given later in this thesis.

During the project Electric RaceAbout has gained a lot of success and records both in Europe and the USA. In summer 2010 ERA took apart to the X-Prize competition and reached the second place. One year later ERA won the Challenge Bibendum E-Rally in Berlin. In addition to the victory, ERA gained also the Prototype & Concept Design Award and Environmental Award.

The same summer ERA was driving in the legendary Le Mans track in Le Mans vers le Futur -event in France and a few weeks later took apart in the E-Miglia Trans-Alp Rally and gained 9th place. In autumn 2011 ERA took over the new lap record of road legal electric vehicles in Nürburgring Nordschleife (Germany) at time 8.42,72. The latest achievement of ERA is the title of the world´s fastest electric car on ice (252 km/h). This was performed on lake Ukonjärvi in Lapland. All these performances have shown that an electric car can be fast, sustainable, energy efficient and reliable at the same time.

In a nutshell Electric RaceAbout is a university project targeted to educate young automotive engineers wishing to learn modern automotive technology and apply theoretical skills to real automotive engineering work. Electric cars are becoming a part of our everyday life and this research is a pioneer project in Finland when researching alternative energy sources for transportation. Electric RaceAbout is also a good example of the fact that already now there is a possibility to get out of oil dependency in transportation and have a good opportunity to use vehicles that do not have any local pollution. In Figure 2 the Electric RaceAbout is heading to the Challenge Bibendum competition in Germany 2011.

Figure 2. Electric RaceAbout leaving to Challenge Bibendum competition in Berlin 2011.

Figure 2 shows the old outfit for Electric RaceAbout. In year 2013 the Electric RaceAbout got its new outfit with a new sporty wing on the back of the car and also new dive plates in order to give more downforce on the racing track. The new outfit is shown later in this thesis in Figure 37.

1.3 Benefits of the New System

A user-configurable BMS -system is in a very important role when prototype level vehicles are designed. This enables changes in the system in a very short time when the right parameters for a specific setup have to be configured. In research and development work, this involves also Electric RaceAbout -project where new configurations have to be tested very often.

Especially with a racing car all the changes in the system have to be configurable immediately when needed. When searching the right parameters for example on the race track, the changes have to be able to be made in a very short time. Fully configurable system enables to do any modifications to the software and thus enables fast prototype tests.

The first three years the Electric RaceAbout used a prototype level off-the-shelf BMS -system provided by the battery vendor. For this reason it was very problematic to make any changes in the system without the help of the manufacturer. Due to this fact, the rapid configuration changes in the system were impossible.

For this reason it was decided to design a new user-configurable battery management system by using a part of the old system and complete it with better components that would be fully configurable for the user. The system was designed to be modular which enables all the submodules to function independently of each other. This has also benefits for future development because all the submodules can be replaced with better modules or at least all the submodules can be improved independently. When the system is modular and fully user-configurable, the new designers are able to improve the system even further.

The real-time control capability was also utilized in the new system. By utilizing real-time based microcontrollers in the vehicle, the reaction for fault situations could be designed to act in very short time. This made the system much safer. For example in the situation where such a fault occurs which forces the high voltage contactors to open during discharging process, the BMS -system sends the order to disconnect the load from the battery. The vehicle control unit disconnects the load and thus the battery current drops down to zero and there will be no arcs when the contactors are opened. This saves also money because the high voltage contactors are very expensive parts.

High voltage safety was also improved by means of a modular design. All the high voltage measurements were designed to happen out of direct contact of hand. More details on safety design based on galvanic isolations in the system are discussed later in the study.

One of the main objectives was also to have a 100 times faster current measurement capability. This would improve the over current detection and make the counters, which are based on current integration, much more accurate. So far the available BMS -systems in the market were capable of reporting current information only 10 times per second. The new CAN -compatible current sensor provided by Isabellenhüette GmbH was capable of delivering current information 1000 times per second. This was a solution to this objective and it improved the real-time supervision of the current remarkably.

With the new BMS -system the team believes that all the EMC -problems were also solved. The old EMC -problems were caused by switching mode power supply inside the old BMS -master unit and this harmful component was replaced by a linear regulator where no electrical switching occurs. The true results will be revealed in the next EMC -tests.

1.4 Thesis Structure

This Bachelor´s thesis represents the design and implementation of the new BMS -system into Electric RaceAbout -electric sports car. It covers the requirements of a professional BMS -system and explains how they were fulfilled in the new system. In addition, the thesis covers part of the concepts behind the control algorithms, which bring the intelligence to the system.

Chapter 2 covers the concept of the energy chain which is used to describe the role of a BMS -system in the system level. It also defines the requirements for a battery management system and lists the tasks of the new BMS -system. Chapter 3 introduces the new modular battery management system design and covers all the submodules and their specific tasks in the system. Additionally it will show the principles how to manage the user-configurable modules in the system. Chapter 4 gives an explanation how to describe battery behaviour with electric equivalent circuits. These circuits are the base for system algorithms. The concept of the open circuit voltage is represented in order to show how it can be used to speed up the charging process and compensate the apparent capacity losses caused by internal resistance of the cells. The dynamic I^2t -current limitation method is also covered in this chapter.

Chapter 5 covers the test results of the new BMS -system and Chapter 6 discusses the improvements that the system could have in future.

2 Background Sections

At the beginning of the study the system objectives of a professional battery management system had to be characterized. This was done by researching the functionality of different battery management systems available in the market [10; 11] and studying the old system [2] of the Electric RaceAbout. Currently there are no standards or regulations for automotive BMS -systems but requirements for such a system were defined with the help of reliable literature [3; 4; 5], technical white papers of IEEE professional association [6] and considerations how the system should work. The definition and requirements of a battery management system are represented in the following chapters. First the concept of the energy chain is introduced in order to show the role of the BMS- system in the system level. Then the specific tasks for the new system are defined as separate categories and the exact functions which fulfil these tasks are listed correspondingly in these categories.

2.1 Energy Chain

The energy chain [4, p. 2] is a useful concept in order to understand the energy conservation from mains to the load in an electric vehicle. The links of the chain are charger, battery and DC/AC -converter. Electrical energy from the mains is fed to the battery through the charger during the charging process. In the charger the electrical energy is transformed into magnetic energy in a transformer and then back into electrical energy. The electrical energy is stored into the battery in the form of chemical energy. Respectively in discharging process the chemical energy in the battery is converted into electric energy which is transferred to the DC/AC -converter which transfers the energy by converting the energy first into magnetic energy and again back to electrical energy which is then consumed by the motor load. The energy chain is shown in Figure 3.

Figure 3. Energy chain from the mains to the load [13].

The idea in the energy chain is that all the three links are made as efficient as possible. This makes the overall efficiency for the chain as good as possible.

2.2 BMS -system in the Energy Chain

The energy chain is represented modified in Figure 4 in order to show more intuitively that the BMS -system should have a full control to the queue in order to protect the links in the chain.

Unfortunately, often the BMS -system does not have direct control to the load because usually the system sets only battery limitations for the motor controller and this device has to obey these limits when controlling the load. That is, the BMS -system sets particular battery power and battery current limits and these are the maximum values that the inverter has to obey. Of course these limits vary according to the situation during the discharging process. For example in the case when the BMS -system notices that the battery is too warm, it can request the motor power to be reduced by lowering the maximum battery current limit. If the battery current is still too high after a while, in the extreme cases the BMS has to open the contactors in order to protect the battery.

In an electric car the battery is the most expensive part which means that the BMS -system is responsible especially for the battery. The protection of other links such as the charger and the DC/AC -converter are carried out by means of pre-charge sessions which are protecting the power electronics in the devices from rush currents.

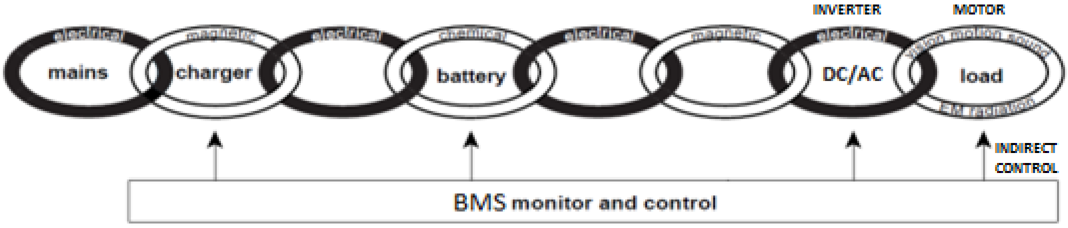


Figure 4. The BMS controls the links between the mains and the load [13].

As shown in Figure 4, usually the BMS -system is able to control directly all the links in the chain and by announcing the battery limits for the DC/AC convert, it is also possible to control the load indirectly. However, these days also the links have intelligence which means that BMS -system can control them by asking them to do some specific work. For example the BMS -system can ask the charger to reduce the charging current or even to interrupt it during the charging process. In addition to intelligent links in the chain, the modern modular system design principle brings freedom to the selection between different link candidates. This means that by using the modular design in the energy chain the charger does not have to be some specific charger. It could be any charger which is connected to the communication link in order to allow data transfer between BMS -system and the charger. In the same way if the designer finds more efficient inverter, the old inverter can be replaced in order to increase the overall efficiency of the chain. However, the most important thing to understand is that the BMS -system should be able to control these links directly or at least indirectly in order to protect especially the battery.

2.3 Requirements of New BMS -system

This chapter lists the requirements of the new BMS -system. BMS executes tasks which define the behaviour of the system. Generally the tasks of the BMS -system were defined to:

- supervise the battery
- protect the battery
- estimate the battery´s state
- maximize the battery´s performance
- share calculated data and control external devices
- protect the links in the energy chain
- protect the user / driver

These tasks can be thought as separate categories which include the exact functions in order to fulfil the requirements. The main idea in this allocation is that the first task (supervise the battery) is the base task which provides the information for the other tasks. The base task provides the most fundamental data of the battery and all the other tasks are dependent on this information. In the next chapter the exact functions which fulfil these requirements are listed under the corresponding categories.

2.3.1 Implementation of BMS Tasks

The BMS -system requirements were defined in the previous chapter. On this observation level the functionality of the BMS -system is defined only very generally. For this reason this level does not define how the behaviour is implemented. This chapter shows the requirements as in their own categories and the functions which fulfil these tasks are listed under corresponding categories. This gives a better overview of the system functionality.

In order to **supervise the battery** the BMS -system:

- measures and monitors cell currents in real -time
- measures and monitors cell voltages in real -time
- measures and monitors cell temperatures in real -time

These three measurements are the base measurements for the system. From these measurements all the secondary data can be calculated in order to have more information of the battery. This information affects also to the system control and all the battery limitation calculations.

According to the base measurements the BMS **protects the battery** by:

- preventing the voltage of any cell from exceeding the fixed upper / lower limit provided by the battery manufacturer
- preventing the temperature of any cell from exceeding a fixed upper / lower limit provided by the battery manufacturer
- setting the maximum charge current limit / discharge current limit
- setting the maximum charge power limit / discharge power limit

By processing the base data the BMS **estimates battery´s state** by:

- determining the SOC -state of the cells / battery
- calculating the DOD -state of the cells / battery

- estimating the internal resistances of the cells
- calculating secondary data such as total energy, delivered charge, operating hours and battery cycles since first use

In order to **maximize the battery´s performance** the BMS:

- controls passive balancing

In order to **share the calculated information and control the external devices indirectly** the BMS**:**

- reports to users and external devices via a communication link

The BMS **protects the links in the energy chain** by

- controlling contactors in order to connect and disconnect the battery pack to/from the vehicle
- controlling pre-charge sessions in order to protect capacitive loads in external devices which are connected directly to the battery

Finally in order to **protect the driver/user** the BMS system:

- calculates the isolation resistance in order to inform possible ground faults for the driver
- opens the interlock circuit in the vehicle if some dangerous error occurs such as the vehicle crashes in an accident. This disconnects the battery from the vehicle by opening the contactors

The challenge with these functions arises from the fact that the battery parameters change as functions of multiple factors. For this reason all the calculations are only estimates that suffer from measurement errors. The most important function parameters are current, voltage and temperature (I, V, T) which are specified by the battery chemistry. These three parameters define the SOA -limits of the battery. All the listed functions were implemented in order to keep the battery inside the SOA and to give fresh information of the battery for the user and external devices in the vehicle [3;4;5].

2.4 Modular System Design

The system design was decided to be modular in order to give freedom to the disposition of the system devices. The modular system design of the new battery management system is illustrated in Figure 5.

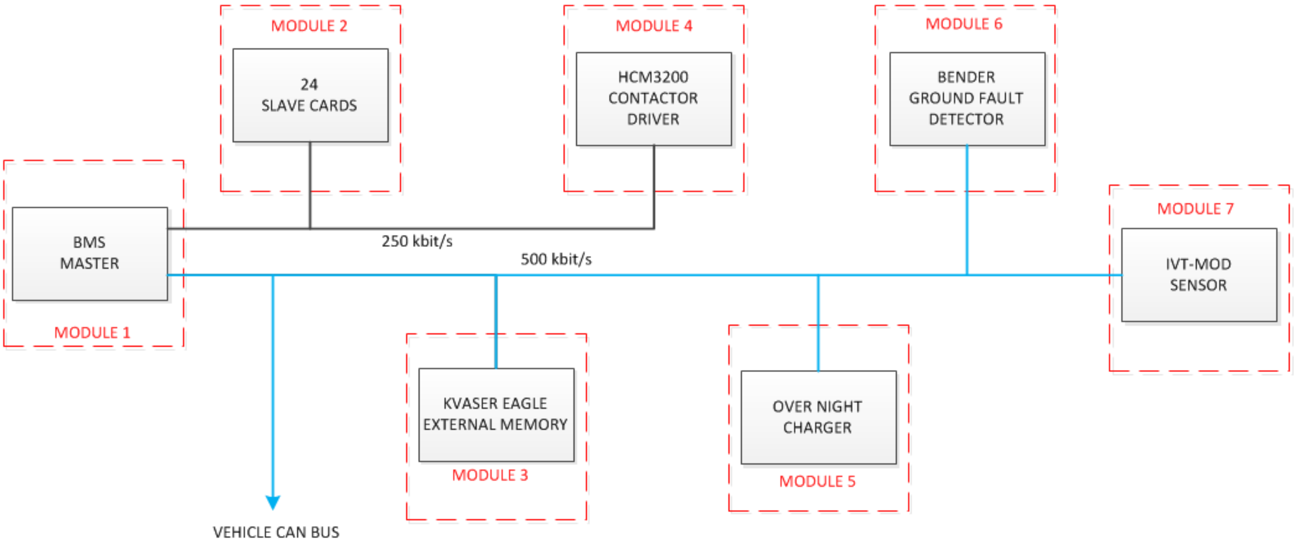


Figure 5. Modular system design of the new BMS -system.

As shown in Figure 5 the modular design is an approach that subdivides the system into smaller modules that can be independently created, improved and then used in different systems to drive multiple functionalities. The system modules are reusable and the interfaces of them are designed in the way that different module mixes can be easily created. The modules are independent of each other which means that if any of the modules is removed or replaced with another part, it does not affect to the functionality of the other modules.

2.5 CAN -bus as Communication Link

The communication in the new battery management system between the system devices was carried out with two separate CAN -busses. These CAN -busses were also shown in Figure 5. The first CAN -bus (250 kbit/s) was implemented between the BMS -master and the slave cards. Also the HCM3200 I/O -module was included into this bus. The second bus is the faster CAN-bus (500 kbit/s) called CAN-A. This is the largest CAN -bus in the vehicle and rest of the other CAN -compatible devices except inverters were connected to this bus. More descriptive illustration is shown in Appendix A

In practice the CAN -bus reduces a lot of wiring harness as a communication link because the information is transferred in serial format and according to the CAN -bus specification ISO 11898-1 it needs only two twisted wires for routing the data. Furthermore the CAN -bus is bidirectional and very fault-tolerant when correctly installed. The bus is terminated from the both ends of the bus with 120 Ohm resistors. These resistors prevent signal reflections which interfere the communication between the nodes in the bus. The signal is transferred in a differential format between the CAN-High and CAN-Low wires. The detailed functionality of the CAN -bus is not discussed further in this thesis and thus the reader is recommended to find further information of this type of communication link from other sources. [9]

2.6 Current and Voltage Measurement Methods

There are two ways to measure current in an electric car. One way is to measure with a Hall -effect sensor around the wire where the current flows. The Hall -effect sensor measurement is based on measuring the magnetic field around the cable which is proportional to the flowing current. Another way to measure current is to use a shunt resistor. This kind of resistor has usually a very small resistance and when current goes through it, this generates a voltage across the resistor which is proportional to the current according to the Ohm´s law.

Both current measurement methods were implemented to the new battery management system. This chapter gives more detailed information of these measurement methods and covers their benefits and drawbacks.

2.6.1 Current Measurement with Hall -Effect Sensor

The Hall -effect sensor measures the magnetic field around a current carrying wire and produces an output voltage proportional to the measured magnetic field. This voltage is called a Hall -voltage. The Hall -voltage is analysed in the sensor and converted to the corresponding current value with the measurement electronics in the sensor. Finally the measured current value is sent to the CAN -bus where the BMS -master is able to read it. This kind of Hall -sensor by Ashwood was implemented in Electric RaceAbout. The data sheet of the sensor is shown in Appendix E.

The great benefit of a Hall -effect sensor is that it is automatically galvanically isolated from the measurement point. The drawback is that Hall -effect sensors suffer from error sources such as an initial electrical offset, thermal drift, nonlinearity and magnetic hysteresis [7; 8]. Of all these four errors, the most important ones to keep in mind are linearity and electrical offset. The other errors will be generally small because they are cancelled out during cycle integrations. The electrical offset results in SOC drifting in electric cars which has to be compensated. The concept of the SOC has been not introduced before in this thesis and it will be covered in Chapter 4.5. It was mentioned here because the electrical offset affects in great detail to this parameter and thus this parameter has to be compensated somehow. More of this topic will be introduced in Chapter 4.5.

The electrical offset means that if the battery current is really zero amps, the sensor gives something else than zero out. Thus the BMS -master can understand that there is for example three amperes running in the measured cable due to the error caused by the offset. This brings error also to different counters such as total energy counter and total delivered charge counter, which are based on the measured current. However in the sensor used in Electric RaceAbout, the offset problem has already been compensated with internal electronics every time when the sensor is powered up and by using closed loop technique [7]. Electric RaceAbout was equipped with two of these Hall -effect sensors by Ashwood because one sensor was not capable of measuring 1000 amperes currents. The total battery current is calculated in Elekrobit6120 by summing the values of these two sensors. These two sensors were decided to be used because firstly in the test point of view and secondly because of having redundancy in the current measurements. That is, the sum of the Hall -effect sensor values were used to compare the Hall -effect sensor value to the value given by the BMS -system that was mainly based on shunt resistor method for measuring current. The shunt resistor based measurement is introduced in the next chapter.

2.6.2 Current Measurement with Shunt Resistor

A shunt resistor is another way to measure current. It is based on Ohm´s law. The current flows through the shunt resistor and produces a voltage over the resistor. This voltage is proportional to the flowing current. Usually a current of 1000A produces 50mV voltage over the resistor. The voltage should be very low because the more the voltage is the more it dissipates energy into the heat. For the reason that the voltage produced by the shunt resistor is so low, the signal must be amplified that computers can understand clearly the value of the flowing current. The benefit is that measuring the current with a shunt resistor, there are no offset problems. However as discussed above, there are some energy losses when the current flows through the resistor. Furthermore the shunt resistor does not have galvanic isolation from the high voltage cables because it is connected in series with the cables.

There is also one error factor which results from temperature differences. The temperature drift changes also the resistance of the resistive element which produces error in the proportion between the current and voltage. This can, however, be compensated with measurement electronics if the sensor is professional enough.

In Electric RaceAbout the old BMS -system had a shunt resistor which was located in series between the negative DC -bus and negative battery cables. The signal wires had to be twisted pair because this prevented the errors in signal caused by electromagnetic induction. In the new BMS -system the current measurement is also mainly based on a shunt resistor but this resistor is included in ASIC -circuit which forms a sensor called IVT-MOD. Now also the signal processing has been done already inside the sensor and the current value is sent directly to the CAN -bus. This new sensor was obtained because it was capable of measuring current 1000 times per second and thus report the current value into the CAN -bus much more faster than any other sensor in the market. This capability was an important improvement in the new system. More detailed information of the IVT-MOD -sensor is represented in Chapters 3.1.5. and 3.3.4. The sensor module offered also high voltage measurement capability which is discussed in the next chapter.

2.6.3 High Voltage Measurements

The BMS -master needed a high voltage sense in order to verify the state of the contactors, control the pre-charge processes safely and measure the total battery voltage. This was one of the great improvements in the new BMS -system from the safety point of view. Earlier the high voltage sense cables had to be routed out of the high voltage distribution box to the BMS -master because the master unit was standing on the HV -box. This means that high voltage pins were available in one connector that was connected to the old BMS -master. This increased the risk of a high electric shock although the old BMS connectors were protected from direct contact of hand. The old high voltage connection in BMS -master is shown in Figure 6.

Figure 6. High voltage connections available in direct contact of hand in the old BMS -system.

As shown in Figure 6, all the HV -measurement cables were routed through a circular connector which was reachable by the user in the old system.

In the new system all the high voltage measurements were provided by the new IVT-MOD sensor that was introduced in the previous chapter. In addition to its capability to measure current, the sensor includes also three high voltage measurement channels. Similar to current information, also the voltage measurements are delivered into the CAN -bus where the BMS -master is able to read them. In future the manufacturer of the IVT-MOD module is able to provide the sensor which contains the galvanic isolation between the high voltage measurement side and the signal side on the circuit board. Due to the loss of the isolation the galvanic isolation between the sensor module and the vehicle had to be added with the help of DC/DC converter and CAN-Repeater -device based on optocoupling like discussed in Chapters 3.1.5 and 3.1.6.

3 Design of New Modular Battery Management System

This chapter introduces the submodules of the new modular BMS -system. The role of each submodule in the system is described in order to build a sufficient overview of the overall system for the reader. Many of the submodules were chosen to be user-configurable devices which was one of the main purposes of this study. Due to this fact the principles how to manage the user-configurable devices are touched upon in order to give a good overview for the new designers who will maintain and develop the system even further in the future.

3.1 System Modules and Their Management

In modern vehicles the functionality is carried out with distributed systems thus spreading intelligence also for the subparts in the system. This reduces a lot of wiring harness and distributes also the tasks for various subsystems. The new BMS -system for Electric RaceAbout was also composed from various subparts which have their own vital role in the whole system. This chapter introduces all the parts which were chosen for the new BMS -system. Because all of the subparts are replaceable with other suitable components and possible to improve independently, the system design is expressed to be modular. Hence all the parts of which the whole system consists of, are called submodules. The overall system level design can be found in Appendix A.

3.1.1 Elektrobit 6120 FPGA Microcontroller as BMS -master

The BMS -master is the heart of the BMS -system. This device is responsible of all the system control functions. The master collects all the data from the submodules and analyses it. According to this data the BMS -master controls the system. The master is connected to the other subparts via CAN-bus which provides the very fast way to exchange data between the other nodes. This device is a real-time computer which calculates information all the time and takes care of the well-being of the system. The BMS -master of Electric RaceAbout is shown in Figure 7.

Figure 7. Elektrobit6120 as real-time BMS-master.

The Elektrobit 6120 microcontroller in Figure 7 was decided to take the role of the BMS- master in Electric RaceAbout because it had proved its capability in real-time conditions earlier as a vehicle control unit. This microcontroller is fully configurable by the user and it provides connections for two high speed CAN -busses and number of analog and digital I/O pins. The first CAN -bus channel (0) was used for the 500 kbit/s vehicle CAN -bus called CAN-A and the second channel (1) was used for data exchange with the slave cards in the battery pack. The latter CAN -bus exchanges data in the rate of 250 kbit/s. Also the control device of high voltage contactors was connected to this slower CAN -bus. The programming of Elektrobit 6120 was carried out with model-based code in Simtools environment. This environment is built on the Matlab Simulink environment. In addition to Simulink code blocks the Simtools GmbH provides code blocks for accessing the I/O pins and CAN -messages in the code. More detailed information of configuration methods of Elektrobit 6120 is represented in Chapter 3.3.1

3.1.2 Slave Cards

The battery pack contains 24 slave cards which measure together 286 cell voltages and 144 cell temperatures. These slave cards are often called only as slaves. The BMS -master polls information from the slaves every second through the 250 kbit/s CAN-bus. The slave cards take the sample of all cells and send the information in 0.1 second back to the CAN -bus. Every slave card has its own identification number which can be used in diagnostic meaning if any information is lost in the CAN -bus. An extracted sample of the CAN -bus discussion between the BMS -master and the slaves is shown in chapter 3.4. Figure 8 shows one slave card that basically consists of measurement electronics and shunt resistors in order to balance the cells. The balancing method is discussed in Chapter 4.6.

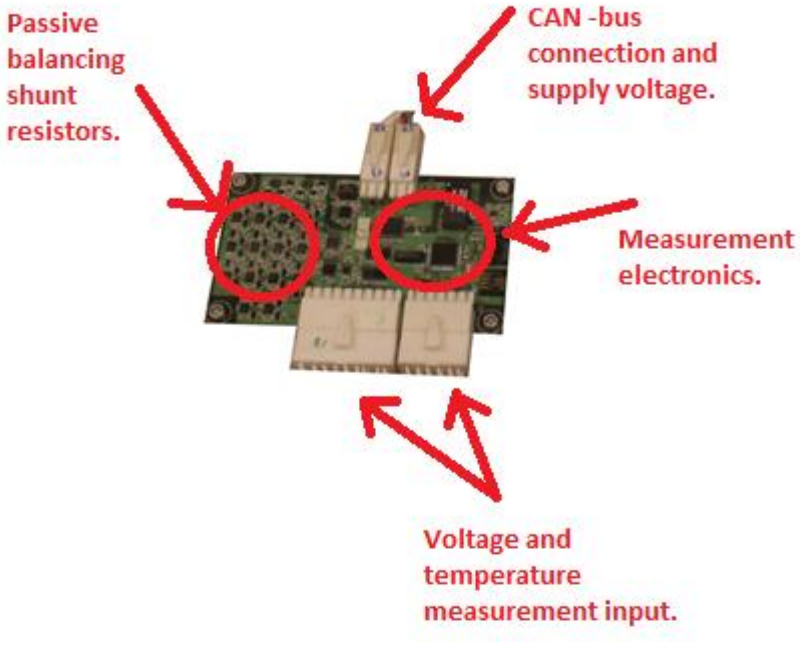


Figure 8. One of the slave cards in the battery pack.

The slave cards include 1 kV galvanic isolation between individual battery cells and rest of the vehicle. The measurement range for the cell voltage is 0-5 V and the temperature range for measurements is -20 - 100 ºC. The slaves are under the direct control of the BMS -master. The supply voltage is 6.6 V and this supply voltage has been produced from the low voltage system of the vehicle with the help of a regulator circuit and a cooling plate. The slaves are dummies because they cannot process any measurements without an order and they do not perform any processing.

The BMS -master sends a freeze command every second to the CAN -bus. All the slave cards detect this order at the same time and take a sample from the cell voltages and cell temperatures. After the measurement the slave cards return the sampled values by sending them back to the CAN -bus. Hence in every second BMS -master is able to have new fresh data of the cell voltages and temperatures.

3.1.3 Exertus HCM3200 as High Voltage Contactor Driver

Elektrobit6120 does not have any high current outputs which meant that a stand-alone CAN -controlled I/O module had to be added to the BMS -system. This device is Exertus HCM3200 controller and it is controlled through the CAN -bus in order to switch the state of the high voltage contactors. The device is shown in Figure 9.

Figure 9. HCM3200 I/O module as high voltage contactor driver.

This controller was connected to the internal battery management system CAN -bus in parallel with slave cards because it turned out that it did not support the rate of vehicle CAN -bus (500 kbit/s). BMS -master controls the state of all four high voltage main contactors and two high voltage relays in the vehicle´s distribution box. The sense wires of all four main contactors were connected to the inputs of Exertus HCM3200 in order to ensure the real state of the contactors. Everytime when any of the main contactors is closed or opened, the state information of the sense wires is sent to the CAN -bus by the contactor driver and thus the BMS -master receives the information of the contactor states immediately. This brings safety to the contactor control when all the orders to control contactors can be compared to the control. This device was mainly configured by changing parameters of built-in functions. If the user wants to have more complex functionality, it is possible to program PLEX-code and download it into the device. More detailed description of the device configuration method is represented in Chapter 3.3.2.

3.1.4 Kvaser Eagle as External Non-volatile Memory

Elektrobit 6120 does not include any non-volatile memory which could have stored informative counter values such as total delivered energy, total delivered charge and total operating hours of the BMS -system. The solution for the problem was founded from the data logger device called Kvaser Eagle. This device is shown in Figure 10.

Figure 10. Kvaser Eagle as non-volatile memory.

The Kvaser Eagle CAN -bus monitoring device is fully user-configurable and with the event-triggered t-script language it was configured to act as an interactive external memory in the system. At the moment when the vehicle is switched off, the BMS -master starts to store the latest total counter values such as previously mentioned energy and charge counters to the non-volatile external memory in one second interval. After few seconds the whole vehicle is powered off. Later when the vehicle is switched on, the BMS -master polls the stored counter values from the memory and starts to update them. During charging or discharging the BMS -master stores the counter values every 30 seconds into the memory. This keeps the counter values as fresh as possible in the memory ready for the case that latest values can be extracted at any time for further use.

This device was connected to the 500 kbit/s CAN -bus in the vehicle and the communication was designed to happen with three CAN -messages per stored information. The first message by Elektrobit6120 triggers the storing mode on in the Kvaser Eagle and the second message is used to poll the newest data from the memory. The third message is the answer by the Kvaser Eagle and this message contains the last stored value extracted from the memory.

In future this device can be used as an intelligent node because the device can be configured in many different ways to achieve the most suitable and effective logging for any situation. The device supports up to 32 trigger conditions and it can store data up to 32 GB. More detailed information of the configuration methods with Kvaser Eagle is represented in Chapter 3.3.3.

3.1.5 IVT-MOD Current and High Voltage Measurement Module

Electric vehicles need a proper way to measure current in real-time conditions in order to supervise current limits during charging or discharging process. There are currently two ways of measuring current [3, p. 54]. The first way is to use a shunt resistor which produces a voltage over the resistor according to Ohm´s law when the current flows through it. Hence this voltage is proportional to the flowing current. Another way is to use Hall - effect sensors which are measuring the magnetic field produced by the current carrying wire. This magnetic field is proportional to the flowing current in the wire. Both the methods have their own benefits and drawbacks. These were discussed more detailed in Chapter 2.6. In Electric RaceAbout the main current measurement is carried out with the shunt resistor module which is shown in Figure 11.

Figure 11. IVT-MOD high precision shunt sensor.

The sensor in Figure 11 is called a IVT-MOD sensor. The name comes from the fact that there are different kind of built-in features available which can be chosen by the customer in order to modify this sensor for different applications. The available features of this sensor are:

- Galvanic Isolation
- Over current detection
- Hardware trigger
- Six ranges of current measurement
- Up to three voltage measurement channels
- Digital communication (CAN, SPI)
- Temperature measurement

In Electric RaceAbout the IVT-MOD high precision shunt sensor was used to measure battery current and high voltage busses inside the high voltage distribution box. The sensor sends automatically the measured values in a 1ms interval to the vehicle´s CAN-bus (500kbit/s). The BMS -master reads the values from the CAN -bus and calculates the dynamic current limits and supervises the battery voltage. In addition the high voltage measurement capability was used to ensure the state of the high voltage contactors. This information is compared to the contactor status information by HCM3200 I/O module especially in pre-charge sessions. Unfortunately the manufacturer could not offer galvanic isolation between the high voltage measurements, the supply voltage of the sensor and the CAN-bus connection which meant that the supply voltage was referenced to the same ground than high voltage measurements were referenced. This led to the situation that the galvanic isolation for the CAN- bus and the supply voltage had to be designed by the user in order to ensure the electrical safety of the system. The supply voltage of the sensor was galvanically isolated with a DC/DC -converter installed between the supply wires and the sensor. The CAN -bus was isolated with a device called CAN-Repeater described in Chapter 3.1.6.

The vehicle was equipped also with two Hall - effect sensors by Ashwood which measure also the battery current. By comparing this Hall -effect sensor value to the IVT - MOD shunt resistor the reliability of the new shunt resistor could be ensured to be right. This brings redundancy to the system.

3.1.6 CAN-Repeater as Galvanic Isolation in CAN -bus

The galvanic isolation of the CAN -bus between the IVT-MOD sensor and the vehicle CAN- bus was carried out with a product called CAN -Repeater by Peak Systems. This device enabled a galvanic isolated connection thus establishing decoupling between two high speed CAN -busses with the same bit rates. This isolation is based on opto-couplers where the signal is transmitted in the form of light. The electrical isolation is up to 5kV. Below in Figure 12 is an illustration of the physical connection between two CAN -busses.

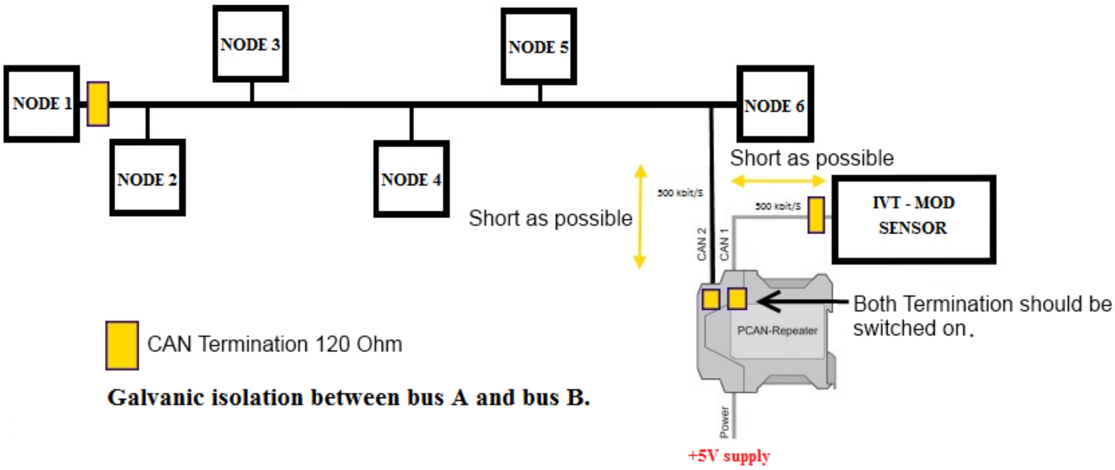


Figure 12. CAN-Repeater providing galvanic isolation between two CAN-busses.

In Electric RaceAbout the CAN -bus A (Figure 12) means the CAN -bus between the IVT-MOD sensor and the CAN- Repeater. Respectively the CAN -bus B (Figure 12) means the CAN -bus between the CAN -Repeater and the vehicle CAN- bus network. The CAN -Repeater is bidirectional which means that the CAN -messages can be sent in both directions from A to B and vice versa.

There are three things to keep in mind when this device is used. Firstly the both CAN-busses have to work with same bit rate and secondly this isolation device cannot be used to extend any CAN- busses. The last thing to remember is that both parts of the CAN -busses have to be terminated with 120 Ohm resistors in order to prevent reflections in the bus.

3.1.7 Pre-charge Resistor

The use of the pre-charge resistor is essential when significant capacitive loads are connected to the high voltage battery of an electric car. This kind of capacitive loads can be found especially in intermediate circuits of inverters and battery chargers. The pre-charge resistor is connected in the series between the battery and the capacitive load during the pre-charge session. When the battery is connected to the load there will be a short inrush current in order to charge up the capacitors up to the level of the battery. The pre-charge resistor limits the inrush current. The pre-charge session is finished typically in under one second and after that the battery can be connected to the loads directly thus passing the pre-charge resistor circuit. Without the proper use of the pre-charge resistor during the pre-charge session the result can be a break down in the capacitive loads or welding contactors which is not desirable.

The pre-charge resistor is especially designed for pre-charge sessions thus being capable of taking high energy impulses during the pre-charge of capacitive loads. During the study a new type of pre-charge resistor was installed into the system. According to the manufacturer the resistor is capable of having a 6.76 kJ energy impulse per one pre-charge session. The voltage rate is 700 V and the maximum current impulse is 32A under 0.3 seconds. The difference in size between the new and the old pre-charge resistor in Electric RaceAbout is remarkable and this can be seen in Figure 13.

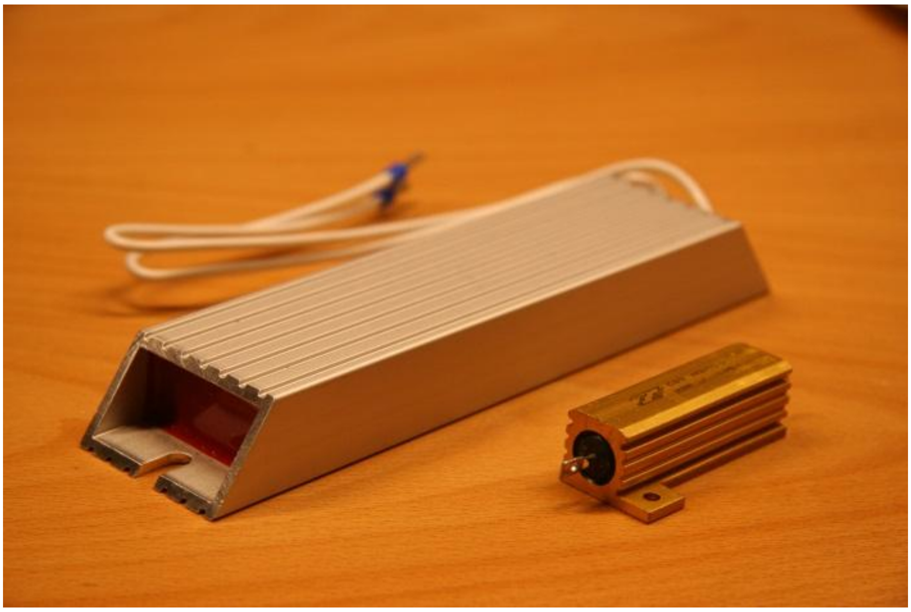


Figure 13. The new pre-charge resistor is much more bigger than the old pre-charge resistor.

The new pre-charge resistor is on the left side in Figure 13. Earlier there were problems with the smaller pre-charge resistors which could not stand the energy impulse during the pre-charge session. This resulted in burning resistors. With the new resistor there have been no problems during the pre-charge session because according to its technical properties there is no such an energy during the pre-charge session which would burn the resistor.

3.1.8 High Voltage Contactors

The vehicle includes four high voltage main contactors and two pre-charge relays which are responsible of galvanically connecting and disconnecting the high voltage battery to the vehicle or the battery chargers. The contactor and relay models are shown in Figure 14.

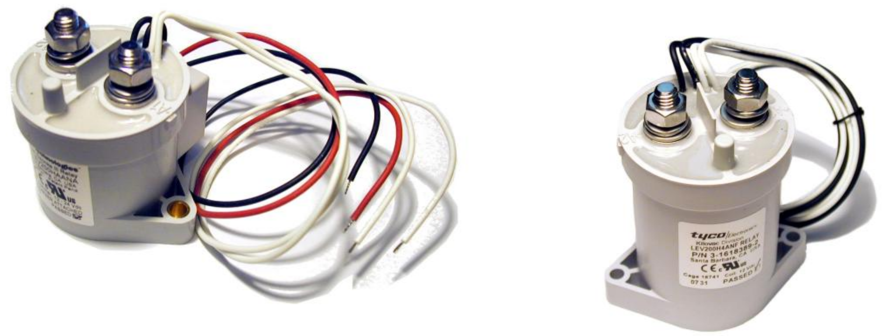


Figure 14. The high voltage contactor on the left side and the relay on the right side.

The contactors are controlled by Exertus HCM3200 I/O module with 12V supply voltage. In Electric RaceAbout all these contactors are controlled by grounding the negative supply wire thus closing the contactor. Pre-charge relays in series with pre-charge resistor are used in pre-charge session of capacitive loads thus preventing high inrush currents which could explode the intermediate circuits in inverters and other power electronic devices which are connected directly to the high voltage busses. All the four main contactors are equipped with sense wires which are used as digital inputs for Exertus HCM3200 I/O module. Always when the contactor is closed, the input value for I/O module is a logical one. Respectively when contactor is open, the digital input is a logical zero. The state of the contactors is sent to the internal CAN -bus of the BMS -system and thus the BMS -master knows the state of the contactors all the time. This information was used to verify all the orders from the BMS -master to the HCM3200 I/O module. For example during the pre-charge session the BMS -master orders to close one high voltage pre-charge relay and one high voltage main contactor. After the order the BMS –master can read from the CAN –bus if the right relay and contactor were closed in order to find that there were no system control errors.

There is a built-in device called Economizer in the contactor module which takes care of the current regulation for the contactor in order to lower the energy consumption. The economizer controls the contactor with pulse width modulation which results in pulsing current taken from the HCM3200 I/O module. At the beginning of the study it was tried to control the contactors without economizers. The pulse width modulation was produced by HCM3200 I/O module but it turned out that I/O module was not able to control the contactor with same frequency than the economizer does. Due to this fact the contactors were equipped with built-in economizers and thus controlled with digital states such as on and off. The measurements of the behaviour of an economizer in high voltage contactor can be found in Appendix B.

3.1.9 Brusa NLG5 Overnight Charger

Electric RaceAbout can be charged up with a CAN -controlled Brusa NLG5 3.3 kW overnight charger in 10 hours. There is also a possibility to connect three of these chargers in parallel which increases the charging power up to 9.9 kW. Respectively this decreases the charging time down to 3 hours. This NLG5 charger is galvanically isolated from mains by a RF transformer which increases the use of the charger in safety point of view. The manufacturer reports the efficiency of the charger to be 90 %.

The use of the charger is very simple. When the BMS -master has done an initial check of the system, it starts to control the charger in order to allow charging. The charger is controlled with one CAN -message (0x618h) which contains the control parameters such as charging state (ON/OFF), maximum charge power, maximum charging voltage and maximum charging current. The charger obeys these parameters and the charging is stopped when it is complete or any errors occur. The charger information can be read from the CAN -bus with a data logger in order to get more information of the charging process. The Brusa NLG5 air cooled overnight charger is shown in Figure 15.

Figure 15. Brusa NLG5 charger.

As shown in Figure 15, the charger is air-cooled and it has only three connectors. The charger control connector is used for the communication between the BMS -master and the charger. The other two connectors on the right side are connected to the mains (AC) and to the battery (DC). During charging process the BMS -master reads information of input (AC) and output (DC) currents and voltages from the CAN -bus. From this information it calculates the mains power, mains energy, charger DC power, charger DC energy and the efficiency of the charging process.

3.1.10 CHAdeMO Fast Charger Interface

Electric RaceAbout can be charged up in 30 minutes according to the CHAdeMO -standard. This capability was implemented by a CHAdeMO compatible Move&Charge -charger. This charger supports CHAdeMO -standard which enables to charge up CHAdeMO -compatible vehicles in 15 to 30 minutes. In this time Electric RaceAbout is charged up to 90 %. In order to make Electric RaceAbout compatible with the CHAdeMO protocol, a special CHAdeMO -interface box was also installed into the vehicle in order to change data between the BMS -master and the fast charger. The connector interface of the charging cable is a standard and it is shown in Figure 16.

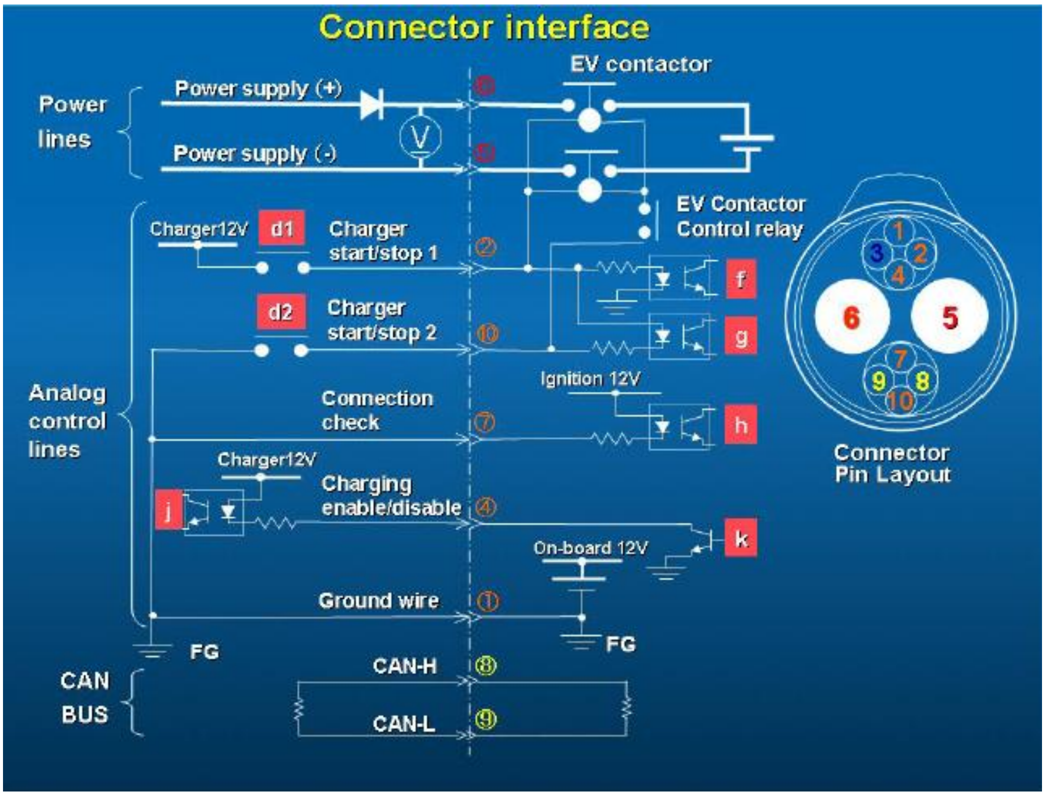


Figure 16. The connector interface between CHAdeMO charger and Electric RaceAbout.

As shown in Figure 16, there is a CAN -bus between the charger and the vehicle in order to change real-time data. The main idea in CHAdeMO standard is that the vehicle itself is the master and it controls the charger with CAN -messages. The commercial interface box between the charger and the vehicle converts the orders from the vehicle into the form of CHAdeMO protocol.

3.1.11 Bender Ground Fault Detercor

According to UCENE Regulation No. 100 there has to be sufficient insulation resistance from both battery terminals referenced to the ground potential in electric vehicles. According to the regulation the insulation resistance is defined to be 500 Ω/V. By using this value the insulation resistance for Electric RaceAbout can be calculated and the result is 165 kΩ from both battery terminals referenced to the ground when the nominal battery voltage is 330V. The ground fault detector used in Electric RaceAbout is shown in Figure 17.

Figure 17. Ground fault detector by Bender

As shown in Figure 17, the ground fault detector has two separate measurement connectors for high voltage measurements. The other connector provides connection for CAN -communication link and supply voltages. The status output is also included to the latter connector and this indicates whether the measured insulation resistance becomes lower than 165 kΩ thus a ground fault has been detected. The ground fault detection is informed for the user by switching on a red light in the cockpit of Electric RaceAbout. Once the ground fault detector is powered up it performs an initialisation and starts the *Speed Start Measuring* -mode which produces the first estimated insulation resistance during a maximum time of 2 seconds. After that the *continuous measurement mode* starts to run and in this mode the measurement is carried out automatically in every 5 minutes.

3.2 Galvanic Isolations in the System

When dealing with high voltages the galvanic isolation has a vital role from the safety point of view for the user and the devices in the system. In Electric RaceAbout there were three galvanic isolations implemented into the system providing safety for the user and the system devices. The first galvanic isolation is implemented in slave cards which are measuring directly the cell voltages. That is, the voltage measurement side of the slave card was galvanically isolated from the supply voltage and the CAN -bus side. This isolation is up to 1 kV. The second galvanic isolation occurs in the current measurement method with a Hall -effect sensor measuring battery current directly around the battery cable where the current flows. The measurement is based on the magnetic field which automatically brings galvanic isolation to the measurement. This was discussed already in Chapter 2.6.1. The third galvanic isolation is carried out in the high voltage bus measurement module. The IVT-MOD measurement module measures high voltage busses in the high voltage distribution box and the signal path from the module to the rest of the system in the vehicle was galvanically isolated with a CAN -bus isolator called CAN -Repeater. The isolation is based on optocouplers which provides the isolation up to 5 kV. The supply voltage of the IVT-MOD sensor was also galvanically isolated with a DC/DC converter between the vehicle and the sensor module.

After having obtained all the necessary subsystem parts and studying their use the software implementation of the system was ready to begin. All the subsystems were placed carefully so that all high voltage parts were galvanically isolated already in the high voltage distribution box. This made the system safer to handle compared to the old battery management system where high voltage bus measurements were taken out from the high voltage distribution box and connected to the old BMS -master as discussed in Chapter 2.6.3.

3.3 Methods to configure user-configurable devices in the system

So far this thesis has covered all the submodules that form the whole BMS -system and explained their purpose in the system. This chapter represents the basic principles how to configure the user-configurable devices in the new BMS -system. It covers the configuration methods of Elektrobit6120 microcontroller, HCM3200 I/O module and Kvaser Eagle data logger. These devices have their own chapters respectively.

3.3.1 Configuration of Elektrobit6120

The BMS -master was programmed in the Simtools environment with model-based code. The compiler is able to compile most of the blocks used in Simulink. In order to access the interfaces of Elektrobit6120 microcontroller, a special library provided by Simtools is needed. This library was delivered with the microcontroller. Simtools -library includes blocks for reading and writing CAN -messages, controlling digital and analog I/O pins and many other useful blocks for required in real-time computing applications. The high level model-based code makes the language very powerful and fast to use. The whole software architecture consists of tasks which include all the control functions of the BMS -master. Only a few graphics of the task view and programmed functions are shown in this thesis in order to keep the knowledge of specific code snippets inside the Electric Raceabout team.

An incomplete part of the task view during the design phase of the study is shown in Figure 18.

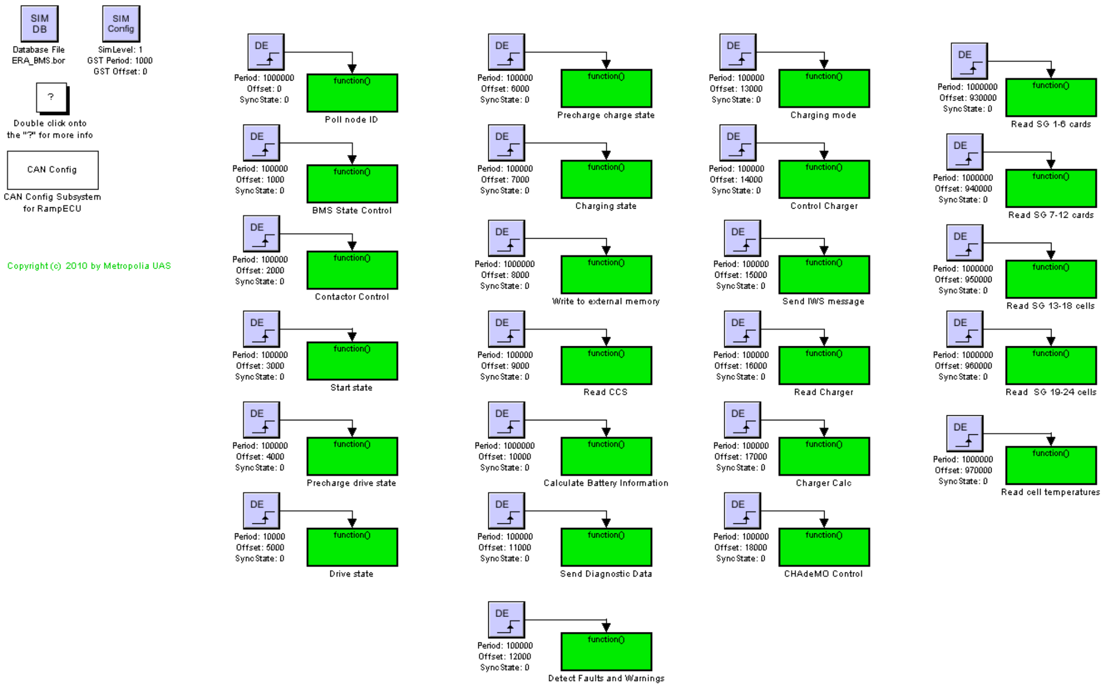


Figure 18. Overview of Elektrobit6120 task view.

Figure 18 shows that the BMS -master has tasks (green boxes) such as contactor control, reading of cells and calculation of the battery information. These are exactly part of the tasks which were ordered to have in a professional battery management system in Chapter 2.3. It can be seen also that the tasks are driven in cycles within a specific interval and with a specific offset. Inside the green task boxes there are the exact code snippets which will be executed in the specified interval.

The BMS -system control was based on a state flow diagram which is represented in Figure 19. This Figure shows that BMS -master runs in seven main states which are:

- error state
- start state
- pre-charge (drive side) state
- drive state
- pre-charge (charge side) state
- charge state
- shut down state

Additionally the parallel states such as *measurement state*, *counter value update state* and *counter saving state* start to run with the main states immediately when the initial system check is passed after the system is powered up. The complete state flow diagram of the system is shown in Figure 19 below.

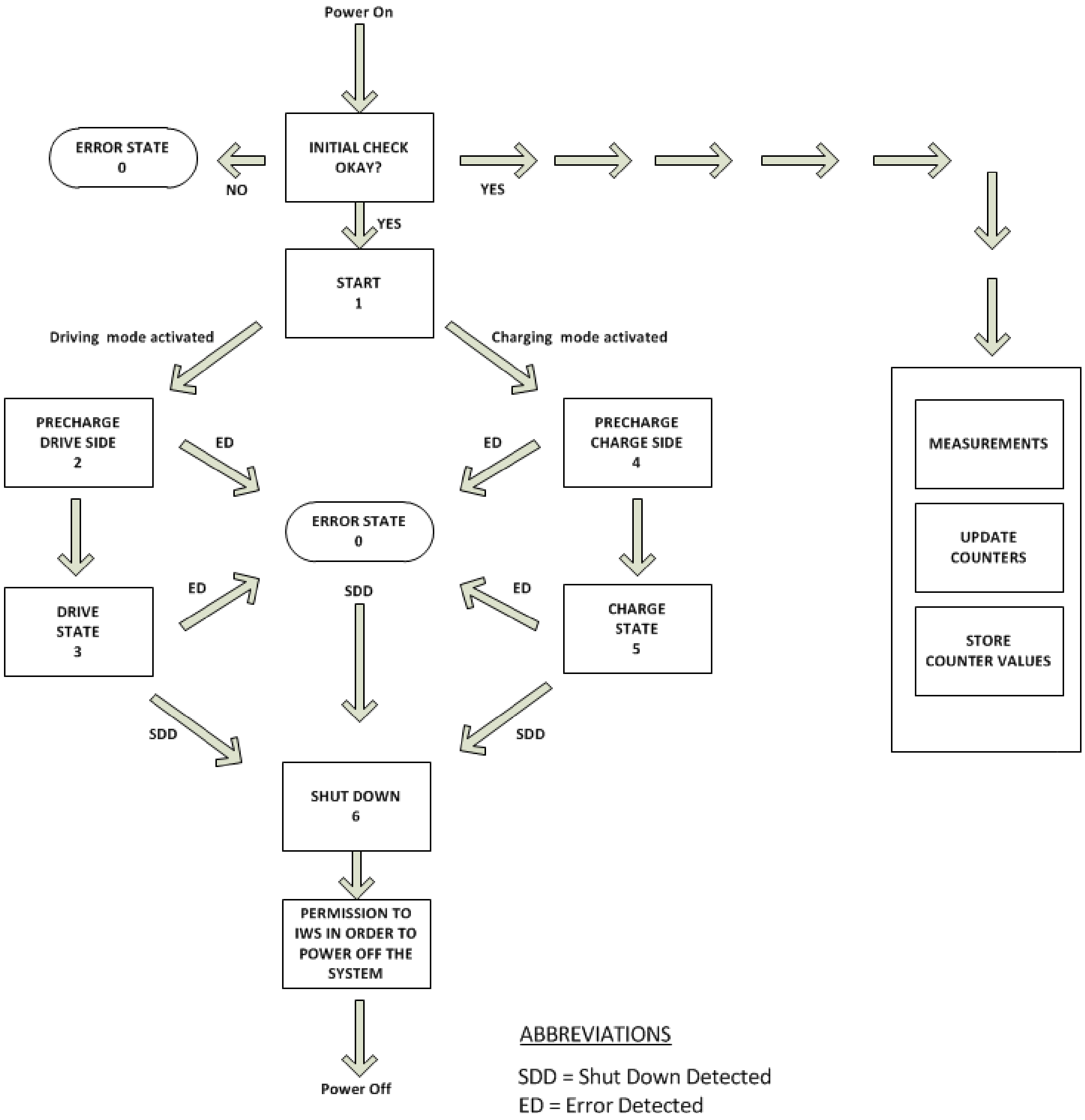


Figure 19. Complete state flow diagram of the new BMS -system

The implementation of the state flow diagram in Figure 19 was produced in Simtools and the exact code snippet is shown in Figure 20.

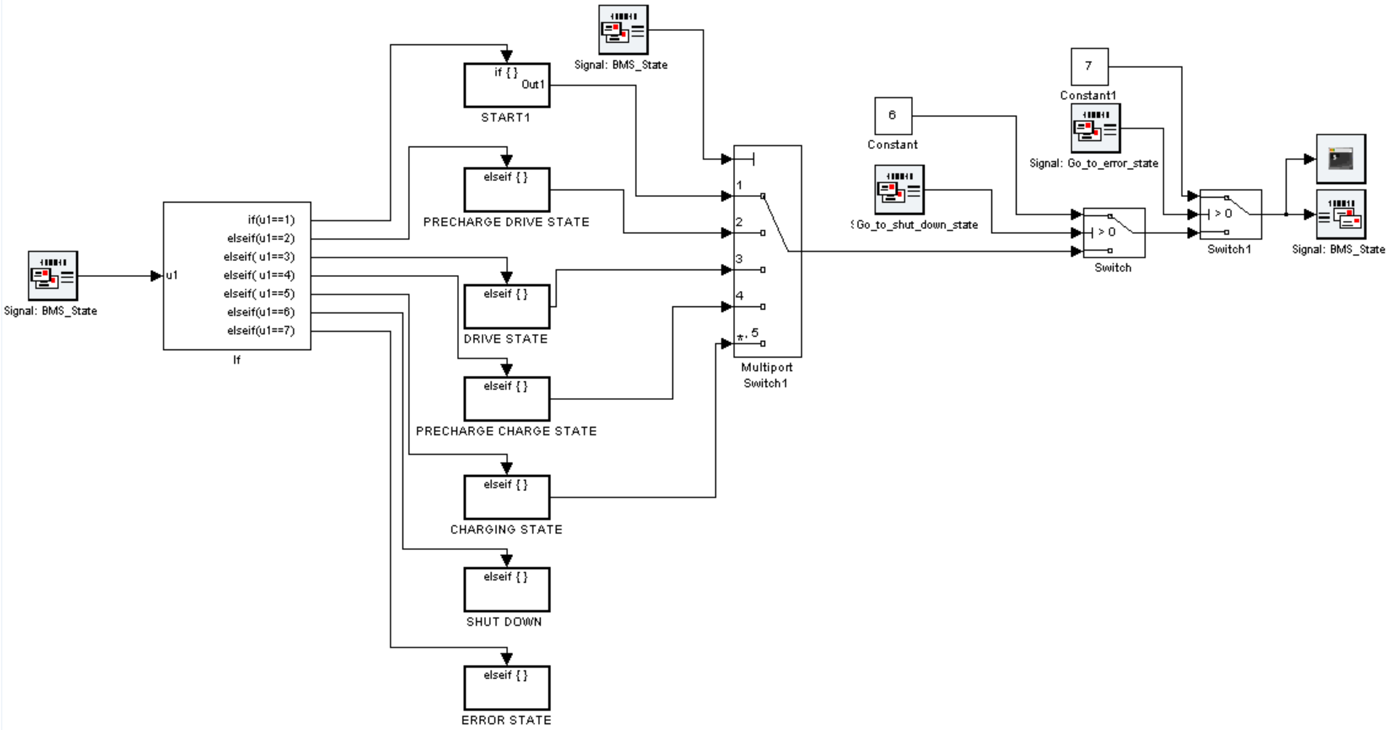
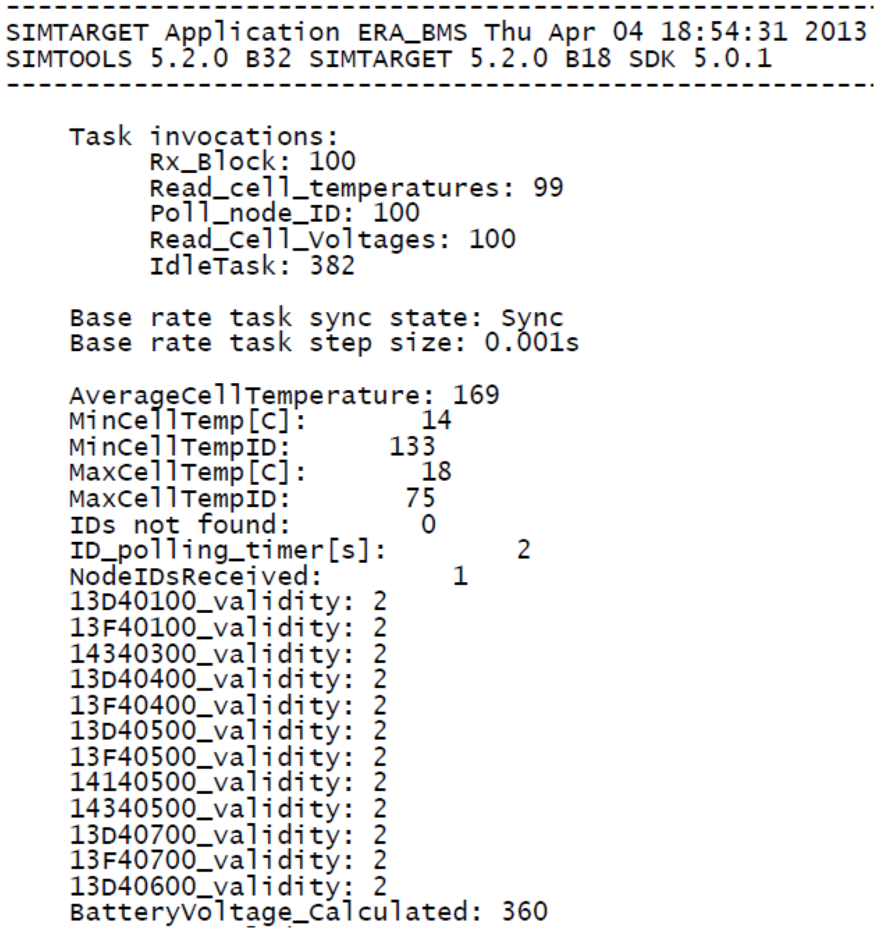


Figure 20. The BMS state machine programmed with Simulink and Simtools.

The basic structure of the BMS code was built around the state machine that was represented in the Figure 20. In the figure it can be seen that BMS has multiple states such as start state, pre-charge state and the drive state. When the BMS -master is powered on, it will wake up automatically in the start mode. This is the mode where it does some initial checks of the contactors and the cells before proceeding to the next state. If all the initial checks were successful, the BMS -master checks if it has been activated in driving or charging mode. This information affects to the state flow whether it starts to proceed with pre-charge session in charging state or in driving state. The intelligence of the BMS -master was built in the way that it can never return to its previous state. The only way is to continue in the state where it is at particular moment or move to the next state according to the information of the system parameters it has. The diagram in Figure 19 shows also that if an error occurs in any time, the BMS -master goes into error state. Similarly if the BMS -master detects that the charging or driving is stopped, it goes to the *shut down* mode where it stores all the important total counter values into the external memory of the system before the system is powered down.

When the code snippets are finished they are compiled in the Simtools environment and the compiler checks whether there is any bugs in the code. If the code was successfully compiled it can be downloaded into the Elektrobi6120 through Ethernet cable. When the compiled code has been downloaded into the Elektrobit6120, it will start to run when the device is reset or powered on again.

The Elektrobit6120 provides a way to observe parameter values in terminal emulator such as TeraTerm. This is a convenient way to follow changing parameters when the code is executed. The Figure 21 shows some of the parameter values which were observed during the design phase of the code.



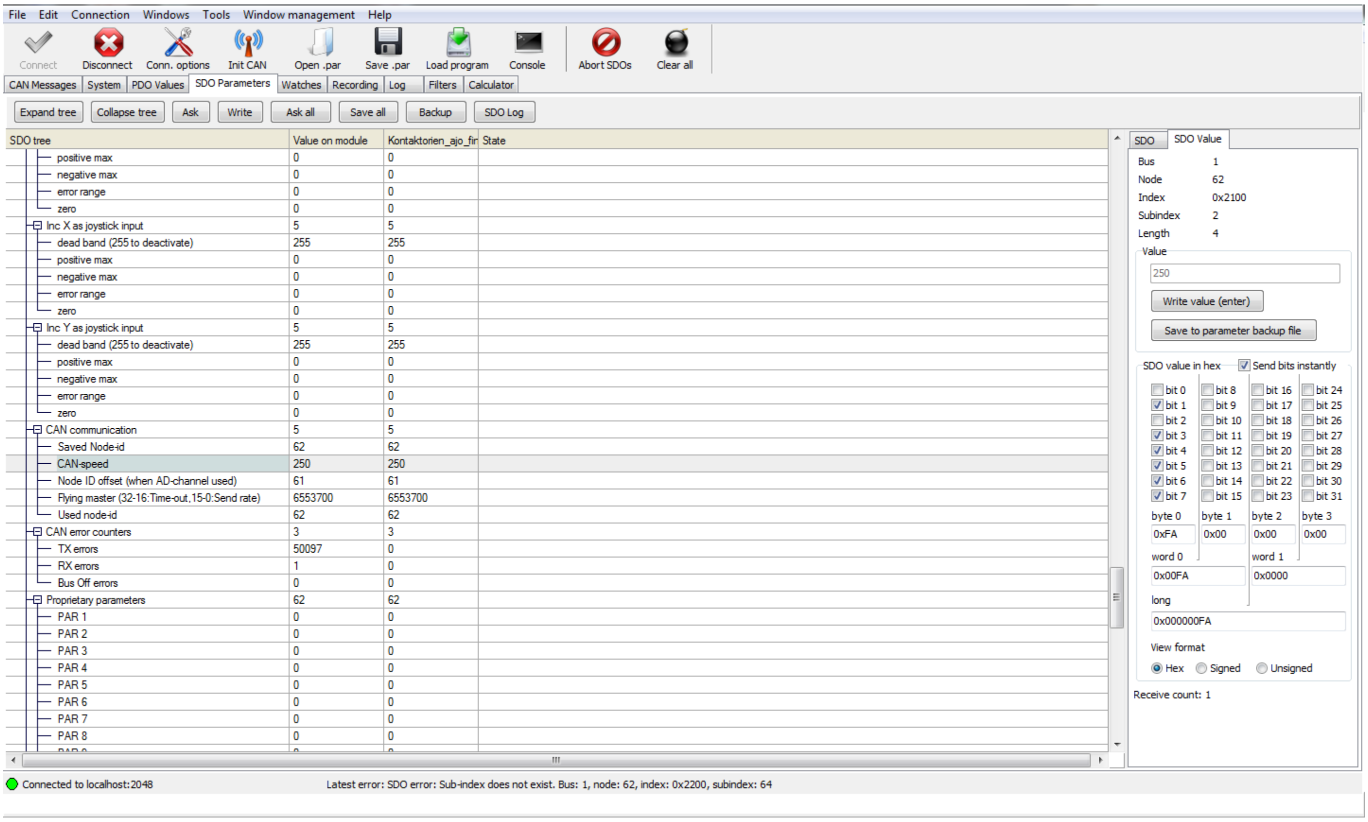
```
------------------------------------------------------
SIMTARGET Application ERA_BMS Thu Apr 04 18:54:31 2013
SIMTOOLS 5.2.0 B32 SIMTARGET 5.2.0 B18 SDK 5.0.1
------------------------------------------------------

    Task invocations:
         Rx_Block: 100
         Read_cell_temperatures: 99
         Poll_node_ID: 100
         Read_Cell_Voltages: 100
         IdleTask: 382

    Base rate task sync state: Sync
    Base rate task step size: 0.001s

    AverageCellTemperature: 169
    MinCellTemp[C]:       14
    MinCellTempID:      133
    MaxCellTemp[C]:       18
    MaxCellTempID:       75
    IDs not found:        0
    ID_polling_timer[s]:        2
    NodeIDsReceived:        1
    13D40100_validity: 2
    13F40100_validity: 2
    14340300_validity: 2
    13D40400_validity: 2
    13F40400_validity: 2
    13D40500_validity: 2
    13F40500_validity: 2
    14140500_validity: 2
    14340500_validity: 2
    13D40700_validity: 2
    13F40700_validity: 2
    13D40600_validity: 2
    BatteryVoltage_Calculated: 360
```

Figure 21. TeraTerm -console program enables the observation of system parameters.

As shown in Figure 21, the minimum cell temperature has been 14 °C and the total battery voltage has been 360V during the system parameter observation. This tool is a very convenient way to check that Elektrobit6120 reads and calculated the different parameter values correctly especially if any part of the code has been changed during the software design.

3.3.2 Configuration of Exertus HCM3200 I/O -module

In order to control high voltage contactors the Exertus HCM3200 I/O -module had to be configured to obey orders sent by the BMS -master through the CAN -bus. The I/O module parameters are configurated with Canto2 software by using a special USB-CAN converter. The parameters are first defined in parameter file in Canto2 and then downloaded through the CAN -bus into the device. The I/O module is a CANOpen device and Canto2 software enables the user to configure the SDO and PDO parameters of the device. The parameter setup view of the Canto2 software is shown in Figure 22.



SDO tree	Value on module	Kontaktorien_ajo_fir	State
positive max	0	0	
negative max	0	0	
error range	0	0	
zero	0	0	
Inc X as joystick input	5	5	
dead band (255 to deactivate)	255	255	
positive max	0	0	
negative max	0	0	
error range	0	0	
zero	0	0	
Inc Y as joystick input	5	5	
dead band (255 to deactivate)	255	255	
positive max	0	0	
negative max	0	0	
error range	0	0	
zero	0	0	
CAN communication	5	5	
Saved Node-id	62	62	
CAN-speed	250	250	
Node ID offset (when AD-channel used)	61	61	
Flying master (32-16:Time-out,15-0:Send rate)	6553700	6553700	
Used node-id	62	62	
CAN error counters	3	3	
TX errors	50097	0	
RX errors	1	0	
Bus Off errors	0	0	
Proprietary parameters	62	62	
PAR 1	0	0	
PAR 2	0	0	
PAR 3	0	0	
PAR 4	0	0	
PAR 5	0	0	
PAR 6	0	0	
PAR 7	0	0	
PAR 8	0	0	

Bus 1
Node 62
Index 0x2100
Subindex 2
Length 4
Value 250

byte 0 0xFA
byte 1 0x00
byte 2 0x00
byte 3 0x00
word 0 0x00FA
word 1 0x0000
long 0x000000FA

Receive count: 1

Connected to localhost:2048

Latest error: SDO error: Sub-index does not exist. Bus: 1, node: 62, index: 0x2200, subindex: 64

Figure 22.   The parameter view of Canto2 software for HCM3200 I/O module.

As shown in Figure 22 there are many parameters to configure the setup of HCM3200 I/O module. However the most important parameters are *CAN -speed* (object 2100h, subindex 2) and *Output type selection* (object 2004h, subindex 3) due to the remote control of the contactor states. There are some built-in functions already inside the I/O module which makes the configuration a lot easier for the user. For example there is already a built-in function for controlling some outputs on and off with specific CAN -messages read by the I/O module. This kind of functionality was used also for Electric

RaceAbout in order to switch contactors on and off. It is also possible to program PLEX -programs to have more sophisticated functionality if there is no suitable built-in function in the module.

The I/O module was configurated to send heart beat signal every 100ms according to the CANOpen protocol and this is how the BMS -master knows that I/O module is awake during the operation of BMS -system.

The list of exact available parameters can be found from the CANopen profile list of HCM3200 I/O module. When the user has changed any parameter of the module, the values are saved into the module by clicking “save all” button in Canto2 software. In order to ensure that parameters are set right in the module one should check the refreshed value from the column called “Value on module” in Canto2 software. When this equals to the written parameter value, the value is stored correctly into the memory of HCM3200 I/O module.

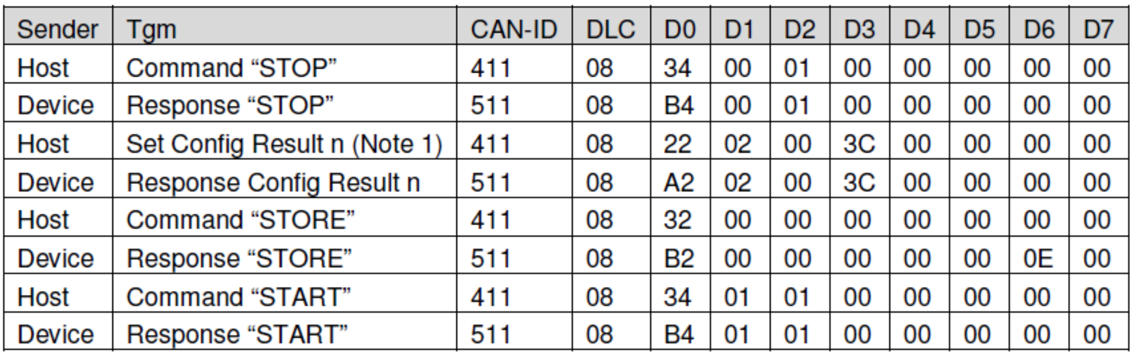
3.3.3 Configuration of Kvaser Eagle

The Elektrobit6120 microcontroller does not have any non-volatile memory on its own. This meant that the BMS -master was not able to store any counter values such as total energy counter or total charge counter after it had been powered off. The solution was to use the Kvaser Eagle CAN -bus data logger as a user-configurable device in order to store important data sent by the BMS -master. The Kvaser Eagle is configured with event-based t-script language. This means that the Kvaser Eagle reacts to different events which trigger some functionality. In Electric RaceAbout the Kvaser Eagle was configured to store the counter values sent by the BMS -master every second and just before the vehicle is powered off, the values are still into the non-volatile memory of Kvaser Eagle. When the vehicle is powered on again, the BMS -master requests the counter values from the memory and the Kvaser Eagle send the values back to the CAN -bus. Now the BMS -master is able to store the latest counter values and continue increasing or decreasing them depending on the situation. This is just one of the functions that Kvaser Eagle has and it can be configurated as the user wishes. This means that the data logger offers further development chances if needed.

The created t-script file for Electric RaceAbout can be found in Appendix D. This file is commented in order to guide reader to understand the script better. The script is saved in the folder that user wishes and it is compiled with the command line in Windows in order to produce a file called *filename*.txe. If any database files are used, they have to be added to the compilation order in the command line. After the script is compiled, the Memorator Tools -software is opened in Windows and the bms.kmc configuration file is opened. This file contains already all the necessary parameters for the Electric RaceAbout. After initialization of the memory card, the new compiled t-script is browsed in the script section of the software and after this the file is downloaded into the memory of the Kvaser Eagle through the USB -cable. After downloading the configuration file into the Kvaser Eagle the device is ready to be used in the vehicle. All the exact compilation orders of the t-script are kept inside the Electric RaceAbout team.

3.3.4 Configuration of IVT-MOD Module

The IVT-MOD sensor is able to measure current and voltage values cyclic with user-defined interval when correct settings are first performed. The configuration method of the sensor is very simple and it was carried out via the CAN-bus. Basically the only change to the default sensor configuration was to adjust the cyclic rate, which determines the interval how often the sensor sends the wanted information to the CAN-bus. This chapter introduces how the measurement interval of the second voltage measurement channel (U2) was changed to 60 ms. The same procedure is repeated everytime when some settings are done. The setup session is shown step by step in Figure 23.



Sender	Tgm	CAN-ID	DLC	D0	D1	D2	D3	D4	D5	D6	D7
Host	Command “STOP”	411	08	34	00	01	00	00	00	00	00
Device	Response “STOP”	511	08	B4	00	01	00	00	00	00	00
Host	Set Config Result n (Note 1)	411	08	22	02	00	3C	00	00	00	00
Device	Response Config Result n	511	08	A2	02	00	3C	00	00	00	00
Host	Command “STORE”	411	08	32	00	00	00	00	00	00	00
Device	Response “STORE”	511	08	B2	00	00	00	00	00	0E	00
Host	Command “START”	411	08	34	01	01	00	00	00	00	00
Device	Response “START”	511	08	B4	01	01	00	00	00	00	00

Figure 23. Configuration of measurement interval in IVT-MOD

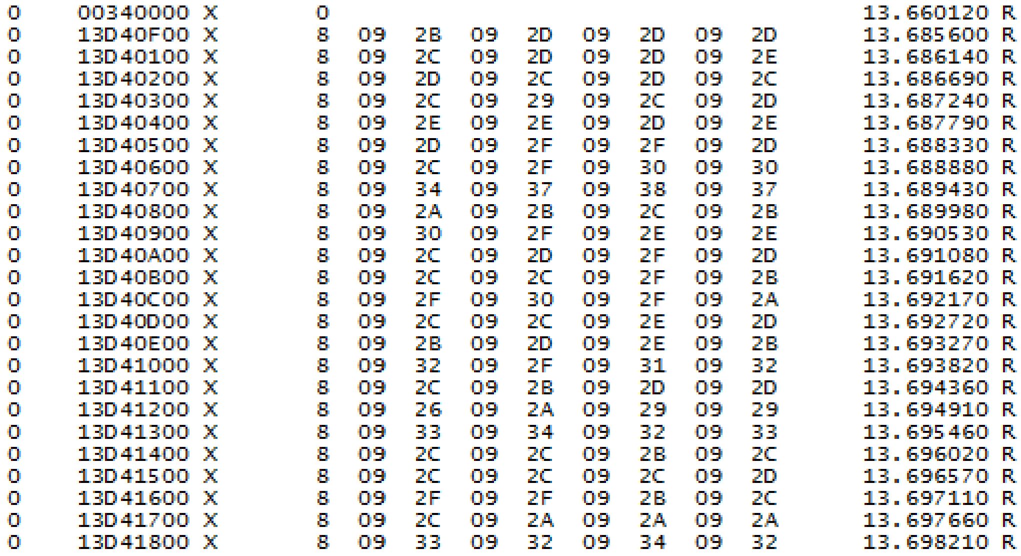
As shown in Figure 23, always when the host sends something for the sensor, the sensor confirms the changes. Figure 23 shows detailed how the interval of U2 channel in the IVT-MOD sensor was changed to send information cyclic every 60 ms. First when the device is powered up, the host device (for example a data logger) sends a stop command. The sensor answers that it was stopped. Then the host sets the interval to 60 ms (3C in fourth data byte section) for the U2 channel (22 in first data byte section). After that the sensor confirms again the settings. Next comes the storing phase, where host stores the settings and correspondingly the sensor responses that everything was stored. At last the host starts up the sensor in measurement mode and again the sensor confirms that. All the exact meanings for individual CAN-commands and bytes are introduced in the special document of the IVT-MOD sensor and this document is kept inside the Electric RaceAbout -team. However the configuration method was clearly introduced in the Figure 23.

3.4 Communication with Slave Cards

It was necessary to figure out the communication between the BMS -master and the slave cards in order for the software development to be started. This was carried out by logging the internal CAN -bus between the BMS -master and the slaves. From the log files it was quite easy to draw conclusions of which CAN message IDs were carrying the information of cell voltages and cell temperatures. This was still maybe the most difficult part of the study because already in the beginning it was noticed that BMS -master started to lose some CAN -frames which included important information. This led to the research work with the manufacturer who reported that the problem was caused by internal bugs in the provided code blocks. However these problems were solved together with the support by Simtools GmbH.

Appendix F shows the complete CAN -matrix that points out all the cell voltage and temperature CAN -message IDs and their signals. Furthermore some control messages in order to blink LED -lights of slave cards, balance the cells and to send a freeze command which takes samples of the cell voltages and temperatures have been listed in the same Appendix F. However this appendix is not shown in the public version of this thesis in order to keep the knowledge inside the Electric RaceAbout team. By using these commands the BMS -master is able to supervise all the 286 cell voltages and 144 cell temperatures in the battery pack through the CAN -bus.

Figure 24 below shows a short communication interval between the BMS -master and the slave cards.



```
0    00340000 X      0                                          13.660120 R
0    13D40F00 X      8   09   2B   09   2D   09   2D   09   2D   13.685600 R
0    13D40100 X      8   09   2C   09   2D   09   2D   09   2E   13.686140 R
0    13D40200 X      8   09   2D   09   2C   09   2D   09   2C   13.686690 R
0    13D40300 X      8   09   2C   09   29   09   2C   09   2D   13.687240 R
0    13D40400 X      8   09   2E   09   2E   09   2D   09   2E   13.687790 R
0    13D40500 X      8   09   2D   09   2F   09   2F   09   2D   13.688330 R
0    13D40600 X      8   09   2C   09   2F   09   30   09   30   13.688880 R
0    13D40700 X      8   09   34   09   37   09   38   09   37   13.689430 R
0    13D40800 X      8   09   2A   09   2B   09   2C   09   2B   13.689980 R
0    13D40900 X      8   09   30   09   2F   09   2E   09   2E   13.690530 R
0    13D40A00 X      8   09   2C   09   2D   09   2F   09   2D   13.691080 R
0    13D40B00 X      8   09   2C   09   2C   09   2F   09   2B   13.691620 R
0    13D40C00 X      8   09   2F   09   30   09   2F   09   2A   13.692170 R
0    13D40D00 X      8   09   2C   09   2C   09   2E   09   2D   13.692720 R
0    13D40E00 X      8   09   2B   09   2D   09   2E   09   2B   13.693270 R
0    13D41000 X      8   09   32   09   2F   09   31   09   32   13.693820 R
0    13D41100 X      8   09   2C   09   2B   09   2D   09   2D   13.694360 R
0    13D41200 X      8   09   26   09   2A   09   29   09   29   13.694910 R
0    13D41300 X      8   09   33   09   34   09   32   09   33   13.695460 R
0    13D41400 X      8   09   2C   09   2C   09   2B   09   2C   13.696020 R
0    13D41500 X      8   09   2C   09   2C   09   2C   09   2D   13.696570 R
0    13D41600 X      8   09   2F   09   2F   09   2B   09   2C   13.697110 R
0    13D41700 X      8   09   2C   09   2A   09   2A   09   2A   13.697660 R
0    13D41800 X      8   09   33   09   32   09   34   09   32   13.698210 R
```

Figure 24. Short communication interval between BMS-master and slave cards

As shown in Figure 24, the BMS -master sends the CAN -message ID 0x00340000 (29-bit extended format) with zero payload in order to poll the information from the slave cards. This CAN -message ID is so called *freeze command* that will reach all the slave cards at the same time in the CAN -bus. After the slave cards have received the freeze command, they will take a sample of the cell voltages and temperatures which they measure. The slave cards send the measurement results back to the CAN -bus in 0.1 second. The *freeze command* is sent once a second by Elektrobit and this means that the BMS -master has 0.9 seconds time to read the values from the CAN -bus.

From Figure 24 it can be seen that the returned CAN -messages by the slave cards are in 13D4*xx*00 format, where *xx* means the slave card ID in hexadecimal format. The message payload consists of eight bytes. One cell voltage is written in 16 bits which means that in one CAN -message there are four cell voltages according to the full payload. When considering that the bytes are in the Motorola order, it can be noticed that the first two bytes inform the cell voltage to be 092B in hexadecimal format and converted to decimal it means 2347 mV. The next cell is 092D in hexadecimal format and respectively converted decimal value is 2349 mV. The rest of the communication messages between the BMS -master and the slave cards are shown in the confidential Appendix F and this file is available only for the Electric Raceabout team. Only the principle is shown here. By understanding the communication method between the BMS-master and the slave cards it was a good start to form a base for the software development.

The Chapter 3 introduced the design of the new modular BMS -system in Electric RaceAbout. All the submodules of the system were introduced and the methods how to configure the user-configurable devices were shown. The next chapter covers the system control functions and mainly the ideas behind them. These functions bring the intelligence to the system in order to keep the battery in safe operating area as discussed in Chapter 1.1.

4 Ideas behind Control Algorithms

This chapter introduces the main ideas behind the system control algorithms which were implemented in the new battery management system during the study. It will also touch on the theoretical improvements which could be done in order to determine the state of the battery even more accurately. However these improvements would need a lot of battery measurements and testing which was out of scope in the study.

The Chapter 4.1 begins by introducing the internal resistance of a cell and shows how difficult it is to define its exact value due to its dynamical character. With the help of internal resistance Chapter 4.2 introduces the electrically equivalent circuit model for the battery in simple and more complex form. In Chapter 4.3 is shown how the simple circuit model was used in order to calculate the open circuit voltage of the cells which enables to use voltage translation method for determining the SOC -level for the cells. As an improvement the Coulomb counting method, which is discussed in Chapter 4.4, is combined with the voltage translation method and thus the SOC –calculation becomes more accurate. As a result the use of the combined technique is represented in Chapter 4.5. Finally Chapters 4.6 and 4.7 cover the battery balancing method and discusses the dynamical battery current limit calculation method respectively.

It is crucial to understand that all the battery parameters such as SOC, DOD, cell resistance and cell capacity are rough estimates because in real life they change in function of multiple factors. This makes the battery estimation a very complicated task.

4.1 DC Resistance of the Battery Cells

The control functions in Elektrobit6120 were designed to take into account the effect of the internal resistance of the cells. Usually battery manufacturers announce the AC impedance for the cells which is useless for the user. The cell resistance is really DC resistance because the direct current flows through the cells. There are many applications where this parameter is utilized. One of them is the energy efficiency calculation of the battery, which is covered in this chapter. Furthermore, the concept of the open circuit voltage calculation is based on the information of internal resistance. This concept is covered in Chapter 4.3. Some BMS -systems calculate the state of health value

(SOH) for the battery which is also partly dependent on the internal resistance. However this calculation was not implemented into the new BMS -system.

As an example, the battery efficiency in Electric RaceAbout is calculated in order to show that the internal resistance really matters when dealing with large traction batteries. The battery efficiency indicates the percentual part of the energy which can be used from all the energy in the battery in order to do work. The internal resistance wastes energy into the heat in form of I^2R which makes the battery warm and even hot on the race track. From the equation it can be seen that the lost energy is proportional to the cell current and thus the lost energy increases when the cell current increases. In Electric RaceAbout the internal resistance of a cell is nominally 0.55 mΩ [Appendix C] which means that the total resistance *R* of the battery pack with configuration 143s2p is:

$$R = \frac{R1 * R2}{R1 + R2} = \frac{143 * 0.00055\Omega * 143 * 0.00055\Omega}{143 * 0.00055\Omega + 143 * 0.00055\Omega} = 0.039325\Omega$$

When the terminal voltage of the battery is 330V and the drawn current is 1000A the delivered power by the battery is:

$$P\mathrm{bat} = U\_terminal * I = 330V * 1000\,A = 330\,kW$$

With the same 1000A current the battery wastes heat:

$$P = I^2R = 1000^2 * 0.039325\Omega = 39325\,W \approx 40\,kW$$

This value equals almost seven medium-sized 6kW sauna stoves. With these two values the efficiency of the battery can be calculated:

$$Eff_{bat} = \frac{Delivered\ battery\ power - wasted\ power}{Delivered\ battery\ power} * 100 = \frac{330kW - 40kW}{330\,kW} * 100$$

$$\approx 87\ \%$$

According to the theoretical results the battery is very energy efficient even when the battery is used near its limits. It can be seen also that when the battery current is decreased down to 300A, the battery efficiency increases up to 96%.

During the study there was no time to develop an algorithm which would estimate the internal resistance of the cells. This kind of algorithm would need several battery tests and measurements in order to verify its reliability. For this reason a constant value of internal resistance for a cell was used in order to carry out the open circuit voltage calculations which have certain benefits for the system control. These benefits are discussed later in the study.

The constant value for the cell resistance was taken from the battery datasheet provided by the battery manufacturer in Appendix C. However, in real life this parameter is not constant because it changes in function of many factors like shown in the next chapter. Still by using the constant value from the datasheet it was the best approximation because any verified algorithms for the estimation of the internal resistance were not available.

4.2 Dynamic Internal Resistance

In real life the internal resistance is dynamic and it varies in function of many factors. In order to calculate the value of the dynamical resistance there must be a change in the current and voltage like represented in the following formula:

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

The dynamic resistance varies at least in functions of SOC, current, temperature and cycle life. The direction of the current has also effect on this parameter. Theoretical graphs of internal resistance and its changes affected by the mentioned factors are shown in x-y planes in Figure 25.

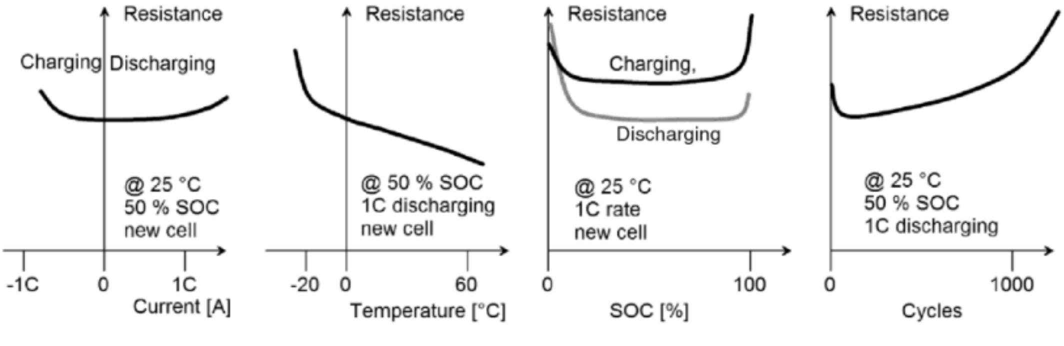


Figure 25. The dynamic resistance depends on many factors [12].

This reveals how many things have to be taken into account when estimating the internal resistance of the cells. However in the new BMS -system, like discussed before, the internal resistance was assumed to be a constant value provided by the battery manufacturer which is a much better estimation than having an incorrect algorithm estimating this parameter. In future the BMS -master will measure and estimate the cell resistances by taking account some of the changing parameters which were shown in Figure 25. However, this needs precise battery testing which was out of scope during this study.

4.3 Electrical Equivalent Circuit for Battery

The most intuitive way to understand the battery behaviour is to observe it with the electrical equivalent circuit of the battery. A simple circuit of the battery is shown in the Figure 26. This model was used in the new BMS -system in order to calculate the open circuit voltage of the maximum and minimum cell voltages.

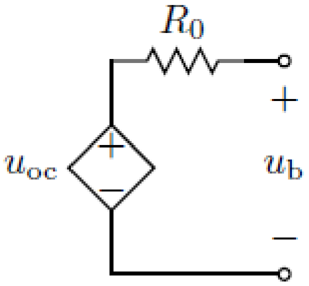


Figure 26. Simple battery model with internal DC resistance.

The parameter u_{oc} in Figure 26 describes the open circuit voltage of the battery. The parameter R_0 is the internal DC resistance and the u_b is the terminal voltage of the battery. The terminal voltage is the one that the BMS -system is able to measure directly. When the current flows out of the battery, the terminal voltage has a little bit lower potential compared to the open circuit voltage. This is caused by the internal resistance which produces a voltage drop when the current is flown through it. Correspondingly when the battery is charged and the current flows into the battery, the terminal voltage is a little bit in higher potential compared to the open circuit voltage because the internal resistance produces again the voltage drop but now in the opposite direction because the current flow is reversed. When the current is zero, the open circuit voltage is the same than the terminal voltage because there is no voltage drop over the resistor.

In the new BMS -system the open circuit voltage of the minimum and maximum cells was calculated in order to estimate the SOC -value of the battery. The SOC -calculation method, based on the voltage translation, is discussed in Chapter 4.5. Knowing the open circuit voltage of the cells can also speed up the charging process. This is shown in Chapter 4.4 where the IR –compensation method is discussed.

The drawback of the simple battery model is that it does not describe the electrical inertia that slows down the changes in the cell voltage. In real life after bringing the cell current down to zero, it takes time until the cell reaches its final open circuit voltage. This is called a relaxation time and it can be modelled with RC -networks added to the simple circuit model which was shown in Figure 26. Thus a more accurate battery model is shown in Figure 27.

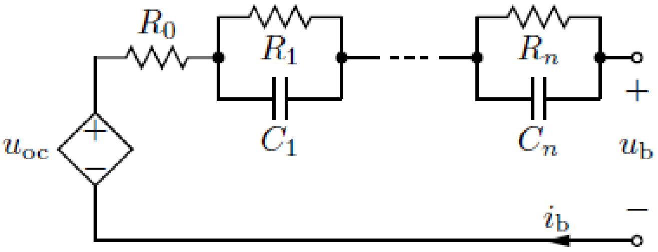


Figure 27. More accurate battery model.

The problem of this representation in Figure 27 is that the correct parameters have to be found out by testing the cells in different kind of test cycles. This was out of the scope during the study, but in future this kind of battery model can be parameterized by testing the battery cells in different kind of charging and discharging cycles.

By increasing the number of RC -networks in Figure 27 the battery model could be made more accurate but this demands more calculation power from the BMS -master.

In the new BMS -system the BMS -master was programmed to calculate the open circuit voltages for the minimum and maximum cell voltages by using the simple battery model that was shown in Figure 26. When the BMS -master calculates and controls the battery according to open circuit voltages, it does *IR -compensation.* The benefits of this compensation method are discussed in the next chapter.

4.4 IR -compensation during Discharging and Charging Process

Battery manufacturers provide fixed cut-off voltages for their batteries in order to stop the charging or discharging process when the limits are reached. These limits vary often according to the temperature of the battery. The recommended charge cut-off and discharge cut-off points for the batteries in Electric RaceAbout are shown in battery datasheet in Appendix C.

As shown in Figure 26 the internal resistance of a cell increases in function of the used battery cycles. Furthermore, it is shown that the capacity of a cell decreases in the function of same cycles.

It is also true that the loss of active material in the cells decreases the capacity of the cell but also increasing internal resistance has its own affect to the phenomenon. That is, the most of the “lost capacity” is just apparent and can be corrected by IR-compensation method which means that the BMS -master analyses the open cell voltages instead of terminal voltages. In order to do this, the BMS -master must know all the time the resistance of the cell which is not easy. The reason for this was shown already in Figure 25.

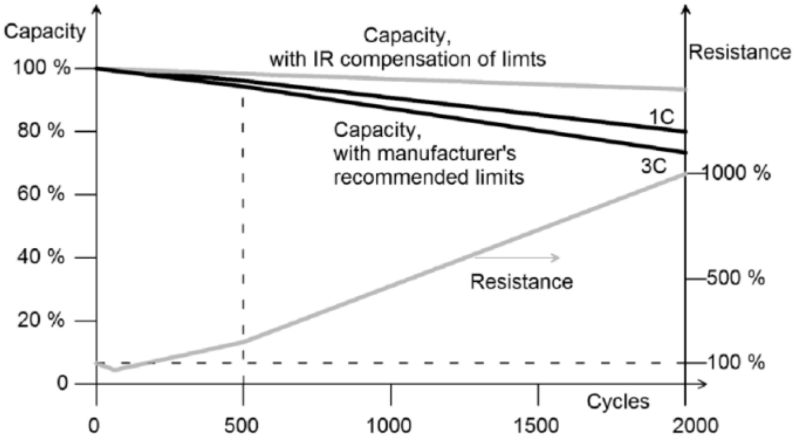


Figure 28. Increase of resistance has a relation to decreased capacity [12].

The reason for the apparent loss of capacity results from fixed cut-off voltages which are used in control algorithms. When the charging and discharging processes are supervised according to terminal voltages without taking into account the effect of increasing internal resistance the charging process will be stopped too early and respectively discharging process will be stopped also too early. After hundreds of cycles the terminal voltage of a cell reaches the lower and upper fixed cut-off points much more earlier compared to a cell that has gone through just tens of cycles. This leads to the apparent losses. As a solution the IR -compensation can be used in order to estimate the open circuit voltage of a cell. For the mentioned reasons at the beginning of this chapter the open circuit voltage is the best indicator of battery state during the charging or discharging processes. This gives a better sense for the BMS -system.

The fixed cut-off voltages should be taken as recommended open circuit voltages of the cell. The exact fixed cut-off points which take account the internal resistance and the battery current of the cell, can be calculated in the following way:

Charging stop point:	Fixed terminal voltage by manufacturer + IR compensation
Discharging stop point:	Fixed terminal voltage by manufacturer + IR compensation

Because the direction of the current is different for the charging process compared to discharging process, the equations are dependent on the sign of the current.

In these equations it is assumed that discharging the battery represents the negative cell current and charging the battery represents the positive cell current.

Another way to measure open circuit voltage is to measure directly the cell voltage when no current is flowing. As discussed in Chapter 4.3, in this case the open circuit voltage equals the terminal voltage. However the measurement cannot be done for a while after the current has been reduced to zero. This is because the battery is taking the *relaxation time* until the cell reaches its final open circuit voltage. This can take up to half an hour which means that the IR -compensation is by far the most preferred way to estimate the open circuit voltage.

As a further benefit the IR -compensation can speed up the charging process when a CCCV charging profile is used. This can be seen in Figure 29.

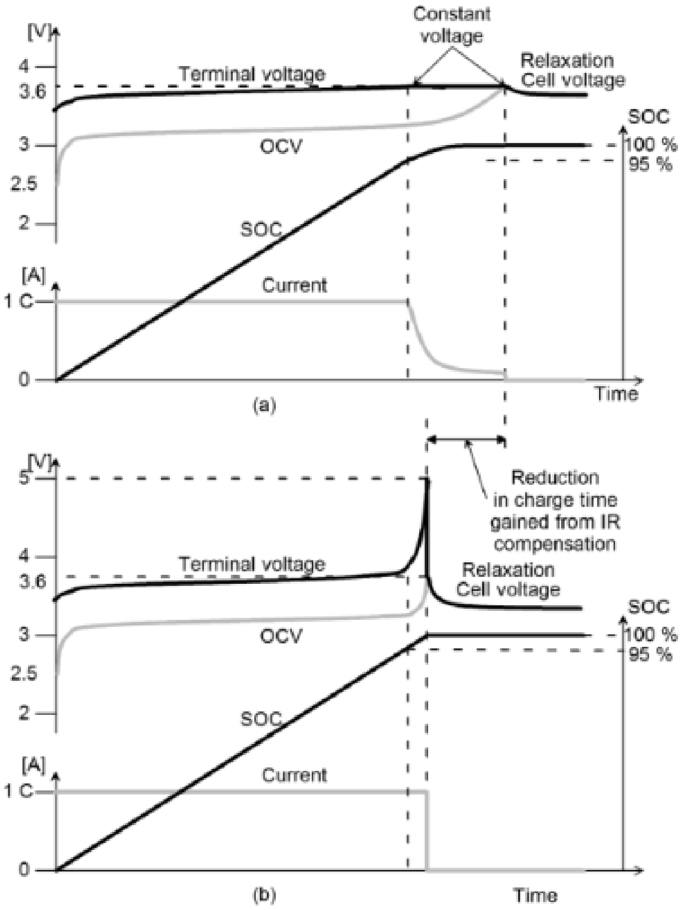


Figure 29. Reduced charging time when IR -compensation is utilized [12].

From the Figure 29 it can be seen that the IR –compensation method makes the constant current stage longer during the CCCV charging process. This saves time because the battery is charged up with constant current until the open circuit voltage of the cell reaches the fixed cut-off point.

Correspondingly when the battery is discharged, the BMS -master estimates the open circuit voltage of the cells and the battery is totally discharged when the lowest open cell voltage reaches the lower cut-off point set by the designer. Without the IR -compensation the BMS -master would stop the discharging process too early which would mean that after the current would be reduced down to zero the terminal voltage would still indicate that the battery could be discharged.

In summary the open circuit voltage calculation in the new BMS -system was used to utilize all the available energy from the battery pack without interrupting the discharging or charging process too early according to the misleading terminal voltage. Furthermore, the charging process was made a little bit faster because in CCCV -charging profile the constant current phase could be made longer. The open circuit voltage was also partly used to determine the SOC -level for the cells and thus also for the battery in order to indicate how much charge in the battery is able to be used. The SOC -calculation method is introduced in the next chapter.

4.5 SOC Estimation

The SOC estimation gives an indication of how much longer the battery can be used before it has to be charged up again. As an analogy to combustion engine vehicles it represents the fuel gauge in electric vehicles. Mathematically the SOC -level of a cell can be determined with formula:

$$SOC\_cell\ [\%] = \frac{Available\ charge\ in\ the\ cell}{Nominal\ capacity\ of\ the\ cell}$$

If we have a 50Ah cell which has 30Ah charge left to use, more quantitatively it can be expressed that the SOC -level of the cell is:

$$SOC_{cell}[\%] = \frac{30\ Ah}{50\ Ah} = 60\%$$

This means that the cell has 60 % charge left before it has to be charged up again. The cell SOC -level should not be mixed up with the battery SOC -level. The difference between these two is discussed in the Chapter 4.6 which covers also the cell balancing.

The problem with the SOC -parameter is that it cannot be measured directly. This makes a big difference compared to combustion engine vehicles because there is a separate sensor which senses the fuel level in the tank and thus the available energy is much more easier to determine. However in electric vehicles such as Electric Race-About the SOC -value is only an estimation which means that in the best case the SOC determination is science and in worst case it is just a wild guess. That is, due to changing battery parameters there are no way of having precise SOC -value at any time.

In the study the SOC -estimation was based on two methods. These two methods were voltage translation method and Coulomb counting method. The combined use of these two methods is shown in Figure 30. This figure represents the characteristic curve for lithium -ion based cells.

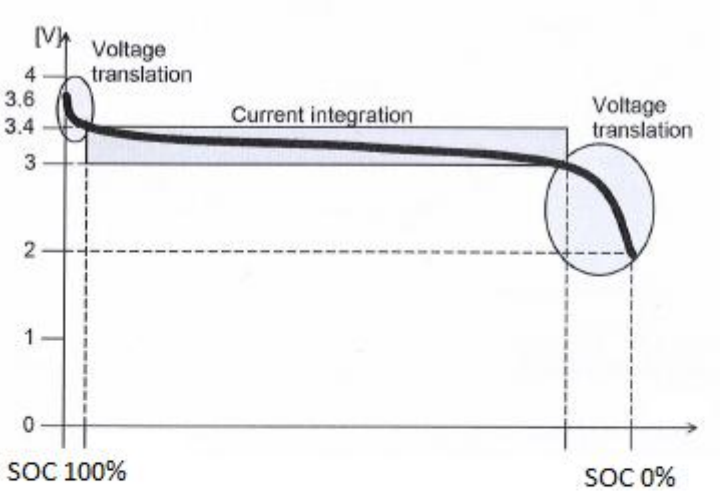


Figure 30. OCV vs SOC curve for Lithium-ion based cells [12].

Like shown in Figure 30, the open circuit voltage versus SOC -curve is very steep in both ends of the SOC -spectrum. The SOC -value can be found out from these parts of the curve by calculating the open circuit voltage of the cell and converting it to the right SOC -value with the help of a look-up table. This look up-table is created by the designer after having a supervised discharge cycle where a test cell is discharged from the upper fixed cut-off point down to lower fixed cut-off point. Another way is to try to have this information straight from the battery manufacturer. In the both ends of the curve a small change in SOC -axis produces a big difference in OCV -axis because the differential coefficient is very big compared to the flat part of the curve between these areas. This is why the open cell voltages can be converted easily to the SOC –value, which is quite good estimation. However like discussed above, this works only in the both ends of the curve. The flat part of the curve is very bad area to use voltage translation because the differential coefficient is very small.

As a solution the Coulomb counting method was used in this area. In Coulomb counting method the current is integrated in respect to time in order to calculate the relative value of the charge of the cell. This requires that the BMS -master knows all the time the initial DOD of the cell before it increases or decreases this value. The DOD means depth of discharge which tells how much the cell is already discharged. By knowing the the capacity of the cell, the DOD -value can be converted into SOC -value.

As an example it is considered a cell that has a capacity of 50Ah. The BMS -master knows that the initial DOD -value of the cell is 15 Ah. Now the cell is discharged by 10Ah more. With this information the SOC -level of the cell can be determined in the following way:

$$SOC_{cell} = \frac{Cell\ capacity - initial\ DOD - DOD}{Cell\ capacity} * 100 = \frac{50Ah - 15\ Ah - 10\ Ah}{50\ Ah} * 100$$

$$\approx 50\ \%$$

This means that the BMS -master has to know all the time the DOD -value of each cell in the battery. Furthermore it has to know the capacity of each cell in order to calculate the SOC -level for every single cell.

However like discussed in Chapter 2.6 there is always error in the current measurements despite the sensor that is used during the measurement. With Hall -effect sensors this error is mainly caused by the electrical offset and with shunt resistor based sensors the error is caused by the temperature drift. Although these errors are compensated with internal electronics and algorithms in the sensors, a small error in current measurement causes still a remarkable error in SOC -estimation over the long time. This error is shown in Figure 31.

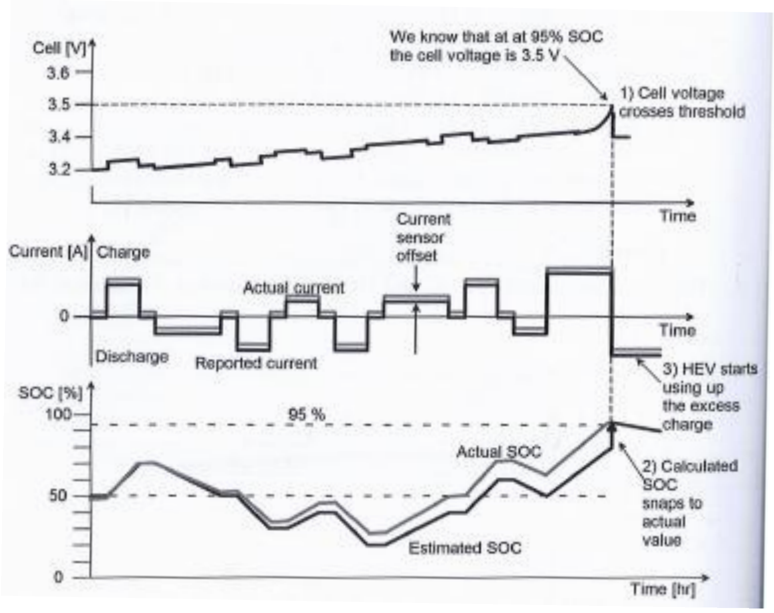


Figure 31. SOC drifting caused by offset in the current sensor [12].

For this reason, the BMS -master needed a way to fix the error when possible. By including certain voltage threshold points into the SOC -calculation algorithm the errors caused by the sensor offset was compensated in these points. In Figure 31 the SOC -value error has increased a lot over the time and when the cell voltage reaches the threshold point the BMS -master sets the cell SOC automatically to the right value which is based on the OCV vs SOC curve discussed in the beginning of this chapter.

This means that mainly the SOC -calculation was based on Coulomb counting but OCV vs SOC -curve information was used to compensate the errors caused by the current sensor.

4.5.1 Cell SOC versus Battery SOC

So far this this thesis has introduced how the SOC -value of a single cell was determined with the combined technique of Coulomb counting method and open cell voltage translation method. However the battery pack consists of several cells and each of the cells has different capacity although the battery manufacturer would announce the nominal capacity to be some exact value. In the case where the battery would be balanced at the top, the cells which are connected in series would be discharged in different rates due to the differences in their capacity. This comes from the fact that the discharge rate of the cells, which are connected in series, is a function of the cell capacity because all the cells in this string see the same current.

That is, when the battery is discharged, the cell that has lowest capacity will be discharged down to the lower fixed cut-off point in shortest time. This cell determines the battery capacity which can be used in order to calculate the SOC -value for the battery. One must keep in mind that this case is only when the battery was balanced before the discharge cycle was started. The way how the battery is balanced in Electric Raceabout is discussed in Chapter 4.6.

In the real world the battery will be almost always unbalanced which means that the SOC -levels of the cells are at different levels between individual cells. Because of the different SOC -levels between the cells, there will be two different cells which will determine the capacity of the battery. The first cell that reaches the upper fixed cut-off point defines the SOC 100% -level and correspondingly the first cell which reaches the lower fixed cut-off point defines the SOC 0% -level. The charge which flows out of the battery when the battery is discharged from 100% down to 0% will determine the battery capacity. Naturally the unbalanced battery has a lower capacity than compared to the balanced battery.

By converting the DOD -value of the battery into the SOC -value according to the formulas in Chapter 4.5, the SOC -level of the battery could be determined. This gives the estimated information for the driver how long one can drive before the vehicle has to be charged up again.

The way how the balancing method was designed in the study is discussed in the next chapter.

4.6 Final Voltage Based Cell Balancing

Due to differences in self-discharge currents between individual cells, the battery gets imbalanced over the time like discussed in Chapter 4.5. This phenomenon is not dependent on the cell resistance or cell capacity. It is only dependent on the variation of the cell leakage between the cells.

The balancing is used in order to bring the SOC -levels of the cells closer to each other when the battery is imbalanced. This maximizes the usable capacity of the battery. However, Lithium- ion based cells have a very low self-discharge current rate which means that the balancing is not necessary very often.

The battery pack in Electric RaceAbout consists of 286 cells. The configuration is 2p143s which means that there are two parallel strings of cells and in both strings there are 143 cells connected in series. In the case of this kind of series connections the first cell that reaches the lower fixed cut-off point during discharging, will be the limiting factor of the battery. Although the other cells in the same cell string could be discharged more, the same current flows through the weakest cell and it would be discharged more. This would under discharge the battery and bring it outside the SOA which is not acceptable.

Correspondingly when the battery is charged up, the cell that reaches the upper fixed cut-off point at first, will determine when the battery is fully charged. Although the other cells in the string could accept more charge, the same current would charge the most charged up cell and it would be over charged. This would also bring the battery out of SOA which is not acceptable.

In imbalanced battery these two cells will determine the capacity of the battery like discussed in the previous chapter. In very imbalanced battery, the usable energy will be very low and the battery becomes almost useless because both ends of the limits will be reached very soon.

As shown in Chapter 4.5, in Figure 30 the OCV versus SOC -curve is very steep when the cell is almost fully charged up. This is the place where the balancing takes place if needed. This is because the comparison between the cells is very easy to make in this area according to the OCV of the cells. Ideally the same OCV voltage represents the same SOC -level between different cells in the battery. In real life all the cells do not have the same nominal capacity although they are sold with some specific nominal capacity by the battery vendor. This means that there are tiny differences in the SOC -levels between the cells even if they have the same OCV. However it is precise enough to estimate that the SOC -levels equal between the cells if they have same open circuit voltage at the top end of the OCV vs SOC –curve.

The balancing process in theory is shown in Figure 32.

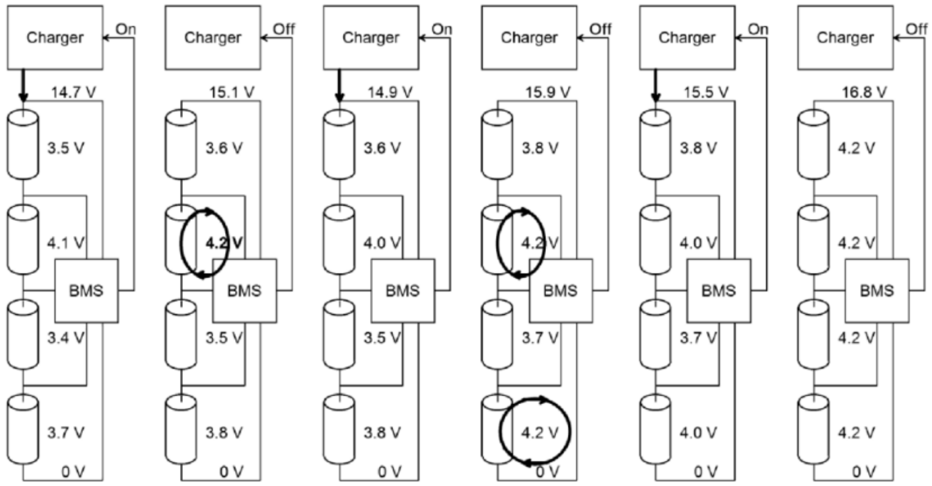


Figure 32. BMS balances battery cells [12].

As shown in Figure 32, there are four cells are connected in series and the battery management system supervises their cell voltages. During the charging process, the second cell of the series connection reaches its upper fixed cut-off point earlier than the other cells in the string. The other cells could be charged up more, but then the second cell in the string would be over charged. By connecting a resistor in parallel with the cell, it can be discharged without discharging the other cells. Now the cell voltage drops down to 4.0 volts which means that the charger can be turned on again. After a while the two of the cells in the string reach their upper fixed cut-off points which means that the balancing is started again in order to discharge these two cells. By charging and balancing one after another, all the cells will be balanced and they will all reach the 4.2V which means that their SOC -levels are balanced. This has maximized the energy which has been charged up into the battery.

This method is called top -balancing because the cells are in balance when they are fully charged. Like mentioned many times before in this thesis, after the battery is balanced, the cell with the lowest capacity will determine the battery´s capacity.

The resistors, which are used to discharge the cells, are placed on the slave cards which measure directly the cells. These resistors are shown in Figure 33.

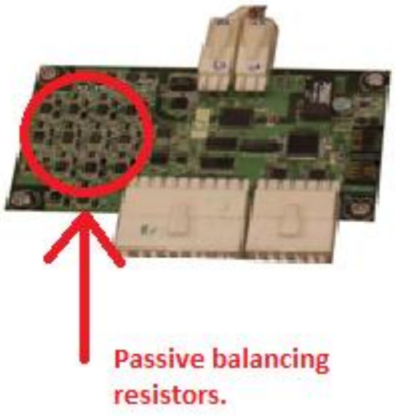


Figure 33. Resistors on the slave card which are used for passive balancing.

As shown in Figure 33, there are 16 resistors on the circuit board because each slave card is able to measure 16 cells. The way of balancing the battery with this kind of method is called *passive balancing*. During *passive balancing* the resistors will convert the electrical energy from the cells into the heat. In theory this heat could be used to heat the battery pack in colder weathers.

The resistors are connected in parallel with the cells by controlling transistors on the circuit board. The control of transistors is carried out with CAN -messages by the BMS -master.

The balancing was designed to be started in the end of the charging profile if the maximum cell voltage was 100mV higher compared to minimum cell voltage. By balancing the battery according to this rule, the maximum energy in the battery pack was utilized in Electric RaceAbout.

4.7 Battery Current Limitation

The battery current limitation was produced with a dynamic I^2t -algorithm. This algorithm is based on the battery current value and the time. The battery manufacturer has defined that the battery can deliver a 10C current for 10 seconds before the battery current has to be limited. The 10C current means 1000A current because Electric RaceAbout uses two 50Ah cell strings in parallel. The BMS -master compares the nominal current limit (600A) to the flowing current every 10 ms. Because the maximum current for the battery is 1000A, the difference between nominal current limit is 400 A. The maximum I^2t value was derived by using this 400A current difference in order to find the right limit value for the I^2t counter. The time variable in the following formula is 1000 because 10s is 1000 *10ms and the counter runs every 10 ms.

$$I^2t = (400A)^2 * (1000) = 160000000 = 160 * 10^6$$

According to the formula above, when the counter limit value reaches $160*10^6$, it means that a 1000A current has flown 10 seconds and the battery current limitation has to be started. The limitation works also for bigger currents but then the counter value will be reached earlier. This makes the algorithm dynamic.

The Figure 34 shows the more intuitive description of the I^2t -algorithm.

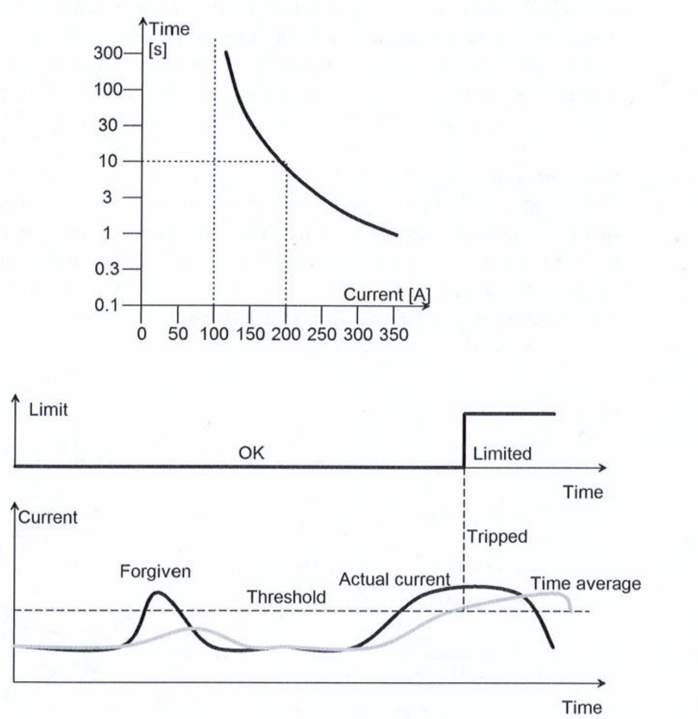


Figure 34. The I2t – algorithm forgives short over current peaks [12].

As shown in Figure 34, the first over current peak is forgiven because it is very short in time which means that the counter value does not reach the counter value limit although the current is bigger than allowed. However, the next over current peak is much longer in time which causes the over current limitation to be activated. In this case the counter value limit was reached.

5 System Test Results

This chapter covers the test results of the study. The tests were carried out in the Automotive Laboratory of Metropolia University of Applied Sciences. Due to the late delivery times of some system parts such as the IVT-MOD sensor, the system was not completely tested in stand-alone mode during the study. Furthermore, a lot of time was used in order to reprogram the BMS -master because already from the beginning of the study it was losing CAN -frames which caused a lot of trouble for the development of the system. These problems were related to internal firmware problems of the device. However, just before the deadline of the study the BMS -master problems were solved with the help of the manufacturer. This enabled to test the calculation capability and reliability of the new BMS -master in parallel with the old BMS -system. The results were good because the new BMS -master was able to determine exactly the same parameter values compared to the old BMS -master. Furthermore the new BMS -master was able to announce the identification numbers for the extreme cells. This helps the user to find the exact cells in the battery pack which differ significantly from the others.

In order to verify the functionality of the new BMS -master, Electric RaceAbout was tested on a dynamometer. This enabled to stress the battery with high currents such as 1000A in order to observe how the new BMS -master calculates and forwards the measurement data in such a wide measurement range for cell voltages and cell currents.

Figure 35 shows the test screen of the data logger which was used in order to visualize the data from the CAN -bus.

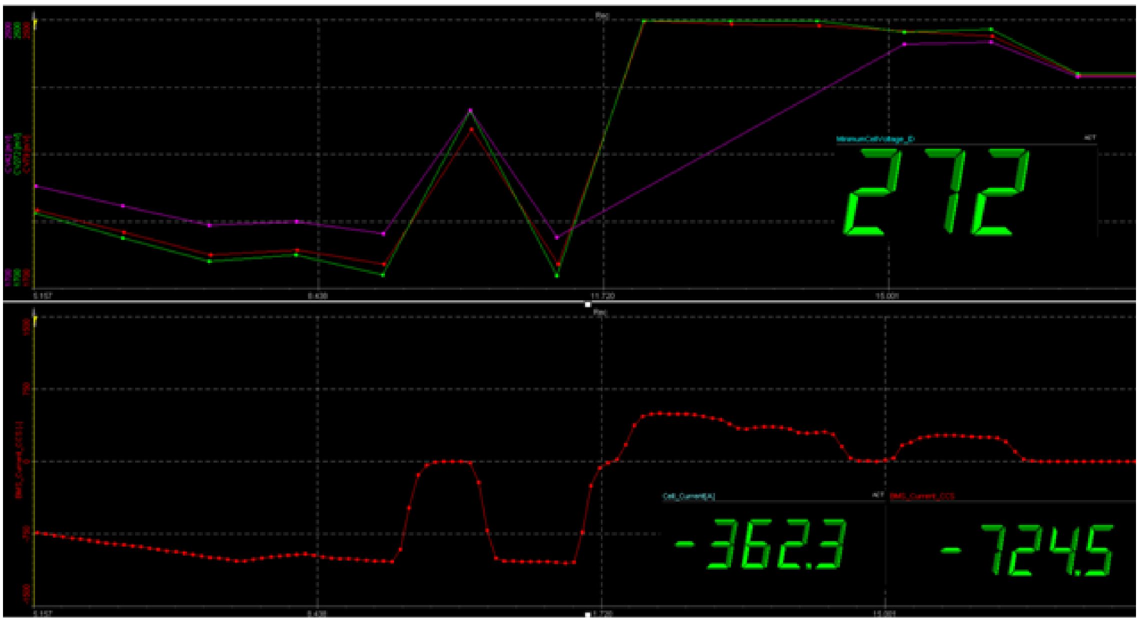


Figure 35. Three minimum cell voltages in respect of time during pulse current test.

In Figure 35 is shown three cell voltages in respect of time (upper graph). This data was read directly from the internal CAN -bus of the BMS -system where the slave cards reported their measurement results every second during the test accelerations. The current which flows through these cells is shown below this graph. In the cell voltage graph the digital number represents the ID -number for the cell which carries the minimum voltage at particular moment. Correspondingly the graph which represents the cell current has also a digital meter called *Cell_Current[A]* which shows the value of the cell current in decimal format. Another digital meter was added in order to represent the total battery current. This digital meter was named *BMS_Current_CCS*.

With these graphs the cell identification function was verified to work correctly. The number 272 shows the cell ID which carried the lowest voltage at that particular moment. This value was determined by the new BMS -master and it was sent to the CAN -bus where the data logger was able to receive that. The old BMS -system had a service tool that was used also to double verify that the new BMS -master calculated the IDs correctly. The results of the cell identification were correct because also the old BMS -master reported the same ID number at the same time. From the graph below it can be seen that the drawn current was over 360A at that time.

Another test view is represented in Figure 36 below.

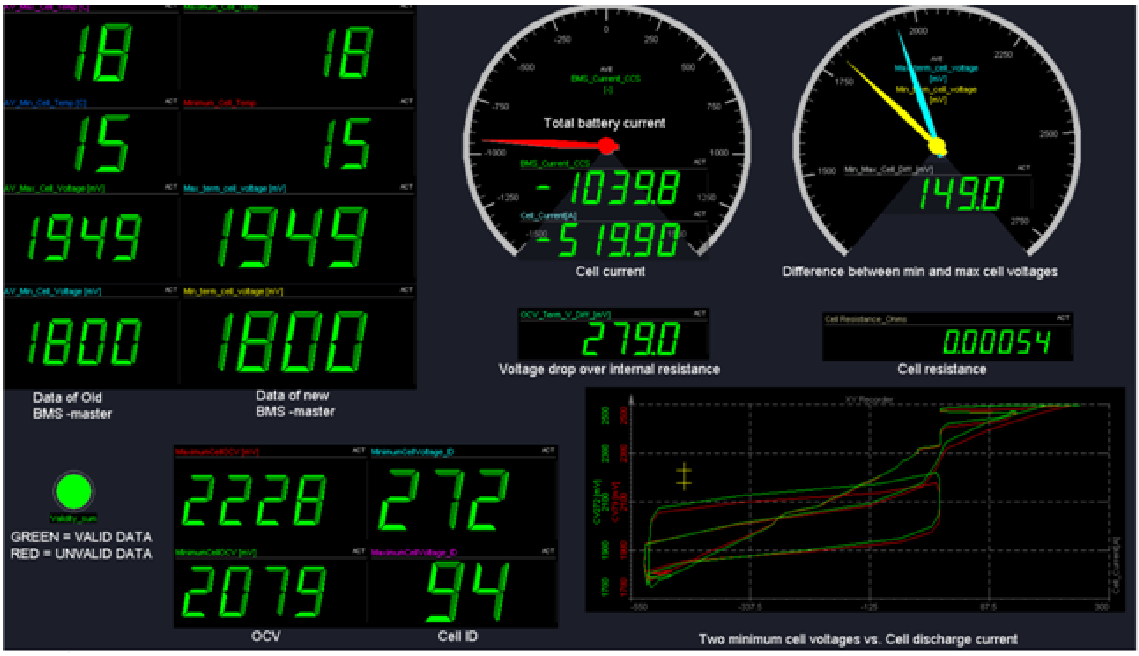


Figure 36. A different test view during the dynamometer test.

As shown in Figure 36, all the other values calculated by the new BMS -master equals to the values calculated by the old BMS -master. The new BMS -master reported the same maximum and minimum cell voltages and temperatures compared to the old BMS -system. Below this data is represented a green light which indicates whether the data from the slave cards is valid or not. During the dynamometer tests the light was all the time green which indicated the data to be valid. The OCV calculation seemed to work also because during the discharge process the OCV should really be a little bit in higher potential compared to the terminal voltage. The OCV was verified to be correct because the internal resistance value was also calculated correctly based on cell open circuit voltage, terminal voltage and the cell current. As shown in right side of the Figure 36, the internal resistance value was about 0.55 mΩ. This is the value which was used as a constant resistance value for the cells (obtained from the battery´s data sheet in Appendix C) when no better approximation was available. Next to the OCV calculation the minimum and maximum cell IDs are reported. These values are very important information when the weakest and strongest cells in the battery are searched at particular current profiles.

The graph in the lower right corner represents the two minimum cell voltages in respect to their discharge current. This way it was easy observe the behaviour of the cell differences in function of the discharge current and see how both of the cells responses to specific currents. However this observation must be seen as a play back of the measurements in respect to time which gives more information for the user.

The two last gauges represent the total battery current and cell voltage differences between the maximum and minimum cells. At the time when the maximum discharge current was present, the maximum cell voltage difference was 290 mV which means that it was easy to notice that the cell voltage of the weakest cell dropped a lot more compared to the strongest cell during the pulsing current up to 1000A. This gives a good intuition in order to notice that all the cells are really different although they are same products. Thus every cell has to be supervised individually.

Based on the measurement results it can be drawn a conclusion that the base measurements of the BMS -system work correctly. These base measurements are cell current, voltage and temperature measurements. The secondary calculations such as total charge and total energy counters were also verified to work correctly with the help of TeraTerm -console program. Due to a late delivery time of IVT-MOD sensor, it was not tested during the study.

During the system control tests the contactor control with Exertus HCM3200 I/O module was verified to work and the information of the contactor states were received correctly through the CAN -bus in real-time.

In summary all the system parts were tested separately and in parallel with the old BMS -system during the study but due to late delivery times of IVT-MOD sensor and problems with the Elektrobit6120 microcontroller, the complete test without the old system had to be done after the dead line of this Bachelor´s thesis.

6 Discussion and Conclusions

By making reverse engineering of the old system, measuring cells, configuring three microcontrollers and using fault-tolerant CAN-bus as a communication, a new proper BMS -system was designed and partly implemented into Electric RaceAbout during the study. There were several time delays during the study because of the delivery of the system devices and also because of the problems with the BMS -master, that was losing CAN -frames. However, these problems were solved just before the dead line of this study which enabled at least to test the reliability of the new BMS -master.

The only decent tests were carried out on the dynamometer in order to stress the battery with high currents and observe the reliability of the new BMS -master. As a result based on the dynamometer tests the new BMS -master was verified to be reliable. By knowing this, the system can be completed in a few more weeks. This enables the full testing possibilities on a race track with the new complete BMS -system.

The control of the battery was based mainly on open circuit voltage calculation and dynamic current limitation algorithm. The system intelligence was based on a state machine which determined the control orders of the BMS -master and ensured that the BMS -master works in the right mode according to the environment variables given by the user and the other system devices.

The system became a lot safer to handle because all the high voltage measurements were designed to take place in the high voltage distribution box where all the high voltage connectors would be out of direct contact of hand. Furthermore, the real-time based control made the system very fast in its responses and thus the system became more controllable also in error cases such as when crossing the over current limit.

The modular system design and user-configurability makes the system reconfigurable and this enables the further development and rapid changes in the system when needed. Furthermore, the help of any manufacturers is no longer needed because all the control is in the designer´s hands.

After the system is fully completed, the functionality of the system will be only a matter of the code snippets and their testing.

New batteries from Kokam (Korea), were ordered during this study. The new BMS -system will supervise these batteries in future. This brings the opportunity to research the battery with the new BMS -system and all the test can be produces by new code snippets. This is exactly where to this study aimed - prototype level research and development work.

Like any system, also the new BMS -system does have ways how to improve it. One improvement would be to have a mathematical model of the battery behaviour for different discharging and charging processes. This would help to determine the battery´s state even better. However, this requires a lot of battery tests in order to find the right parameters for the battery model.

The internal resistance was assumed to be a constant value although this parameter changes according to many other battery parameters such as SOC and battery current. A good algorithm for estimating the internal resistance of the cells would give more information of the battery and the new BMS -system could take all the benefit out of the IR -compensation method. This would improve the estimation of the OCV of the cells which would improve correspondingly the SOC –determination.

Fortunately for the study, all the improvements are related to the new code snippets which was one of the targets in this study.

Although Electric RaceAbout has gained a lot of success in different competitions and also set several records in previous years the story of this flagship is not yet finished. Electric RaceAbout lost its record in Nürburgring in summer 2012 when Audi R8 e-tron set the new record in time 8:09.099. During winter 2012 the Electric RaceAbout got a lot of important improvements such as a new aerodynamical setup (Figure 37) and new motor controllers.

A new torque vector control was developed in order to improve the driving capabilities on the race track. One of the improvements was also the new user-configurable BMS -system of which this thesis was written. The new BMS -system enabled to order brand new batteries which are fitted into the vehicle in near future in order to get back to the Nürburgring Nordschleife as soon as possible.

Figure 37. ERA wears new aerodynamical setup in 2013. The colour is imaginary [14].

As shown in Figure 37, Electric RaceAbout wears a new sporty wing in order to improve aerodynamics of the vehicle and produce more down force. Furthermore one pair of dive plates was installed to the front bumper in order to produce more down force on the front axle. With these improvements combined with the new and updated drivetrain components Electric RaceAbout is again one step towards world´s fastest electric sports cars.

The team believes strongly that the new improvements are sufficient at least to improve remarkably the last record of Electric RaceAbout in Nürburgring Nordschleife.

References

[1] Bender GmbH (2011). *A-Isometer IR155-3203 / IR15-3204 preliminary data sheet.* Grünberg: Dipl.-Ing. W. Bender GmbH & Co. KG

[2] AeroVironment (2009). *BMS specification datasheet*. *Confidental*.

[3] Andrea, D. (2010). *Battery Management Systems for Large Lithium Ion Battery Packs.* Norwood, MA 02062: ARTECH HOUSE.

[4] Bergveld H.J., Kruijt Wanda S. and Notten Petter H.L. (2002). *Battery Management Systems, Design By Modelling.* The Netherlands: Kluwer Academic Publishers.

[5] Husain I. (2011). *Electric and Hybrid Vehicles, Design Fundamentals.* Boca Raton, Florida: CRC Press, Taylor & Francis Group

[6] IEEE AUTOTESTCON (2008). *Automotive Battery Management Systems*, (Sept. 2008) [WWW document] . http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4662684 (Accessed April 4, 2013)

[7] LEM Components (2013). *Isolated current and voltage transducers. Characteristics-Applications-Calculations. 3rd Edition.* Switzerland.

[8] Portas R. & Colombel L. (2007). *Accuracy of Hall-Effect Current Meas urement Transducers in Automotive Battery Management Applications using Current Integration.* White paper*: LEM S.A, Switzerland*

[9] Paret D. (2007). *Multiplexed Networks for Embedded Systems. CAN,LIN,FlexRay, Safe-by-Wire...West Sussex, England: John Wiley & Sons Ltd*

[10] Reap Systems(2013). *BMS21 Outline Specification. Confidental. Release 1.0.0.*

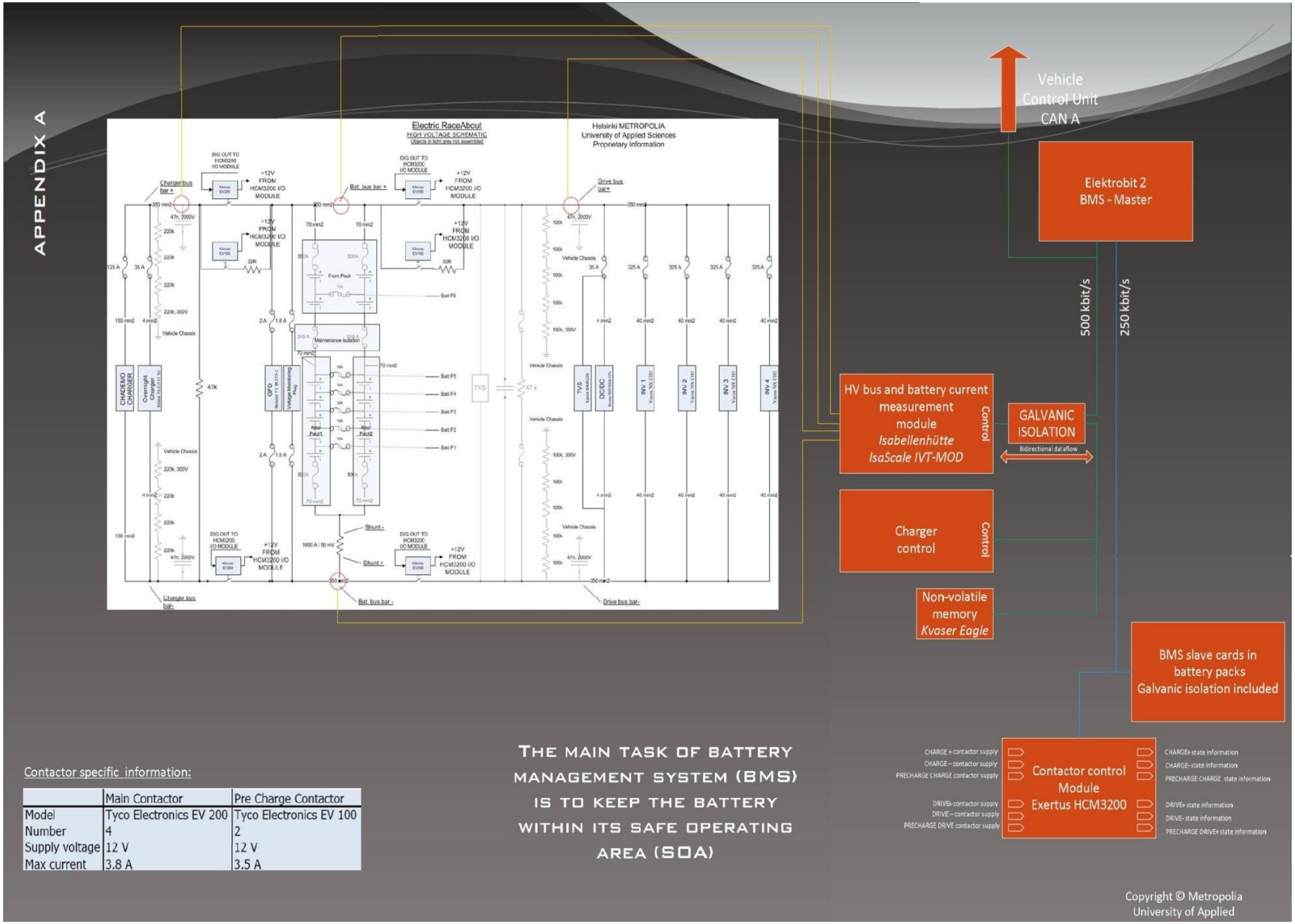
[11] TRITIUM (2012) Tritium User´s Manual Battery Management System, (August 2012) [WWW document] http://tritium.com.au/wpcontent/uploads/2012/08/TRI67.011v1_BMS_Users_Manual.pdf (Accessed January 5, 2013)

Permissions

[12] Reproduced by permission from Davide Andrea*, Battery Management Systems for Large Lithium Ion Battery Packs*, Norwood, MA: Artech House, Inc., 2010. © 2010 by Artech House, Inc.

[13] Reproduced by permission from Springer Science and Business Media, *Battery Management Systems Design by Modeling*, 2002.

[14] Reproduced by permission from Iiro Laine, *Photo Designer, Electric RaceAbout -team,* 2013.



APPENDIX A

Contactor specific information:

	Main Contactor	Pre Charge Contactor
Model	Tyco Electronics EV 200	Tyco Electronics EV 100
Number	4	2
Supply voltage	12 V	12 V
Max current	3.8 A	3.5 A

THE MAIN TASK OF BATTERY MANAGEMENT SYSTEM (BMS) IS TO KEEP THE BATTERY WITHIN ITS SAFE OPERATING AREA (SOA)

Copyright © Metropolia
University of Applied

High voltage contactor measurements with economizer

This document represents the measurements between HCM3200 I/O module and high voltage contactor equipped with economizer. At first the document represents control wire currents and voltages measured between the HCM3200 I/O module and economizer. Then the same measurements have been carried out for control wires between economizer and contactor. The idea behind the measurements was to clarify how the economizer drives the contactor and try to control the contactor without the economizer in the new BMS-system. This turned out very hard to implement because HCM3200 I/O module can´t drive the contactor coil with as high frequency as the economizer does. The PWM frequency is limited to 1 kHz by HCM3200, which can be noticed as a tiny flicker noise. As represented in the measurements, the economizer drives the contactor with 20 kHz which is practically out of the range that human being can hear.

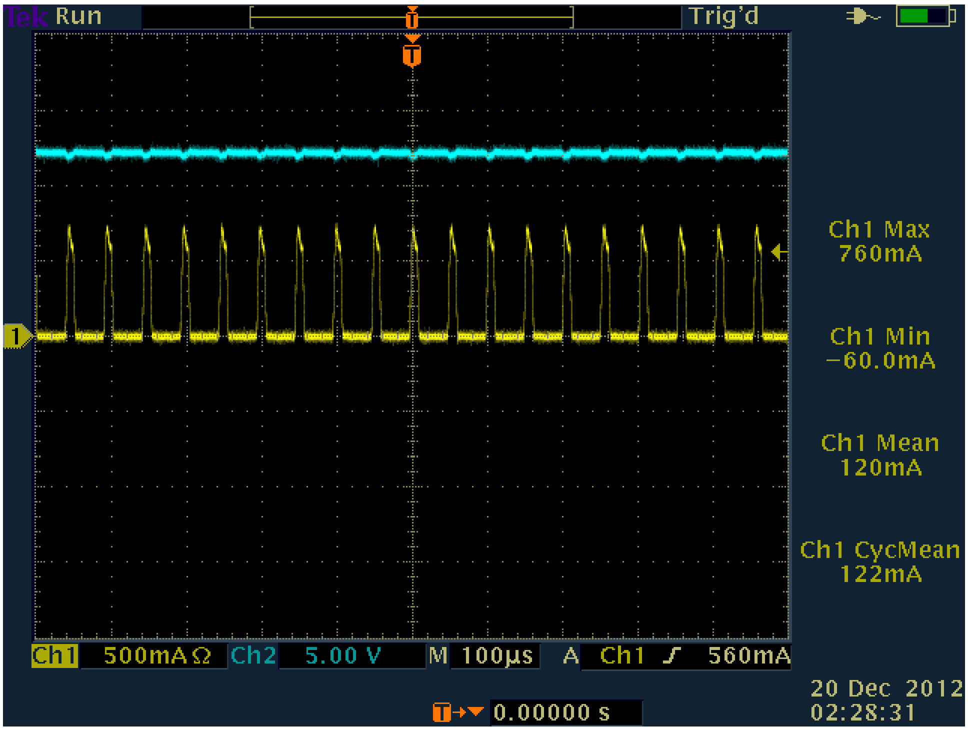


Figure 1: The current flowing in the positive supply wire between economizer and I/O module. (Yellow)

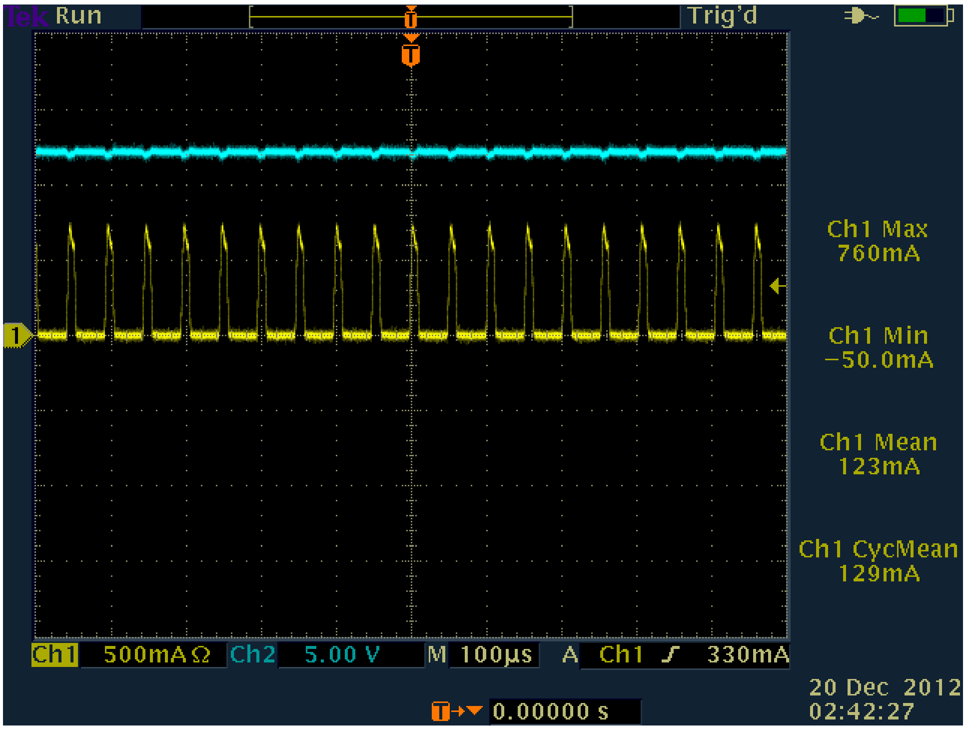


Figure 2: The current flowing in the negative supply wire between economizer and I/O module. (Yellow)

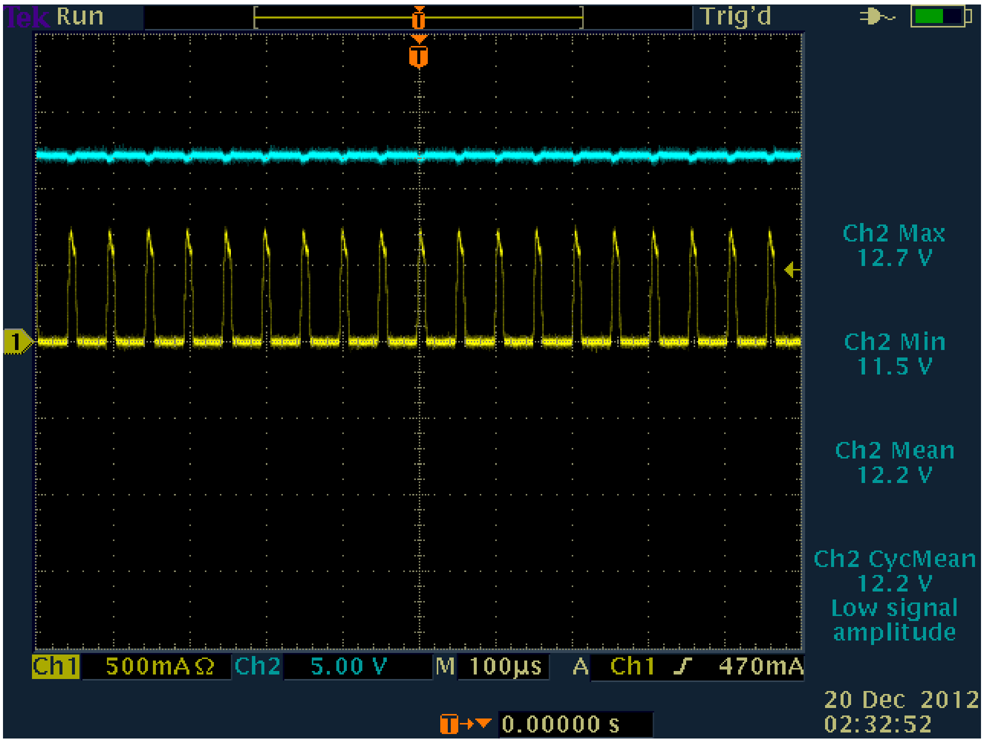


Figure 3: Supply voltage of economizer (Blue)

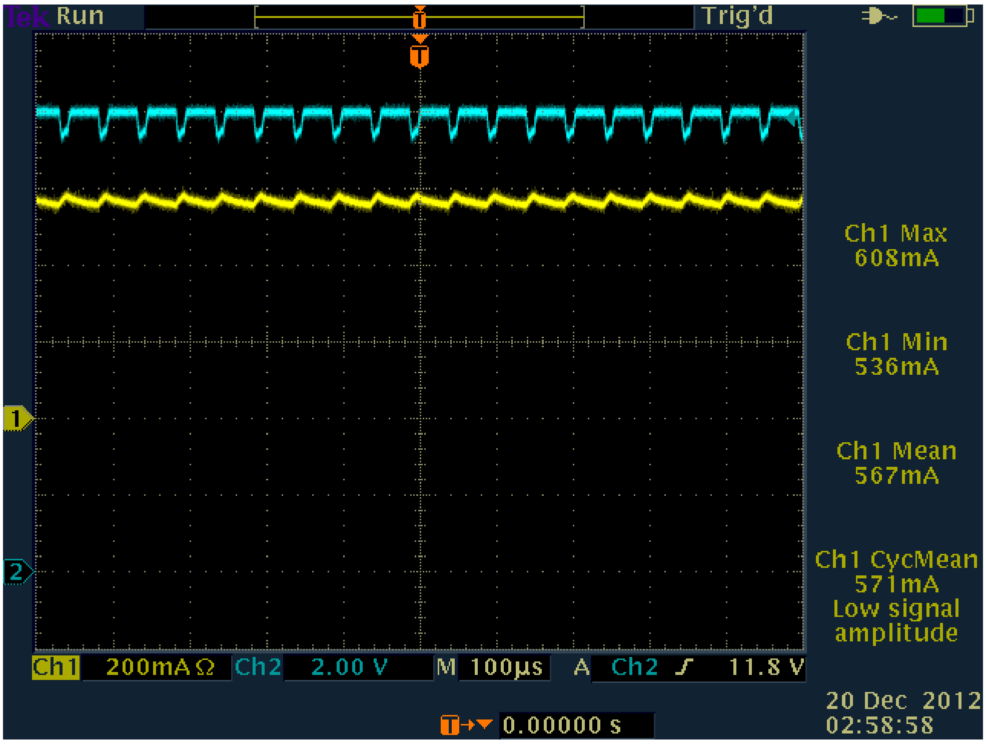


Figure 4: The current flowing in the positive supply wire between economizer and contactor. (Yellow, note scaling!)

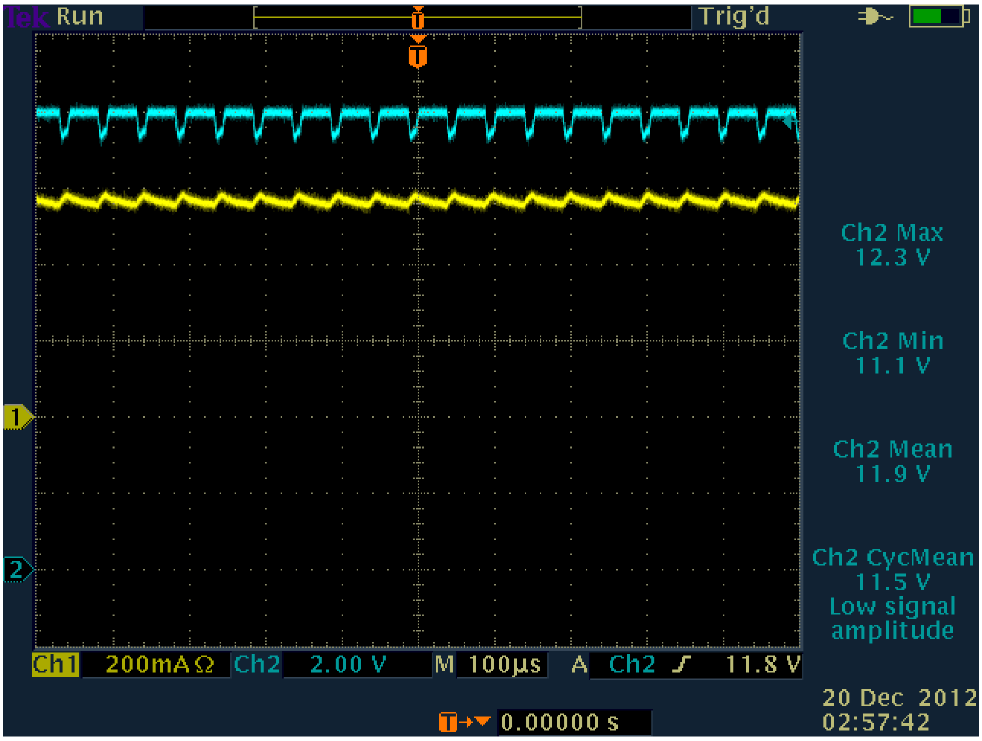


Figure 5: The voltage against the ground in positive supply wire between economizer and contactor (blue, note scaling!)

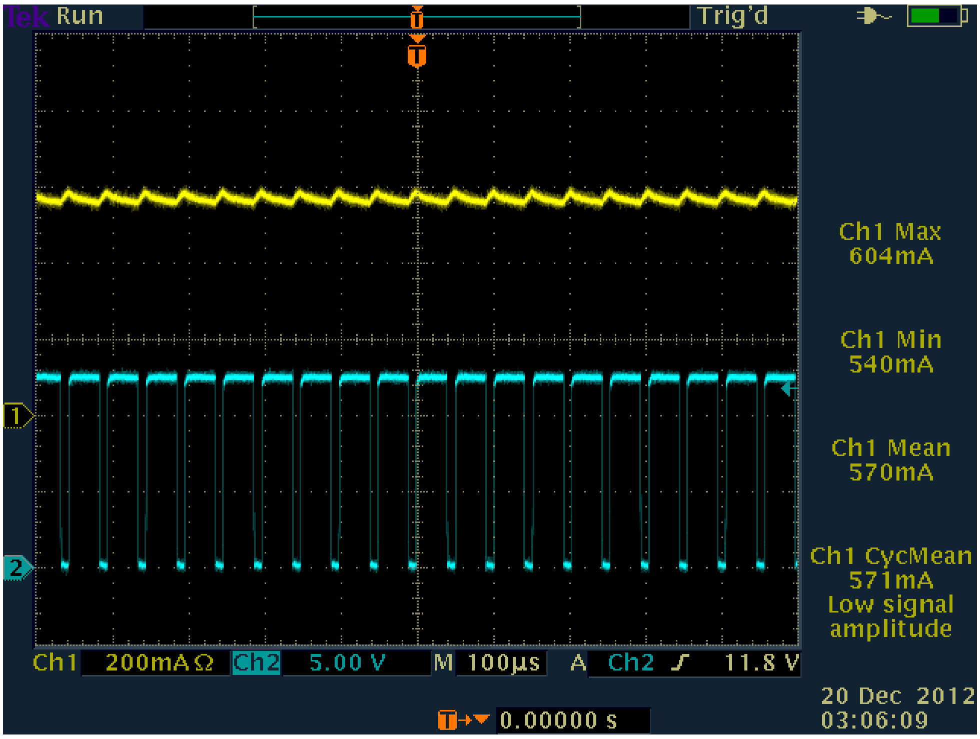


Figure 6: The current flowing in the negative supply wire between economizer and contactor. (Yellow, note scaling!)

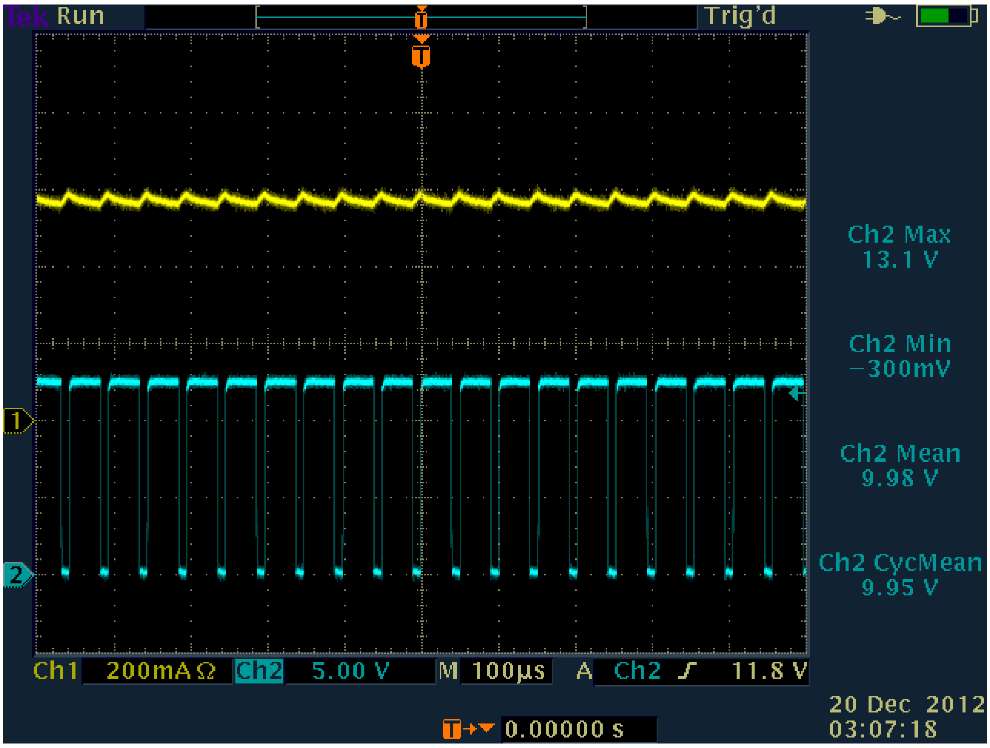


Figure 7: The voltage against the ground in negative supply wire between economizer and contactor (blue, note scaling!) The voltage across supply wires between economizer and contactor was measured to be 1,96 V. So this is the voltage across the contactor coil, which is controlling the relay mechanism.

When we connect a capacitor in parallel with the economizer supply wires the pulsing current will have lower amplitudes. This is shown below:

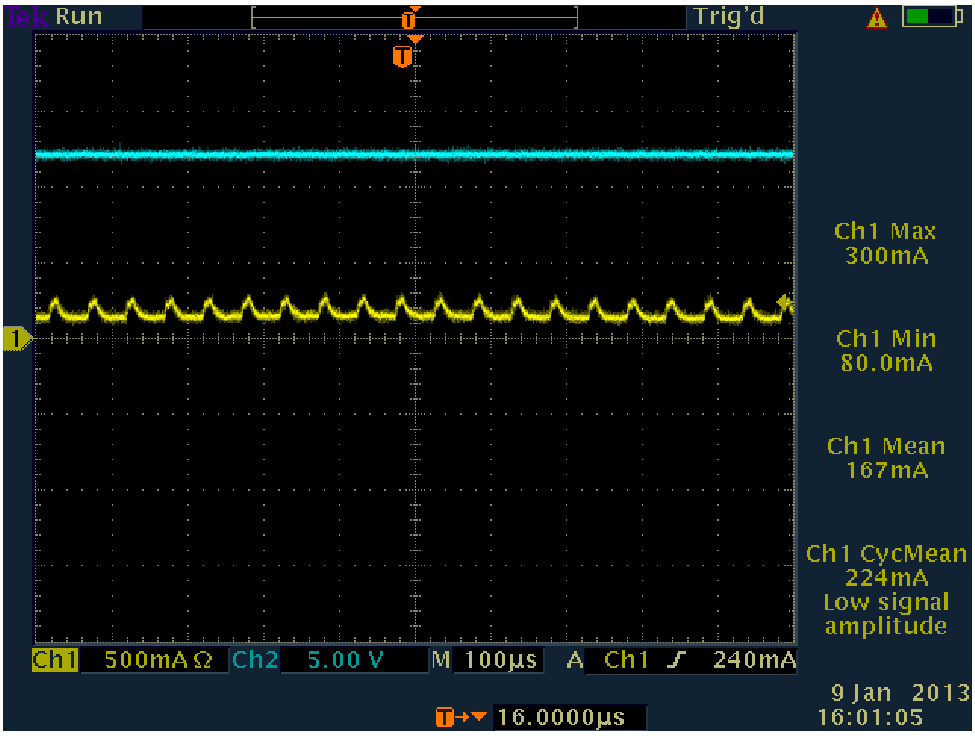


Figure 8: The current flowing in the positive supply wire between economizer and I/O module. (Yellow) Compare with figure1.

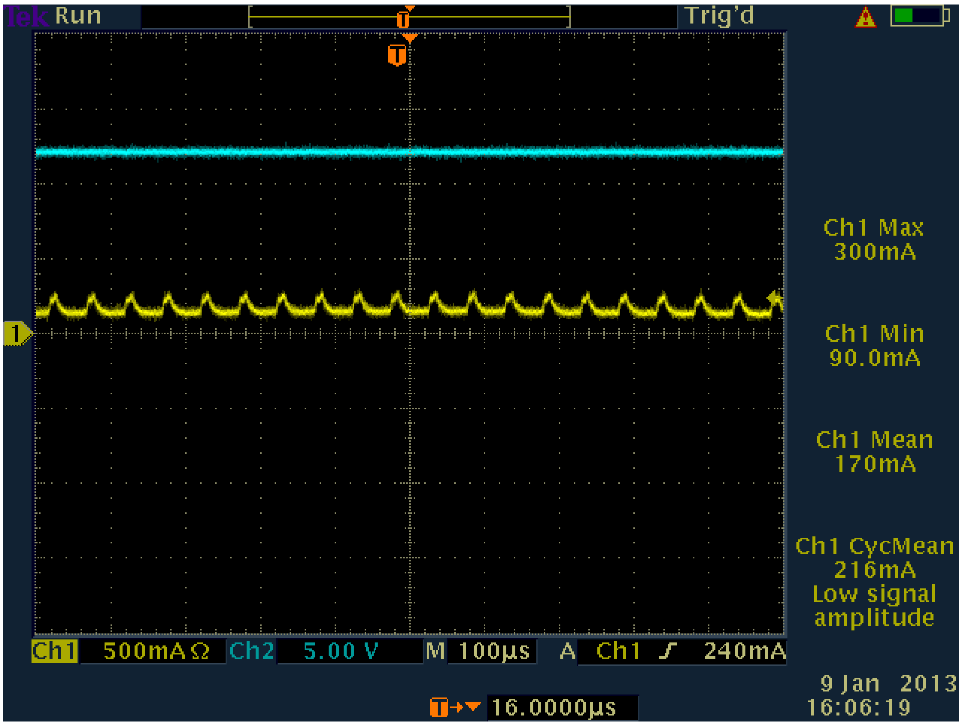


Figure 9: The current flowing in the negative supply wire between economizer and I/O module. (Yellow). Compare with figure 2

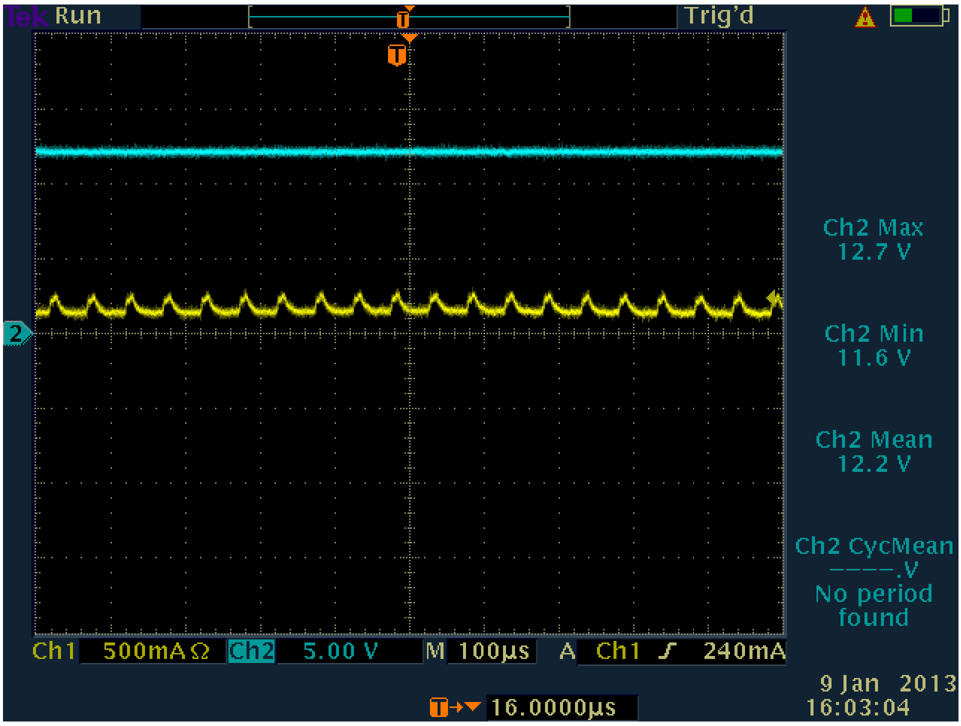
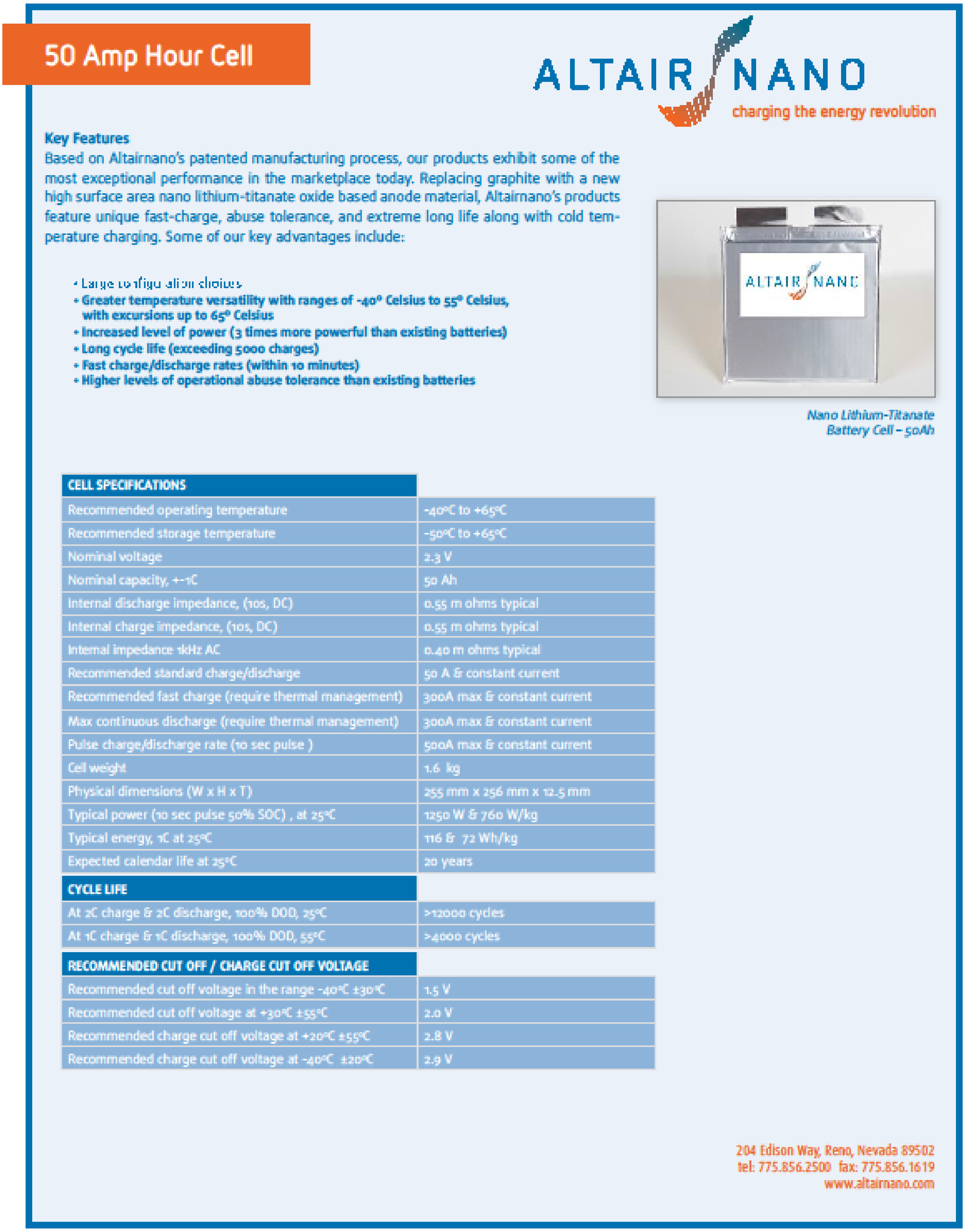


Figure 10: Supply voltage of economizer (Blue). Compare with figure 3.



50 Amp Hour Cell

ALTAIR NANO
charging the energy revolution

Key Features

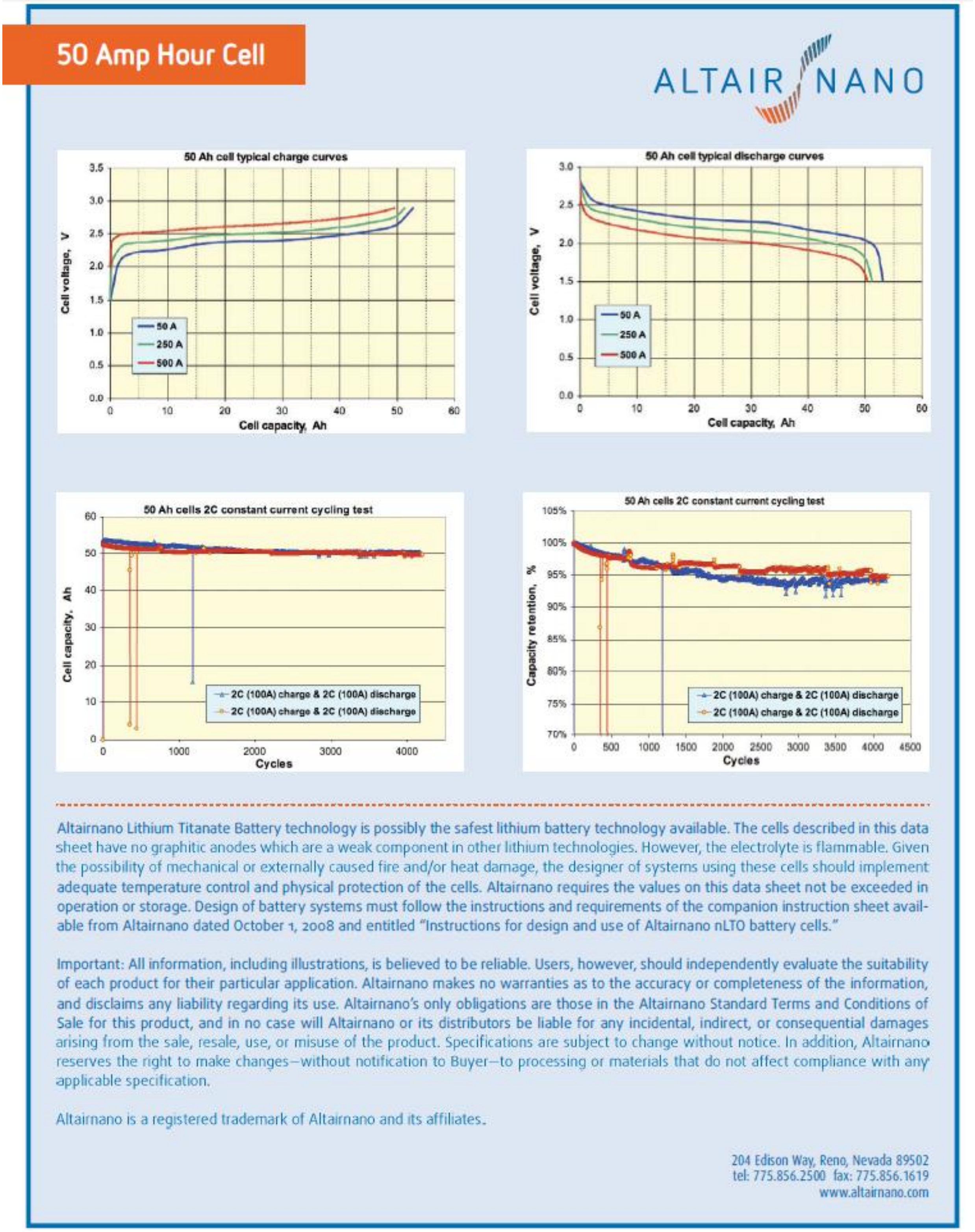
Based on Altairnano's patented manufacturing process, our products exhibit some of the most exceptional performance in the marketplace today. Replacing graphite with a new high surface area nano lithium-titanate oxide based anode material, Altairnano's products feature unique fast-charge, abuse tolerance, and extreme long life along with cold temperature charging. Some of our key advantages include:

- Large configuration choices
- **Greater temperature versatility with ranges of -40° Celsius to 55° Celsius, with excursions up to 65° Celsius**
- **Increased level of power (3 times more powerful than existing batteries)**
- **Long cycle life (exceeding 5000 charges)**
- **Fast charge/discharge rates (within 10 minutes)**
- **Higher levels of operational abuse tolerance than existing batteries**

Nano Lithium-Titanate Battery Cell – 50Ah

CELL SPECIFICATIONS	
Recommended operating temperature	-40°C to +65°C
Recommended storage temperature	-50°C to +65°C
Nominal voltage	2.3 V
Nominal capacity, +-1C	50 Ah
Internal discharge impedance, (10s, DC)	0.55 m ohms typical
Internal charge impedance, (10s, DC)	0.55 m ohms typical
Internal impedance 1kHz AC	0.40 m ohms typical
Recommended standard charge/discharge	50 A & constant current
Recommended fast charge (require thermal management)	300A max & constant current
Max continuous discharge (require thermal management)	300A max & constant current
Pulse charge/discharge rate (10 sec pulse)	500A max & constant current
Cell weight	1.6 kg
Physical dimensions (W x H x T)	255 mm x 256 mm x 12.5 mm
Typical power (10 sec pulse 50% SOC) , at 25°C	1250 W & 760 W/kg
Typical energy, 1C at 25°C	116 & 72 Wh/kg
Expected calendar life at 25°C	20 years
CYCLE LIFE	
At 2C charge & 2C discharge, 100% DOD, 25°C	>12000 cycles
At 1C charge & 1C discharge, 100% DOD, 55°C	>4000 cycles
RECOMMENDED CUT OFF / CHARGE CUT OFF VOLTAGE	
Recommended cut off voltage in the range -40°C ±30°C	1.5 V
Recommended cut off voltage at +30°C ±55°C	2.0 V
Recommended charge cut off voltage at +20°C ±55°C	2.8 V
Recommended charge cut off voltage at -40°C ±20°C	2.9 V

204 Edison Way, Reno, Nevada 89502
tel: 775.856.2500 fax: 775.856.1619
www.altairnano.com



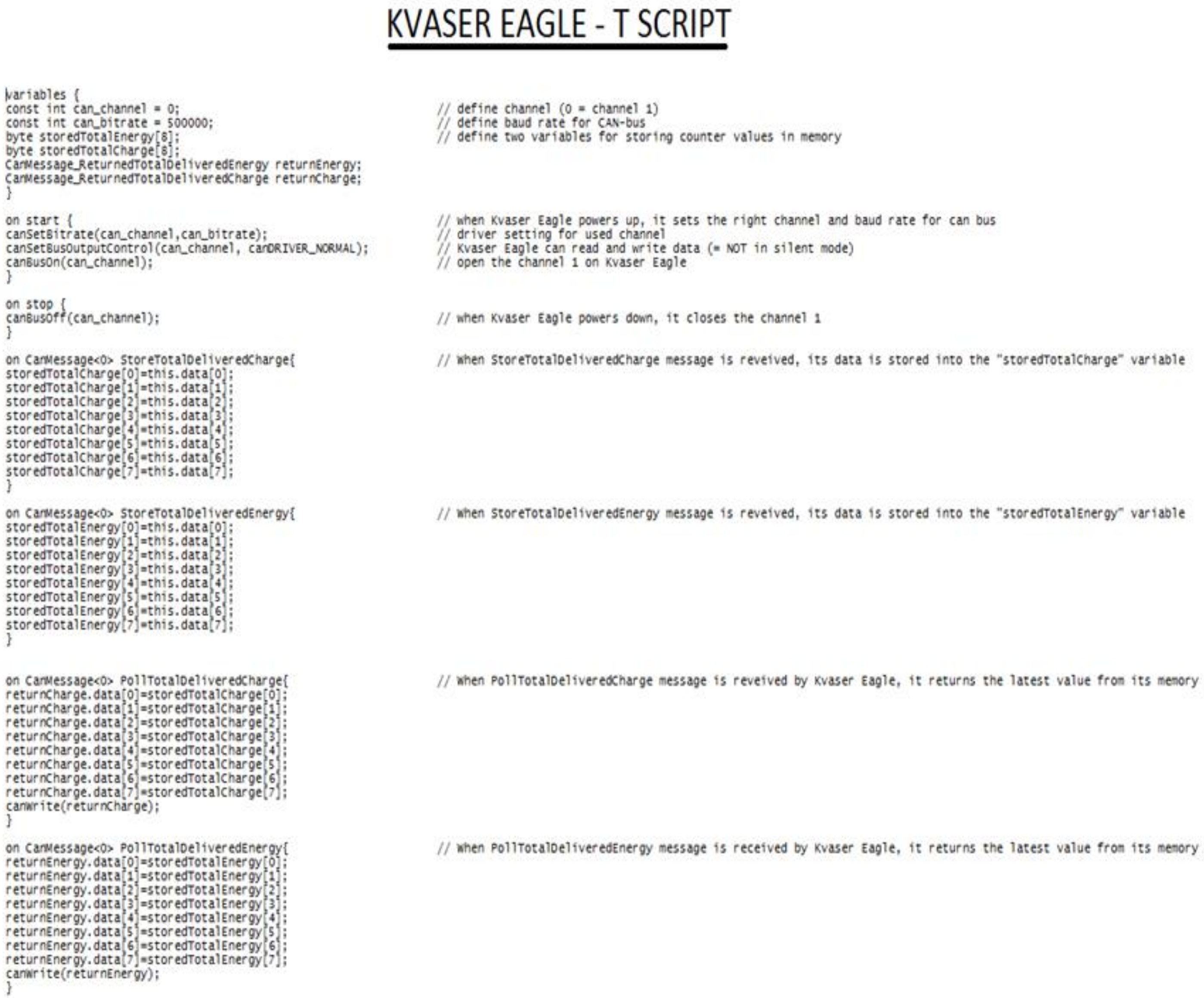
50 Amp Hour Cell

Altairnano Lithium Titanate Battery technology is possibly the safest lithium battery technology available. The cells described in this data sheet have no graphitic anodes which are a weak component in other lithium technologies. However, the electrolyte is flammable. Given the possibility of mechanical or externally caused fire and/or heat damage, the designer of systems using these cells should implement adequate temperature control and physical protection of the cells. Altairnano requires the values on this data sheet not be exceeded in operation or storage. Design of battery systems must follow the instructions and requirements of the companion instruction sheet available from Altairnano dated October 1, 2008 and entitled "Instructions for design and use of Altairnano nLTO battery cells."

Important: All information, including illustrations, is believed to be reliable. Users, however, should independently evaluate the suitability of each product for their particular application. Altairnano makes no warranties as to the accuracy or completeness of the information, and disclaims any liability regarding its use. Altairnano's only obligations are those in the Altairnano Standard Terms and Conditions of Sale for this product, and in no case will Altairnano or its distributors be liable for any incidental, indirect, or consequential damages arising from the sale, resale, use, or misuse of the product. Specifications are subject to change without notice. In addition, Altairnano reserves the right to make changes—without notification to Buyer—to processing or materials that do not affect compliance with any applicable specification.

Altairnano is a registered trademark of Altairnano and its affiliates.

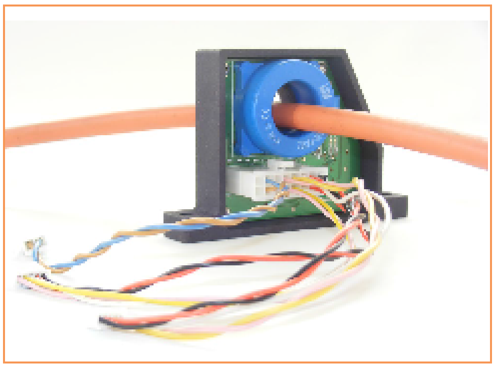
204 Edison Way, Reno, Nevada 89502
tel: 775.856.2500 fax: 775.856.1619
www.altairnano.com



KVASER EAGLE - T SCRIPT

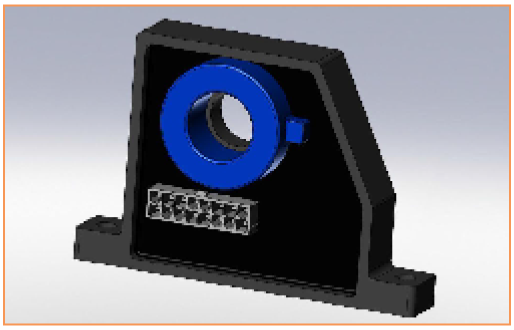
```
variables {
const int can_channel = 0;                               // define channel (0 = channel 1)
const int can_bitrate = 500000;                          // define baud rate for CAN-bus
byte storedTotalEnergy[8];                               // define two variables for storing counter values in memory
byte storedTotalCharge[8];
CanMessage_ReturnedTotalDeliveredEnergy returnEnergy;
CanMessage_ReturnedTotalDeliveredCharge returnCharge;
}

on start {                                               // when Kvaser Eagle powers up, it sets the right channel and baud rate for can bus
canSetBitrate(can_channel,can_bitrate);                  // driver setting for used channel
canSetBusOutputControl(can_channel, canDRIVER_NORMAL);   // Kvaser Eagle can read and write data (= NOT in silent mode)
canBusOn(can_channel);                                   // open the channel 1 on Kvaser Eagle
}

on stop {
canBusOff(can_channel);                                  // when Kvaser Eagle powers down, it closes the channel 1
}

on CanMessage<0> StoreTotalDeliveredCharge{              // When StoreTotalDeliveredCharge message is reveived, its data is stored into the "storedTotalCharge" variable
storedTotalCharge[0]=this.data[0];
storedTotalCharge[1]=this.data[1];
storedTotalCharge[2]=this.data[2];
storedTotalCharge[3]=this.data[3];
storedTotalCharge[4]=this.data[4];
storedTotalCharge[5]=this.data[5];
storedTotalCharge[6]=this.data[6];
storedTotalCharge[7]=this.data[7];
}

on CanMessage<0> StoreTotalDeliveredEnergy{              // When StoreTotalDeliveredEnergy message is reveived, its data is stored into the "storedTotalEnergy" variable
storedTotalEnergy[0]=this.data[0];
storedTotalEnergy[1]=this.data[1];
storedTotalEnergy[2]=this.data[2];
storedTotalEnergy[3]=this.data[3];
storedTotalEnergy[4]=this.data[4];
storedTotalEnergy[5]=this.data[5];
storedTotalEnergy[6]=this.data[6];
storedTotalEnergy[7]=this.data[7];
}


on CanMessage<0> PollTotalDeliveredCharge{               // When PollTotalDeliveredCharge message is reveived by Kvaser Eagle, it returns the latest value from its memory
returnCharge.data[0]=storedTotalCharge[0];
returnCharge.data[1]=storedTotalCharge[1];
returnCharge.data[2]=storedTotalCharge[2];
returnCharge.data[3]=storedTotalCharge[3];
returnCharge.data[4]=storedTotalCharge[4];
returnCharge.data[5]=storedTotalCharge[5];
returnCharge.data[6]=storedTotalCharge[6];
returnCharge.data[7]=storedTotalCharge[7];
canWrite(returnCharge);
}

on CanMessage<0> PollTotalDeliveredEnergy{               // When PollTotalDeliveredEnergy message is received by Kvaser Eagle, it returns the latest value from its memory
returnEnergy.data[0]=storedTotalEnergy[0];
returnEnergy.data[1]=storedTotalEnergy[1];
returnEnergy.data[2]=storedTotalEnergy[2];
returnEnergy.data[3]=storedTotalEnergy[3];
returnEnergy.data[4]=storedTotalEnergy[4];
returnEnergy.data[5]=storedTotalEnergy[5];
returnEnergy.data[6]=storedTotalEnergy[6];
returnEnergy.data[7]=storedTotalEnergy[7];
canWrite(returnEnergy);
}
```

CANbus Current Sensor



- The CCS is based around a closed loop Hall Effect current sensor with 3 Measuring ranges available.
  1. +/- 300 Amp, 200 mA resolution.
  2. +/- 600 Amp, 400 mA resolution.
  3. +/- 1200 Amp, 800 mA resolution.
- The Hall Effect current sensor is filtered to provide a 1.5 KHz signal bandwidth.
- Single rail +12 V power supply
- Configurable CAN 2.0 B compliant interface,
- NominalCAN setting is for 500 kbps bus with 5 Hz broadcast. The Current value is typically broadcast as a signed word.
- 12 V 4 A Contactor Driver with built in suppression and configurable coil voltage modulation.
- Switchable 12 V output to power to Battery Management Modules downstream of Current Sensor.

- Digital Switch input which can be used for auxiliary contact or key switch monitoring.
- Built in Temperature sensor to monitor pack ambient temperature and correct sensor thermal drift.
- The CCS can provide a coulomb counting function for SOC calculation.
- Low Power standby mode with wake up on Digital input or CANbus activity.
- The CCS is galvanically isolated from the primary conductor and common to the vehicle Chassis Ground. For voltages above 150 V D.C. power cable with suitably reinforced insulation should be used in line with functional safety requirements.
- Operating Temperature Range -40 C to +85 C



Pin Out

- The mating Power and Data Connector is a Female Molex Mini-Fit Jr. 16 Way with the following pin assignment;

• GND	16. GND
• BMM switched power	15. +12 V In
• Fault line out	14. Fault line in
• CAN Low	13. CAN Low
• CAN High	12. CAN High
• SWITCH In	11. GND
• Contactor Return	10. GND
• +12 V Contactor Feed	9. +12 V Switch Feed

- The Fault/ Continuity line from the BMM modules is monitored by the CCS. The CCS can assert the line if a current based fault event occurs.
- The CCS monitors for excessive charge or discharge current and sets appropriate warning messages and fault conditions.

Ranked No.1 in Top 25 Fastest Growing Cleantech Companies in Europe

Ashwoods Automotive Ltd.
www.ashwoodsenergy.org

Bob Beckwith, Global Applications Manager, 01392 341 157
mobile 07918 768 024, bob.beckwith@ashwoods.org